SPECIFIC INTERNAL SURFACE :THE "FORGOTTEN?"PETROPHYSICAL MEASUREMENT!
OR
APPLICATION OF FRACTAL PORE MODELS FOR IMPROVED PERMEABILITY ESTIMATIONS FROM LOGS!

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Abstract

The paper fosters a "revitalisation" of the "Clausthal Concept" and its application for an improved permeability prediction from logs by quantifying the fractal behaviour of specific internal surface as input for modified Kozeny / Carman- type of equations .

Introduction

In most of the commonly used analytical approaches to calculate permeability from logs**,** Kozeny/Carman-type equations (Carman 1956) are applied, which are based on simple capillary bundle models .

$$K = \Phi/ 2T* 1/ S^2_{por}$$

In these equations permeability is derived from porosity Φ , and the two microstructure parameters tortuosity T (very often replaced by an empirical "constant"), and the mean effective hydraulic radius, which is inversely related to the specific internal surface S_{por}, defined as the ratio of surface area to (pore-) volume.

In many of the empirical permeability equations S_{por} is replaced by quantities related to "irreducible" or bound water volumes or is sometimes expressed by parameters derived from mean grain sizes or pore size distributions from capillary pressure curves. Especially for diagenetically altered consolidated reservoir rocks, the complicated internal pore structures could not be described by these models and lead to unrealistic permeability estimations , unless empirically calibrated "fiddle" parameters were introduced, which have no general physical meaning and thus are only valid for special facies types and/or for local investigations.

Though specific surface area is a key petrophysical parameter for the understanding of the physics and relationships of porous media, it was never fully integrated into standard and special core analysis programmes.

Why has this key measurement been nearly totally "forgotten" in the past ? Maybe in the early days it was too difficult and laborious to measure (e.g. by BET adsorption-/desorption isothermes, Image Analysis). But more importantly is it mainly the lack of

petrophysical understanding and concepts to correctly evaluate and interpret Spor measurements!?

If you simply insert a measured high resolution BET surface or a highly smoothed surface derived from Image Analyses (IA) into the Kozeny/Carman equation, the calculated permeability can indeed be several orders of magnitude "wrong", i.e. you tend to systematically underestimate in the case of BET or to overestimate in the case of low resolution IA! This probably led to the "blame" and neglect of the specific surface area measurements as input for improved formation evaluation techniques .

The "Clausthal Concept"

The so-called "Clausthal Concept" – derived in the early eighties at the Petrophysics department of Clausthal University, Germany- provides conversion factors between the smoothed specific surface relevant for hydraulic flow processes and the specific surface derived from the different physical measurements (for example BET adsorption method, NMR surface relaxivity, excess surface conductivity). These conversion factors could be verified experimentally in the lab on a broad scope of very different reservoir rocks covering 8 decades of permeabilities from the micro-Darcy to the Darcy range.

These "surface magnification " factors , which depend on the resolution of the "yardstick" used for the measurement, could also analytically and theoretically be derived by application of the "Pigeon Hole Model" (Pape, Riepe, Schopper 1982) for self similar fractals according to Mandelbrot (1977) (See Fig.1).
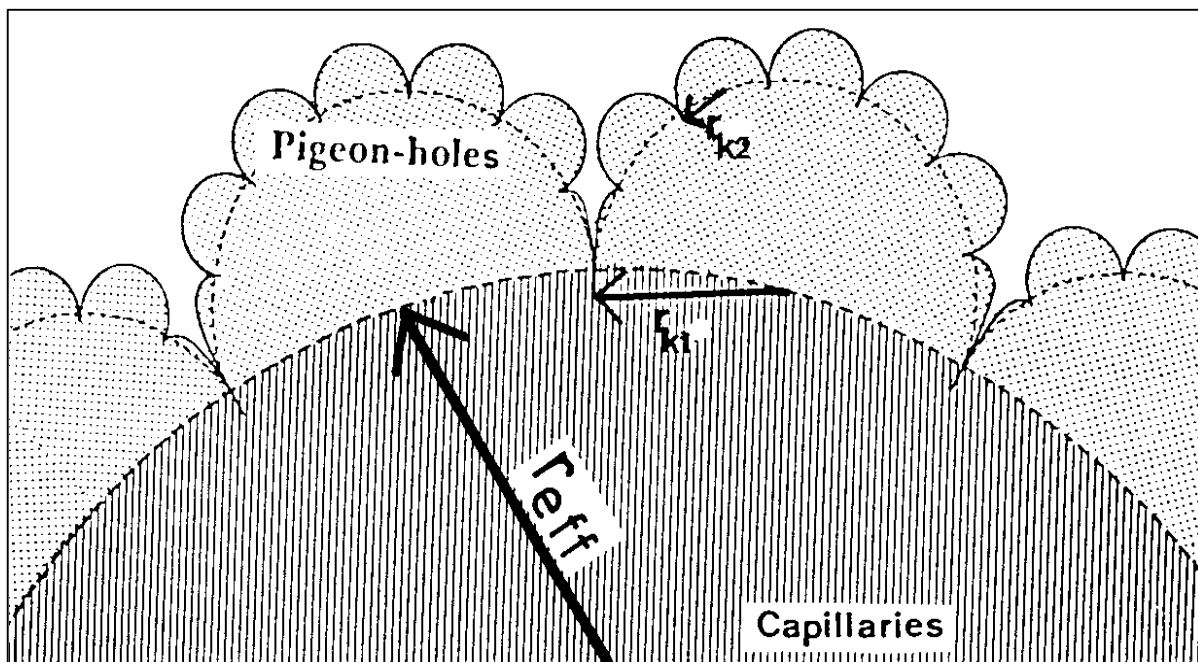
Fig. 1: The "Pigeon Hole" pore model for self similar fractals

The "PARIS Equation"

By calculating the "fractal dimension" of the BET surface area, a new generalised Kozeny/Carman-type equation, the so-called "PARIS-Equation" (**PA**pe, **RI**epe, **S**chopper 1981),could be derived :

$$K= 475.3/F * (S_{por,BET} / q_0)**-3.1085$$

From this equation permeability K (in Darcies) can be calculated from:
- Formation (resistivity) factor F (by assuming that the "hydraulic" tortuosity can be described by the "electrical" tortuosity as derived from a generalised Archie-type equation),and
- Specific internal surface S_{por} (in $1/\mu m$), which can be measured by a BET-adsorption method on core plugs, but on drill-cuttings, too (see Fig .2).

(Please note that the porosity does no longer explicitly enter into this equation, but it is indirectly "hidden" within the formation factor and S_{por}).
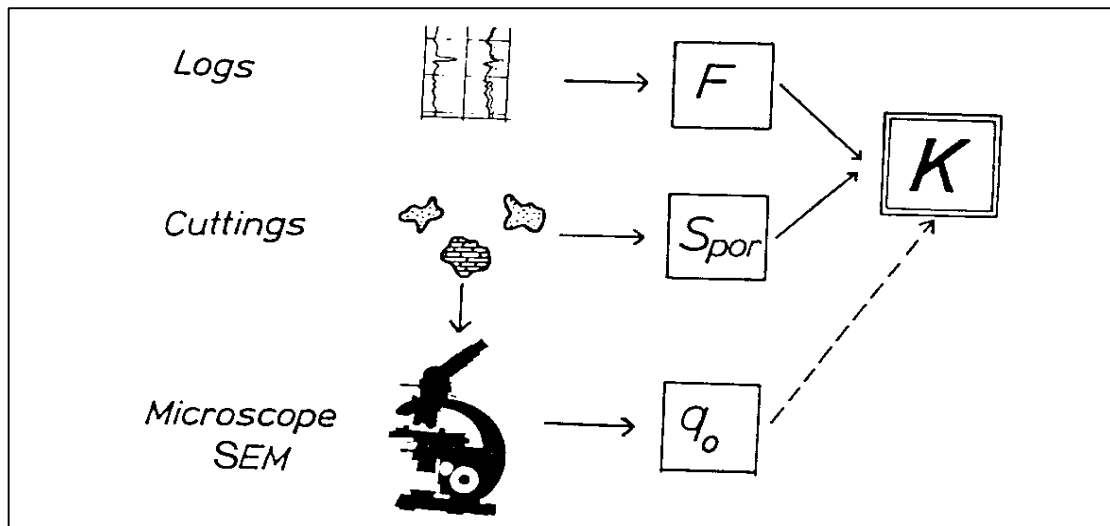
Fig. 2: Calculation of Permeability from the "PARIS Equation"

Application to Logs

The next important step is to get away from any lab measurement and to apply this type of equation to parameters, that can be derived continuously in situ by well logging methods. Laboratory measurements on a large number of different sedimentary reservoir rocks confirmed tight relationships of the specific surface to many different petrophysical parameters (Riepe1979, 1984), for example:

-Electrical parameters: surface ("excess"-) conductivity, electrochemical self-potential (Membrane-Potential) derived from SP, Complex Conductivity (dielectric constant, permittivity) from IP measurements or Dielectric Logs, or

-NMR parameters**:** spin surface relaxation time , bound water volumes BVI and/or "Free Fluid Index "(FFI), or
-Thorium concentration (only in case of a geochemical equilibrium for Th-adsorption and if the contributions from heavy minerals can be corrected), which can be obtained from natural GR-spectra (for example from NGT, SPECTRALOG) .

The "Budapest Equation"

If we insert the experimentally derived correlations for NMR parameters into the "PARIS equation", we get the so called (simplified) "Budapest equation" (see Fig.3; Pape, Riepe, Schopper 1985):

$$K_{NMR} = 475.3/F * [(1/T_{rock}* c_{NMR})/q_o]**-3.1085$$

where T_{rock} represents the mean spin surface relaxation time (in sec) of the (fully water saturated) rock sample, and c_{NMR} is the surface relaxivity "constant "(in sec/μm).
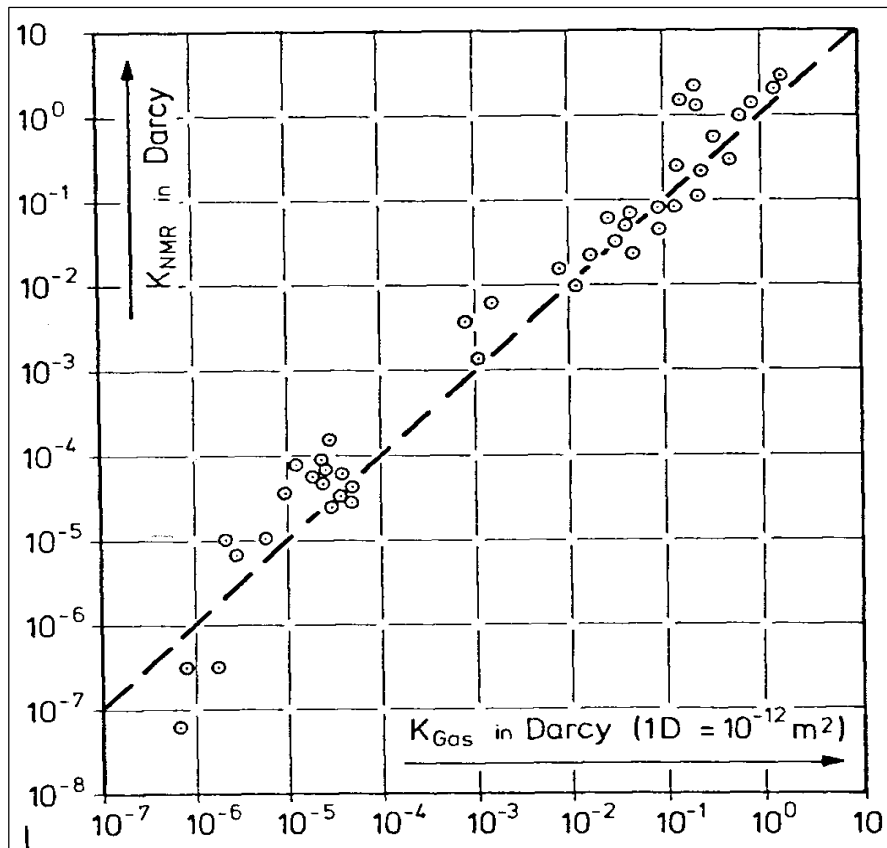
Fig. 3:Comparison of the Gas-Permeability measured in the laboratory with the NMR-Permeability calculated from the "Budapest Equation".

A value of 0.66 sec/ μm for various sandstones had been empirically derived from laboratory measurements of BET surface and NMR relaxation curves on identical plugs (see Fig 4; Riepe 1984).
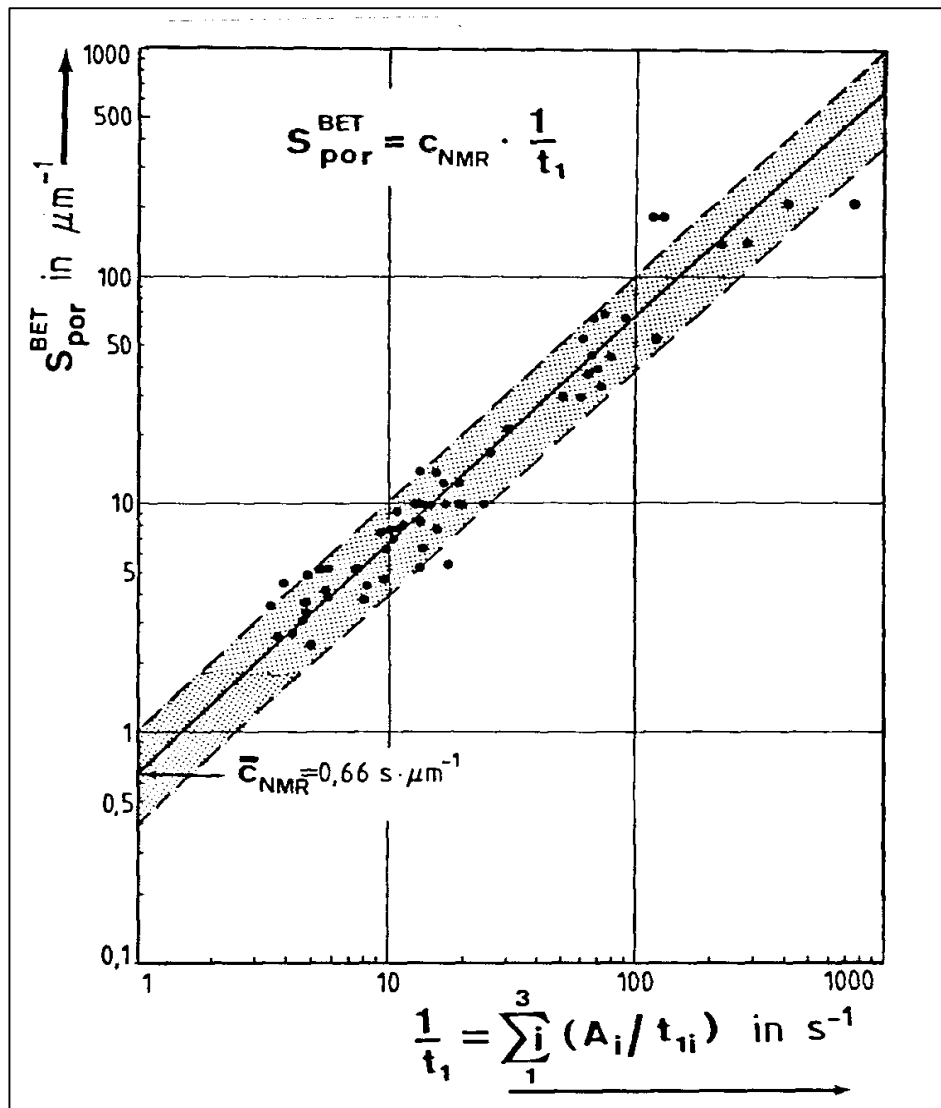
Fig. 4: Correlation of the specific internal BET-surface per unit pore volume with the mean spin relaxation time.

The permeability values calculated from this equation matched within one order of magnitude with Klinkenberg- and Forchheimer corrected gas- or liquid permeabilities measured in the laboratory in the range from 0.1μD to 10 Darcies for a great variety of sedimentary rocks from oil and gas wells and outcrops (see Fig.3).

The "Aberdeen Equation"

If we replace the BET surface by the correlation with the Thorium concentration c_{TH}, we get the so called "Aberdeen equation" (Pape, Riepe, Schopper 1986):

$$K_{Th}= 475.3/F* \{[(1-\Phi)/\Phi*\rho_{mtx} (c_{Th}/a_{Th})**2] / q_0\}**-3.1085$$

Here a_{TH} represents an empirically derived mean Th-adsorption density per unit surface (see Fig.5).

(Please note, that in this equation the additional parameters porosity Φ and matrix- or grain density ρ_{mtx} enter in order to transform the correlation as derived for the specific surface per unit mass S_g (in m**2/g) into the specific surface per unit pore volume S_{por} (in $1/\mu m$)).
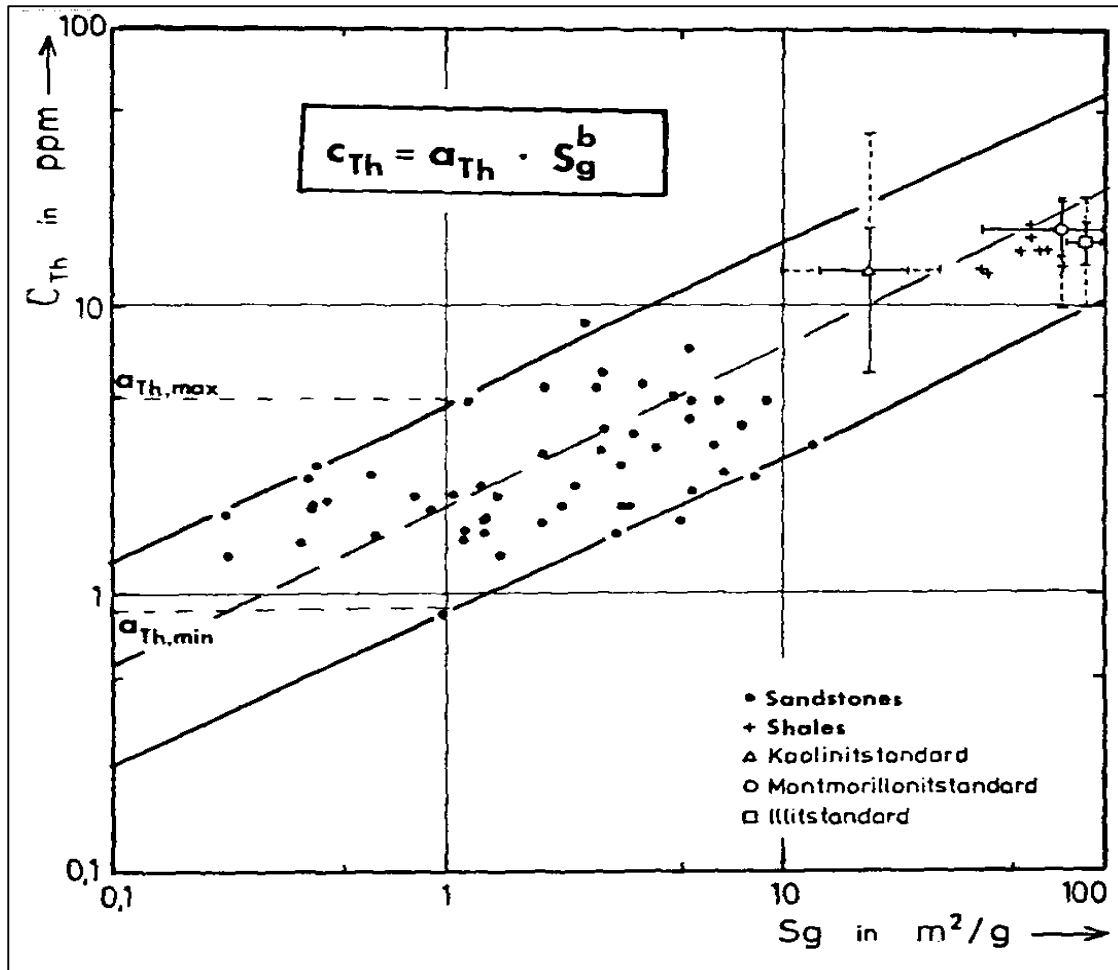

Fig. 5: Correlation of the specific internal surface per unit (grain-, matrix) mass with the Thorium concentration from natural GR-spectra.

Permeability values calculated from this equation from Thorium concentrations as measured from logs and in the laboratory matched within one order of magnitude with permeabilities measured in the laboratory in the range from 0.1μD to 10 Darcies for a great variety of sedimentary rocks from oil and gas wells and outcrops (see Fig. 6).
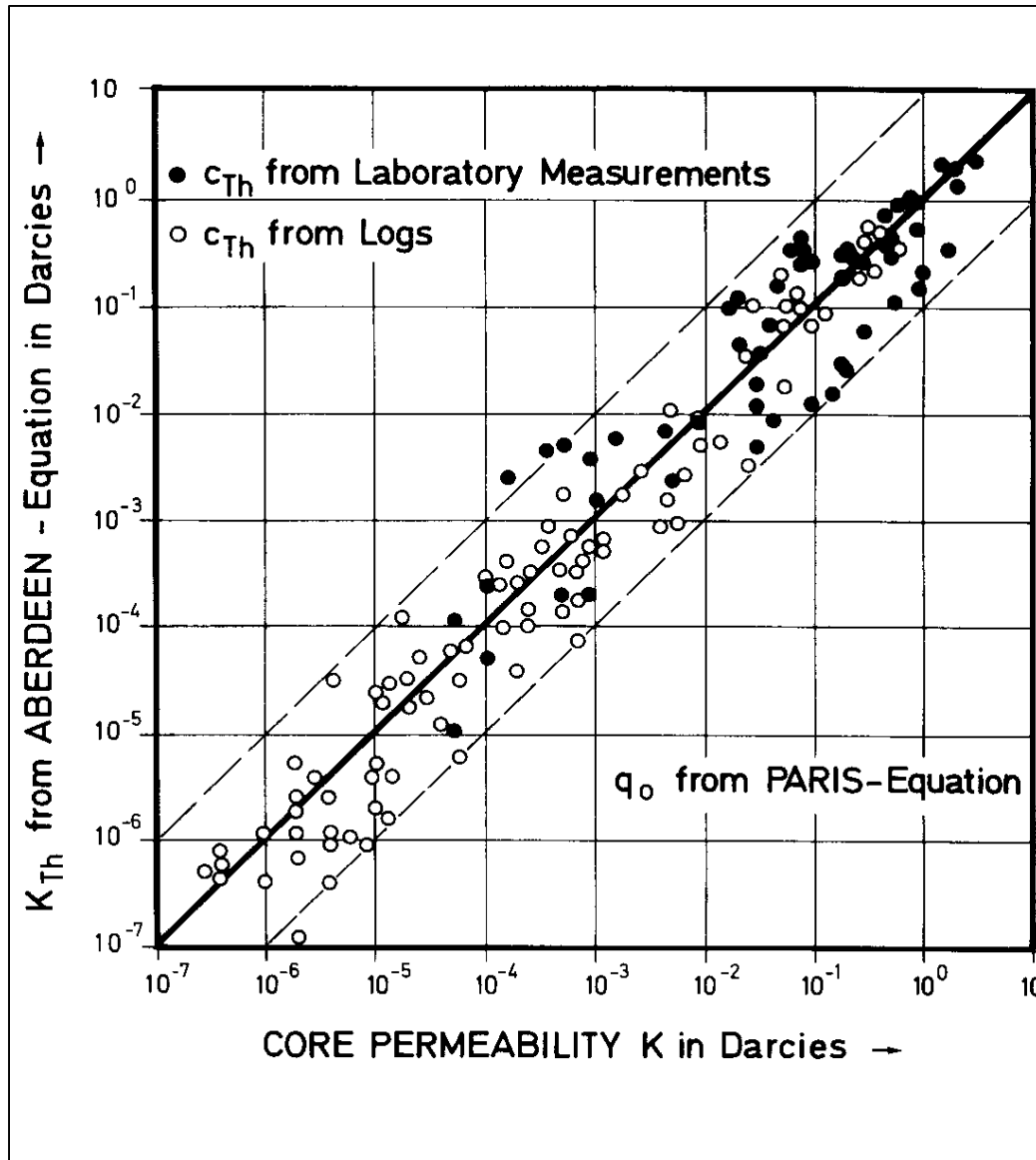
Fig. 6:Comparison of measured laboratory permeability with the "Th-permeability" as calculated from the "Aberdeen Equation" with Thorium- concentrations from logs and cores.

It should be mentioned that in all these concepts and equations an additional dimensionless "lithology factor" q_o enters, which takes into account "abnormal" S_{por} values due to surface smoothing ($q_o<1$) or surface magnifications ($q_o>1$), representing special diagenetic developments (e.g. additional lamellae by clay minerals or iron oxide encrustations). In the laboratory these q_0 factors can be directly determined from the deviations from the ideal line for the "PARIS equation" ($q_0=1$ for ideal self similar surface structures), if permeability, formation factor and the specific surface $S_{por,BET}$ have been measured on identical plugs (see Fig.7).
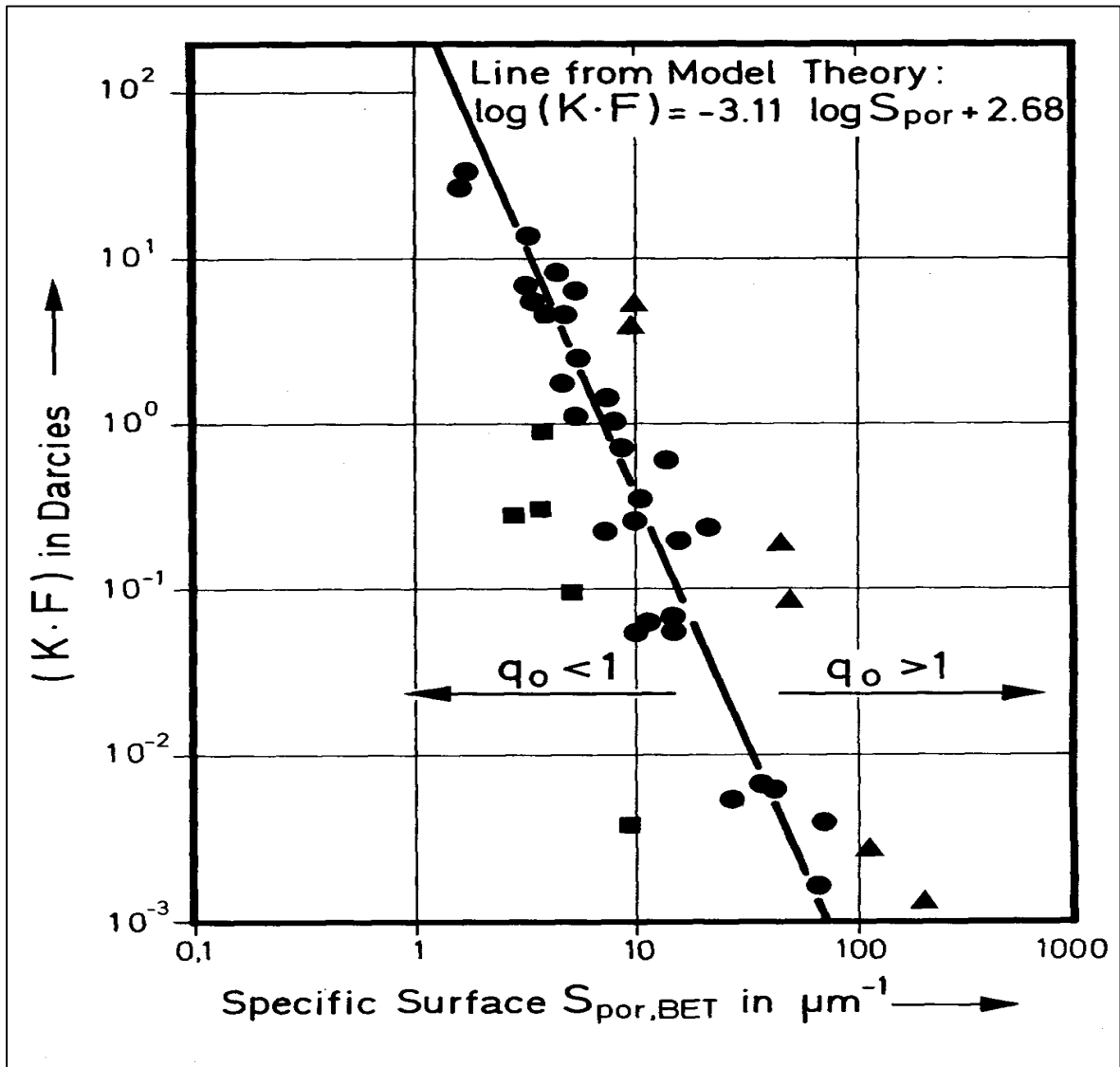
Fig. 7: Experimental verification of the "PARIS- equation" and quantification of the "lithology factor q_o from deviations of the ideal model line.

Further geological or petrographic "control" - for example on thin sections and/or SEM images at different magnifications- is still recommended to identify these " anomalies" within the pore structures and thus to support the understanding of the deviations from the simplified pore models .

Practical Experiences

Though the validity of the principal petrophysical concepts could be confirmed in the laboratory, the direct application of the above equations to field logging data was very limited and problematic in the past. Due to tool limitations in vertical resolution and depth of investigation, and due to disturbing environmental/ borehole effects, the requested petrophysical (e.g. electrical and NMR-) parameters could not be acquired with sufficient accuracy .

Thorium Concentration

Thus during the eighties and early nineties only the application of the "Aberdeen equation" was investigated, as the natural GR spectra (i.e. the Th –concentrations) were routinely available in many wells. In spite of a few promising examples for a Rotliegendes gas field in Germany (Schopper et al 1987), the general correlation between specific surface and Th-concentration is rather "broad" and very often disturbed by unpredictable geochemical peculiarities,(for example by heavy minerals). Thus attempts to improve permeability predictions -which are still mainly based on porosity/permeability crossplots- in some UK oil fields in the North Sea by the Aberdeen equation were not successful.

Electrical Parameter

The application of the electrical concepts require clear salinity contrasts between the formation waters and the (conductive) muds, and well defined invasion profiles in order to quantify and separate the conventional "volume" conductivity term from the "surface" conductivity term (Pape et al 1984,1987). In many areas with high salinity formation waters and muds, the surface conductivity term is too small and cannot be extracted from conventional resistivity logs.

Nevertheless in fields with rather "fresh" formation waters, together with the latest generations of array tools , which can provide rather distinct radial resistivity profiles at different frequencies, a "renaissance" of this concept is very likely and promising.

NMR Parameter

A real revolutionary breakthrough has been achieved in NMR logging technology in the past five years with the pulse-echo technique and the capability to measure T2 signals below 1ms, that is to detect capillary bound and even clay bound water components. Thus a continuous in situ recording of T2 spectra and its BVI component is possible and well proven, and semi-empirical Kozeny/Carman type equations are well established and extensively published in the previous years to predict permeability from BVI and /or mean T2 values.

Though the physical concept of the NMR interpretation is of a very generic nature, practical experience in previous years with NMR logs in about 20 North Sea oil and gas wells have clearly shown the still existing need for cores to calibrate T2 spectra (e.g. for BVI cut-offs), and to investigate potential effects of wettability changes (by Oil based mud invasion?!) in multiphase flow environments. Further measurements of specific surface will play a vital role to fully understand and calibrate the T2 spectra and surface relaxivity mechanism and its application for permeability prediction . The ongoing investigations will result in a "revitalisation" and potential modification of the old "Budapest equation" and significantly improve the reliability of permeability estimations from NMR-logs.

Conclusions

- Specific internal surface is a key parameter to understand the physics of porous media and to derive equations for permeability predictions from other petrophysical parameters, for example from NMR surface relaxation or surface conductivity.
- With the help of rather simple geometrical models-where the main hydraulic capillaries are superimposed by a cascade of self-similar semicircular "pigeon-hole" structures- the dependence of specific surface from the power of resolution of the different measurements can be calculated.
- These theoretical conversion factors-which represent the fractal behaviour of the specific surface- together with the empirically lab derived correlations for S_{por} with other log derived petrophysical parameters, result in modified Kozeny/Carman type equations for improved permeability predictions from logs.
- The great progress in logging technology now offer the potential to revitalise the application of the "Clausthal Concept" for better in situ permeability estimations.
- The latest NMR pulsed echo logging technology provides the greatest potential for reliable and rather universal permeability predictions from logs.
- Nevertheless a geological or petrographic "control" is still recommended to improve the results, which underlines the need for an interdisciplinary view and the ongoing challenge to fully understand the (petro-)physics and the many times still unpredictable behaviour of the permeability, this "Moody Diva" in petrophysics.

Acknowledgements

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