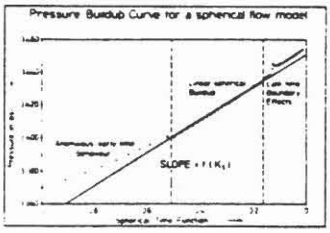
Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland
Permeability Estimation from Logs based on
a new Petrophysical Model

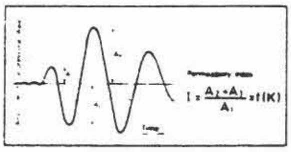
The Clausthal Concept

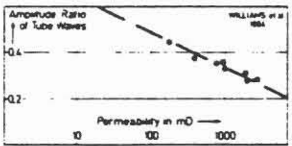
Ia Present Downhole Measurements Related to Permeability

- **Cable Tester (FMT, RFT)**
  - Point Information from Pressure-Buildup/ Drawdown Curves (Horner-type Plots)



- **Acoustic Logs**
  - Attenuation of Compressional Waves
  - Travel time and Amplitude Ratio of Tube Waves





- **Electrical Logs**
  - Infiltration Profiles
  - Irreducible Water Saturation
  - Induced Polarisation
  - Complex Resistivity
  - Interlayer Conductivity
- **Nuclear Magnetic Resonance (NMR-) Logs**
  - Free Fluid Index
  - Spin-Relaxationtime
- **Natural Gamma-Ray Spectrometry**
  - Thorium Concentration

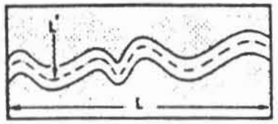
Permeability from Logging Parameters with strong Correlations to Specific Internal Surface!

Authors: J.R. Schopper, H. Pape/TU Clausthal, FR Germany · A. Fülöp/Texaco, FR Germany
L. Riepe*/BEB, FR Germany · R. Wehr*/Dresser Atlas, FR Germany
*formerly TU Clausthal, FR Germany

Ib Linking of Measurable Log-Parameters to Permeability by Structural Models of Intergranular Pore Systems

● **Conceptual Model for a Bundle of Capillary Tubes (KOZENY/CARMAN 1913, 1956):**

$$K = \frac{\Phi}{8T} \, r_{hyd}^2 \qquad (1)$$



Permeability $K = f\left(\text{Tortuosity } T = \left(\frac{L'}{L}\right)^2, \text{ Porosity } \Phi = \frac{V_{por}}{V_b}, \text{ mean effective hydraulic radius } r_{hyd}\right)$

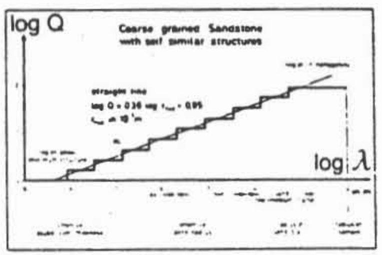
Introducing the Concept of **FORMATION FACTOR** $F = T/\Phi$ and replacing r_{hyd} by the Specific Internal Surface S_{por}

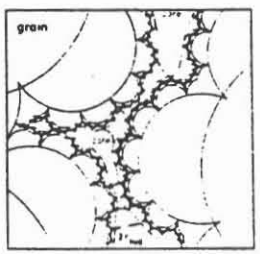
$$r_{hyd} \sim \frac{V_{por}}{S_{abs}} = \frac{1}{S_{por}} \qquad (2)$$

Reduces Permeability Estimation to

$$K \cdot F \sim S_{por}^{-2} \qquad (3)$$

● **New "PIGEON-HOLE"-Model for Self Similar Pore Structures (PAPE, RIEPE, SCHOPPER 1981):**





In real Rocks S_{por} is composed of structures of different order of magnitude, i.e. the pore wall surface has a Fractal Dimension D (according to MANDELBROT 1977). For sedimentary rocks D = 2.36 could be confirmed experimentally.

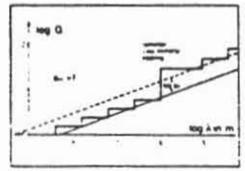
The fractal theory implicates that S_{por} -values, measured by different methods with different "yardsticks" λ_i, are related by a **Conversion Factor Q**

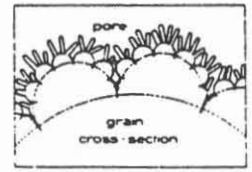
$$\log Q = \log \frac{S_{por}(\lambda_1)}{S_{por}(\lambda_2)} = (2 - D) \log \frac{\lambda_1}{\lambda_2} \qquad (4)$$

Ic Derivation of a General Permeability Equation

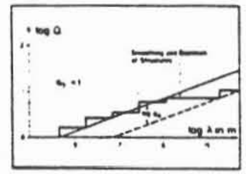
In nature the self similar pore structures can be changed by Diagenetic Processes:

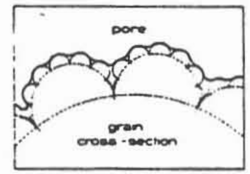
● **An increased surface by additional "Lamellae structures", e.g. by clay minerals:**





● **A smoothed surface, e.g. by cementing minerals**





The influence of both types of surface changes on permeability can be quantified in the model by the introduction of one single **Lithology Factor q_o**

Application of the complex model to hydraulic flow processes results in the

"PARIS" -Equation:

$$\log (K \cdot F) = \alpha \log (S_{por} / q_o) + \beta \qquad (5)$$

The model-constants α and β depend on D from fractal theory and on λ_i from surface area measurement.
In case of S_{por} derived from BET-adsorption measurements:

$$\alpha_{BET} = -3.11 \qquad \beta_{BET} = 2.68$$

if K in Darcies and S_{por} in $\mu m^{-1} = m^2/cm^3$.

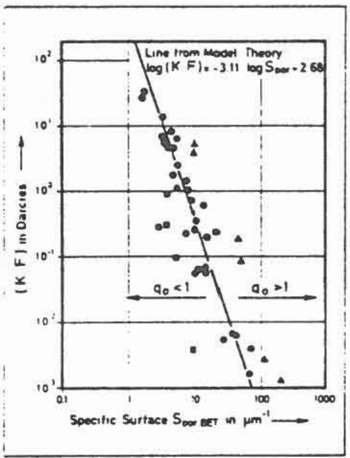
The Lithology Factor q_o can be deduced from empirical correlations combining Core and Log-Data.

Experimental Verification of the Concept

IIa Experimental Proof of the PARIS-Equation

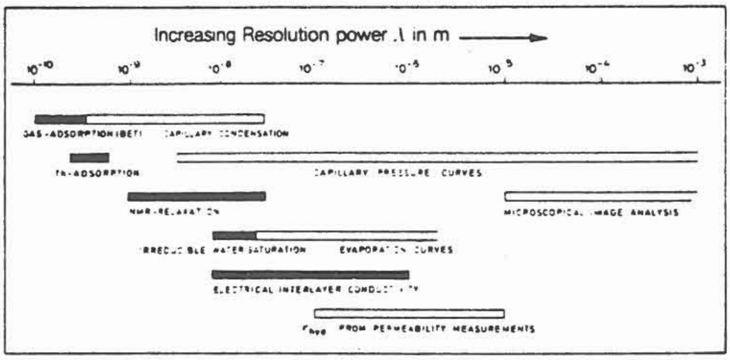
Laboratory measurements on a great variety of sedimentary rocks corroborate the general validity of the model derived PARIS-Equation:

The deviations from the Model Line can be used as a direct method to calculate the Lithology Factor q_o.



Practical application of this Equation needs the use of Log-derivable surface dependent parameters P (S_{por}).

The resolution power of present methods for determining S_{por} is different:



IIb General Flow Chart

for the Derivation and Control of adapted Permeability Equations

Derivation of a Theoretical Relation for each Parameter $P = f(S_{por})$

↕

Experimental Control $P = f(S_{por,\ BET})$

↓

Replacing $S_{por,\ BET}$ by $f^{-1}(P)$ in (5)

↓

Calculation of "Yardsticks" $\lambda_i(P)$ in (4)

↓

Derivation of Equations analogeous to (5) with Calculated Model Constants $\alpha(P)$ and $\beta(P)$ for $\lambda_i = r_{hyd}$

↓

Final Result: $K = f(P, qo)$

↕

Experimental Verification with Core Data

↓

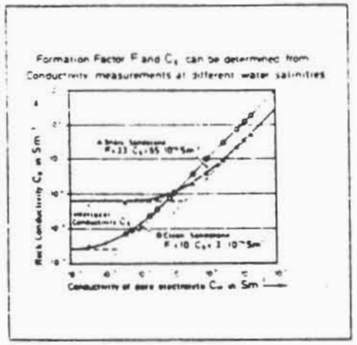
Application to Logging Data

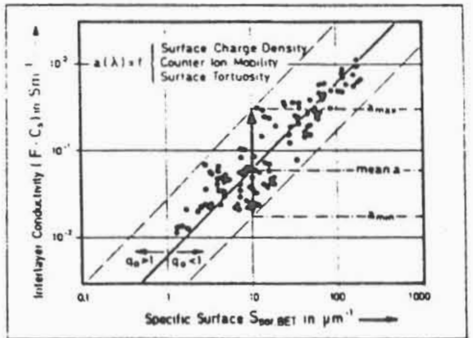
IIc Permeability from Electrical Measurements

General Conductivity – Equation for Porous Media:

$$C_O = \frac{1}{F} C_W + C_S \quad (6) \qquad C_S = \frac{a}{F} \cdot S_{por}$$

Rock Conductivity = Pore Fluid Conductivity + Interlayer Conductivity C_S





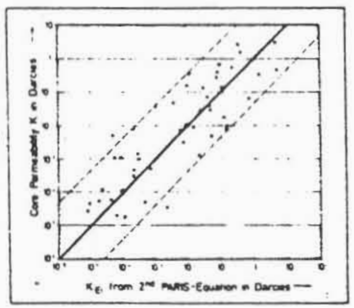
Combination of electrical and hydraulic parameters:

$$C_S = 85.8 \cdot 10^{-3} \cdot r_{hyd}^{-0.677} \cdot F^{-1} \quad (7)$$

C_S in S/m
r_{hyd} in μm

Final Result:
Simplified **"2nd PARIS-Equation" (1984)**

$$K_{El} = 0.58 \cdot 10^{-4} \cdot F^{-4} \cdot C_S^{-3} \cdot q_O \quad (8)$$

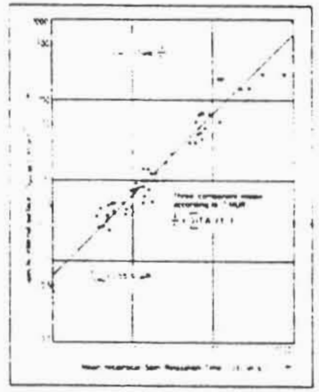


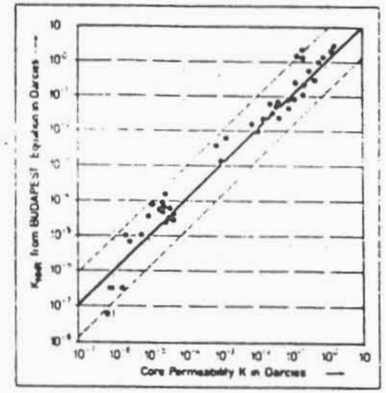
K_{El} in Darcies
C_S in S/m

IId Permeability from Nuclear Magnetic Resonance (NMR)

Based on Correlations of S_{por} with Spin-Relaxationtime t_1 and Free Fluid Index (FFI).

$$S_{por} = \left(\frac{1}{t_1} - \frac{FFI}{\Phi} \cdot \frac{1}{t_w} \right) \cdot C_{NMR} \quad (9)$$

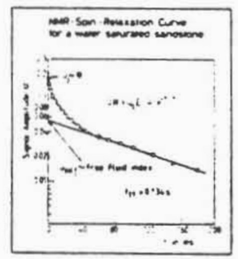




Final Result: Simplified **"BUDAPEST-Equation" (1985):**

$$K_{NMR} = \frac{475}{F} \left(\frac{1}{t_1} \cdot C_{NMR} / q_o \right)^{-3.11} \quad (10)$$

K in Darcies
t_1 in s
$C_{NMR} = 0.66 \text{ s} \cdot \mu m^{-1}$



Permeability from Natural Gamma-Ray Spectroscopy

IIIa Experimental Verification

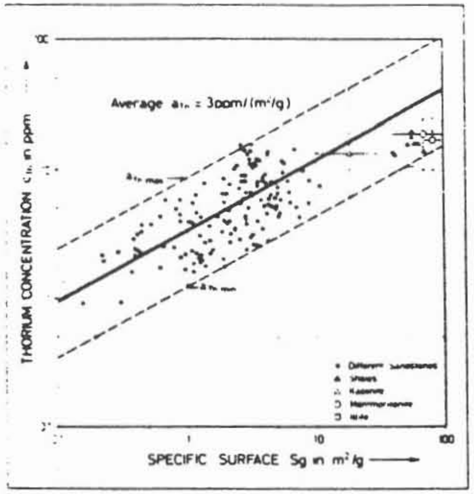
The accumulation of Thorium (Th 4+) in sedimentary rocks is governed by adsorption mechanisms.
Consequently, Th-Concentrations C_{Th} determined from Laboratory GR-Spectra show a direct relationship to Specific Surface S_g referred to the unit rock mass.

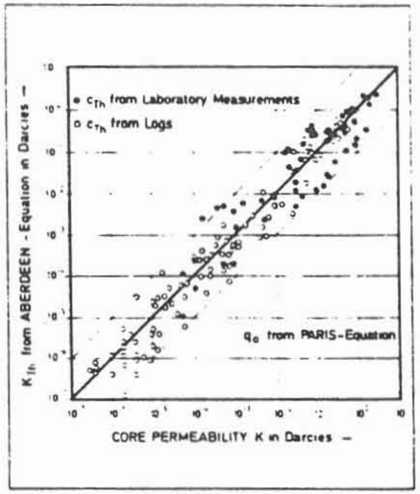
$$C_{Th} = a_{Th} \cdot S_g^{1/2} \qquad (11)$$

$$S_g = \frac{\Phi}{(1-\Phi)} \cdot \frac{S_{por}}{\rho_M} \qquad (12)$$

a_{Th} = Average Mass of Thorium-Ions per Surface Area

ρ_M = Matrix Density in g/cm³





Final Result:

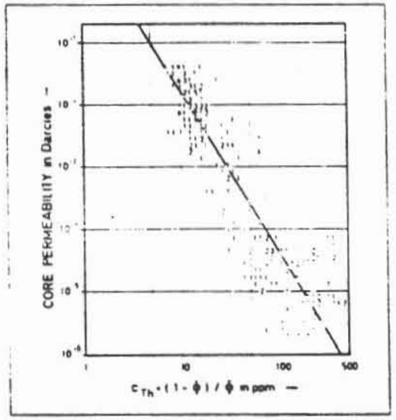
"ABERDEEN-Equation" (1986):

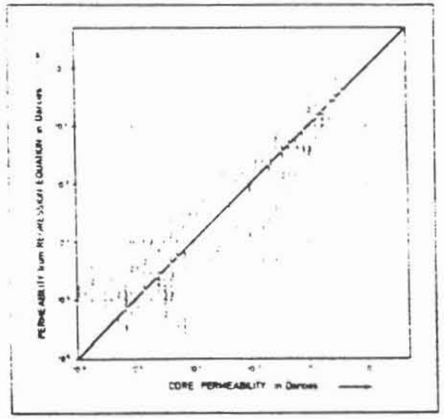
$$K_{Th} = \frac{475}{F}\left[\frac{(1-\Phi)}{\Phi}\cdot\frac{1}{q_o}\cdot\rho_M\cdot\left(\frac{C_{Th}}{a_{Th}}\right)^{2}\right]^{-3.11} \qquad (13)$$

IIIb Field Verification Example

Verification is based on treating Core-Data (K, Φ, F, ρ_M, P_c) and Thorium Content from Spectrometry-Logs

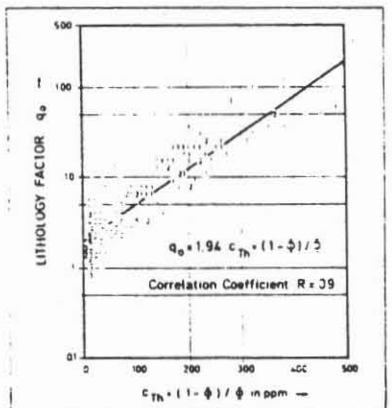
Empirical Proof of the Relationship $K = f(C_{Th})$

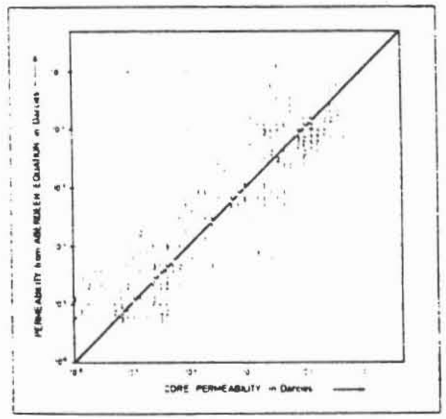


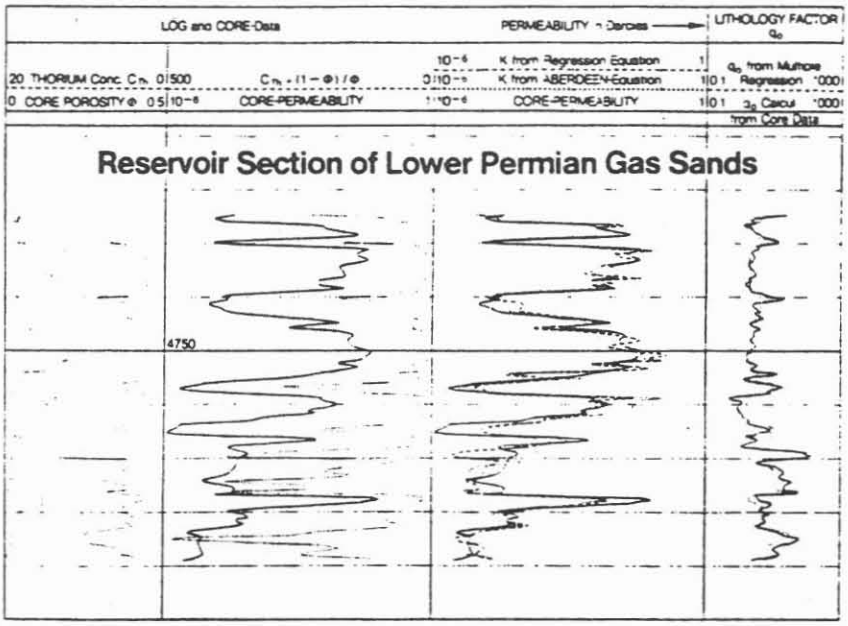


Proof of Model Theory

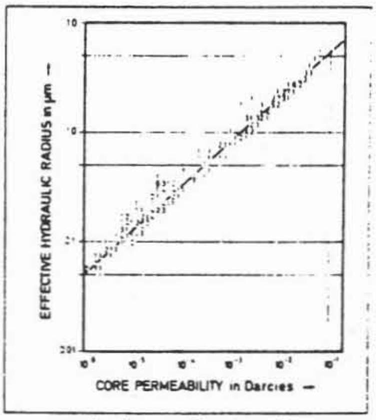
Determination of $q_o = f(C_{Th}, \Phi)$



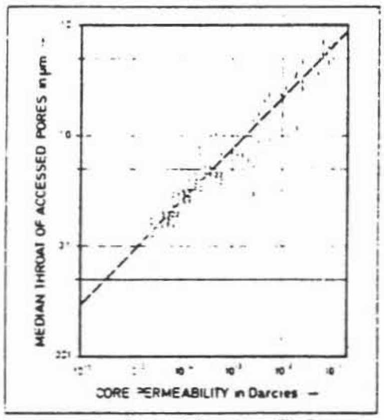




Calculation of hydraulic radius r_{hyd} from Equations (8) and (7):



r_{hyd} results from C_{Th}-Log Data and Φ, F Core Data



r_{hyd} results from Mercury P_c-Curves