Physical Chemistry - E&P Department

THE RF DIELECTRIC RESPONSE OF BRINE-SATURATED SHALY SANDS

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Introduction

Dielectric constant logging evolved out of the need to distinguish between oil and water in regions of low or unknown salinity. This method takes advantage of the large contrast between the dielectric constant of water and those for hydrocarbons and minerals. For frequencies greater than 1 GHz (10^9 Hz), the dielectric constant of rocks is independent of both frequency and salinity.[1] Schlumberger's Electromagnetic Propagation Tool (EPT) was, therefore, designed to operate at 1.1 GHz. However, at this frequency the depth of penetration into the formation is extremely limited, typically on the order of 5 cm.

Since the depth of investigation increases with decreasing frequency, newer dielectric logging tools (e.g. Schlumberger's Deep Propagation Tool (DPT) and Dresser Atlas' Dielectric Log) have been developed which operate at fixed frequencies in the range 25 to 50 MHz. In this frequency region, dielectric constant measurements of brine and oil saturated rocks become frequency dependent and the petrophysical interpretation of the dielectric constant is not well understood.

Based on a model of induced polarization in shaly sands, Vinegar and Waxman[2] noted a reciprocal frequency dependence for the clay dominated dielectric constant at low frequencies. They described Poley et al's data by two mechanisms, a frequency dependent dielectric constant proportional to Q_v and a frequency independent molecular dielectric constant, determined by the pore fluids and their volume fraction in the rock. They predicted that clay electrochemical polarization would be the dominant mechanism, even at frequencies as high as 10^6 Hz. A study of the effective dielectric constants of sandstones over extended frequency ranges was, therefore, begun at BRC. Initial measurements on sandstones saturated with low salinity brine indicate that shaliness (i.e., Q_v) is the key to understanding the dielectric behavior in the 25-50 MHz range.

Samples

Eight rock samples were used in this initial study. Seven of these were machined from specimens used in previous induced polarization studies.[3] All samples were precision-machined disks 1 inch in diameter and 1/4 inch in thickness with their faces parallel to less than 0.12°. A summary of their petrophysical properties is given in Table 1. The samples were 100% brine saturated with 0.01 M NaCl except for the two Big Foot samples at 0.1 M NaCl.

Experimental Technique

Samples were placed between the plates of a General Radio model 1690A dielectric sample holder. This is a precision parallel plate capacitor with a micrometer to adjust plate spacing. It can accommodate material up to 2 inches in diameter and 0.3 inches in thickness. Based on expected dielectric constants for samples and the holder geometry, the upper frequency limit is between 200 and 300 MHz. Since small air gaps between the capacitor plates and samples can cause serious errors, thin disks of brine-saturated tissue are placed between sample and capacitor plates.

Dielectric measurements were made using the microprocessor-based HP4191A RF Impedance Analyzer. The frequency range of this instrument is 1 to 1000 MHz. An HP85 desk-top computer controlled data collection, storage, and analysis. Complete data collection for 200 frequency points takes less than five minutes. A typical computer output is shown in Figure 1. A software operating system has been written which performs all calibrations, impedance calculations, and archiving of raw data for future analysis. Elimination of residual effects from the instrument, sample holder, and/or adapters was extremely important -- appropriate correction procedures have been incorporated into the operating system. The estimated error for the measurements in this study is about 2% except at the low frequency end ($f < 5$ MHz) where errors can be as great as 10 to 100%.

Table 1

Petrophysical Properties of Samples

# Sample	Number	Formation Factor,[†] F*	% Porosity	Q_v (meq/ml)	X-Ray Wt. % Clay	Clay Type
1 Bentheim	A2600	-	23.2	0	0	None
2 Benton Field, IL	3477	15.43	20.1	.034	2	Kaolinite with Chlorite
3 North Slope, AK	3336A	24.1	20.5	.042	10	Kaolinite
4 Bay Marchand, Blk. 2, Offshore, LA	3126B	12.82	24.9	.12	~ 5	Illite, Montmorillonite, Chlorite, Kaolinite
5 McAllen Ranch, TX	3885B	32.36	20.4	.18	~ 25	Illite with Chlorite
6 McAllen Ranch, TX	3891A	43.67	19.2	.385	~ 32	Chlorite with Illite
7 Big Foot, Frio County, TX	3324A	32.36	22.0	.65	?	Montmorillonite Chlorite with Kaolinite, Illite
8 Big Foot, Frio County, TX	3324B	32.47	20.4	.84	?	Montmorillonite Chlorite with Kaolinite, Illite

[†] F* values determined at low frequencies.

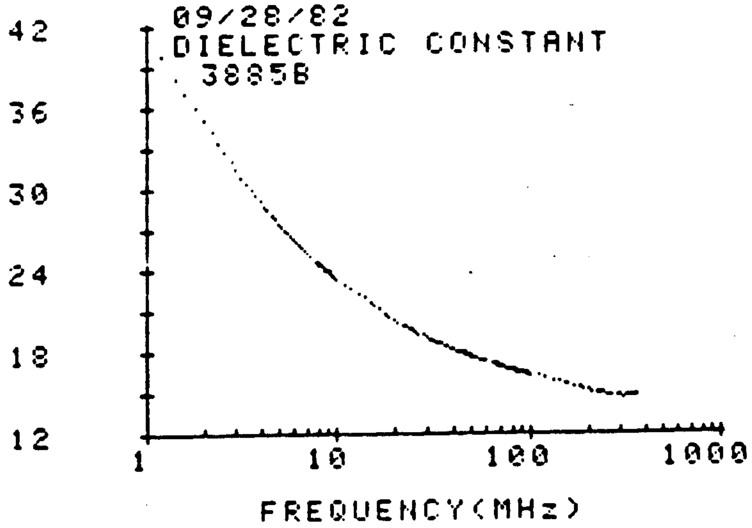

Fig. 1 - Graphical output from HP85 of dielectric constant data for sample 3885B.

Measurements

Dielectric measurements of a moderately shaly sandstone and of a clay-free Bentheim sandstone are shown in Figure 2. The dielectric constant of clay-free Bentheim sandstone agreed with Poley's data on clean sandstones.[1] The striking difference between the samples is the significant frequency dependence of the dielectric constant for the moderately shaly sample compared to the Bentheim. Both sandstones have similar porosities, 23.2 and 19.2 %, for the Bentheim and McAllen Ranch samples, respectively. The only apparent petrophysical difference between these two samples is the shaliness, Q_v.

The dielectric constant appears to consist of a frequency dependent and a frequency independent part. The frequency-dependent component is isolated by subtracting the frequency independent component using Figure 21 in Poley et al.[1] The data in this figure can be fit in the $0 < \phi < 30\%$ porosity range with the empirical equation

$$K_{1.2\ \mathrm{GHz}} = 35\phi + 4.4 \qquad (1)$$

where ϕ is the fractional porosity and $K_{1.2\ \mathrm{GHz}}$ is the frequency-independent dielectric constant at 1.2 GHz. Then

$$\Delta K = K_{eff} - K_{1.2\ \mathrm{GHz}} \qquad (2)$$

where K_{eff} is the effective dielectric constant, measured at frequencies less than 1.2 GHz.

A plot of ΔK versus Q_v is shown in Figure 3 for 5 frequencies from 5 to 200 MHz. The average correlation coefficient for all curves was 0.99. Other investigators[3,4] have shown that the dielectric constant at low frequencies ($<10^4$ Hz) appeared to be highly correlated to Q_v. Although other combinations of petrophysical parameters including formation resistivity factor were examined, the best correlation in this study was with Q_v.

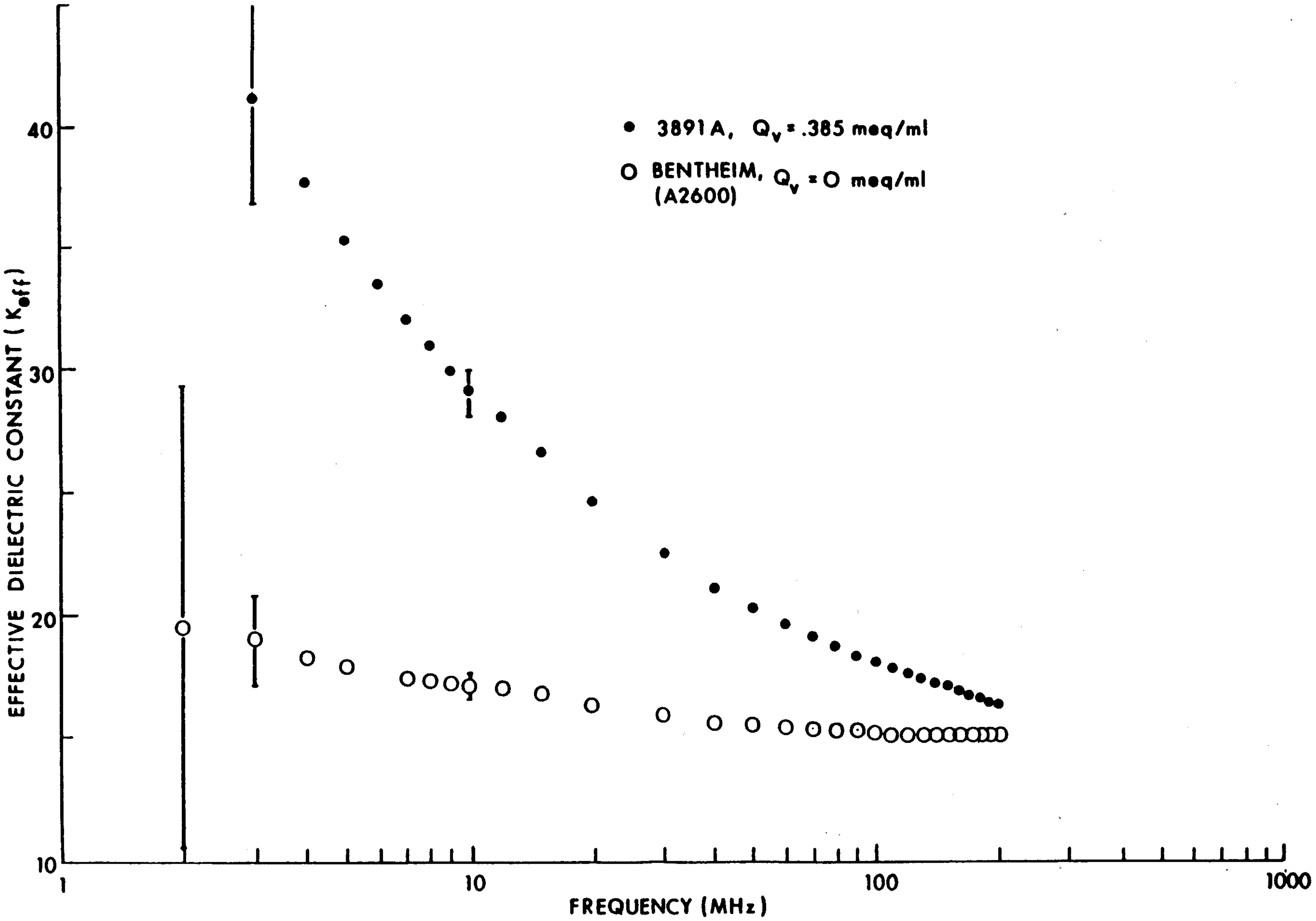

Fig. 2 - A comparison of the dielectric constant data of two sandstones of similar porosity but different Q_v.

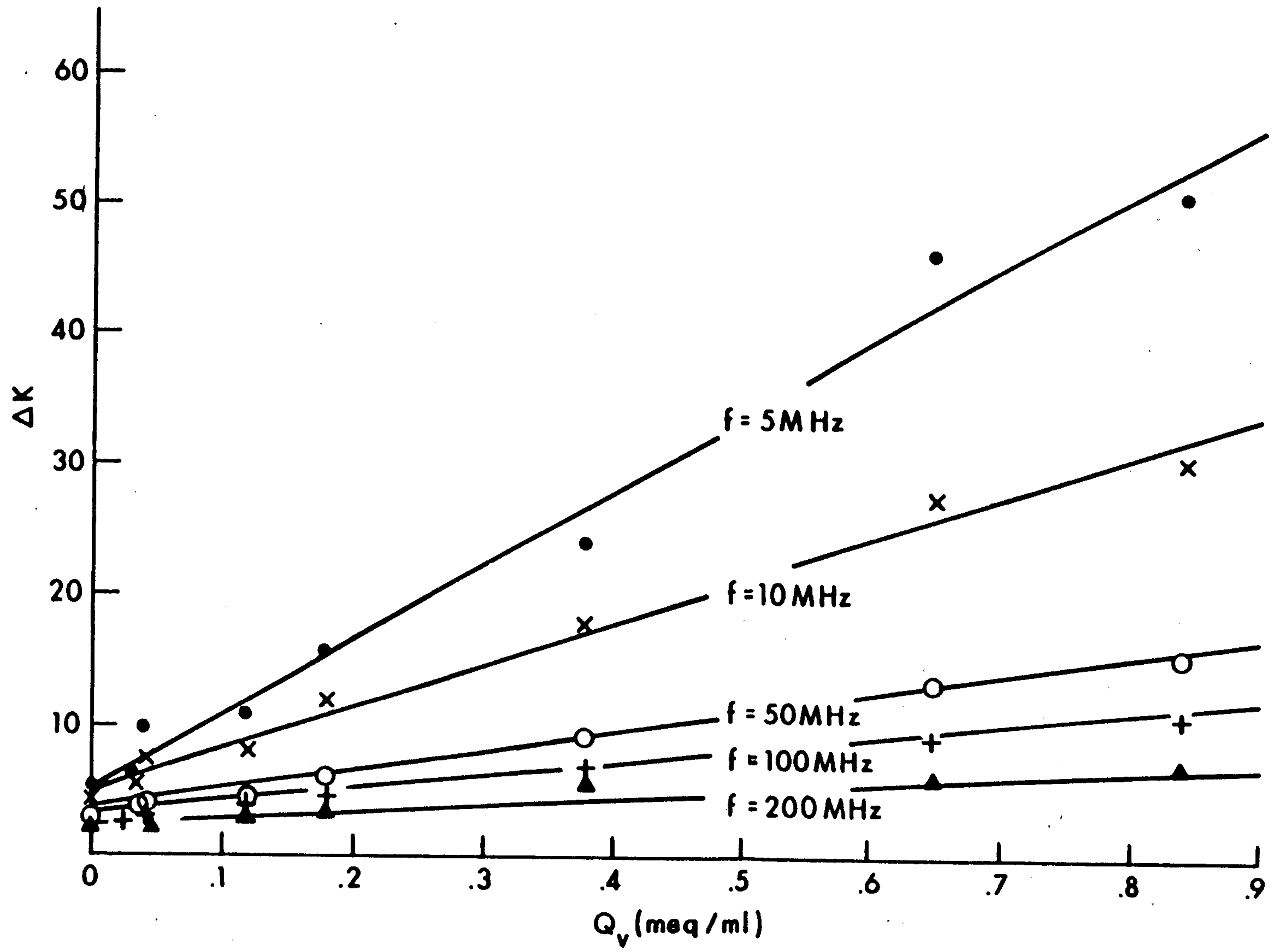

Fig. 3 - Observed correlation between ΔK and Q_V for five frequencies between 5 and 200 MHz. Straight lines are the linear least squares fit to the data at each frequency.

At each frequency a linear least squares fit was performed

$$\Delta K = m\, Q_v + b \tag{3}$$

Figure 4 shows a plot of m versus frequency. A power fit to this data between frequencies 1 and 200 MHz yields

$$m = \frac{126}{f^{0.556}} \tag{4}$$

where f is the frequency (MHz) and m has units of ml/meq. The slope m is very close to having an inverse square root dependence on frequency which is indicative of a diffusion-controlled process. Extrapolating the curve in Figure 4 implies that clay effects become insignificant at frequencies above ~500 MHz. Thus, the EPT (1.1 GHz) will not be affected by shaliness as has already been reported from log evaluation.[5]

Figure 5 is a plot of the calculated values for the intercept b. Mechanisms that could contribute to b are: (1) Maxwell-Wagner interfacial polarization,[6] (2) the Debye-Falkenhagen effect,[7] and (3) possible electrode polarization. Interfacial polarization arises from the trapping of ionic charges in heterogeneous regions between the fluid and rock which are of different conductivity.

Combining equations (1)-(4), the dielectric constant of a low salinity brine-saturated sandstone at the DPT frequency (25 MHz) is:

$$K_{eff} = 35\phi + 21.0\, Q_v + 8.4$$

where ϕ is the fractional porosity. Similar equations may be obtained for other frequencies of interest. These equations suggest a method for determining Q_v using only a RF dielectric log and a porosity tool.

Studies of the dependence on oil saturation and changes in salinity are in progress. Important questions concerning the validity of the Waxman-Smits equation at high frequencies and the frequency dependence of the formation resistivity factor will be studied.

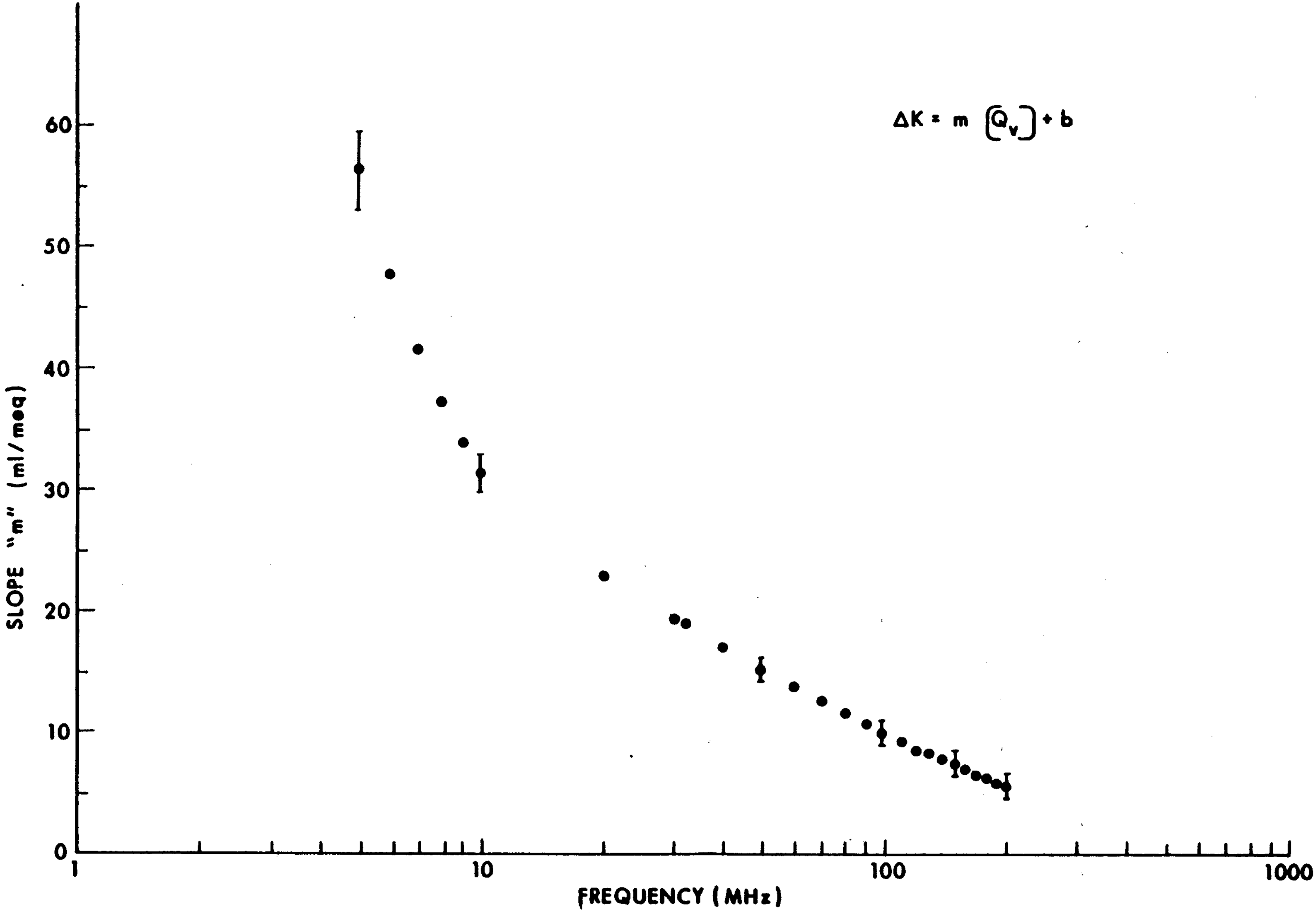

Fig. 4 - Calculated slope of the linear least squares fit of ΔK versus Q_v as a function of frequency.

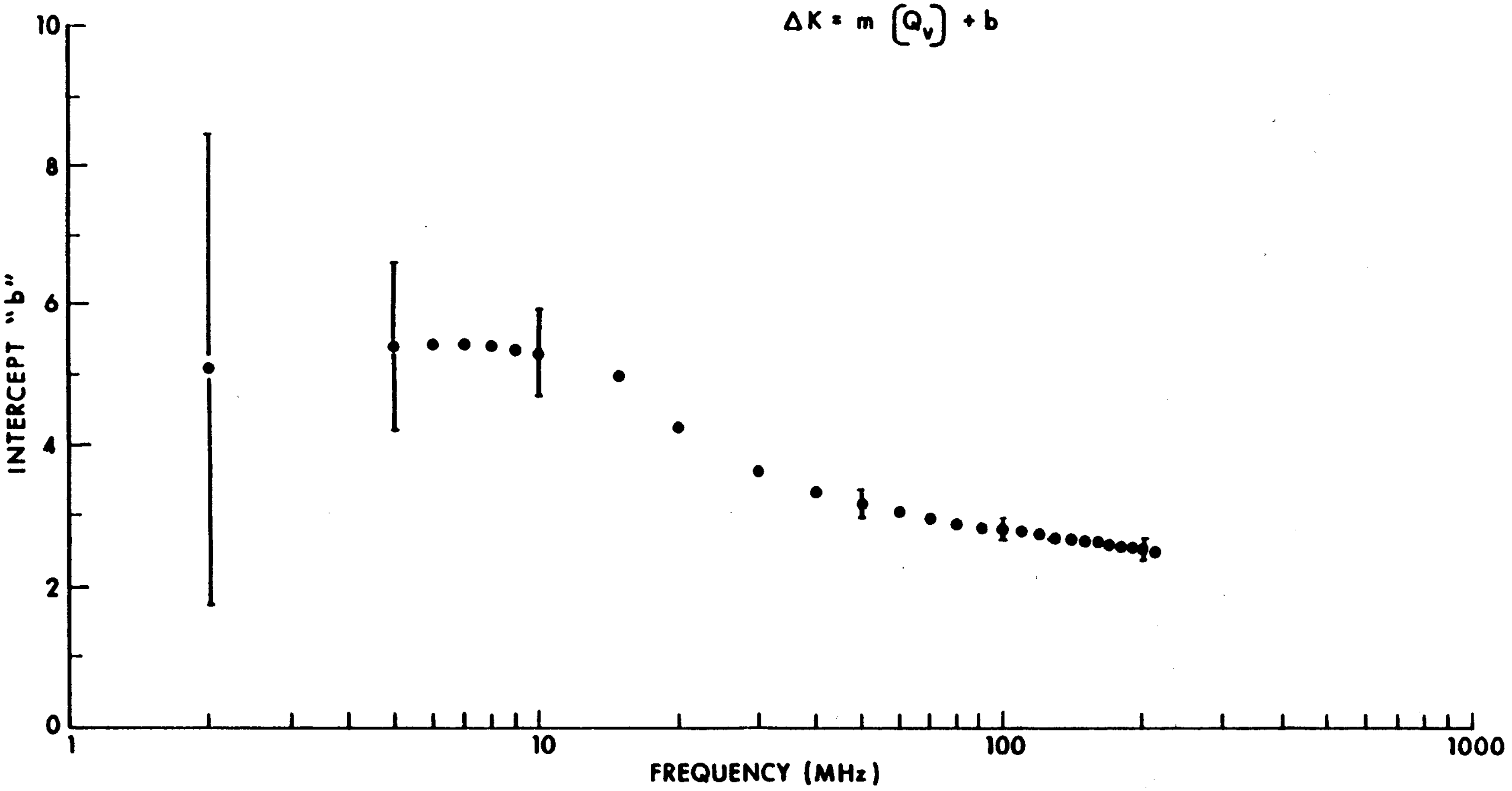

Fig. 5 - Calculated intercept of the linear least squares fit of ΔK versus Q_v as a function of frequency.

Conclusions

1. A dielectric measuring system has been developed for use with reservoir rocks from 1-300 MHz.

2. The clay content of low-salinity brine-saturated shaly sands (Q_v) is shown to be a critical factor in describing dielectric behavior in the RF region.

3. The frequency dependence of the Q_v dielectric term varies approximately as $f^{-1/2}$ which is indicative of a diffusion controlled process.

4. An empirical equation has been derived for K_{eff} which suggests that Q_v can be determined from an RF dielectric log such as Schlumberger's DPT.

5. The extrapolated Q_v dielectric term becomes insignificant at about 500 MHz, confirming that shaliness has no effect in the EPT tool frequency range.

References

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