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Assessing accuracy of gas-driven permeability measurements: a comparative study of diverse Hassler-cell and probe permeameter devices

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Abstract

Permeability is one of the most important petrophysical parameters to describe the reservoir potential of sedimentary rocks, contributing to problems in hydrology, geothermics, or hydrocarbon reservoir analysis. Outcrop analog studies, well core measurements, or individual sample analysis take advantage of a variety of commercially available devices for permeability measurements. Very often, permeability data derived from different devices need to be merged within one study, e.g. outcrop mini-permeametry and lab-based core plug measurements. To enhance accuracy of different gas-driven permeability measurements, device-specific aberrations need to be taken into account. The application of simple one-to-one correlations may draw a wrong picture of permeability trends. For this purpose, transform equations need to be established.

This study presents a detailed comparison of permeability data derived from a selection of commonly used Hassler cells and probe permeameters. As a result of individual cross-plots, typical aberrations and transform equations are elaborated which enable corrections for the specific permeameters. Permeability measurements of the commercially available ErgoTech Gas Permeameter and the TinyPerm II probe-permeameter are well-comparable over the entire range of permeability, with $R^2 = 0.967$. Major aberrations are identified among the TinyPerm II and the mini-permeameter/Hassler-cell combination at Darmstadt University, which need to be corrected and standardized within one study. However, transforms are critical to their use, as aberrations are frequently limited to certain permeability intervals. In the presented examples, deviations typically tend to occur in the lower permeability range < 10 mD. Applying standardizations which consider these aberration intervals strongly improve the comparability of permeability datasets and facilitate the combination of measurement principles. Therefore, the utilization of such correlation tests is highly recommended for all kinds of reservoir studies using integrated permeability databases.

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1 Introduction

Petrophysical properties of sedimentary rocks are decisive parameters for the quantitative and qualitative evaluation of reservoir rocks. One of the most important measurement values is permeability, describing the magnitude of fluid flow through porous media. Reliable permeability values are a prerequisite for the assessment and modelling of hydrocarbon, carbon dioxide capture and storage, and geothermal reservoir rocks (Li et al., 1995; Branets et al., 2009; Dezayes et al., 2007; Grant and Bixley, 2011; Hurst, 1993; Laughlin, 1982) and their economic and sustainable production (Davies and Davies, 2001; Dutton et al., 1991). They are also crucial for hydrological studies (Huysmansa et al., 2008; Todd and Mays, 2005; Al Ajmi et al., 2013) and underground waste disposal, including modelling of fluid flow and potential contaminant spread.

Laboratory-based permeability measurements are commonly performed on core plug samples from well core material. Gas-driven permeability measurements have the advantage to be quickly performed, they are not contaminating the sample, and they do not affect e.g. clay-bearing samples, which in the case of a fluid might swell and destroy the sample. A standard laboratory device for gas-driven permeability measurements is a Hassler cell (e.g. Thomas, 1972), allowing permeability measurements of entire core plug samples under steady state gas flow. Though, the resolution of permeability values measured, e.g. in a well core section, strongly depends on the plug core sampling rate (Goggin, 1993).

During the last decades, non-destructive and cost-efficient mini or probe permeametry became an important analytic tool, providing fast and highly resolving permeability data for both, laboratory and in situ rock outcrop applications (Davis et al., 1994; Sharp Jr. et al., 1994; Goggin, 1988; Dutton and Willis, 1998; Goggin, 1993; Dreyer et al., 1990; Chandler et al., 1989; Hornung and Aigner, 2002; Fossen et al., 2011; Rogiers et al., 2011; Iversen et al., 2003; Huysmansa et al., 2008; Eijpe and Weber, 1971). Most probe permeameters apply a steady-state or unsteady-state gas injection (e.g. Hurst and Goggin, 1995) with gas flow from the probe tip through the sample rock volume. However, some devices do also apply a vacuum, where the gas flow through the sample is inverted. Automated laboratory probe permeametry is commonly applied to core slab surfaces oriented perpendicular to sedimentary bedding, referred to as horizontal permeability (Corbett and Jensen, 1992; Robertson and McPhee, 1990). The resulting permeability maps are further enrolled in rock property analysis and reservoir characterization (Halvorsen and Hurst, 1990; Robertson and McPhee, 1990; Willis, 1998). Mini permeametry has the potential to resolve at the cm-scale bedding-, deformation- and diagenesis-dependent permeability heterogeneities in stratified sedimentary rocks (e.g. Huysmansa et al., 2008). However, mini permeameter and Hassler cell derived permeability data are not directly comparable with one another. Meyer and Krause (2001) document almost constantly higher probe-derived permeability values than those from Hassler cell measurements. The opposite applies to Hassler cell derived permeabilities obtained from cataclastic deformation bands in reservoir sandstones, which were found systematically higher than plug-derived permeability values (Torabi and Fossen, 2009). Sutherland et al. (1993) discuss the advantages but also limitations of probe permeametry, emphasizing the need of standardized experimental conditions.

The combination of permeability data obtained from different approaches, e.g. from a probe permeameter and a Hassler cell, within one study therefore needs to be dealt with caution. Here, it is of crucial importance being aware of the scaling of rock heterogeneities and possible discrepancies between the measuring results. In this study, four air-driven permeameters are tested for comparability among each other. In order to assess the accuracy of different Hassler cell and mini-perm devices, similarities but also potential discrepancies are evaluated. Ultimately, research studies integrating different permeameter devices, e.g. for field and laboratory analysis, shall benefit from a much higher accuracy by applying transfer functions for a standardization of permeameter measurements.

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2 Samples, methods, and specifications

2.1 Sample material

For this study we used 51 cylindrical and horizontally (parallel to bedding) drilled sandstone sample plugs of a standardized 1 inch (2.54 cm) diameter and 5 cm length.

To provide an almost homogeneous sample material, very well to well sorted, fine- to medium grained, massive sandstones were selected. Prior to permeability measurements the sample plugs have been oven-dried at 60 °C for three days, until a constant weight has been reached. Permeability measurements have been performed in the long axis of the core plug to ensure comparability of the different measuring-concepts and to exclude orientation-related anisotropy effects. The dataset presented here (Table 1) covers a permeability range over six orders of magnitude, from 10^{-2} to 10^{3} mD. Samples with low and moderate permeabilities of 0.02 to 300 mD are derived from the Triassic Buntsandstein (sample numbers 1–13 and 43–51) and Keuper (sample numbers 14–38) of southern Germany. Highly permeable samples (600 to > 2700 mD) have been selected from two reservoir rocks: the Lower Cretaceous Bentheim Sandstone (sample numbers 40–42) which forms the host rock of a hydrocarbon reservoir in northwest Germany and the Netherlands (cf. Roll, 1972), and the Late Ordovician Dibsiyah Formation (sample number 39) of the Wajid Group in the Kingdom of Saudi Arabia (Kellogg et al., 1986; Al Ajmi et al., 2013), which is part of a regional mega-aquifer system (GTZ-DCO, 2007). The samples have generally been selected to cover the full range of permeability in order to properly compare the different permeameter types. However, the samples of the individual formations do not represent the full range of occurring permeabilities there.

2.2 Methods and devices

Four gas-driven permeameter devices using three different concepts for permeability determination have been compared within this study: (I) two Hassler cells (Fig. 1a),

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(II) a mini (or probe) permeameter using air injection (Fig. 1b), and (III) a vacuum probe permeameter (Fig. 1c).

2.2.1 Hassler cells

Darcy's Law describes the horizontal, laminar flow of a fluid under steady-state conditions in porous media with the known length and area of the sample. The permeability (K) according to Darcy's Law (Darcy, 1856) is given by:

$$K = Q\eta L / A\Delta P \quad (1)$$

with K: permeability of the medium in [m^2] or [mD], $1\,\text{mD} = 9.86923 \cdot 10^{-16}\,\text{m}^2$, Q: flowrate, discharge volume per second in [m^3 s^{-1}], η: viscosity of the fluid in [Pa s], L: length of the sample in [m], A: the cross-sectional area of the sample in [m^2], ΔP: pressure difference between injection and outflow in [Pa].

Gas slippage at low pressures or high velocity flow effects, such as turbulences, however, are neglected by this equation. Devices facilitating different pressure stages allow the Klinkenberg correction (Klinkenberg, 1941) and determination of an intrinsic permeability. A minimum of three, better five subsequent measurements at equal flow rates but at different backpressure steps and resulting differential pressures can be performed with Hassler cell devices. They are designed for uni-variant sample geometries, allowing a variable core plug length but demanding a constant sample diameter. Permeability measurements can only be applied in the long-axis direction of the sample plug. Therefore, the sample orientation is of basic importance, especially in heterogeneous rocks, where reservoir qualities are constrained by those sections with the lowest permeability.

The ErgoTech Digital Steady State Gas Permeameter (**H**assler-cell **E**rgo**T**ech = HET) at the Geological Institute of RWTH Aachen University is a laboratory-based instrument with an attached Quick Action Hassler cell, hosting standard rock plugs of 1 inch (2.54 cm) diameter and a length of 7.6 cm maximum. The sample is sealed by

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a rubber sleeve under a confining oil pressure of 50 bar. The operating-gas temperature is measured with 0.1 °C accuracy. The HET is equipped with three mass flow meters of 20, 200, and 2000 $cm^3 min^{-1}$ maximum. The applied back-pressure steps in the HET comprise measurement against atmospheric pressure, 20, 25, 30, and 35 psi, resulting in a measuring range of 0.01 mD to 10 D.

The gas permeameter at the Institute of Applied Geology at the Technical University of Darmstadt combines a Hassler cell (**H**assler-cell **Da**rmstadt = HDA) with a mini (or probe) permeameter (MDA) in one device. The HDA can be operated with Hassler cells of different diameters at a sealing air pressure of 10 bar and with freely selectable backpressure steps up to 6 bar. Flow rates are sensible from 0.001 $cm^3 min^{-1}$ up to 2000 $cm^3 min^{-1}$, allowing the measurement of a 1 µD to 6 D permeability range at 2.5 cm plug diameter. Measuring time for medium to highly permeable samples is roughly 5 to 10 min. This device can also be used to determine permeability for different fluids and automatically corrects for viscosity and temperature effects.

Main components of both devices are a downstream controller in front of the Hassler cell, gas flow monitors of different ranges behind the Hassler cell, followed by an upstream controller to realize backpressure. Pressure gradient within the sample is metered by a differential pressure gauge directly at the upstream and downstream sample endings by additional non-percolated probes to avoid friction. These parameters are used as a direct input into the Darcy equation, together with temperature and pressure corrected air viscosities and volumes.

2.2.2 Probe permeameter gas-flow geometry in rock samples

For all kinds of mini permeameter devices, the knowledge about gas flow geometry is crucial in order to get area (A) and length (L) parameters as input for the Darcy equation (Eq. 1). However, quantifying these parameters represents a major problem as flow trajectories are not parallel, not equally spaced, and not of the same length (Fig. 2a). For absolutely homogenous and anisotropic samples a so-called geometric factor (L/A) can be modelled and calculated even for different sample geometries to replace the length (L) and area (A) parameters of the Darcy equation. In the geoscience practice, natural samples are investigated which can almost never be considered as isotropic, nor homogenous due to depositional and diagenetic effects. Therefore, a significantly better accuracy of the results can be archieved when a calculated geometric factor is replaced by an empirical factor, closely adapted to a certain rock type (Fig. 2b). Hence, we recommend measuring a set of samples with both devices, the Hassler cell permeameter and in the same direction (plug faces) with a mini-permeameter. From this data set an empirical geometry factor can be determined by balancing averaged mini-permeameter values of both plug faces with Hassler cell measures. This set of test-samples should cover the whole range of permeabilities of a rocktype. Rocktypes should be chosen, representing all types of potential controls affecting pore space geometry and sample architecture, e.g. lithology, detrital grain composition, degree and type of cementation, and sedimentary fabrics. To keep it simple even for non-geologists, such a suite of rocktypes could be for example limestones with and without visible sedimentary structures, and a group of heavily diagenetically overprinted limestone showing leaching, microkarst, fracturing, or patchy cementations. Similarly, such test sets should be established for sandstones.

2.2.3 Mini (or probe) permeameters

The mini permeameters have been applied attached to the end-faces of the core plug samples, providing horizontal permeability data of the core plug long-axis directions. These measurements can then be directly compared to Hassler cell derived permeability measurements. Mini or probe permeameter measurements are governed by seal tightness which is strongly influenced by seal surface pressure, the angle of the probe-tip with the sample surface, and the roughness of the sample surface. Potential leaking has large influence on the measuring results. The seal tightness of these devices is achieved by a tight contact between nozzle, sealing rubber, and sample surface and can be further improved by a ring of putty. For a better comparison of applied probe tip seals, Goggin et al. (1988) use the dimensionless probe-tip seal size, defined as

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b_D = (external seal radius)/(internal seal radius). A minimum size of b_D = 1.5 is recommended by Suboor and Heller (1995), whilst Meyer and Krause (2001) apply a b_D of 2.19.

Mini-permeameter Darmstadt

The Darmstadt permeameter can be operated also in a mini-permeameter mode (**M**inperm **Da**rmstadt = MDA), using air injection (Fig. 1b). The MDA is mounted on a static with automatic seal pressure control to ensure constant tightness conditions. It injects at a diameter of 4 mm and seals an area of 25 mm of diameter (b_D = 6.25). Different sealing tips are used to adjust for curvatures of samples. Plugs of all diameters, any plane surface or irregular shaped samples can be handled. It delivers a three-dimensional apparent permeability, which can be used to quantify anisotropy at small-scale. By applying geometric factors, the apparent permeability of the miniperm-mode is adjusted to results of the HDA Hassler-cell mode by experiments as described in Sect. 2.2.2. The measurable permeability range is almost identical to the HDA-device. A single measurement takes roughly 30 s for medium to highly permeable samples and for a complete 3-D survey 12 single measurements are recommended.

The same sensors as in Hassler-cell operation mode are used, but as it releases gas into the atmosphere, no backpressure can be applied and all parameters have to be measured in the upstream branch of the device. Parameter corrections are applied identical to the Hassler-cell operation mode. To test leakages of the tip seal or in the device, samples which are considered to have no permeability are measured. In this case, an alloy plug in the same dimensions as a core plug was used. The results were below the sensitivity of the sensors, so we assume a complete technical tightness. We recommend such a test for any other devices.

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TinyPerm II probe permeameter

The mini permeameter "TinyPerm II" (**M**iniperm **T**iny**P**erm = MTP) of New England Research Inc. was applied at the GeoZentrum Nordbayern, University of Erlangen-Nürnberg. It is a portable hand-held air-permeameter (Fig. 1c) which can be used in the laboratory or in the field directly on the surface of sample plugs, well cores, hand specimens, and plane, cleaned outcrop walls. The MTP probe tip consists of a 22 mm-sized rubber nozzle with an inlet diameter of 9 mm. To prevent leakage between probe tip and sample surface, the nozzle was additionally equipped with an impermeable expanded rubber ring of 9 mm inner diameter (inlet) and 27 mm outer diameter, providing a 9 mm thick seal around the inlet. The application of this additional seal is highly recommended to optimize MTP measurements. As the expanded rubber is very flexible, it tightens the surface roughness of the sample which prevents leaking and forces the air to trespass only the rock sample. Here, the probe-tip seal size b_D according to Goggin et al. (1988) is $b_D = 3.0$. To provide reproducible testing conditions and a uniform contact pressure during operation, the MTP device was mounted in an upright static position. The probe nozzle is pressed against the rock sample and subsequently a vacuum is generated in the inner part of the instrument. According to the manufacturer (New England Research Inc.), a micro-controller monitors the volume of withdrawn air from the rock and the transient vacuum. After the vacuum is dissipated, the micro-controller computes a characteristic value according to the measured parameters. This TinyPerm II value (T) is provided after the measurement of one sample and is linked to air-permeability (K) through Eq. (2) (according to the TinyPerm II operational manual):

$$T = -0.8206 \log_{10}(K) + 12.8737 \quad (2)$$

where K is the permeability in millidarcies (mD).

This equation needs to be applied to all values provided by the MTP-device after the measurement of one sample, to calculate the correct permeability in millidarcies. Empirical experiments show that the value T also correlates with measuring time (Fig. 3).

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The technical tightness of the MTP-device was then tested with a perfectly flat and polished solid aluminium block, simulating a non-permeable sample. In the ideal case, the vacuum should not dissipate when impermeable materials are measured. Over a measuring period of four hours, the device indicates a slow decay of the vacuum. The extrapolation of this decay delivers a time-span of 10 h and 9 min for the entire dissipation of the vacuum. Applying the correlation of measuring time vs. TinyPerm value (Fig. 3), a measuring time of 10 h and 9 min provides $T = 14.08$, which equals an apparent permeability of the solid aluminium block of 0.034 mD (calculated using Eq. 2). This technical tightness defines the lower measuring boundary of the TinyPerm II, limited to 0.034 mD. Since the TinyPerm II device was originally designed for a hand-held field application, the manufacturer indicates a lower measuring boundary of approximately 10 mD, which is equivalent to a measuring time of about five minutes (Fig. 3). Longer measuring times and thereby lower permeabilities may only be realized in the laboratory where the device can be mounted on a static rack.

3 Comparison of Hassler cell and mini (probe) permeameter measurements

When permeability measurements from different Hassler cells, different mini permeameters or a mixture of Hassler cell and mini permeameter measurements are integrated in one study, system-immanent discrepancies between the applied devices should be taken into account and, where necessary, should be corrected. Therefore, transform equations for the used devices need to be determined and applied for comparison. All permeability measurements conducted with the four devices used in this study are listed in Table 1 and plotted in Fig. 4. The results are then cross-plotted to visualize the correlation of the different permeability devices and, if necessary, to receive transform equations for correction and standardization (Figs. 5 and 6).

3.1 General trends of measuring results

The permeabilities of all 51 core plug samples have been measured with each of the four permeameter devices and are plotted in Fig. 4 for comparison. General permeability trends and magnitudes, and the aberrations of the respective permeability devices are discussed. The most eye-catching aberrations are shown by the TinyPerm II mini-permeameter (MTP), which in the majority of cases, determines higher permeabilities than all other devices. Markedly higher values are recorded in 47 % (24 samples), similar values in 37 % (19 samples), and slightly lower values in 18 % (9 samples) of the cases. Other typical aberrations are documented by the Hassler cell in Darmstadt (HDA), showing pronounced lower permeabilities in $\sim 18\,\%$ of the cases (9 samples). These negative aberrations are, however, limited to permeabilities of < 10 mD. Obviously most aberrations, positive and negative, range in the same order of magnitude like the respective measuring results of the other devices.

3.2 Individual comparison of permeability devices

The combination of permeability values obtained from different approaches, requires a profound understanding of potential discrepancies between the applied devices. The individual measurement results of all four permeameters are cross-plotted against each other (Figs. 5 and 6) to obtain particular information on their systematic similarities and discrepancies.

3.2.1 Hassler cell measurements: HET vs. HDA

The Hassler cells (HET and HDA) generate well-correlating measuring results, with a coefficient of determination of $R^2 = 0.959$ (Fig. 5a). Most of the presented Hassler cell measurements are almost identical or very close to each other (36 samples = 71 %), plotting near the bisectrix (solid line). In most cases, a one-to-one correlation between the two Hassler cells applies very well. Though, major deviations have been observed in the measuring interval between 1 and 10 mD. Here, the HDA shows markedly lower values than the HET. The permeability values of seven samples deviate as much as one order of magnitude. Minor aberrations are within the same order of magnitude.

3.2.2 Mini permeameters: MDA vs. MTP

The MDA-MTP cross-plot (Fig. 5b) indicates major aberrations of the two mini-permeameter devices from each other. In the lower permeability range (< 40 mD), the TinyPerm II (MTP) tends to provide lower values than the Darmstadt mini-permeameter (MDA). Though, at permeability values > 40 mD, the MTP typically indicates higher values. Individual partial regression lines can be drawn separately for the two sections. These best-fit lines are almost parallel to the bisectrix, with only a slight shift towards lower or higher values. The coefficient of determination R^2 of MDA vs. MTP is very good, with 0.968 for the permeability range < 40 mD and 0.972 for > 40 mD.

3.2.3 Hassler cell vs. mini-permeameter measurements

Figure 6 compares Hassler cell measurements of the ErgoTech (HET) and the Darmstadt (HDA) devices with mini (or probe) permeameter measurements of the TinyPerm II (MTP) and the Darmstadt device (MDA). Both mini-permeameters, MTP and MDA, show high coefficients of determination (R^2) with the Hassler cells of the HET-device (R^2 = 0.967 and 0.964, see Fig. 6a and b) and the HDA-device (R^2 = 0.898 and 0.939, see Fig. 6c and d). Permeability measurements of the MTP and the HET devices plot very close to the bisectrix (Fig. 6a), showing that measurement values of these two permeameters can largely be correlated one-to-one. However, provided permeability values may also differ to various degrees within distinct sections of the cross-plots. The TinyPerm (MTP), for example, exhibits deviations from the general Hassler cell trend (HET and HDA) at a permeability range of ∼ 45 to 120 mD (Fig. 6a and c).

A different type of aberration can be observed from a cross-plot of the mini-permeameter MDA and the HET-Hassler cell (Fig. 6b). There, the best-fit line is ro-

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tated counter-clockwise compared to the bisectrix. Below ~ 40 mD, The MDA indicates higher permeabilies than the HET-device. At ~ 40 mD however, a turn-around point occurs, above which the MDA tends to deliver mostly lower permeability values than the HET.

The Darmstadt Hassler cell (HDA) provides an example of typical system-immanent deviations of measuring results. At permeability values < 10 mD, the HDA provides much lower permeabilities than all other devices (Figs. 5a, 6c and d). This constant "underestimation" by the HDA-device is particularly well illustrated in a cross-plot with measurement results of the two mini-permeameters (Fig. 6c and d) revealing that permeability values < 10 mD are largely scattered and not correlating very well.

3.3 Discussion of measuring results

To enhance accuracy of different gas-driven permeability measurements, device-specific aberrations have been documented from Hassler cell and mini-permeameter measurements. Permeability over- and under-estimations either by mini-permeameters or Hassler cells may result from variable factors.

Sealing quality and surface roughness play an important role in leak tightness of mini-permeameters. Here, permeability over-estimations of mini-permeameter devices (Figs. 4, 6a–d) may be attributed to sub-optimal probe tip sealing, especially when sample surfaces are very rough (e.g. coarse-grained sandstones).

Permeability under-estimations, however, require other explanations. Covering only a very limited surface, mini-permeameter measurements are susceptible to even small-scale rock heterogeneities. For instance, individual, stronger cemented parts may deliver lower permeabilities in punctual mini-permeameter measurements. Additionally, a strong contact pressure of the mini-permeameter probe may slightly force the sealing rubber towards the inner part of the probe tip. This would also narrow the inflow/outflow tube diameter to a certain degree. The effect of a reduced in- or outflow diameter then results in an apparent lower permeability. This may explain the documented under-estimations of mini-permeameter measurements compared to the Hassler cell devices.

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Hassler cell measurements provide a permeability value which is integrated over a given rock volume. Individual and spatially limited sections of enhanced cementation within this rock volume affect bulk permeability only little, whereas they have a much more pronounced effect on point measurements (Fig. 2b). Cross-plots further indicate, that the HDA Hassler cell tends to provide systematically lower permeabilies compared to the other devices (Figs. 5a, 6c and d) at a permeability range of < 10 mD. This is due to the technical specifications of all kinds of ultra low range gas flow meters. In general they show a much higher pressure drop compared to mid or high range sensors, which changes flow conditions in the sample.

For better comparison and for merging permeability data sets which have been generated with different devices, permeability measurements need to be standardized for one permeameter type.

The presented cross-plots show that permeability measurements from different devices correlate very well, with coefficients of determination (R^2) between 0.898 and 0.972. Frequently, they are in good accordance with the bisectrix, indicating that the plotted datasets can roughly be correlated one to one. Though, the good correlation is not equally distributed across the entire range of permeabilities. There are a number of aberrations which need to be considered when datasets generated by variable measurement devices shall be merged.

One-to-one-correlations can be applied when the TinyPerm II (MTP) mini-permeameter is used together with the ErgoTech Hassler cell (HET) (see Fig. 6a). The slightly increased MTP-permeability values within the permeability class of ~ 45–120 mD are within the regular range of aberration. MTP-measurements in the respective permeability range can be corrected, but not necessarily need a correction.

One-to-one correlations can be used only to a limited extend when the HDA Hassler cell is combined with any other of the devices considered in this study. Restrictions occur in the permeability interval of 1–10 mD, when using the HDA and HET Hassler cells (Fig. 5a), and at permeabilities < 10 mD, when the HDA is combined with the mini-

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permeameters MTP (Fig. 6c) or MDA (Fig. 6d). As discussed above, the HDA-Hassler cell constantly provides lower permeabilities there.

The standardization of MDA mini-permeameter and HET-Hassler cell measurements requires a correction across the entire range of permeabilities, applying the respective transform equations outlined in Fig. 6b. The standardization of MDA measurements for HET permeability follows the transform equation $HET = 0.6096\,MDA^{1.1282}$, where "MDA" describes the permeability measured with the MDA-device. As a result, the corresponding HET-permeability is obtained. Due to the rotation of the best-fit line (Fig. 6b), this transform becomes more effective in very low permeability classes < 1 mD or at high permeabilities > 1000 mD, and can be largely neglected at a range of 10–100 mD.

In studies, where the two mini-permeameters MTP and MDA are applied, minor corrections are necessary to standardize for one device. The cross-plot (Fig. 5b) illustrates a very good correlation, but the MTP vs. MDA permeability measurements are displaced sub-parallel to the bisectrix. At permeabilities < 40 mD, MTP values are slightly decreased, and vice versa slightly enhanced at higher permeabilities > 40 mD. Therefore, two different transforms need to be applied for standardization of MTP or MDA measurements (Fig. 5b).

All presented cross-plots demonstrate that it is of crucial importance to document major aberrations prior to the use of different permeameters within one study. A general rule how a specific device will compare to others cannot be established and has to be defined by empirical measurements.

4 Conclusions

Permeability data of reservoir rocks mainly derive from core plug measurements using Hassler cell devices. On the other hand, probe permeameters have the advantage of providing closely spaced, non-destructive permeability data, which are mostly suitable to gain 3-D permeability, estimates of anisotropy-effects, and heterogeneity.

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In studies, where both techniques are applied, it is of paramount importance to guarantee comparability of the obtained datasets. Permeability measurements derived from four different Hassler cell and mini-permeameter devices have been compared to document their correlation. As a result of permeability cross-plots, device-typical aberrations and transform equations are elaborated which enable corrections for specific Hassler cell or probe permeameter data. The application of simple one-to-one correlations is highly critical, as aberrations and trends may occur across the entire range of permeabilities or may only be confined to certain permeability intervals.

Though, only in some cases, one-to-one correlations between different permeameters can be effected. Here, the Hassler cell of the ErgoTech Gas Permeameter (HET) and the TinyPerm II (MTP) mini-permeameter show the closest match over the entire range of permeability ($R^2 = 0.967$). The combination and standardization of permeability data derived from other devices, however, requires various corrections.

With this study we show a methodology to better integrate mini-permeameter data with the commonly wider-spaced and more interpolative core plug permeability values derived from Hassler cell measurements. Hence, it is possible to benefit from the advantages of both concepts.

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Table 1. Permeability dataset of 51 sandstone sample plugs, measured with four different devices: the Hassler cells of the ErgoTech Gas Permeameter (HET) and the Gas Permeameter Darmstadt (HAD), and the mini-permeameters New England Research TinyPerm II (MTP) and Miniperm Darmstadt (MDA). Permeability values are given in mD.

	Hassler cells		Mini permeameters	
Plug No.	ErgoTech Gas Permeameter (HET)	Gas Permeameter Darmstadt (HDA)	New England Research TinyPerm II (MTP)	Miniperm Darmstadt (MDA)
1	0.32	0.35	0.26	0.43
2	2.07	2.07	1.89	2.38
3	1.75	1.36	1.88	3.45
4	0.48	0.40	0.37	0.42
5	56.50	60.10	63.56	45.48
6	42.30	40.30	36.78	50.17
7	27.94	27.50	23.41	29.64
8	115.78	114.80	145.03	97.19
9	214.08	148.20	173.08	72.74
10	18.53	18.10	20.52	22.32
11	7.35	6.10	2.22	3.04
12	46.07	49.50	30.64	39.38
13	20.79	28.60	13.93	22.99
14	5.00	0.80	6.05	6.06
15	3.45	0.10	1.32	4.71
16	10.75	3.20	13.25	12.86
17	9.65	9.53	5.72	11.95
18	11.36	1.80	11.11	13.85
19	7.19	3.40	5.86	9.08
20	44.08	37.80	74.04	34.13
21	67.30	65.00	134.95	61.71
22	54.25	47.10	81.65	48.15
23	4.23	2.45	4.74	5.80
24	0.97	0.90	8.73	3.36

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Table 1. Continued.

Plug No.	Hassler cells: ErgoTech Gas Permeameter (HET)	Hassler cells: Gas Permeameter Darmstadt (HDA)	Mini permeameters: New England Research TinyPerm II (MTP)	Mini permeameters: Miniperm Darmstadt (MDA)
25	1.78	0.60	3.09	4.46
26	63.07	58.30	115.10	54.69
27	62.86	63.10	160.48	55.29
28	71.62	73.30	118.56	62.55
29	101.82	107.70	196.39	91.13
30	88.89	96.30	185.95	53.10
31	89.94	101.10	138.79	70.12
32	1.57	0.28	2.05	5.16
33	11.88	11.39	10.75	14.64
34	56.00	53.30	88.47	44.86
35	111.70	124.50	176.83	62.60
36	85.29	90.80	181.58	74.96
37	49.72	67.00	120.42	52.17
38	95.96	104.00	203.47	77.00
39	597.35	680.00	445.57	808.84
40	2722.26	2685.40	4561.96	2250.72
41	2217.45	2370.10	4020.81	2857.35
42	2167.00	2256.90	2772.34	1899.75
43	2.43	1.90	3.02	3.60
44	0.77	0.80	1.72	3.60
45	1.73	1.00	1.26	1.56
46	0.52	0.60	1.20	1.53
47	0.17	0.10	0.39	0.62
48	0.07	0.10	0.10	10.29
49	925.76	151.60	812.27	487.99
50	1759.82	1766.20	1441.14	1113.45
51	859.91	980.10	678.75	403.92

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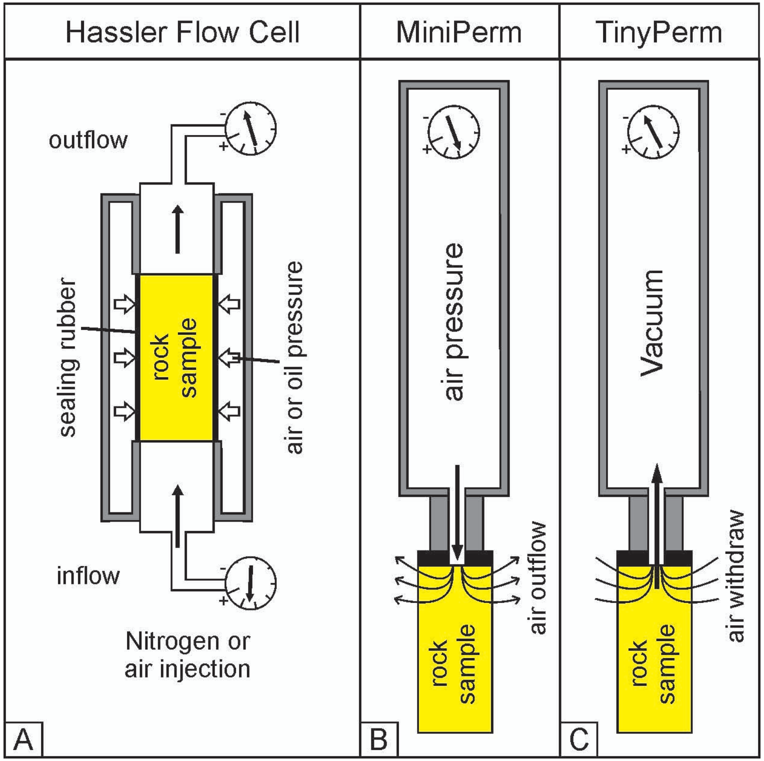

Fig. 1. Principles of permeability measurements: **(A)** Hassler cell, **(B)** mini (probe) permeameter using air injection, **(C)** mini (probe) permeameter applying a vacuum.

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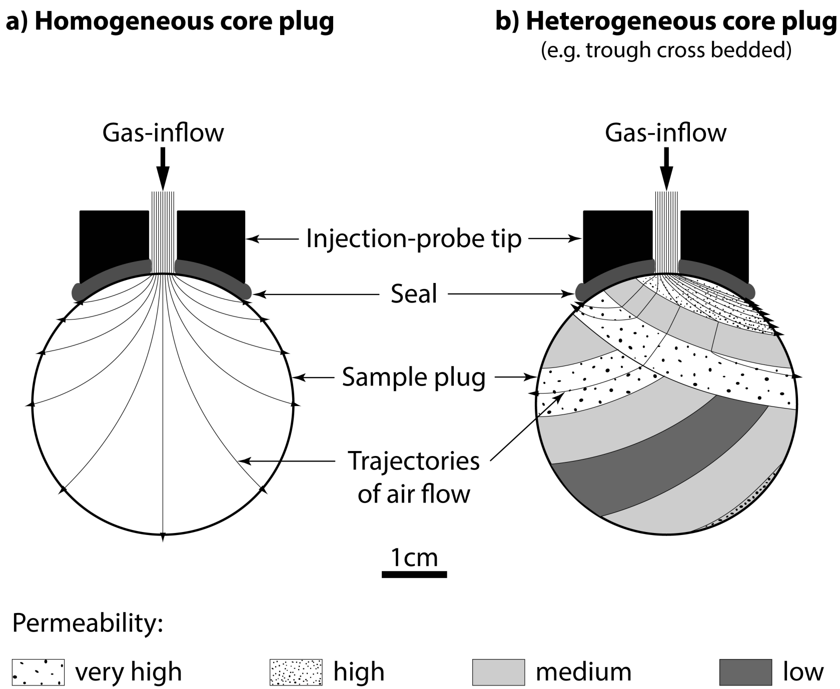

Fig. 2. Gas flow trajectories for **(a)** homogeneous samples and **(b)** for heterogeneous samples, e.g. comprising depositional or diagenetic anisotropies. Such structures strongly affect flow geometry by inducing preferential flow, which creates serious issues in determining flow length and area for permeability measurements.

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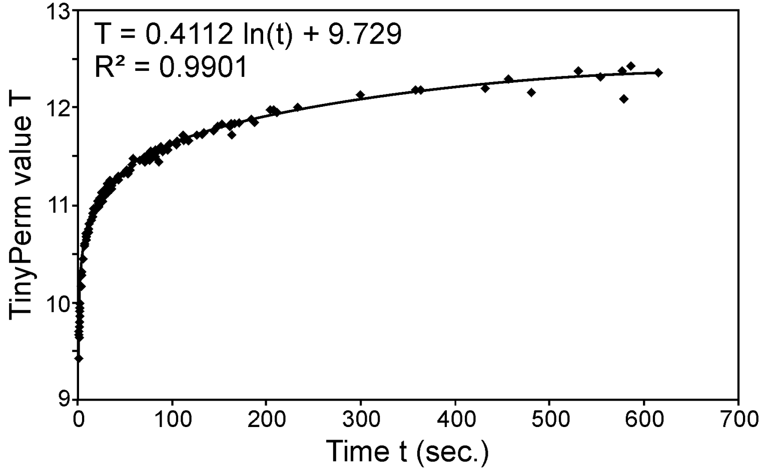

Fig. 3. Cross-plot of TinyPerm II value (T) with needed measuring time (t) in seconds. Note the asymptotic behaviour of the regression line with increasing measuring time.

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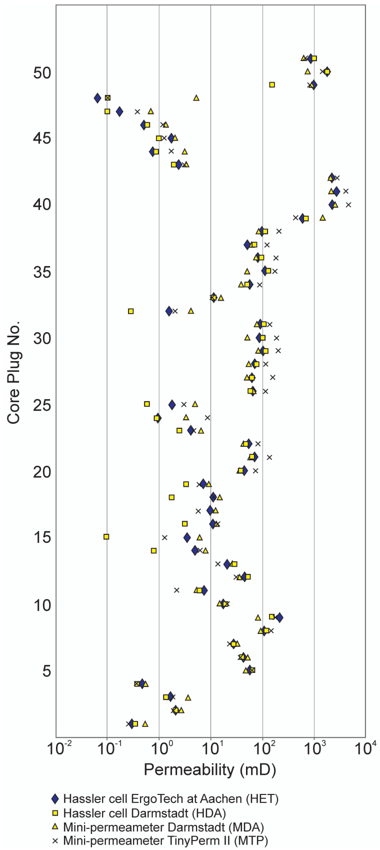

Fig. 4. Permeability data derived from 51 core plug samples, measured with four different air-permeameters: The Hassler cells of the ErgoTech Gas Permeameter (HET, blue diamonds) and the Gas Permeameter Darmstadt (HAD, yellow squares), and the mini-permeameters Miniperm Darmstadt (MDA, yellow triangles) and TinyPerm II (MTP, crosses).

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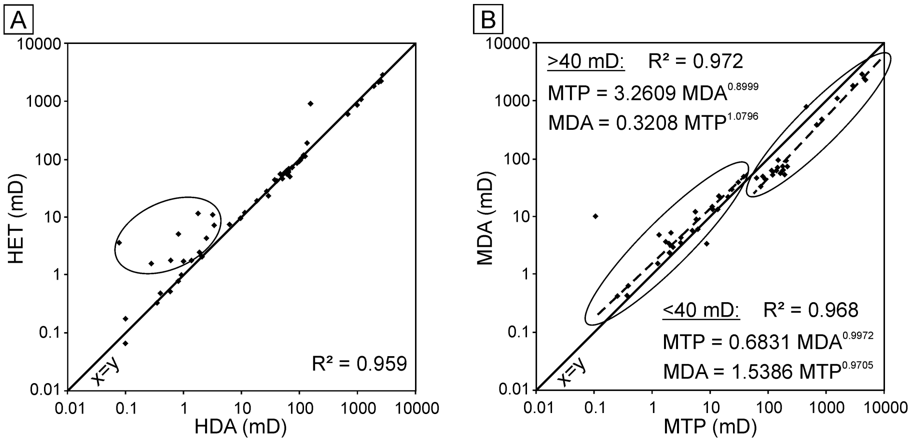

Fig. 5. Comparison of different gas permeameters: **(A)** The Hassler cell devices ErgoTech Gas Permeameter (HET) vs. Gas Permeameter Darmstadt (HDA), and **(B)** the mini-permeameters Miniperm Darmstadt (MDA) vs. TinyPerm II (MTP). The bisectrix ($x = y$) indicates positive or negative aberrations of the measuring results and the dashed line indicates the regression line of the resulting transform equations for standardization. Note the bi-logarithmic scales.

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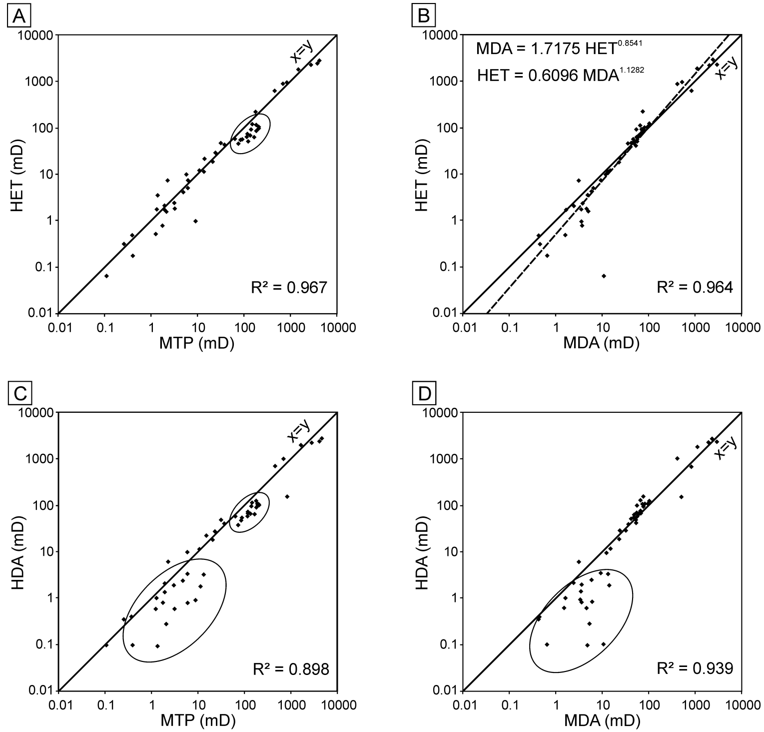

Fig. 6. Comparison of Hassler cell vs. mini permeameter measurements: ErgoTech Gas Permeameter (HET) vs. TinyPerm II (MTP) **(A)** and Miniperm Darmstadt (MDA) **(B)**, and the Gas Permeameter Darmstadt (HDA) vs. TinyPerm II (MTP) **(C)** and Miniperm Darmstadt (MDA) **(D)**. Permeability plots **(C)** and **(D)** exhibit strong scattering below 10 mD. The bisectrix ($x = y$) indicates positive or negative aberrations of the measuring results and the dashed line indicates the regression line of the resulting transform equations for standardization. Note the bi-logarithmic scales.

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