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NUCLEAR MAGNETIC RESONANCE VERSUS AIR/BRINE CAPILLARY PRESSURE PERMEABILITY CORRELATIONS : HOW GOOD ARE OUR ASSUMPTIONS IN THE EMPIRICAL DETERMINATION OF PERMEABILITY ?

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ABSTRACT

The estimation of permeability from nuclear magnetic resonance (NMR) logs has largely been a result of correlations adopted from capillary pressure research. Equations developed by Timur, Coates et al., Swanson, and Rapoport and Leas all provide different solutions in the empirical determination of permeability. A number of questions arise when one attempts to apply these formulae in reservoir evaluation:

1. Can these equations be validated using a capillary pressure database and how sensitive are the key input parameters?
2. What level of accuracy and precision can be expected using indirect permeability estimates?
3. Are the equations based on ambient data applicable at reservoir conditions?

The above issues were addressed by testing permeability correlations on a diverse sandstone data set using 160 air/brine capillary pressure curves and basic core analysis data. Data from twenty fields around the world with a broad range of geological ages, depositional environments, shaliness, porosity and permeability are included. Leverett and Corey laboratory sandpack data as well as stressed and unstressed core data from 0.02 to 22,900 millidarcys are included in the database.

Swanson's permeability correlation, derived from unstressed mercury injection data, predicted permeability from the air/brine apex point with little need for statistical adjustment--although the standard error was a factor of two. Capillary pressure and permeability data measured at reservoir stress also fit the original equation; however, Swanson's correlation provided the best permeability prediction from unstressed data. A permeability prediction equation dependant on surface to pore volume ratios published by Rapoport and Leas and modeled after the work of Carman-Kozeny was found to provide good agreement with much of the laboratory data set. Timur and Coates et al. equations performed similarly for unstressed data and both methods overestimated stressed permeability with standard errors of about a factor of three.

A new equation based on the work of Swanson and Corey that uses relative permeability and capillary pressure performs as well as Swanson's equation but surpasses the Timur and Coates et al. equations in single phase permeability predictions. In addition the method defines critical water saturation and can be used to estimate the fractional flow of water during production. Given Corey's capillary pressure parameters, a preselected relative permeability to water, e.g. .01, is used to compute the critical water saturation and define this point on the capillary pressure curve. Permeability is then calculated from a ratio determined at this point analogous to that in Swanson's method.

Applicability of the various permeability correlations for use with NMR logs was tested on a core dataset from a field with very shaly sands. Measurements included air/brine and mercury injection curves and T_2 distributions.

INTRODUCTION

One of the primary goals of Nuclear Magnetic Resonance (NMR) logging is the derivation of permeability. In the literature there are several proposed correlations relating permeability to various NMR quantities, which include porosity, pore-size distribution, and Free Fluid Index (FFI).

Seevers[1] was the first to compute an NMR permeability, rigorously based on the Carman-Kozeny equation. Later came empirical methods, the Timur-Coates formulae[2,3,4] and the Schlumberger-Doll Research (SDR) formula[5] , which are currently used by logging companies as part of their commercial service. Recently, Marschall et al.[6] proposed computing permeability from an NMR analog to the Swanson parameter from capillary pressure theory.

Verification of these methods rests on core studies carried out by the authors and others on core databases of varying sizes and diversity. Measurements, all under ambient conditions, include NMR properties and conventional and special core analyses -- with capillary pressure experiments often playing a key role. The end result in each study is a formula with certain constants fixed to best describe the database at hand. In the field, logging companies use these fixed constants in the Timur-Coates and SDR equations in the absence of core derived calibrations specific to the well in question.

Against this background, a number of questions arise with respect to NMR log permeability:

1. How well do the various correlations perform in predicting permeability in a core database different from the author's original one? In particular, are the fixed constants generally applicable ?
2. How accurate are the correlations ?
3. Do correlations derived from ambient data also predict downhole permeability, i.e., at reservoir stress?

These questions are addressed in two parts : a capillary pressure section and an NMR section. The reason for the capillary pressure section is twofold : several of the NMR permeability correlations under consideration originated with capillary pressure research and the linkage between capillary pressure curves and NMR pore-size distributions noted by previous authors[6,7,8,9] will be explored further.

In the capillary pressure section, permeability correlations are tested against a diverse sandstone data set consisting of 160 air/brine capillary pressure curves and basic core analysis data. The Timur-Coates equations with the author's constants showed a skewed trend versus the data, with overestimation of permeability progressively increasing as permeability decreased. For the stressed dataset the overestimation was even higher. If the constants were adjusted by regression, then both equations predicted permeability with a standard error of about a factor of three.

Swanson's correlation[10], originally tested on mercury injection curves, predicted both stressed and ambient permeability in the air/brine dataset with no need to adjust the original constants. A standard error of about a factor of two agrees with Swanson's error estimate, which was later confirmed by Kamath[11].

A new correlation presented in this paper performed comparably to Swanson's and better than the Timur-Coates relations. In addition to predicting permeability, the new equation estimates Free Fluid Index, which is another major goal of NMR logging.

Seevers's NMR permeability estimator, fallen into disuse in recent years, has an exact analog from capillary pressure research published in 1951 by Rapoport and Leas[12], of which Seevers was apparently unaware. The Rapoport and Leas method predicts both stressed and ambient permeability in the air/brine dataset about as well as Swanson's equation and also estimates Free Fluid Index. In addition, the method is a purely theoretical version of the Carman-Kozeny equation with no adjustable constants, at least for a well defined subset of our database. This result supports Seevers's NMR method and implies that his method has only one adjustable constant, surface relaxivity.

In the NMR section, a case history is presented involving a field with very shaly sands. NMR log permeability is intended to help identify those sands capable of commercial production. Core data available for the study include petrophysical properties, capillary pressure curves and NMR measurements on the same set of plugs. Modified versions of the Timur and Coates models proved to be the most practical estimators of permeability from NMR logs.

In what follows, the fundamental concepts of NMR technology, described elsewhere[9,13], will be assumed.

CAPILLARY PRESSURE SECTION

DATABASE

In the database are capillary pressure curves on 160 sand and sandstone samples, along with measurements of porosity and permeability. The sand samples are data collected on laboratory sandpacks by Leverett[14] and Brooks and Corey[15]. Sandstone samples are from cores taken in twenty oilfields around the world. These fields are located onshore and offshore U.S.A, Venezuela, the North Sea, West Africa, Siberia, China and Indonesia. Ninety percent of the curves were measured with air displacing brine--exceptions being air displacing oil for one oilfield and the Brooks and Corey data, and oil displacing brine for another oilfield.

Measurements were carried out by a variety of service company and oil company laboratories over a period of time ranging from 1941 (Leverett) to the present day. Both centrifuge and porous plate data appear in the sandstone samples, and special methods were employed by Leverett, and Brooks and Corey on the sandpacks.

Three quarters of the samples (124) were measured at ambient stress and the remaining 36 samples, from five oilfields, were measured at reservoir stress. Both air and Klinkenberg permeabilities appear in the ambient samplesl, but all the stressed samples are Klinkenberg corrected.

Geologic ages include Tertiary, Cretaceous, Jurassic, Triassic and Permian. Environments of deposition include eolian, lacustrine, deltaic and deepwater submarine fan.

Porosity ranges from 7.8 to 48.2 percent and permeability ranges from .02 to 22,900 millidarcys, as can be seen in a plot of porosity versus permeability for all samples, Figure 1. Note the anomalous position of the NMR samples (high porosity, low permeability) which by this and other measures are unusual reservoir rocks.

All of the capillary pressure curves have been fitted with Corey's[16] curve fitting parameters, Sr, Pe and λ, defined by

$$Se = (Pe / Pc)^{\lambda} \qquad (1)$$

and

$$Se = (Sw - Sr) / (1 - Sr) \qquad (2)$$

where Se is effective saturation calculated from water saturation, Sw ,and the residual saturation, Sr, all fractional. Pe is entry capillary pressure, Pc is capillary pressure and λ is a dimensionless parameter characterizing pore-throat size distribution. High values of λ (greater than one) imply narrow distributions and low values (less than one) imply broader distributions.

PERMEABILITY EQUATIONS

In this section, proposed permeability correlations will be defined in a manner suitable for testing with the capillary pressure curve database. Companion NMR equations will also be presented based on two relations between capillary pressure and NMR quantities.

Free Fluid Index (FFI) can be related to a saturation, S, found at a certain point on the capillary pressure curve. According to how the point is defined, it may be called "irreducible" (Swi) or residual (Sr, after Corey) or critical (Sw_c, denoting a wetting phase relative permeability cutoff). The generic equation is

$$S = (1 - FFI / \phi) \qquad (3)$$

where S is fractional wetting phase saturation, and FFI and ϕ, porosity, are in the same units.

Capillary pressure, Pc, and NMR relaxation time, $T_{1,2}$, can be related[7] by

$$1 / T_{1,2} = 1 / T_{1,2B} + \rho e \, Pc / \sigma \qquad (4)$$

where the term involving $T_{1,2B}$, bulk fluid relaxation time, is neglected by some authors. Pc and σ, interfacial tension, are in consistent units. The variable ρe is an effective surface relaxivity incorporating intrinsic surface relaxivity and a pore throat-to-body size ratio[6].

Timur's equation[2], derived through regression analysis on a core database of 155 sandstone samples from three North American oilfields, is given by

$$k = .136 \, \phi^{4.4} / Swi^2 \qquad (5)$$

where k is air permeability in millidarcys, ϕ is porosity in percent and Swi is irreducible water saturation in percent measured by centrifugation at 50 psi. Swi has been defined at other pressures by later authors, e.g., 100 psi by Straley et al.[9] Substitution of equation 3 into 5 yields the companion NMR equation

$$k = .136 \, \phi^{4.4} / [100 (1 - FFI / \phi)]^2. \qquad (5 a)$$

Coates's equations[4] are

$$k = [(\phi/10)^2 \quad (100-Swi) / Swi]^2 \qquad (6)$$

and $$k = [(\phi/10)^2 \quad FFI / BVI]^2 \qquad (6 a)$$

are in the same units as equations (5) and BVI, bulk volume irreducible, is defined by

$$BVI = \phi - FFI. \tag{7}$$

Swanson's equation[10] is

$$k = 399\ [\ \phi\ (1-Sw_A) / Pc_A\ ]^{1.691} \tag{8}$$

where Sw_A (fractional wetting saturation) and Pc_A (mercury capillary pressure) are defined at a certain apex point A on the mercury injection curve, where the quantity $\phi\ (1-Sw_A) / Pc_A$ has its maximum. Swanson derived the equation constants from regression on a core dataset with 319 samples from sandstone and carbonate reservoirs.

Marschall et al.[6] derived an NMR analog equation by converting the T_2 distribution into a pseudo-capillary pressure curve using a version of equation 4 in which the T_{2B} term is neglected and interfacial tension is multiplied by cos (140). They validated their method with a set of 17 core plugs from differing reservoirs. A version of their equation can be put in the form

$$k = 399\ [\ BVNW\ \rho_e\ T_2 / \sigma\ ]^{1.691} \tag{8 a}$$

where BVNW, bulk volume non-wetting phase, replaces $\phi\ (1-Sw_A)$. The BVNW variable and T_2 correspond to the point on the pseudo-capillary pressure curve where the term in the brackets has its maximum.

A variation on Swanson's point leads to a permeability correlation with certain advantages. A point on a capillary pressure curve called a critical saturation point is defined by choosing a low wetting phase relative permeability(k_{rw}), such as .01 or lower. Brooks and Corey[15] showed that Corey's parameters can be used to compute k_{rw} by

$$k_{rw} = Se^{\varepsilon} \tag{9}$$

where $\varepsilon = (\ 2 + 3\ \lambda\ ) / \lambda\ .$ (10).

Equation 9 is mathematically identical to equation 7 in reference 6.

If we set k_{rw} to some critical value c, then the critical point on the curve is defined by

$$Sw_c = c^{1/\varepsilon}\ (\ 1 - Sr\ ) + Sr$$

and $Pc_c = Pe / c^{1/\varepsilon\lambda}$

so that permeability can be computed in the style of Swanson by

$$k = a\ [\ \phi\ (1-Sw_c) / Pc_c\ ]^b \tag{11}$$

where a and b depend on c and will be determined by regression. As was done with equation 8 a companion NMR equation is given by

$$k = a\ [\ BVNW\ \rho e\ T_2 / \sigma\ ]^b. \tag{11 a}$$

Rapoport and Leas[12] derived a theoretical permeability equation from the Carman-Kozeny equation

$$k = 1 / 5 \, (1 - So)^3 \, \phi / (S / V)^2 \qquad (12)$$

where So is an "irreducible minimum saturation as indicated by capillary displacement experiments" and S / V is surface area per unit pore volume given by

$$S / V = - \int_1^{So} Pc / \sigma \, dSw$$

where the derivation is specifically for air/brine or equivalent systems. This represents a different approach to the Carman-Kozeny equation from the bundle of capillary tubes model of Purcell[17]. Rapoport and Leas's main insight is that the Carman-Kozeny hydraulic radius (Reference 16, page 86) should be computed from the surface area and volume of the non-wetting phase at So. In effect, this partitions the pore space into large pores contributing most to flow and small pores, occupied by the wetting phase, with negligible contribution. The authors confirmed equation 12 with a set of 27 artificial and natural cores.

Seevers[1], apparently independantly, came to much the same conclusion as Rapoport and Leas in his formulation of the Carman-Kozeny equation for calculating NMR permeability. Seevers's equation is

$$k = A \, FFI \, [(T_1 T_B) / (T_B - T_1)]^2 \qquad (12a)$$

where the term in brackets is V/S of the long T_1 component (large pores) and A is an adjustable constant given by

$$A = \rho^2 / T$$

where ρ is surface relaxivity and T is a Carman-Kozeny constant. If we replace ρ by ρe (equation 4), set T = 5 and assume FFI = (1 - So) ϕ, then equations 12 and 12a are equivalent. Seevers found that equation 12a described core data from five wells, but that A varied by well, ranging from .23 to 11 darcy/sec2. If T = 5, then ρ varied from 1 to 7 micron/sec.

Kenyon et al.[5] tested Seevers's model (equation 12a) with poor results on an NMR dataset that included 67 sandstone plugs from oilfields and outcrops. The authors obtained a better correlation with an empirical equation which has come to be known as the Schlumberger-Doll Research (SDR) equation:

$$k = 4 \, \phi^4 \, T_{2LM}^2 \qquad (13)$$

where T_{2LM} is the mean logarithmic value of T_2. This equation has no counterpart in capillary pressure theory.

STATISTICAL TESTS OF THE PERMEABILITY EQUATIONS

In this section, the above permeability equations are statistically tested with the capillary pressure curve database. Results are shown in Tables 1 and 2 and in Figures 2 to 6. In the Figures, model permeability from the equations is plotted on the x axis versus measured permeability on the y axis and a best fit line (Reduced Major Axis or RMA) is shown compared to the equality line. Standard errors of estimate are quoted as multiplicative factors. A statistical F-test is computed to see if the best fit line is significantly better than the model for all the data (Table 1). In Table 2 the F-test is applied to see if each best fit line determined for the stressed data is significantly different from the best fit line for the ambient data. Variables required in the equations, such as Swi at 50 psi, have been derived using the Corey capillary pressure curve parameters fitted to each laboratory curve.

Figure 2 shows the results for Timur's equation, which overestimates permeability overall, getting progressively worse as permeability decreases. The F-test indicates that the best fit line is not significantly different at the 95 percent confidence level from the original model, equation (3), but just barely. Although Timur's equation has the highest standard error of all the models, a factor of 3.9, the best fit line is a highly significant fit to the data, as is true for all the equations tested.

Visual inspection of Figure 2 shows that the stressed samples are described reasonably well by the best fit line determined for all the samples. By the F-test (Table 2), the best fit line for the stressed samples is not significantly better than the best fit line for the ambient samples when applied to the stressed samples (neither line is shown in the figure). This does not imply that the two lines are the same, but that within the limits of our data, it is reasonable with Timur's model to apply results obtained with ambient data to the estimation of reservoir, i.e., stressed permeability. This conclusion turns out to hold for all of the models tested.

Coates's model, Figure 3, uniformly overestimates permeability in a manner similar to Timur's model. It passes the F-test by a larger margin. Ambient and stressed data are both described by the same line in the figure.

Swanson's equation is very close to the best fit line in Figure 4, with no need for adjustment implied by the F-test. In the range from 1 to 1000 md, the two lines are nearly indistinguishable. Standard error for our data is close to Swanson's original estimate, which was later confirmed by Kamath[11]. To our knowledge, this is the first published confirmation of Swanson's model with an air/brine dataset. As before, the equation describes both ambient and stressed data.

Figure 5 shows the results from regressing a new Swanson analog model, based on equation (11), against the data to determine the constants a and b. For an assumed $k_{rw} = .01$, a and b are 674 and 1.82 with a standard error the same as for Swanson's model.

Figure 6 shows results for Rapoport and Leas's equation on a reduced dataset. In this test, the simplest and most direct method was to assume that Corey's Sr is So in equation (12) and to find S/V by integrating with the Corey parameters. However, the integral is infinite for λ less than one and can be very large for λ slightly above one (broad pore throat distributions). Accordingly, the reduced dataset in the figure represents the 63 samples from ten oilfields and the sandpacks with λ greater than 1.2 (narrow distributions), which nonetheless have a permeability range over four decades.

What Figure 6 shows is that the best fit line is nearly identical to equality, confirming Rapoport and Leas's theoretical equation, which has no adjustable constants. Furthermore, the standard error is similar to what has become a benchmark, Swanson's model[11]. We have found that simple definitions of So can be used to extend these results to the rest of our dataset.

This implies that Seever's equation (12a) is theoretically and empirically sound, with surface relaxivity, ρ, as the only adjustable parameter. For practical application ρ should be fairly constant, which may be true for individual reservoirs, as Seevers found, but is probably not true over a range of reservoirs, as indicated by the poor results obtained for Seevers's equation by Kenyon et al.[5]

NMR CASE HISTORY

This section presents a case history of the search for an NMR log permeability predictor in a formation with very shaly sands. Conventional logs are difficult to interpret in these sands, particularly with regard to producibility. Accordingly, a core was cut in a well and six SCAL plugs were analyzed for petrophysical properties, porous-plate capillary pressure curves and NMR T_2 distributions, with each set of measurements performed on the same plug. All except the NMR measurements were conducted at reservoir stress. Figure 7 shows the T_2 distribution and other data for a typical plug.

In Figure 1, a porosity-permeability correlation is evident for the NMR samples. This is useful, but is potentially misleading because formation shales have high total porosity and can be difficult to distinguish from sands on logs. Also, the indicated correlation may be pessimistic in some of the better quality sands, unfortunately not present in the cored interval.

A median T_2 cutoff of 6 milliseconds applied to the T_2 distributions approximates water saturation, Swi, at 140 psi air/brine capillary pressure with a 0.84 correlation coefficient and a standard error of 5.8 saturation percent. Swi values are high, ranging from 66 to 93 percent. Dean-Stark saturations measured on conventional core plugs (oil-base mud) were in the same range, as were log calculations. On test, these sands flowed oil with no water cut. Plug clay content ranges from 7 to 15 percent by X-ray diffraction and the shaliness factor Qv ranges from .2 to .67 meq/cc from excess conductivity measurements. Wet chemistry Qv is about 50 percent higher.

The NMR permeability equations presented above were tested using T_2 distributions measured on 100 percent water saturated samples, with results shown in Table 3. For reference the first entry is a log-log porosity-permeability correlation. None of the models tested improved on this simple transform, implying that T_2 distributions added no information to what was provided by porosity. This was not the case for permeability computed from the air/brine capillary press curves. Both Timur and Coates (equations 5 and 6) had better correlation coefficents with permeability than did porosity alone.

If a T_2 cutoff is not derived from the air/brine data a different picture emerges. The correlation coefficients for the Timur and Coates NMR permeability models (equations 5a and 6a) reach maxima for cutoffs of 4.5 and 3.5 milliseconds, respectively, and show improvement over porosity alone. However, NMR Swi values would then be from 5 to 11 percent lower than air/brine Swi.

The disappointing results for the Swanson, Critical Saturation and Seevers models in Table 3 can be explained by variations in surface relaxivity, ρ, between plugs, because these models depend on a relatively constant ρ to convert T_2 distributions to pseudo-capillary pressure curves. The counterpart capillary pressure permeability models (equations 8, 11 and 12) all performed better than the NMR models, with correlation coefficients above 0.9. In addition, if each T_2 distribution conversion was tailored to best match the corresponding capillary pressure curve[18], the NMR models all showed improvement, with permeability correlation coefficients of about 0.9.

In the NMR samples under investigation surface relaxivity is unusually high. In converting the T_2 distributions to pseudo-capillary pressure curves approximating the measured capillary pressure curves, the median and maximum ρ values were 48 and 76 microns/sec, well above the upper limit for normal sandstones[18], 30 microns/sec. A possible explanation lies in high concentrations of siderite and pyrite, ranging from 8 to 14 weight percent (combined) by X-ray diffraction. Perhaps more importantly these two minerals are described in most thin sections as pore-lining cements. This may also explain why the T_2 cutoffs are lower than usual for clastics[18].

As a practical matter, adjusted versions of the Timur and Coates NMR permeability models (equations 5a and 6a) appear to be viable methods for computing permeability from NMR logs in these sands. Extension of the correlations into higher permeabilities is desirable but will be dependant on obtaining core from the better quality sands.

CONCLUSIONS

Returning to the questions posed at the beginning of this paper, the following salient points emerge from this study. In the general case :

1. All of the five capillary pressure models tested estimate permeability with high statistical significance.

2. The Swanson and Rapoport and Leas models estimate permeability with a standared error of about two with no need for adjusting the published equation coefficients.

3. The new Critical Saturation correlation performs as well as the Swanson model and affords an estimate of critical water saturation.

4. The Timur and Coates models estimate permeability with standard errors between three and four and do not statistically require adjusted coefficients.

5. For all models, the equations for calculating ambient and stressed permeability are statistically indistinguishable within the accuracy limits of the data. A more refined test with more data may yet uncover differences.

In the special NMR case history:

1. NMR analogs to the best performing capillary pressure models in the general case provided poor results, probably because of variations in surface relaxivity.

2. The Timur and Coates NMR models turned in the best results, but required T_2 cutoffs of 6 milliseconds, substantially lower than for most sandstones.

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TABLE 1

Model	Equation No.	No. of Samples	Standard Error	Standard Error	F test Probability Model vs Best Fit	Best Fit a	Line b
	Author's Results			This Study's Results			
Timur	5	155	2.06	3.84	.030	.150	1.242
Coates	6			3.69	.072	.385	1.055
Swanson	8	319	1.96	2.54	.406	.850	1.103
Critical Saturation	11			2.51			
Rapoport and Leas	12	27	1.29	2.12	.457	1.032	1.016

One tailed F-test is significant below .025
at the 95 % confidence level.

Best Fit Line is a power law :

kcore = a kmodel^b

TABLE 2

		Ambient Samples			Stressed Samples			
Model	Equation No.	Standard Error	Best Fit a	Line b	Standard Error	Best Fit a	Line b	F test Probability Ambient vs Stres
Timur	5	3.959	.186	1.213	3.168	.078	1.330	0.42
Coates	6	3.414	.351	1.077	4.614	.490	.987	0.37
Swanson	8	1.987	.660	1.155	3.764	1.368	.995	0.20
Critical Saturation	11	1.970	.807	1.040	3.988	1.601	.904	0.22
Rapoport and Leas	12	1.945	1.013	1.028	3.038	1.675	.808	0.38

Best Fit Line is a power law :

kcore = a kmodel^b

One tailed F-test is significant below .025
at the 95 % confidence level.

TABLE 3

Model	Equation No.	Correlation Coefficient	Standard Error	Best Fit a	Line b
Porosity vs Permeability		.951	1.333		
Timur	5a	.950	1.340	.033	1.479
Coates	6a	.913	1.463	4.634	.637
Swanson	8a	.741	1.873	.831	1.063
Critical Saturation	11a	.833	1.676	.545	1.257
Seevers	12a	.129	2.527	4.890	.341
SDR	13	.870	1.586	83.490	1.173

Best Fit Line is a power law :

kcore = a kmodel^b

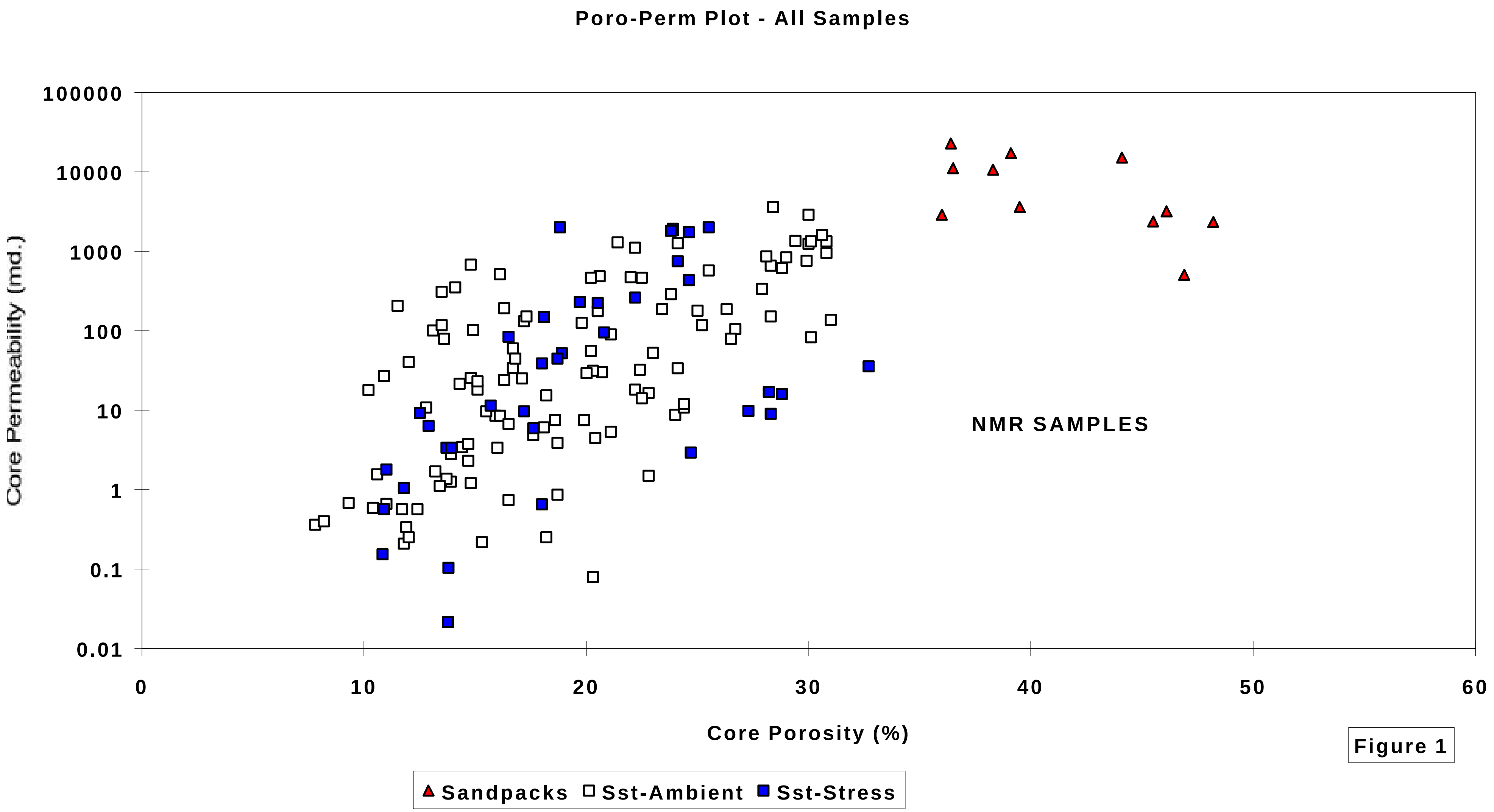

Poro-Perm Plot - All Samples
Core Permeability (md.)
100000
10000
1000
100
10
1
0.1
0.01
0
10
20
30
40
50
60
Core Porosity (%)
NMR SAMPLES
▲ Sandpacks
☐ Sst-Ambient
■ Sst-Stress

Figure 1

TIMUR'S EQUATION

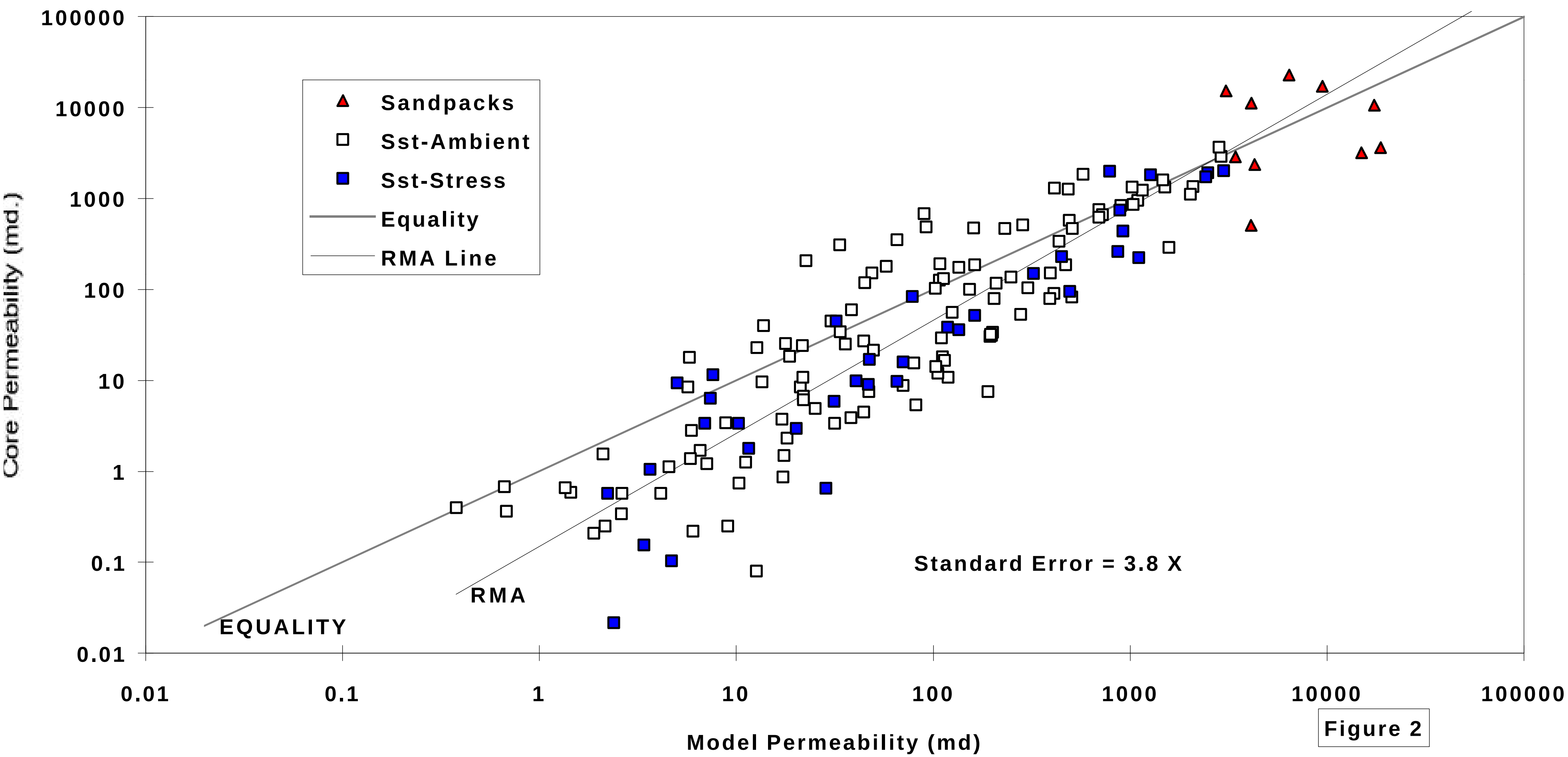


Figure 2

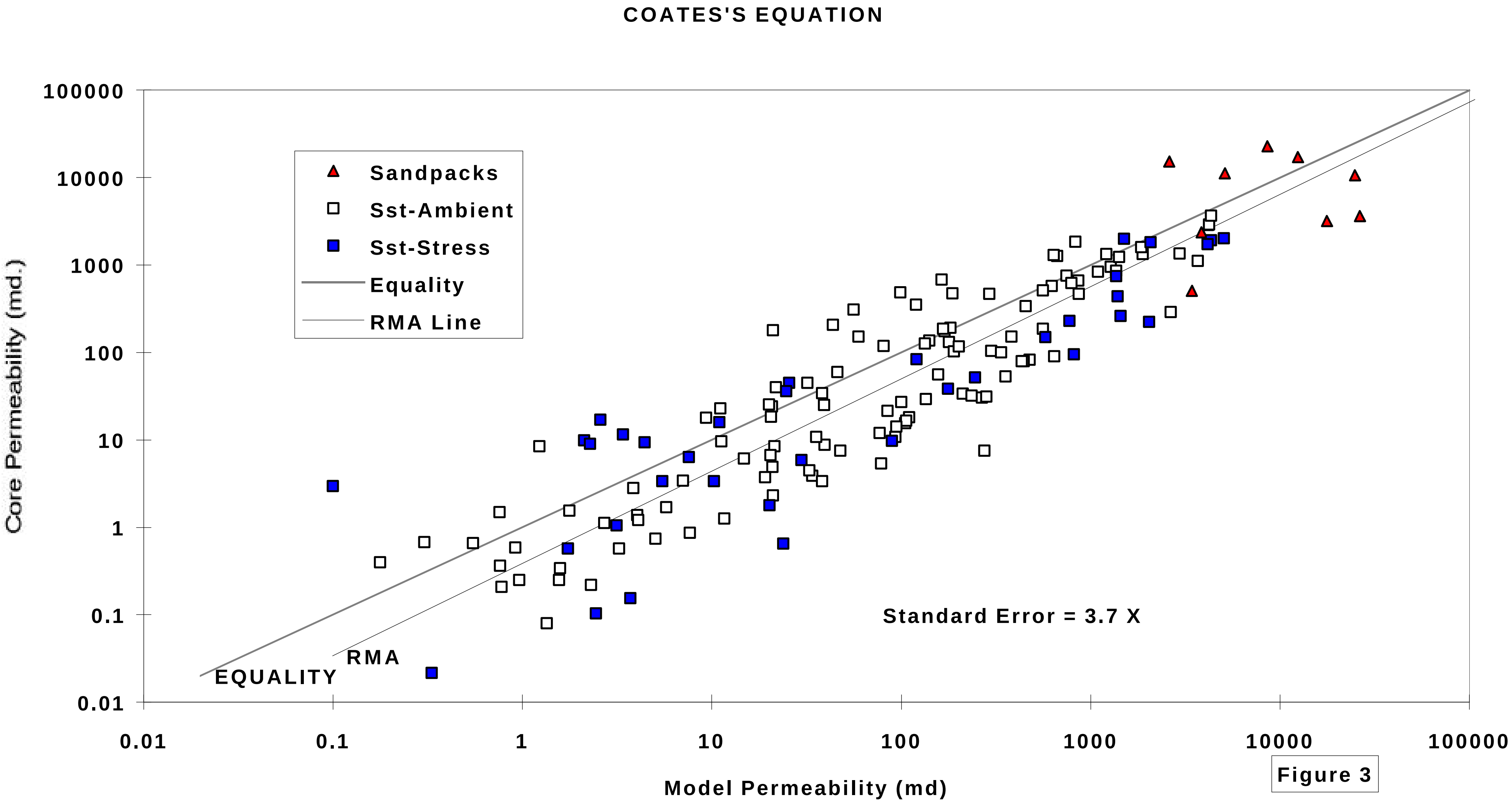

COATES'S EQUATION
Core Permeability (md.)
100000
10000
1000
100
10
1
0.1
0.01
Sandpacks
Sst-Ambient
Sst-Stress
Equality
RMA Line
Standard Error = 3.7 X
RMA
EQUALITY
0.01
0.1
1
10
100
1000
10000
100000
Model Permeability (md)

Figure 3

SWANSON'S EQUATION

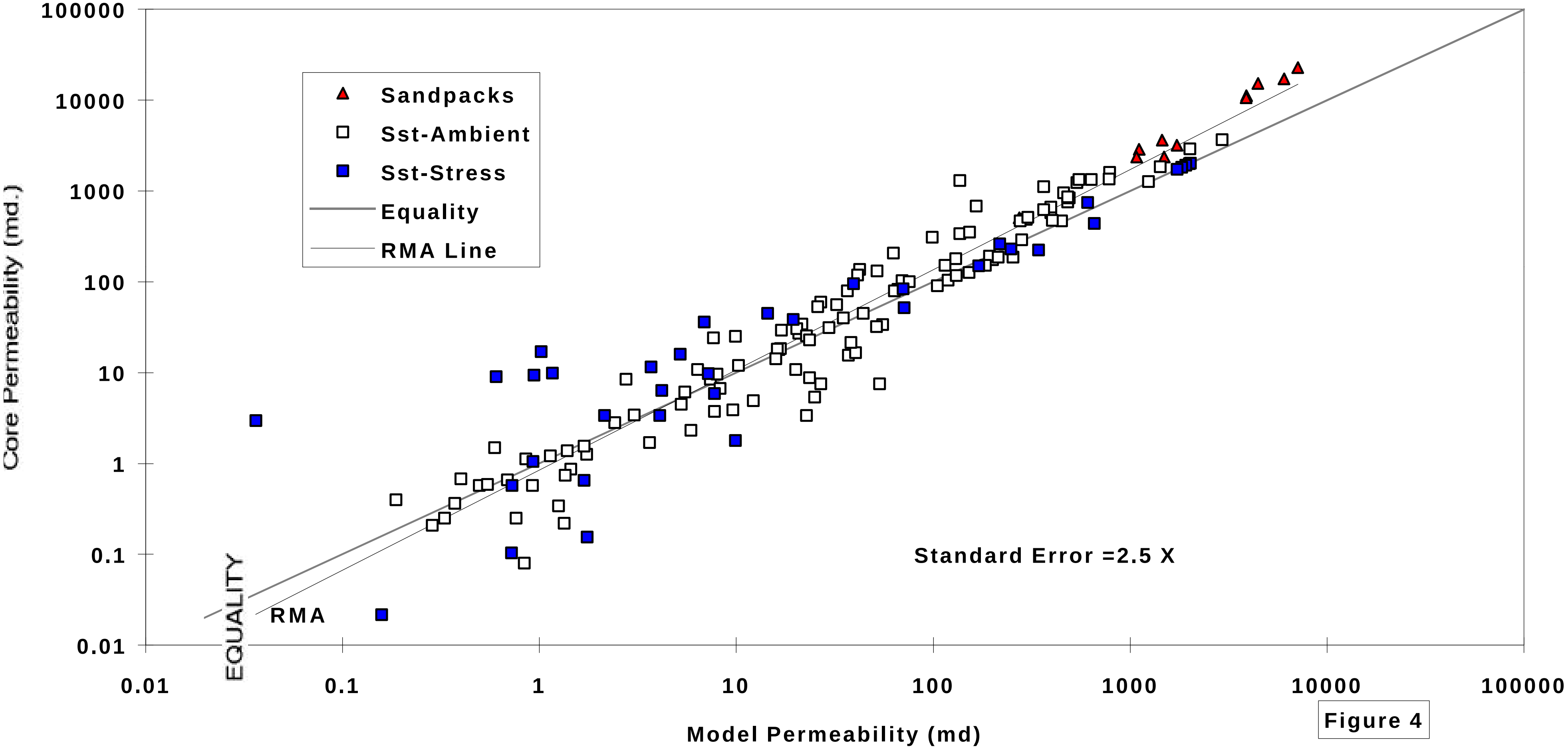


Figure 4

CRITICAL SATURATION EQUATION

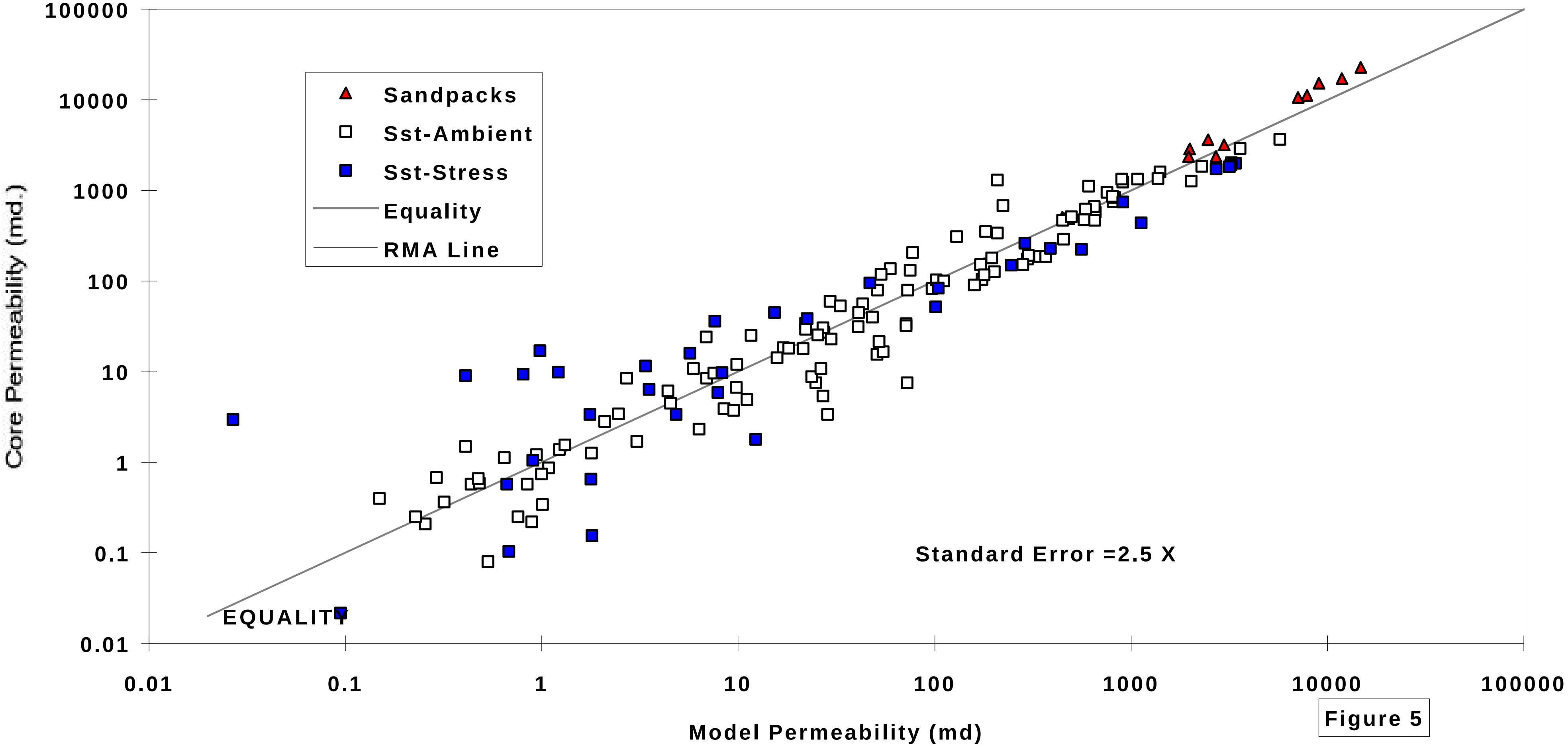


Figure 5

RAPOPORT AND LEAS'S EQUATION

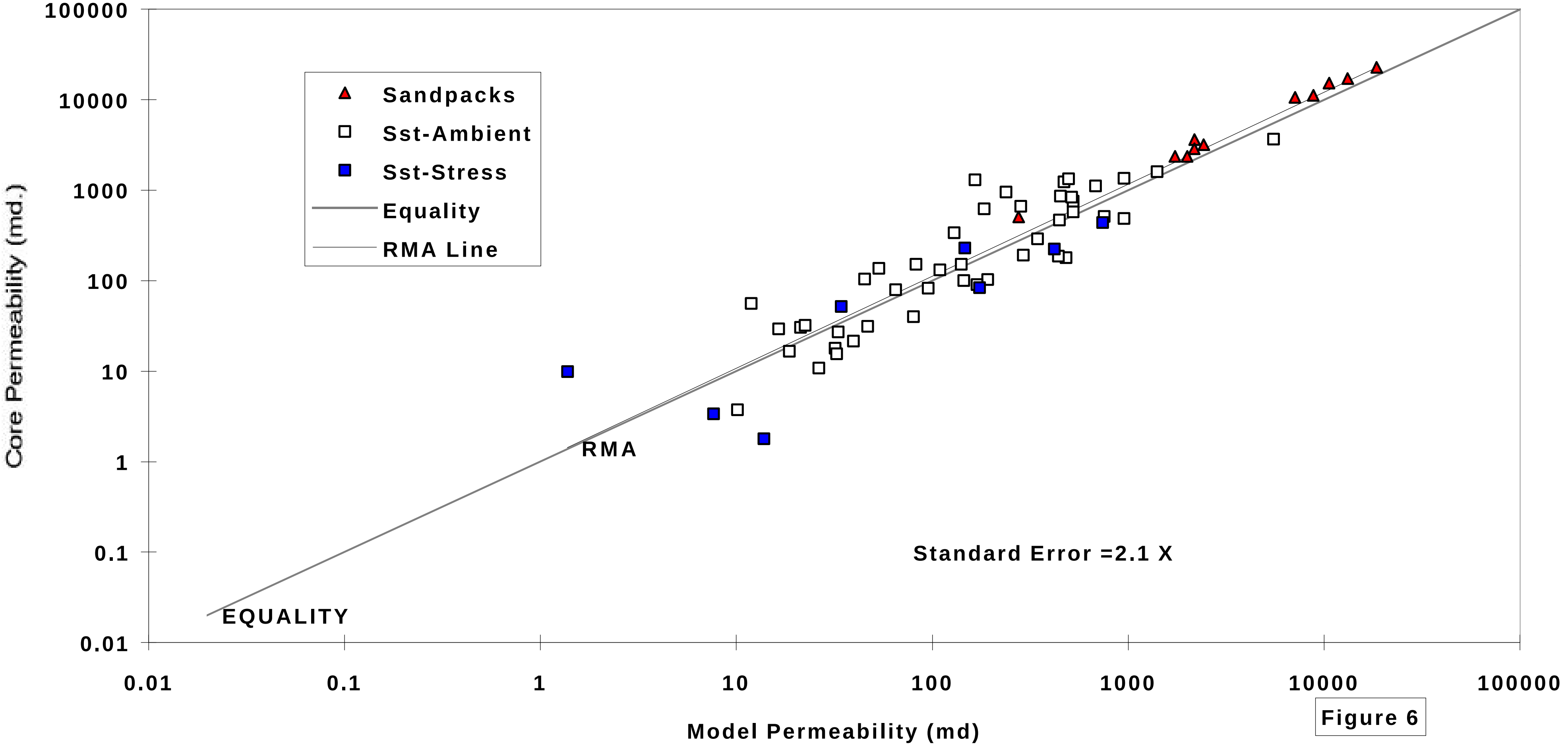
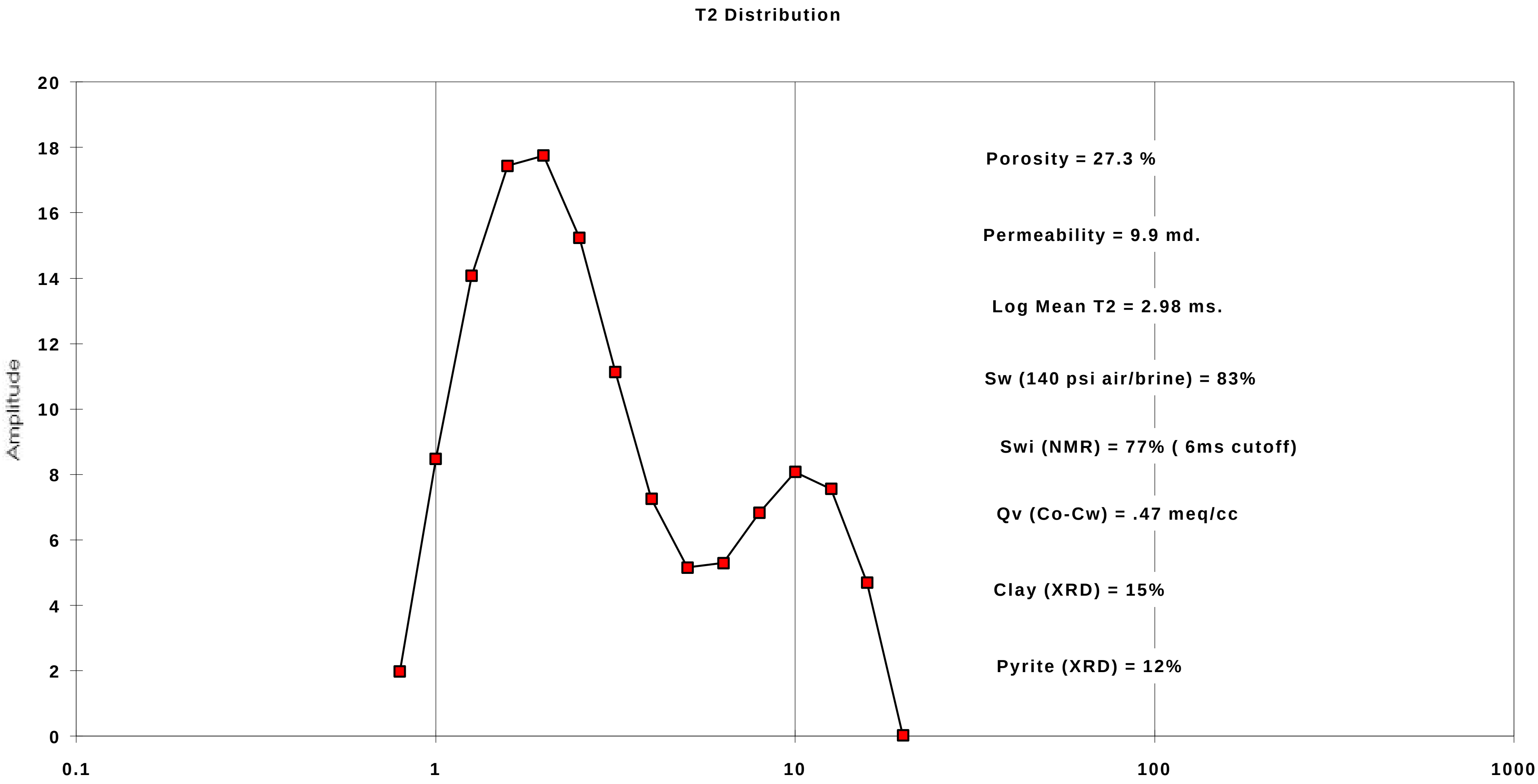


Figure 6



Porosity = 27.3 %

Permeability = 9.9 md.

Log Mean T2 = 2.98 ms.

Sw (140 psi air/brine) = 83%

Swi (NMR) = 77% (6ms cutoff)

Qv (Co-Cw) = .47 meq/cc

Clay (XRD) = 15%

Pyrite (XRD) = 12%

FIGURE 7