The RF Dielectric Behavior of Shaly Sands

A Viable Approach in Terms of Petrophysical Parameters

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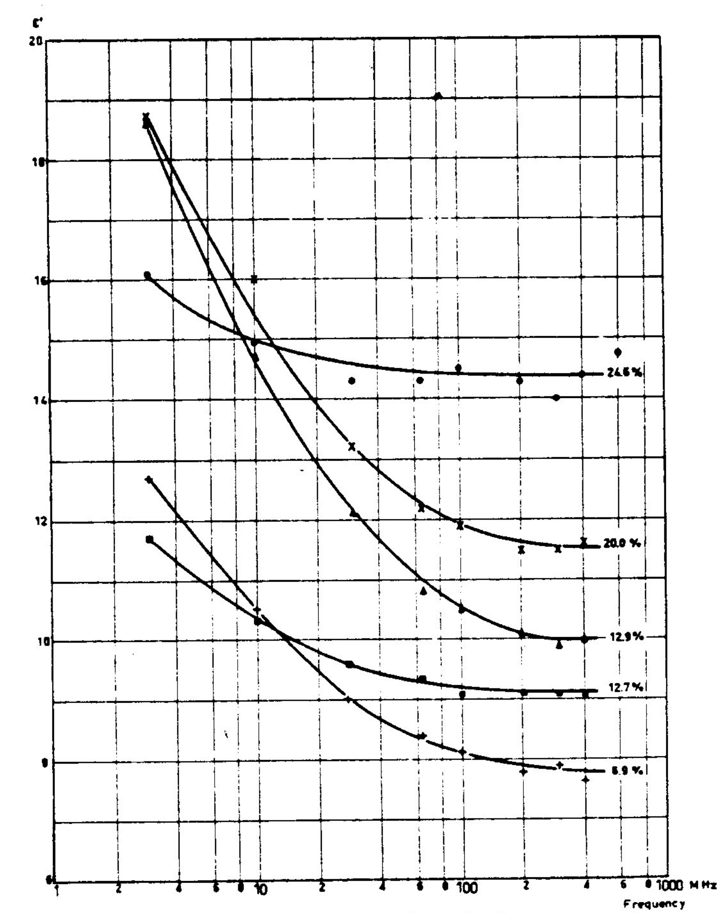
History of Dielectric Logging

- Origins – 1960's pioneering research
- **Motivation** – low salinity formation water (high resistivity) masking the usual contrast with any oil present
  - Simplisitic Idea – exploit the contrast between the relative dielectric permittivity of water (~80), oil & gas (~1-2),and rock (~4-8)
- **GHz region** -- minimal frequency and salinity effects

Dielectric Behavior of Sandstones



The Real Part of the Dielectric Constant of Fresh Water-Saturated Sandstones as a Function of Frequency
FIGURE 4

From Poley et al.

Dielectric Logging Tools

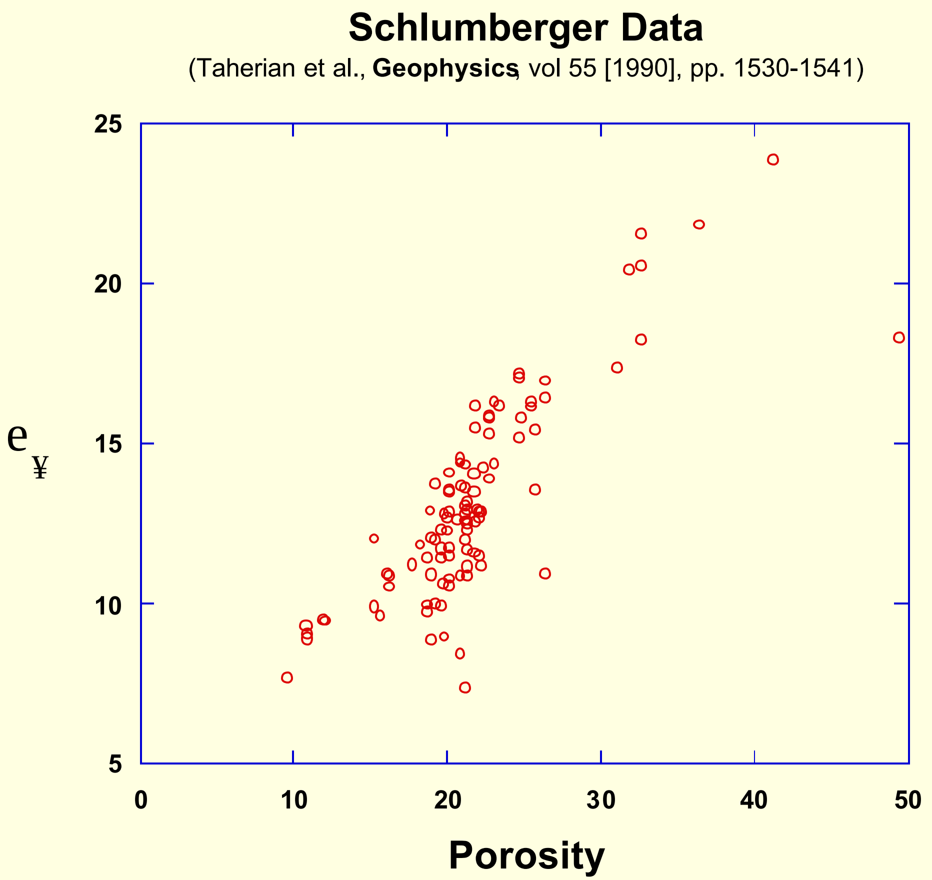
- Initial tools operated around 1 GHz
  - Limited depth of penetration into the formation (a few inches)
- Development of lower frequency (RF) tools (mainly in the 10 – 100 MHz region)
  - Done without any existing/viable interpretation
  - Led to a great amount of research in the 1980's
  - Only one known program succeeded in laying the foundation for interpreting RF tools (M. Rosen's for shaly sands)

Reasons for Failure

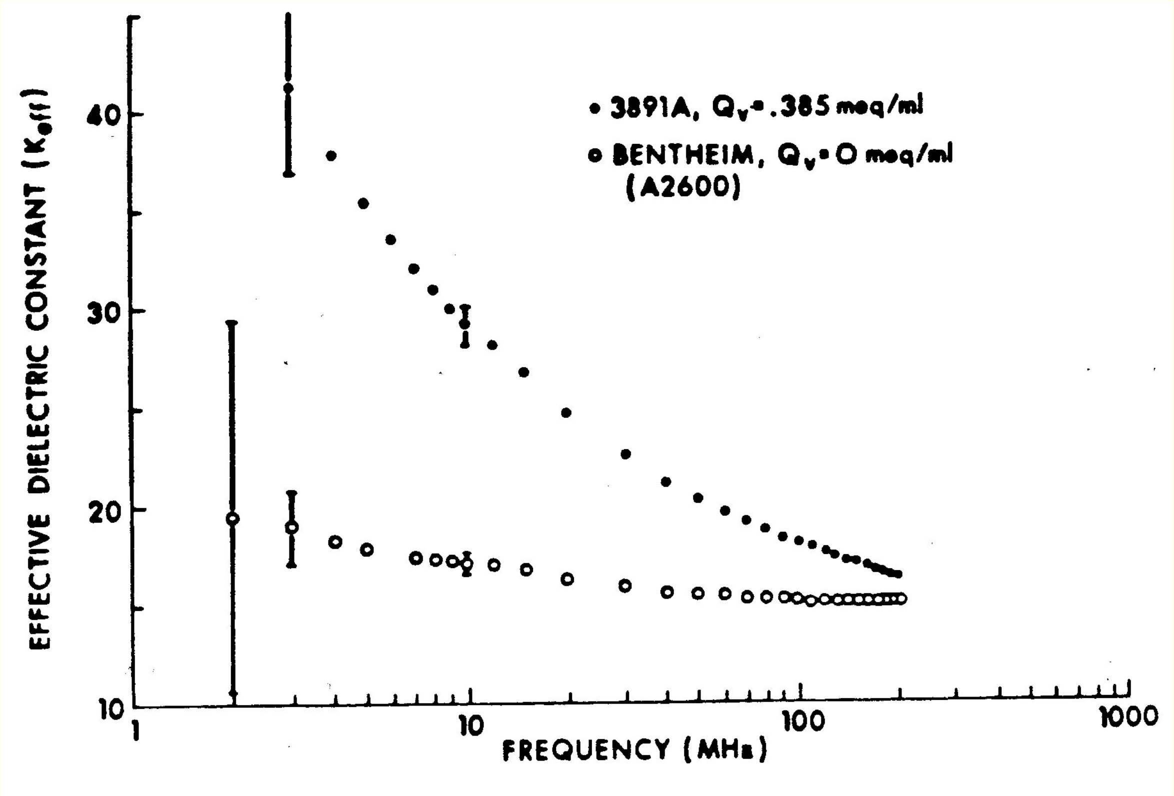
- Lack of a practical approach
- Biased by preconceived and pet ideas
- Failure to examine the trends in the measurements
- Failure to express the behavior in terms of useful petrophysical parameters
  - Platiness – a construct that can help to explain the increase in polarization that is not very useful
- **Bad Data** – probably the most critical factor for failure

BAD Data

(A Summary of Schlumberger's Published Sandstone Measurements)

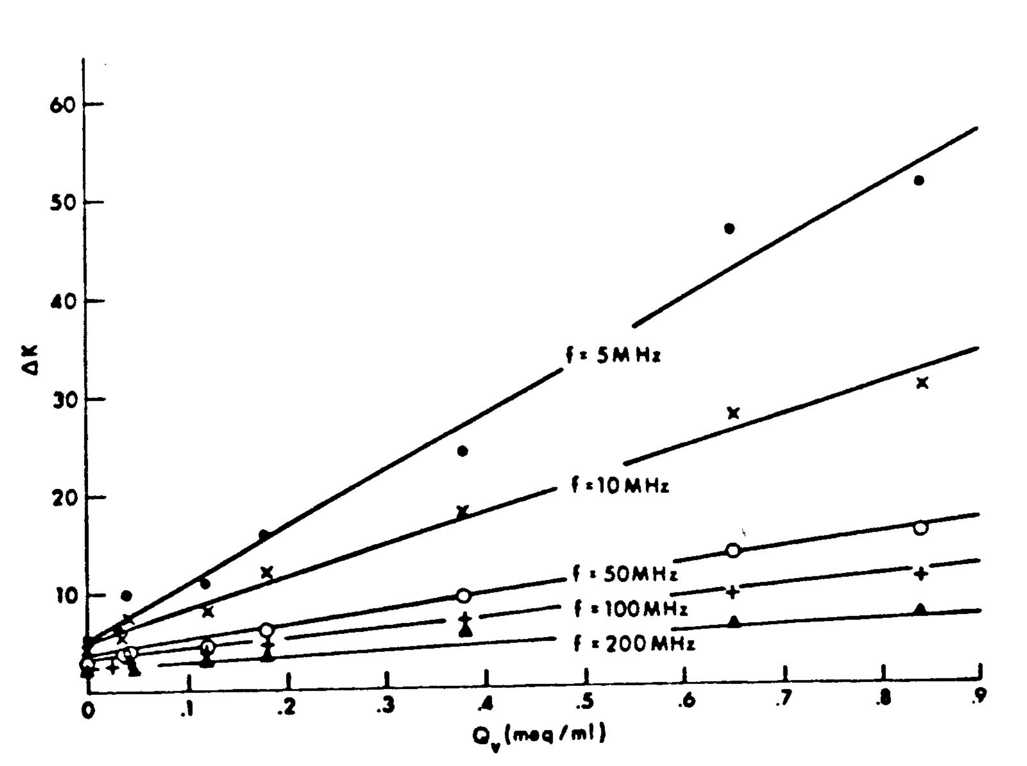


Effect of Clay on the Dielectric Behavior of Sandstones



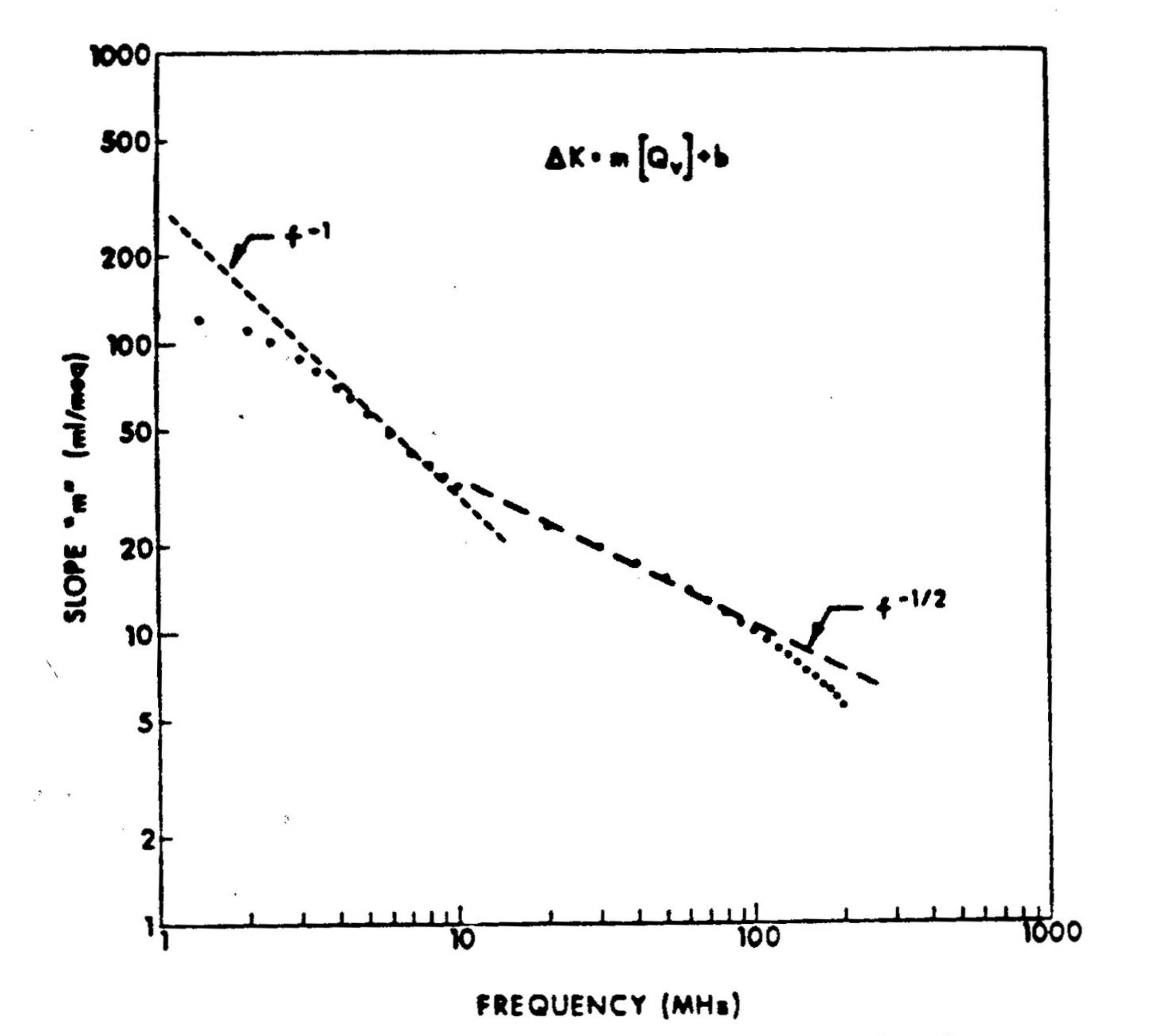
Rosen, 1983

Correlation between Dielectric Dispersion and Shaliness (Q_v)



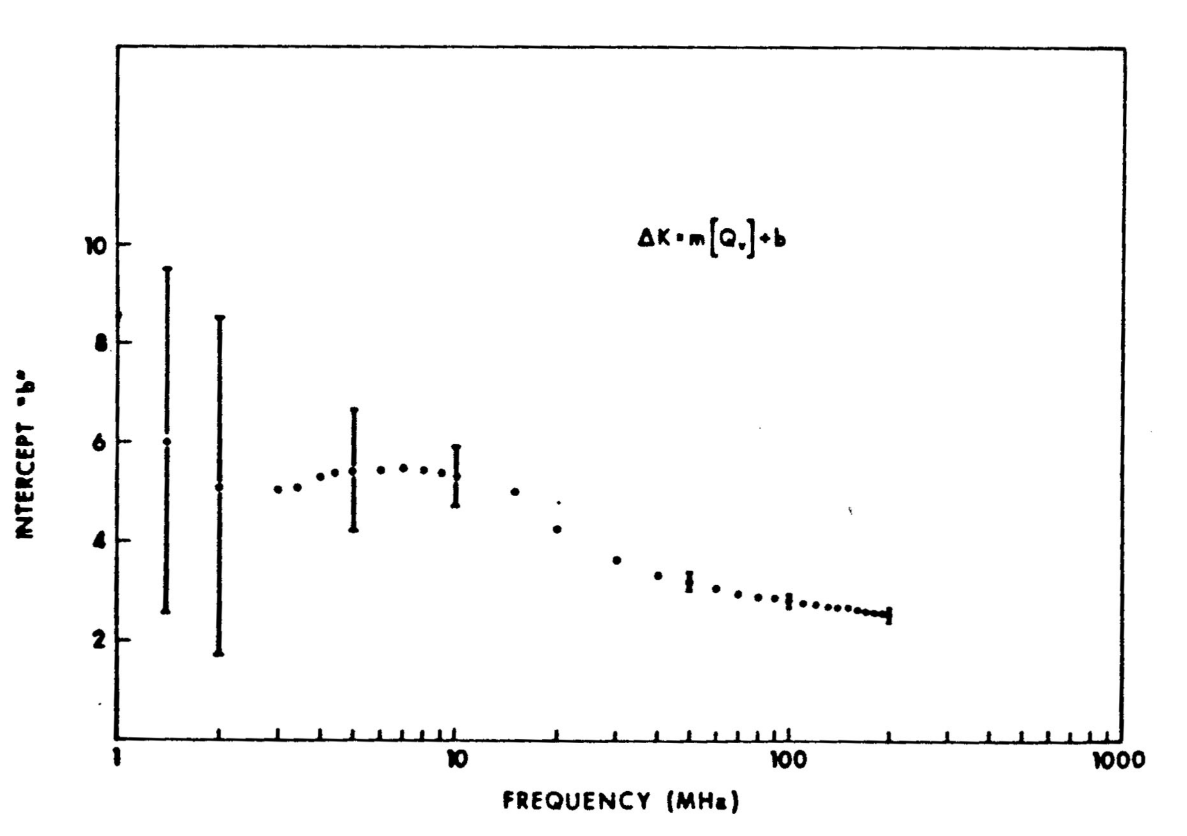
Rosen, 1983

Calculated Slope "m"



Rosen, 1983

Calculated Intercept "b"



Has the appearance of a contribution due to geometry

Rosen, 1983

A New Petrophysical Parameter Q_{bv}

$$Q_{bv} = \phi \, Q_v$$

- Q_v initially worked because the original sample set had little variation in porosity
- Gedanken experiment: If I had 2 rocks with identical Q_v but where one had twice the porosity of the other, they both could not have the same polarization density (i.e., permittivity)
- Therefore, we need to normalize to the total volume, not the pore volume (polarization is a volume weighted phenomenon)
- This has been verified by measurements on samples of varying ϕ taken from Johnson City Test Well #3

Induced Polarization (IP) of Shaly Sands

Vinegar-Waxman Approach

GEOPHYSICS, VOL. 49, NO. 8 (AUGUST 1984); P. 1267-1287

Mistake #1

Assumed that C_q was proportional to Q_v

Needed an "unexplainable" factor of "f" to match their measurements

$$F_q = F^* f$$

$$C_q = \frac{l Q_v}{F^* f} + b_v \qquad F^* = f^{-m^*}$$

$$\text{for } m^* = 2$$

$$\frac{Q_v}{F^* f} = \frac{Q_v}{f^{-2} f} = f Q_v = Q_{bv}$$

Dielectric Equation for Fully Water Saturated Low Salinity Shaly Sands

$$K = e_r^{'} = A\frac{Q_{bv}}{\sqrt{f}} + b(f, f) + 35f + 4.4$$

$$\text{for } \; 10 < f < 100 \text{ MHz and } \; f < .35$$

Shaliness Log

Dual frequency logging tool operating in the 10-100 MHz region

$$K = e_r' = A \frac{Q_{bv}}{\sqrt{f}} + b(f) + 35f + 4.4$$

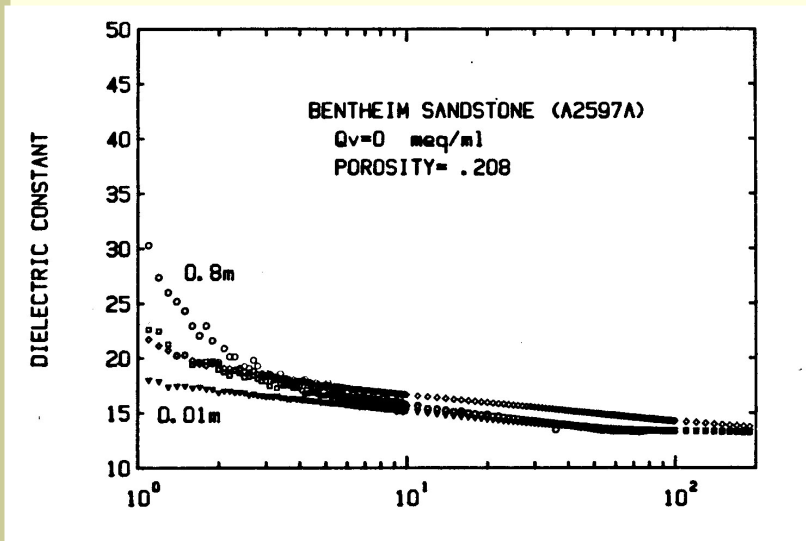
$$\Delta K = K(f_2) - K(f_1) = AQ_{bv} \frac{\sqrt{f_1} - \sqrt{f_2}}{\sqrt{f_1 f_2}} + \Delta b$$

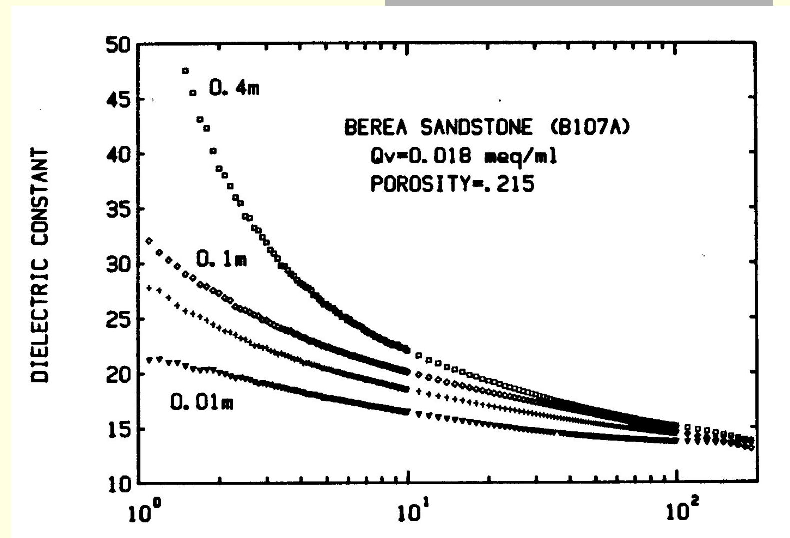
$$Q_{bv} = \frac{(\Delta K - \Delta b)\sqrt{f_1 f_2}}{A\left(\sqrt{f_1} - \sqrt{f_2}\right)}$$

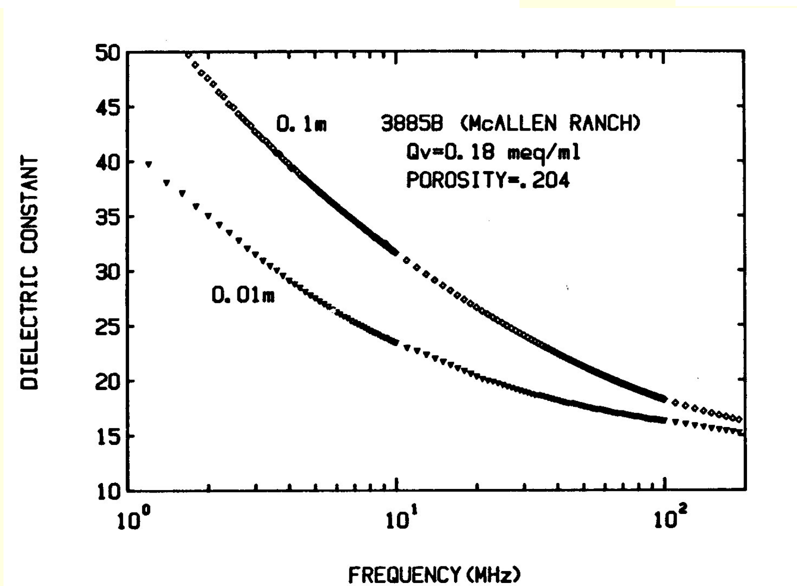
$$f_1 > f_2$$

$$\Delta b = b(f_2) - b(f_1)$$

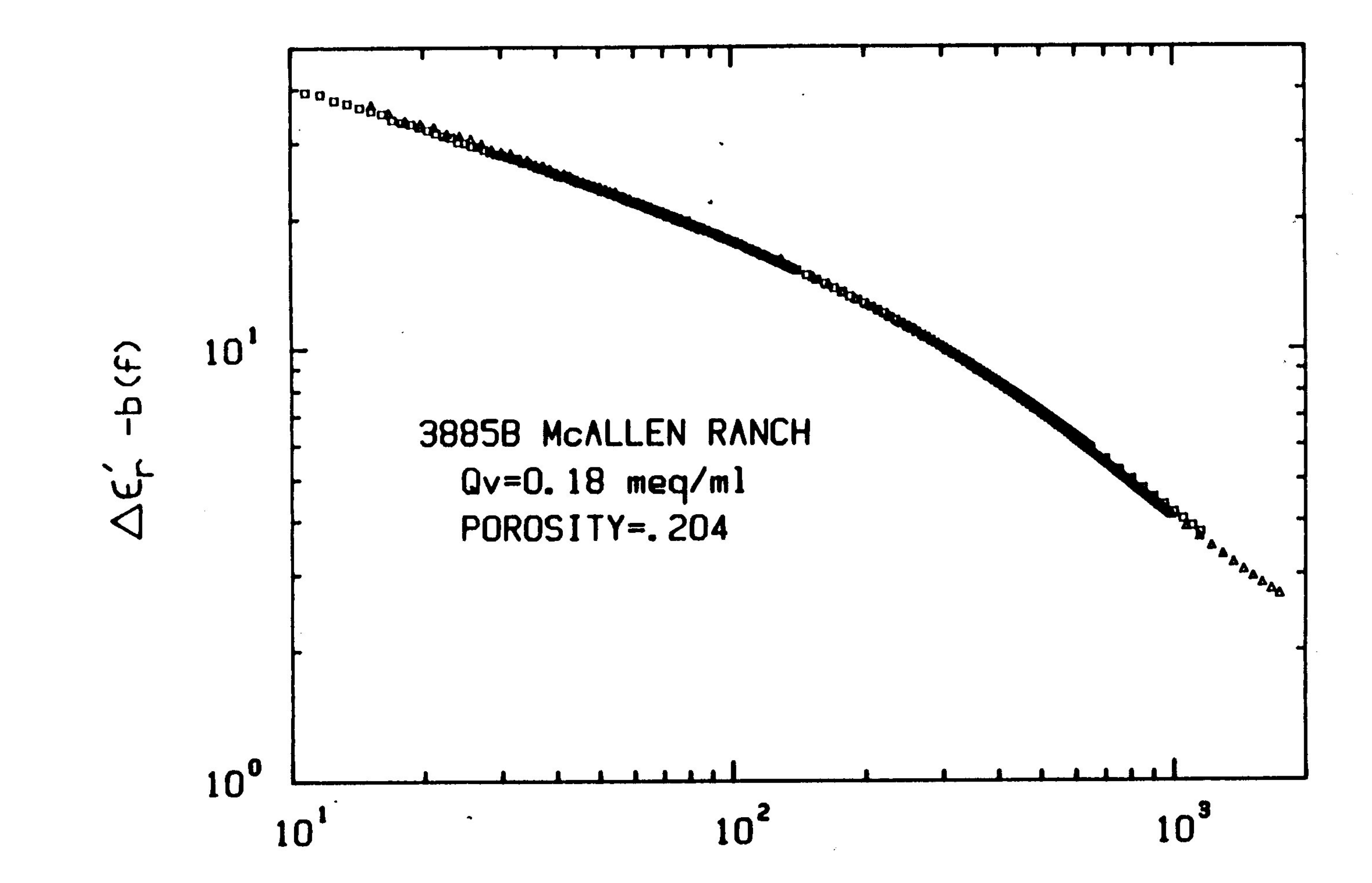
Effect of Salinity on the Dielectric Behavior of Shaly Sands







Normalizing for the Salinity Effect on the Clay Term



Normalized Frequency

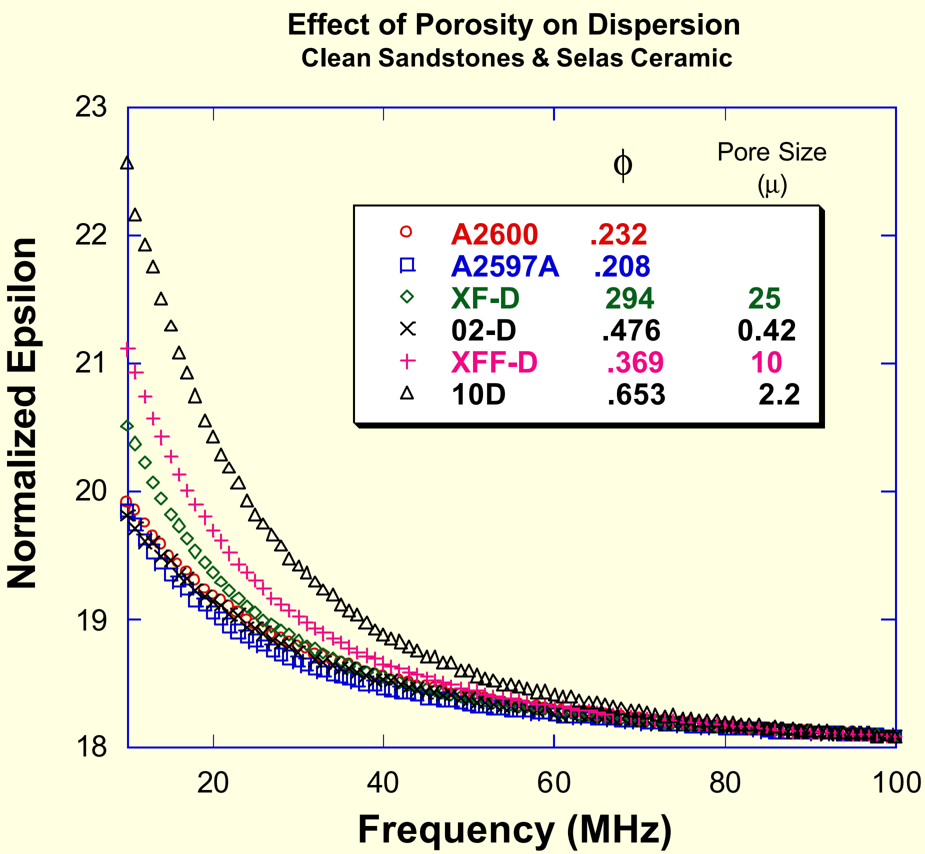
Rosen, 1985

Controlled Geometries

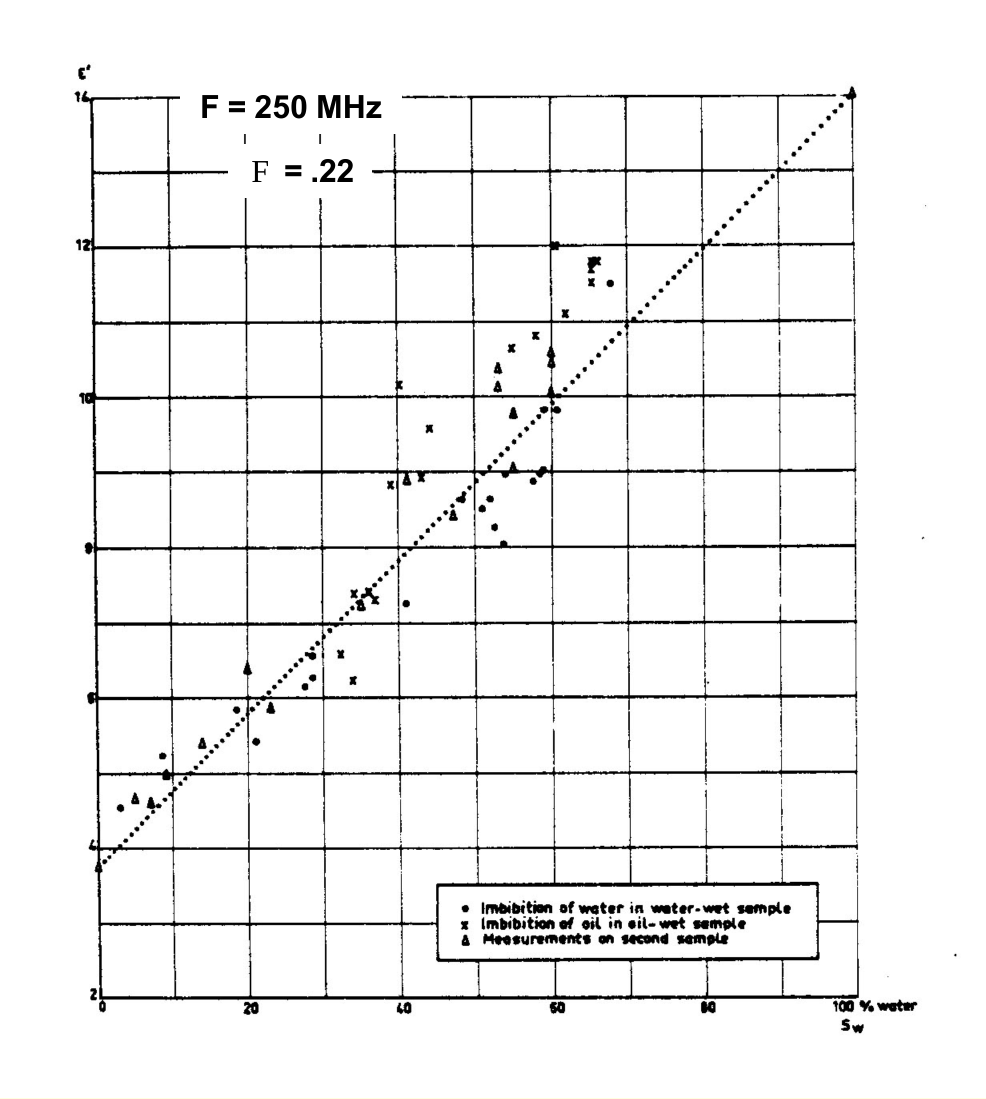
- **Selas Ceramics**
  - Controlled pore size (narrow distribution)
  - Used in some classic NMR R&D
  - Provides additional insight into any porosity dependence of the “b” term in the low salinity shaly sand equation
- **Capillary Arrays**
  - Minimum extreme case for dielectric behavior
  - Good way of investigating the dielectric behavior of fluids

Porosity Dependence of Dispersion

Clay–Free Porous Media

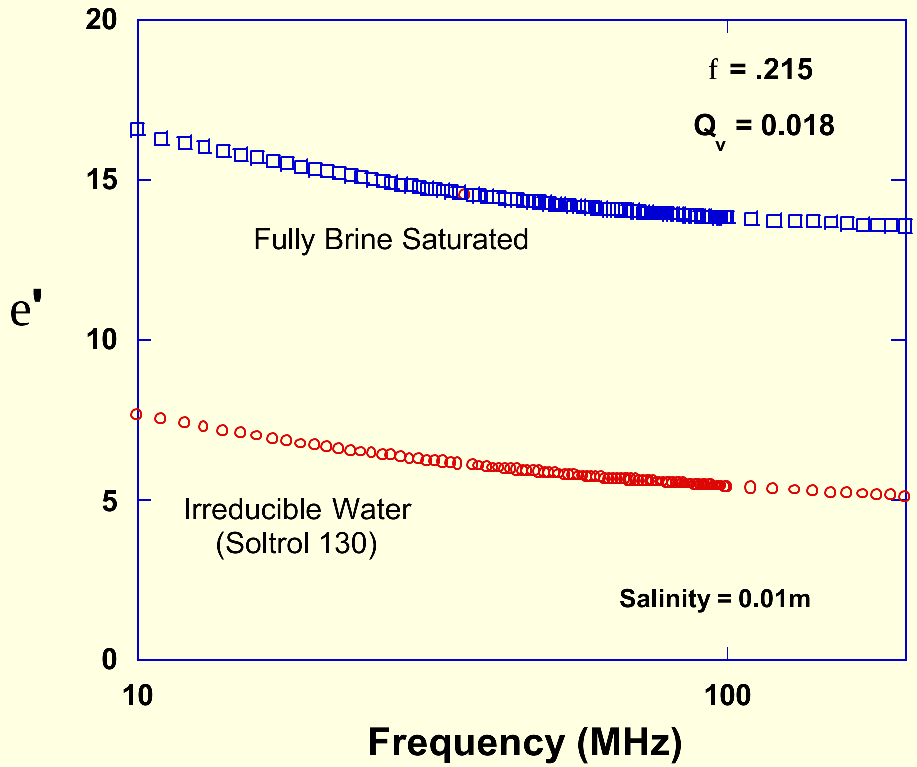


The Effect of Saturation (clean sandstone)



Poley et al., Fig. 20

Dielectric Behavior at Irreducible Water



M. Rosen, 1985

Low Salinity Shaly Sand Equation

$$e_r^{'} = A\frac{Q_{bv}}{\sqrt{f}} + b(f, \mathbf{f}) + e_{HF}^{'} S_w$$

$$\text{where} \quad e_{HF}^{'} = 35\mathbf{f} + 4.4$$

Based on Poley et al.'s Data

A viable approach to interpreting RF Logging Tools (10 – 100 MHz)

CLAY EFFECTS

- **Diffusion limited behavior ($f^{-1/2}$) in the 10-100MHz region**
- **New Petrophysical Parameter Q_{bv}**
  - **a simple but profound breakthrough (the correct parameter for quantifying polarization due to clay from low to high frequencies)**
- **Very Shaly Sands**
  - **Similar behavior to less shaly sands**
  - **Dielectric behavior appears insensitive to salinity**
  - **Bound water effects more important**
- **RF response -- independent of whether the clay is dispersed or laminated**
- **Not important for frequencies > several hundred MHz**

Correcting for SALINITY

- Interfacial (geometry) -- scales with water conductivity
  - Note: Unknown water conductivity is one of the motivations behind dielectric logging
- Clay dependence -- a different approach using measurable formation properties

SATURATION

- **Trends in the open literature indicate a linear dependence**
- **Studied fully brine saturated and irreducible water states**
- **Effects mostly limited to the high frequency term (only for less shaly samples)**

Shaly Sand RF Dielectric Equation

A Unique and Significant Milestone

Three terms:

(1) clay electrochemical polarization

(2) “clean sandstone” (geometry)

(3) high frequency limit value