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THEMATIC ISSUE

# Investigations on fluid transport properties in the North-German Rotliegend tight gas sandstones and applications

**Daniel Albrecht**[1] · **Viktor Reitenbach**[1]

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**Abstract** Tight gas reservoirs are an important part of the world gas resources. Such reservoirs have very low permeability (usually below 0.1 mD) and show a strong stress sensitivity to fluid transport properties and a considerable productivity decline during the production process due to increasing effective stress. In an experimental study, several measurement series were performed on plugs from the North-German Rotliegend tight gas reservoirs to improve knowledge and understanding of the effects of changing stress and pore pressure conditions on reservoir rocks, during gas production. In addition to the experimental study, an Interactive Rock Data Catalog (IRDC) has been developed, which contains a database coupled with a correlation module. The database contains metadata of the fields and wellbores included in the IRDC, the corresponding log data and petrophysical data. The correlation module contains correlations derived both from the study measurements and from literature. The results of this study will enable reservoir engineers to select specific data from the database and process it in the correlation module to generate secondary sets of data, which can then be used for modeling and simulation of tight gas reservoirs.

**Keywords** Tight gas sandstones · Fluid flow properties · Compaction processes · Rock Data Catalog

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✉ Daniel Albrecht
daniel.albrecht@tu-clausthal.de

[1] Institute of Petroleum Engineering (ITE), Clausthal University of Technology, Clausthal-Zellerfeld, Germany

## Abbreviations

| | |
|---|---|
| $K$ | Stress path |
| $k_a$ | Initial permeability |
| $k_g$ | Stress-dependent permeability |
| $p$ | Reservoir pressure |
| $\alpha$ | Biot's coefficient |
| $\varepsilon$ | Total deformation |
| $\varepsilon_0$ | Elastic deformation |
| $\sigma_{eff}$ | Effective stress |
| $\sigma_h$ | Minimum horizontal stress |
| $\sigma_v$ | Vertical stress |
| $\phi$ | Porosity |

## Introduction

With the increase in the world's energy consumption and the change in climate, unconventional energy resources become more and more popular (Gou et al. 2015). An important part of the unconventional energy resources is tight gas reservoirs. Tight gas reservoir rocks are defined by convention as rocks with permeability below 0.1 mD as regard to USA conditions (Bennion et al. 2000; Byrnes 1997; Davis and Holditch 1998) or below 0.6 mD for the conditions in the North German Tight gas reservoirs (Pusch et al. 2005; Haefner 2006). Reservoirs with such a low permeability normally have to be fractured to obtain economical flow rates. The permeability of such fractured rocks is closely related to the spatial geometric features of fractures, the deformation and the stress conditions (Wang et al. 2015). In the North-German Basin, potential tight gas reservoirs can be found in the Permian Rotliegend and Upper Carboniferous formations including a potential for a shade of unconventional shale gas in the Z1 and Z2 cycles of the Upper Permian Zechstein formations (Hammes et al. 2013). There are a number of studies published during the last two decades, which reveal the importance of stress and saturation conditions in tight gas rocks for technical feasibility and economical viability of gas production from tight gas reservoirs. Experimental measurements of Jones and Owens (1980) on a number of tight gas samples showed, that under an isostatic load (without pore pressure), which corresponds to the reservoir conditions, the permeability is reduced by up to one tenth compared with the permeability measured under normal laboratory conditions. The pore space was reduced by 5–10 %. In general, it can be said that the external load on a rock sample can cause a reduction in the volume of rock, with a substantial portion of this volume decrease being due to a decrease in the pore volume. This is reflected by a decrease in the porosity and permeability of the rock. The degree of the permeability reduction is depending on the rock composition, the degree of solidification and the shaping of the pore space (Debschütz 1995). Measurements on medium- and high-permeability sandstones with increasing loading up to 20 MPa show an approximately exponential decrease in permeability down to about 60–90 % of the permeability in the unloaded state (Fatt and Davis 1952).

The fluid transport properties of tight gas reservoirs are controlled by factors like mineral content (especially clay minerals, e.g., illite and chlorite), water saturation state and stress conditions and show a great variability. In general, minerals increase the amount of bound, immobile water. Higher amounts of clay minerals and pore-filling mineral cements, e.g., calcite and anhydrite, result in lower porosity and permeability (Pudlo et al. 2012). Hereby, different types of clay minerals have a different impact on the reservoir quality. Chlorites have a positive impact on the reservoir quality. They prevent strong dolomite cementation, as both minerals compete for dissolved $Mg^{2+}$. Furthermore, thin chlorite coatings protect the grain surfaces from further overgrowth. Kaolinites reduce reservoir quality, but have more impact on the porosity than on the permeability. Illites have the most negative effect on permeability and are often the reason why a reservoir is tight. They can reduce permeability by one to three orders of magnitude (Gaupp and Okkerman 2011).

According to Byrnes (1997) and Davies and Holditch (1998), the permeabilities of tight gas sands vary up to 4 orders of magnitude for a given porosity value and thus cannot be predicted solely as a function of porosity. The permeability of tight gas sandstones decreases with the increase of effective stress. Nevertheless, no unique relationship exists between the permeability measured at ambient stress conditions and those measured at reservoir stress conditions. In this regard, ambient stress conditions refer to the confining pressure used in the laboratory permeability measurements. In this paper, a minimum confining pressure of 3 MPa was engaged to avoid flow between the plug and the Viton-sleeve, in which the plug was inserted during the measurement. On the other hand, reservoir stress conditions refer to the actual pressure conditions in the reservoir.

However, the data sets exhibit a great variability revealing the fact that prediction of permeability at reservoir conditions from the routine permeability measured at ambient stress conditions is not possible. The degree of variability in the relationship increases with the decreasing values of permeability.

As production from a tight reservoir depletes the effective stress increases, leading to compaction of the reservoir and a reduction of its porosity and permeability. This compaction process in turn changes the stresses acting on the reservoir, which significantly deviates from the uniaxial or isostatic stress conditions often applied to simulate reservoir stress conditions in SCAL (Special Core Analysis) laboratory measurements. According to the experimental data obtained from five reservoirs and 16 sandstone outcrops analyzed by Hettema et al. (2000) and Schutjens et al. (2004), the production-induced compaction behavior of these rocks depends on both the effective stress and the effective stress path. Here, the stress path $K$ is defined as the ratio of the change in the minimum effective horizontal stress and the change in the effective vertical stress (Hettema et al. 2000):

$$K = \frac{\Delta(\sigma_h - \alpha p)}{\Delta(\sigma_v - \alpha p)} \tag{1}$$

where $\sigma_h$ and $\sigma_v$ are the minimum horizontal and vertical stress, respectively; $p$ is the reservoir pressure and $\alpha$ is Biot's coefficient. Qiao et al. (2009) determined Biot coefficients for Canadian sandstones by measuring the permeability of each individual plugs under different combinations of confining and pore pressure. The Biot coefficients determined by Qiao et al. vary over a relatively large area. The values increase with increasing permeability. The coefficient is not only a specific material property, but is also related to the permeability. According to Wang (2000), typical values for the Biot coefficient of sandstones are in the range of 0.64–0.85. Laboratory measurements performed by Skomedal and Hettema (2002) with decreasing pore pressure at constant isotropic confining load on sandstones from a Norwegian deposit showed a strong dependence of the compressibility of the rock of the initial porosity. However, the compressibility depends not only on the porosity, but also on other parameters such as the chlorite coatings and the degree of quartz cementation. The Biot coefficients determined in these measurements varied between 0.69 and 0.84.

In this paper, we assume that Biot's coefficient is direction independent as the rock material used for our experiment is isotropic and homogenous and only isostatic stress conditions are considered. Therefore, in a general case when $K < 1$, the increase in mean effective stress per unit of depletion is less than in the idealized scenario when $K = 1$. Whereas, in the elastic domain, the compaction behavior of the sandstones is dominated by the effective stress, the effect of the stress path increases with increasing deviation of the horizontal stress from the vertical stress. In the experiments on the North-German Rotliegend tight gas sandstones it has been found that, for an average effective stress level of 30 MPa, the dilatance boundary, at which the disintegration of the rock begins, corresponds to the deviator ratio of vertical and horizontal stresses of 4 (i.e., $\frac{\sigma_v}{\sigma_h} = 4$) (Pusch et al. 2005).

Experimental measurements by Hoppe (2005) on sandstone samples from North-German tight gas wells to investigate the effects deviatoric stresses (dilatancy) on the permeability showed a link between the mobilization potential for rock fragments (that is the number of potential mobilization events/mm crack length), clay mineralogical properties and the mechanical strength of the samples. A deviatoric loading near the failure line caused in most of the examined plugs to permeability decrease of up to 30 %. Studies by Trautwein (2005) on the poroelastic deformation of Permian sandstones exhibited a linear course of the stress–strain curve. The observed changes in this study of petrophysical parameters were largely reversible and no petrophysical or structural changes were detected. According to Schutjens et al. (2004), in the elastic domain, the compaction-induced permeability reduction mainly depends on the increase of the average effective stress and not on the stress path. Calculations of the pore compressibility from compaction data of the bulk volume lead to an overestimation of the actual pore compressibility. Compressibilities measured under uniaxial stress conditions are more than twice as high as the corresponding values from experiments under hydrostatic conditions. Stronger cementation of sandstones causes a reduction in the dependence of the permeability from the stress path (Ruisten et al. 1999).

For rocks with high effective porosity sensitivity, a small change in the effective porosity can cause a large change in permeability (Zhang et al. 2015). For a better understanding of the stress-dependent behavior of porosity and permeability of tight gas reservoirs as well as the relationship between the permeability under ambient and reservoir conditions, measurements under both ambient and reservoir stress and pressure conditions have been performed on Rotliegend rock samples from a North-German tight gas reservoir. Here, the experiments have been performed for both uniaxial (isostatic) and deviatoric stress conditions covering both elastic and inelastic domains. In the last case, the loading patterns play a significant role. In the inelastic domain, a hysteresis of relationships porosity and permeability vs. effective stress indicates permanent deformations in the rock fabric induced by the loading and unloading cycles. From the results, correlation functions were derived which describe the permeability change as a function of the initial (basic) permeability and effective stress. The data gained from these experiments and from some external sources form the basis of the Rock Data Catalog (RDC). The RDC is a specialized database developed to support reservoir engineers in the modeling and simulation of tight gas reservoirs.

A further possible application of the RDC could be the use of the petrophysical data and correlations implemented in the RDC for sweet spot identification. The viability of economic gas production from Tight Gas Reservoirs strongly depends on reservoir quality. Therefore, identification of high-quality reservoir parts or the so-called sweet spots for determining perforation sections in production wells and planning hydraulic fracturing stimulation is one of the key issues for tight gas reservoir characterization and evaluation. According to investigations by Bennion et al. (2000), the most crucial control factor for an economically viable gas production from the North-American tight gas reservoirs is the prevalence of a water saturation value below the irreducible water saturation level, the so-called subnormal water saturation. The data and correlation functions collected in the Rock Data Catalog could also be used to identify Sweet Spots in Tight Gas reservoirs by means of multiple reservoir quality criteria. Several rock parameters and properties, which affect fluid flow in a reservoir (including lithology, clay content, water saturation, permeability, pore size distribution, etc.) can be identified from coupled production and petrophysical analysis and used to set up a Sweet Spot Index as a measure of reservoir quality. The aim of this paper is to reveal the coupled approach to the experimental determination and correlation of stress-dependent porosity and permeability of the North-German Rotliegend tight gas sandstones as well as the application of the correlated experimental data by means of an interactive Rock Data Catalog.

## Effect of stress path and loading patterns on permeability and porosity of low-permeability Rotliegend sandstones

The decreasing pore pressure in a reservoir during depletion leads to a higher effective stress. This triggers a compaction process, which affects reservoir properties such permeability and porosity. In this study, changes in these parameters have been measured under varying stress conditions. For permeability measurements, a triaxial cell was build and equipped with two Quizix pumps and a

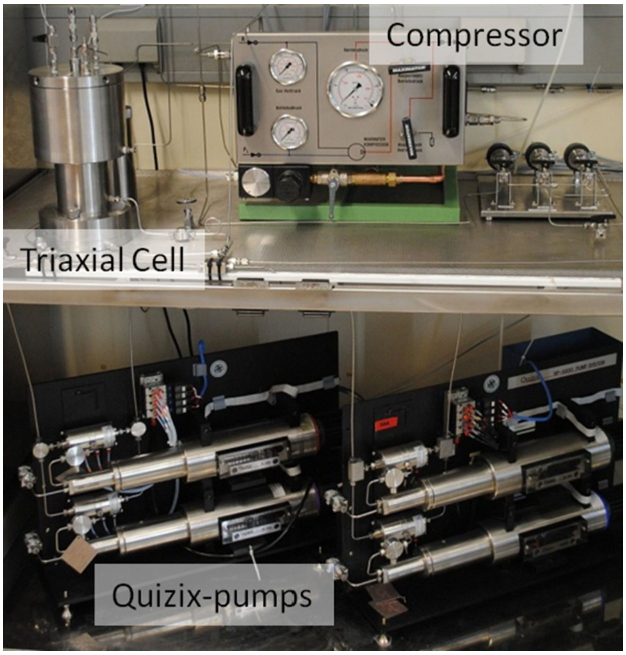


**Fig. 1** Triaxial cell for permeability measurements with peripheral devices

compressor (Fig. 1). With this experimental setup, permeability measurements could be performed while independently controlling the axial and radial loading as well as the pore pressure. The permeabilities were measured on the Rotliegend sandstone samples from a North-German tight gas reservoir under isostatic stress conditions using nitrogen gas.

Results from the previous experimental series (Albrecht and Reitenbach 2014; Albrecht et al. 2010; Haefner 2006) clearly indicate hysteresis effects in the relationship between permeability and effective stress. Large differences were observed particularly under moderate stress conditions in the first (compaction) and the second (expansion) cycles of core plugs that had been stored for a long time under ambient conditions. In this case, deformations, developed over a long storage period, cannot be clearly identified as permanent, but could rather have a different nature. The new experimental series was intended to investigate the extent at which the time-dependent deformation behavior could affect the reservoir quality, especially porosity and permeability, of the Rotliegend tight gas sandstones.

Figure 2 shows the results of repeated permeability measurement series on a low permeable Rotliegend sandstone sample. The first and second series started with low effective stress of 3 MPa which was gradually increased to 50 MPa. Between the first and second series, the plug was extracted from the cell and stored at 45 °C for 4 months in an oven together with silica gel to keep the humidity in the oven as low as possible. This temperature was chosen for storage so as to avoid alterations on clay minerals. The results show that the plug almost completely recovered and regained its initial permeability. The third series was measured directly after the second series without extracting or unloading the plug in between. In this case, the effective stress on the plug was gradually decreased to 3 MPa. The results of the measurements indicate that in the short term the plug shows a creep-like deformation which results in smaller permeabilities. In the long term (i.e., given ample time for recovery), the plug attained its initial permeability value which proves that restoration of the initial deformation state could be associated with the viscoelastic behavior of the sandstone cement. However, this behavior has been observed in relatively small numbers of experiments performed under isostatic stress conditions.

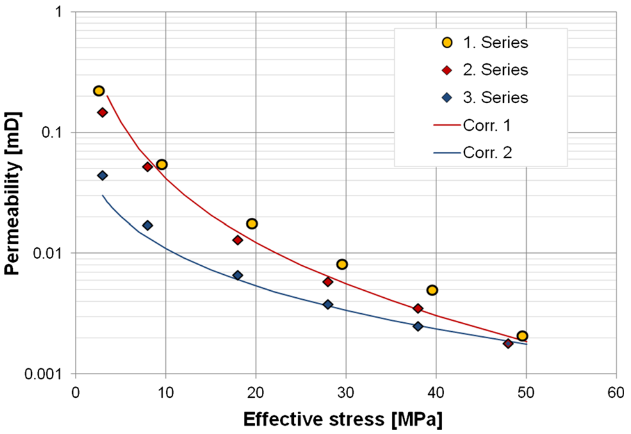


**Fig. 2** Permeabilities measured on a Rotliegend sandstone plug with different loading cycles

Correlation functions were derived from the permeability measurements on several Rotliegend plugs, which describe the permeability change due to stress as a function of the initial permeability $k_a$, measured at the minimum confining pressure of 3 MPa and effective stress $\sigma_{\text{eff}}$. This initial permeability represents the absolute permeability (or the so-called routine permeability) measured under laboratory conditions, but not the actual in situ permeability of a reservoir. As low-permeability rocks are particularly sensitive to stress, for the purposes of analysis of reservoir processes, the permeability measured under reference conditions must be converted to the representative reservoir effective stress conditions by means of correlations derived from the above-mentioned laboratory series. Correlation 1, corresponding to the red line in Fig. 2, can be used to calculate permeabilities $k_g$ for reservoir stress conditions from initial permeabilities measured at laboratory conditions. In contrast, correlation 2, corresponding to the blue line in Fig. 2, depicts how reservoir permeability changes with changing effective stress conditions. Correlation 1:

$$k_g = 2.638 \cdot \sigma_{\mathrm{eff}}^{-0.864} \cdot k_a^{0.63 \cdot \sigma_{\mathrm{eff}}^{0.36}} \quad (2)$$

Correlation 2:

$$k_g = 0.742 \cdot \sigma_{\mathrm{eff}}^{-0.055} \cdot k_a^{0.74 \cdot \sigma_{\mathrm{eff}}^{0.218}} \quad (3)$$

In another series, the porosity of a Rotliegend sandstone sample was measured under different isostatic confining stresses. The aim of these experiments was to evaluate to what extent the compaction process affects the porosity. Are the deformations, which occur at common effective reservoir stresses, elastic and reversible or inelastic and irreversible? Do the time-dependent processes of the deformation recovery play as significant a role as in the case of permeability or not?

The experiments were conducted in the following way. At first, the initial porosity was measured under ambient conditions in a pycnometer using the Boyle–Mariotte law with helium as measurement gas. The porosity measurement under isostatic stress was performed in the triaxial cell shown in Fig. 3. The core plug used for these measurements was bigger than the plugs used for the permeability measurements to be able to detect the relatively small changes in the pore space volume. Therefore, the triaxial cell shown in Fig. 1 could not be used. The core plug was built in the cell in fully water saturated state. By applying stress on the plug, the pore space was compressed with water being pressed out of the plug. This change in the pore space volume was then measured with ISCO pumps, which kept the pore pressure in the sample constant during loading/unloading by retracting or expanding the pump cylinder volumes. The measurement was done with water, as this medium can be regarded as incompressible in contrast to gas. The porosity of the sample was measured in the cell during six loading and unloading cycles. The first chart in Fig. 4a shows the porosity change as a function of isostatic confining stress, whereas the second chart Fig. 4b indicates the time-dependent change of the porosity during the loading and unloading cycles. Like permeability, the porosity of the plugs tested, showed irreversible stress dependence in the time scale of the experiment. Generally, porosity decreases during loading and increases during unloading. Each further sequence of loading and unloading leads to a decrease of porosity compared to the values in the preceding cycle under the same stress conditions. To identify and evaluate the time-dependent deformation effects after the loading cycles had finished, the sample was extracted from the cell and stored in the air bath under similar conditions to those used for conditioning the plugs before compaction experiments. After 14 months of storage, the final porosity was measured under ambient conditions in the same way as the initial porosity (see Fig. 4). The value of porosity measured was very close to the initial porosity value of the plug. Thus, the deformation observed in this experiment is possibly not a permanent deformation in the inelastic domain, but to a type of deformation, which can completely recover after sufficient storage time. This is in complete agreement with the similar permeability relaxation effects described above.

The results of the experiments described above show two distinct effects: a short-term effect and a long-term effect.

When stress is applied onto the rock, a deformation of $\varepsilon_0$ (i.e., the elastic amount of the deformation) occurs almost instantly (this is the short-term effect). Further (viscous) deformation occurs, after a delay, over time (which is the long-term effect). After releasing the stress, the elastic part of the deformation returns almost instantly, while the viscous part of the deformation gradually decreases with a

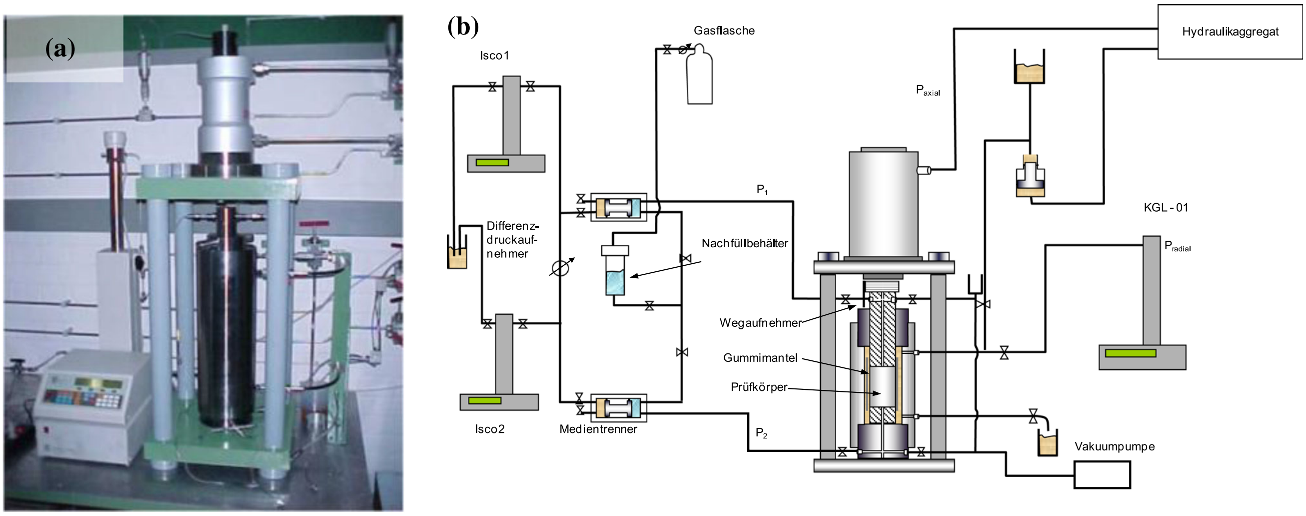
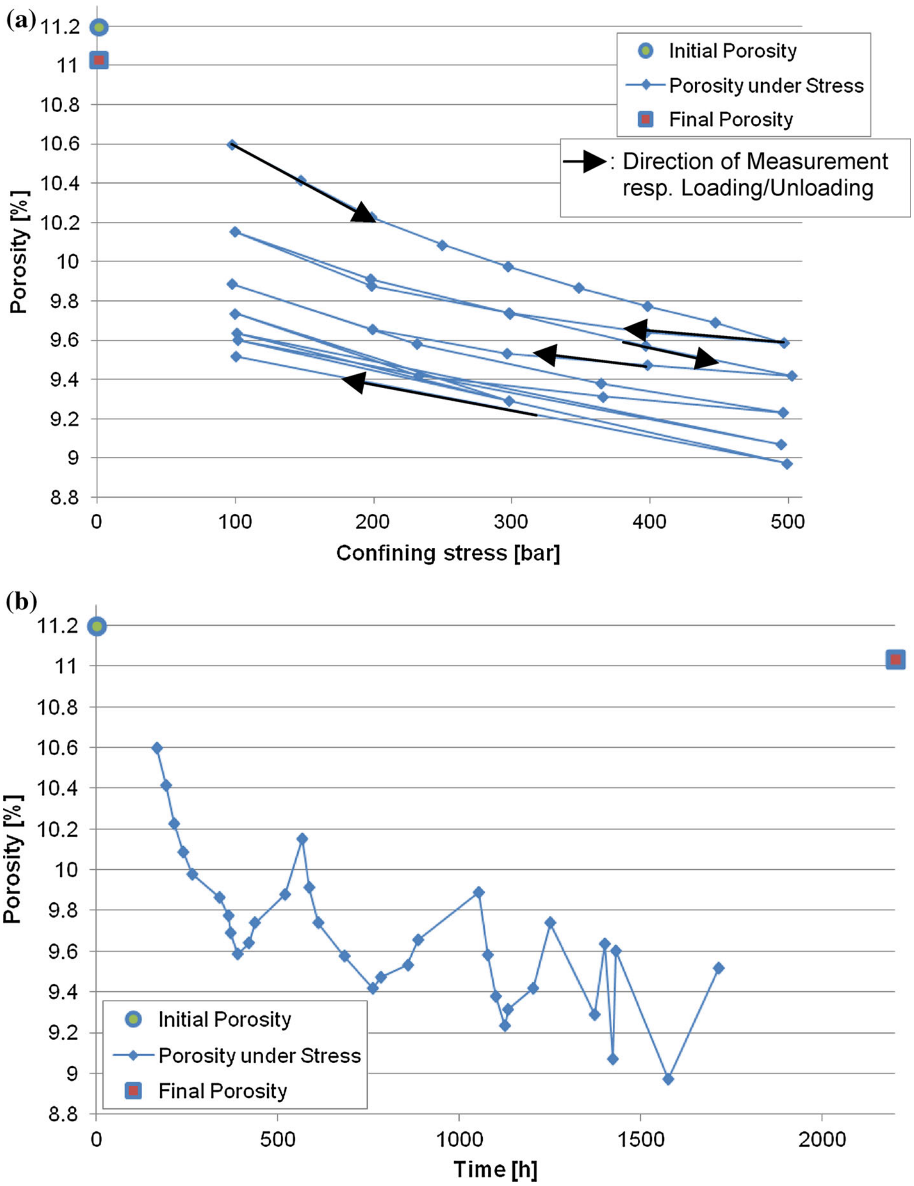


**Fig. 3** Triaxial cell with ISCO pump used for the porosity measurements (Werunsky 2011)

**Fig. 4** Porosity measured during alternating loading (decreasing porosity) and unloading (increasing porosity) of the rock sample



time delay until the initial state is reached. This deformation behavior can be described by a viscoelastic model as shown in Fig. 5.

The porosity–permeability relationship did not change due to the applied stress and corresponds very well to the general porosity–permeability trend for the Rotliegend sandstones (Fig. 6).

## Application of experimental results in modeling and simulation of tight gas formations

The examples of stress-dependent permeability and porosity measurements discussed are representative of the numerous measurements by authors, related to the low-permeability Rotliegend sandstones. The results of these measurements corroborate unambiguously the findings of other researchers (Davis and Holditch 1998; Hettema et al. 2000) that no simple prediction of permeability and

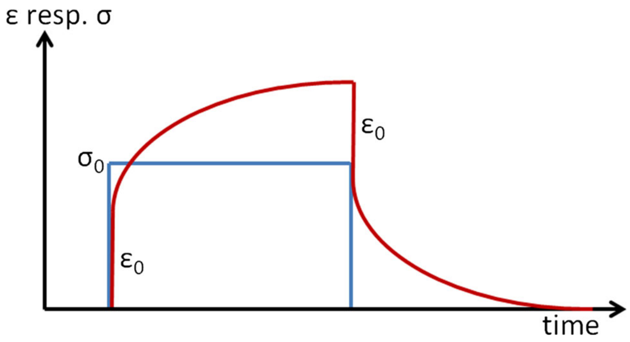


**Fig. 5** Stress (*σ blue line*) and thereby induced deformation (*ε red line*) in a viscoelastic model

**Fig. 6** Poro–perm relationship for Rotliegend sandstone

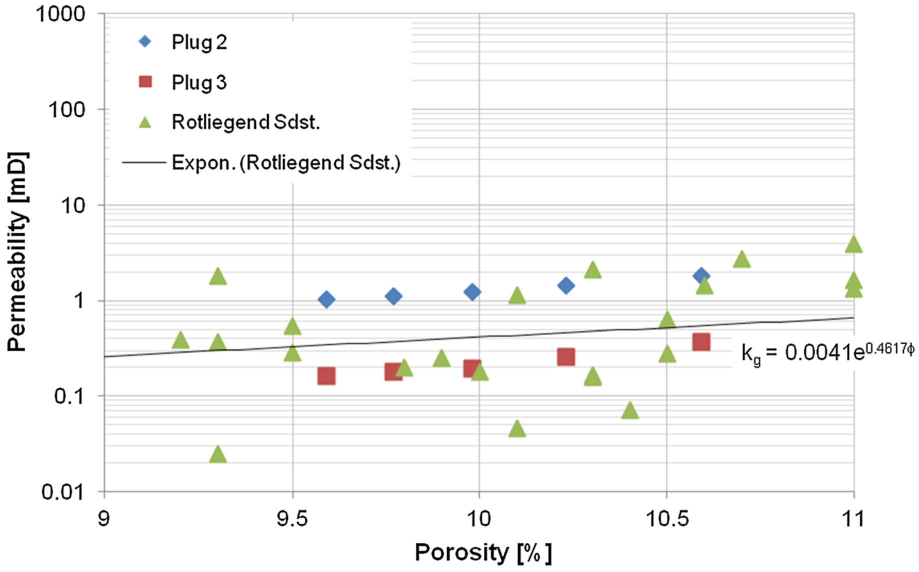
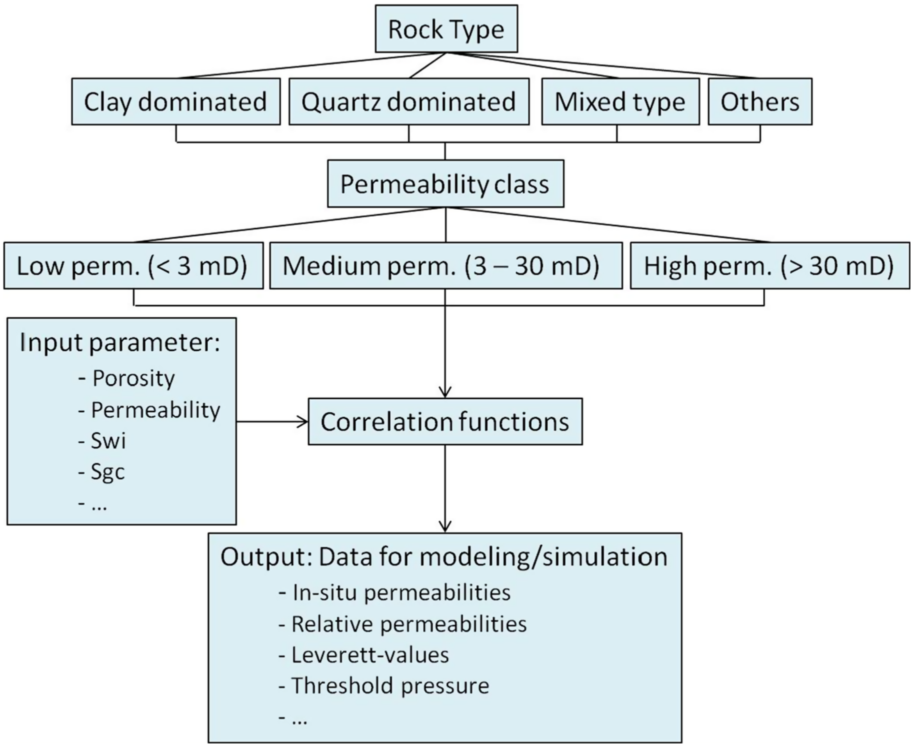


**Fig. 7** Decision structure concept of the Interactive Rock Data Catalog



porosity under reservoir conditions from the routine permeability and porosity, measured under ambient stress conditions, is possible. However, this prediction is possible based on correlations of those reservoir rock properties derived from the experimental results related to particular lithotype, effective stress, stress path and loading patterns. To help a reservoir engineer to select the appropriate correlation function for the prediction of parameters necessary for modeling and simulation tasks using a software program, an Interactive Rock Data Catalog (IRDC) has been developed. The structure and functions of the IRDC and a possible application for sweet spot identification have been described in an earlier publication (Albrecht and Reitenbach 2014). However, in this paper, the authors want to focus on the general idea and concept behind this software tool.

The analysis and development planning of tight gas reservoirs requires an integrated application of petrophysical, reservoir mechanical and production engineering data as a basis for computer-based reservoir modeling and simulation. The petrophysical data required for the modeling and simulation must be task-dependent gathered, analyzed and sorted from different sources. The preparation of input data for analysis and simulation studies requires considerable time, effort and expertise. The modules in commercial simulation software for determining the petrophysical properties needed for the simulation are often not able to predict the influence of the facies, cementation and poro/perm variations in the reservoir rock of gas bearing formations present in the North-Germany Basin. A reservoir engineer without profound petrophysical background might get into difficulties with the selection of the appropriate data and correlation functions for the modeling or simulation tasks. The IRDC contains the information needed for such selections and guides the user through a simple decision path to get to the most appropriate correlation for his purposes. Figure 7 shows a possible decision path starting from the simple information available about the rock properties, e.g., cement type and permeability range, through the basic input data, e.g., laboratory measured permeability values, to the desired output data. The IRDC combines a specialized rock database with interactive data processing modules. On addition to personal experience, IRDC provides an efficient way to generate data sets for reservoir simulation. It also serves as an interface to enable the export of the output data to another reservoir simulation program, e.g., ECLIPSE or PETREL.

## Conclusions

The porosity and permeability of the North-German Rotliegend tight gas sandstones are strongly stress dependent.

During the SCAL laboratory experiments, the porosity and permeability of Rotliegend tight gas core samples measured in successive loading and unloading cycles showed a strong hysteresis, which would make it difficult to predict these properties unambiguously under the reservoir conditions from the measurements of ambient or nearly ambient reference stress conditions.

Special long-term measurements have shown that the test core samples are able to recover from the induced deformations which indicate the viscoelastic behavior of the rock fabric over a long-time scale.

The correlations of the stress-dependent porosity and permeability for different lithotypes of the Rotliegend tight gas sandstones have been derived from this study and numerous open source experimental data.

The Interactive Rock Data Catalog was developed as tool for reservoir engineers. The application areas of the Rock Data Catalog support the characterizing, modeling and simulation of tight gas reservoirs by predicting the reservoir permeability change induced by increasing effective stress during the production. The IRDC could also be used prospectively for identifying sweet spots using petrophysical parameters.

## References

Albrecht D, Reitenbach V (2014) Laboratory measurements of fluid transport properties on tight gas sandstones and applications. Energy Procedia, Elsevier (in press)

Albrecht D, Ganzer L, Pusch G, Reitenbach V (2010) Bestimmung von In-situ Fließeigenschaften von Tight Gas Reservoirgesteinen unter Porendruck mittels Korrelationen aus Labormessungen. Research paper presented at the 2010 DGMK/ÖGEW-Frühjahrstagung held 12–13 April 2010 in Celle, Germany

Bennion DB, Thomas FB, Ma T (2000) Formation Damage Processes Reducing Productivity of Low Permeability Gas Reservoirs. Paper SPE- 60325 presented at the 2000 SPE Rocky Mountain Regional/Low Permeability Reservoirs Symposium and Exhibition held in Denver, Colorado 12–15 March 2000

Byrnes AP (1997) Reservoir characteristics of low-permeability sandstones in the Rocky Mountains. Mt Geol 34(1):37–48

Davies JP, Holditch SA (1998) Stress dependent permeability in low permeability formation, East Texas gas reservoirs: Travis Peak. Paper SPE 39917 presented at the 1998 SPE Rocky Mountain Regional/Low- Penneability Reservoirs Symposium and Exhibition held In Denver, Colorado

Debschütz WG (1995) Hydraulische Untersuchungen an Sediment- und Kristallingesteinen unter variablen hydro- und lithostatischen Druckbedingungen: Trennung strömungscharakterisierender Kenngrößen und Korrelationen mit anderen petrophysikalischen Größen. Dissertation at the Technical University of Clausthal

Fatt I, Davis DH (1952) Reduction in permeablity with overburden pressure. AIME, vol. 195, Technical Note 147, p. 329

Gaupp R, Okkerman JA (2011) Diagenesis and reservoir quality of Rotliegend sandstones in the northern Netherlands—A review. SEPM Special Publication No. 98, p. 193–226

Gou Y, Zhou L, Zhao X, Hou ZM, Were P (2015) Numerical study on hydraulic fracturing in different types of georeservoirs with consideration of H2 M-coupled leak-off effects. Environ Earth Sci. doi:10.1007/s12665-015-4112-5

Haefner F (2006) Simulation of the production behaviour of hydraulically fractured wells in tight gas reservoirs. Edit. Research report of the project DGMK 593-9/2. DGMK, Hamburg

Hammes U, Krause M, Mutti M (2013) Unconventional reservoir potential of the upper Permian Zechstein group: a slope to basin sequence stratigraphic and sedimentological evaluation of carbonates and organic-rich mudrocks Northern Germany. Environ Earth Sci 70:3797–3816

Hettema MHH, Schutjens PMTM, Verboom BJM, Gussinklo HJ (2000) Production-induced compaction of a sandstone reservoir: the strong influence of stress path. SPE Reserv Eval Eng 3(4):342–347

Hoppe M (2005) Reservoir-mechanical and petrographical studies on the effects of deviatoric stress conditions on tight gas sandstones. Dissertation at the University of Technology Claustha

Jones FO, Owens WW (1980) A laboratory study of low-permeability gas sands. SPE 32(9):1631–1640

Pudlo D et al (2012) The impact of diagenetic fluid–rock reactions on Rotliegend sandstone composition and petrophysical properties

(Altmark area, central Germany). Environ Earth Sci (EES) 67:369–384

Pusch G, Gaupp R, Liermann N (2005) Integrated research contributions for screening the tight gas potential in the Rotliegend formation of North-Germany. Eur Oil Gas Mag 4:187–193

Qiao LP, et al. (2009) Determination of Biot's effective stress parameter for permeability of Nikanassin sandstone. Petroleum Society of Canada, PETSOC-2009-105

Ruisten H et al (1999) Influence of reservoir stress path on deformation and permeability of weakly cemented sandstone reservoirs. SPE Reserv Eval Eng 2(3):266–272

Schutjens PMTM, Hanssen TH, Hettema MHH, Meyrour J, de Bree P, Coremans JWA, Helliesen G (2004) Compaction –induced porosity/permeability reduction in sandstone reservoirs: data and model for elasticity-dominated deformation. SPE Reserv Eval Eng 3(4):202–216

Skomedal E, Hettema MH (2002) Effect of pore pressure and stress path on rock mechanical properties for HPHT application. SPE/ISRM 78152

Trautwein U (2005) Poroelastische Verformung und petrophysikalische Eigenschaften von Rotliegend Sandsteinen. Dissertation at the University of Technology Berlin

Wang H (2000) Theory of poroelasticity with applications to geomechanics and hydrology. Princeton University Press

Wang L, Liu JF, Pei JL, Xu HN, Bian Y (2015) Mechanical and permeability characteristics of rock under hydro-mechanical coupling conditions. Environ Earth Sci. doi:10.1007/s12665-015-4190-4

Werunsky F(2011) Mikrowegsamkeiten im Steinsalz und im salinaren Versatzmaterial SVV (Selbstverheilender Versatz)—Ursachen und Wirkungen. Dissertation an der Technischen Universität Clausthal, Papierflieger Verlag, Clausthal-Zellerfeld

Zhang ZT, Zhang R, Xie HP, Gao MZ (2015) The relationships among stress, effective porosity and permeability of coal considering the distribution of natural fractures: theoretical and experimental analyses. Environ Earth Sci. doi:10.1007/s12665-015-4280-3