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"Correlations of Liquid and Air Permeabilities for Use in Reservoir Engineering Studies"

Virgil J. Pugh: Amoco Production Company, Tulsa, Research Center

David C. Thomas: Amoco Corporation, Naperville

Surendra P. Gupta: Amoco Production Company, Tulsa, Research Center

Abstract: Specific (single phase) permeabilities to air, brine and oil are routinely measured in conjunction with relative permeability tests conducted in our laboratories. These data, including the standard air permeabilities, are used to evaluate reservoir quality, to aid in development of a reservoir description, and to approximate reservoir flow characteristics. Specific permeabilities were analyzed for data that have accumulated on numerous reservoirs over the past 40 years. Included are comparisons of specific air permeabilities to both oil and brine permeabilities for 1868 samples from sandstone and carbonate reservoirs, covering a permeability range from 0.1 to 10,000 md. The results show a strong correlation between specific permeabilities and that air permeabilities are valuable in the characterization of reservoir quality.

A correlation of effective oil permeability to air permeability covering a wide range in permeability was developed for a clayey reservoir. This

illustrates a second application for the use of air permeabilities in reservoir descriptions. The correlation was successfully used for predicting effective oil permeabilities from standard air permeabilities measured on cores throughout the field. The method reduced overall core analysis costs by limiting the number of oil permeability measurements required to get a good estimate of reservoir permeability.

INTRODUCTION

Standard core analyses routinely include air permeabilities measured on core plugs that are cleaned and dried. The air permeabilities are frequently used to determine pay cutoffs, reserve estimates and reservoir quality. Air permeabilities are also used to approximate reservoir flow characteristics and to aid in the development of a reservoir description. Some companies, however, put very little faith in gas permeabilities for use in estimating reservoir permeability. For clayey formations, water permeabilities have been suggested as a preferred method to describe reservoir flow characteristics (Reed, 1987).

Empirical correlations between liquid and air permeabilities have been developed which show that air permeabilities can be useful in the characterization of reservoir quality and that liquid permeabilities are not essential in describing many reservoirs.

EXPERIMENTAL METHODS

Permeability measurements that have accumulated on numerous reservoirs (875 wells) over the past 40 years were retrieved from the in-house rock properties database and were analyzed to evaluate relationships between air and liquid permeabilities. Samples used for relative permeability tests conducted by Amoco are cleaned and dried at approximately 230°F at the conclusion of the tests. Specific (single phase) permeabilities to air, brine and oil are then measured. The test samples that were used include core plugs with diameters of 1 1/4" and 2", as well as full-diameter cores.

The liquid permeabilities are determined when the test plugs are saturated with oil and brine prior to making X-ray end scans which are used in the calculation of water saturations for the relative permeability data. The direct measurement of permeability is made during the flow of liquid through a sample saturated with the flowing liquid. The oil and brine permeabilities are measured using the procedures described in API RP-27, Sections II 15, III 28-31, and IV 55-61. Standard air permeabilities are measured using the procedures described in API RP-40, Sections 3.5.15.1 and 3.5.15.2.

RESULTS

Comparisons of the various specific permeabilities to air and liquid (oil and brine) are shown in Figures 1 through 6. Correlations have been developed for air permeability versus oil and brine which cover all rock types. Separate correlations for air permeability versus brine permeability are also shown for sandstones, limestones and dolomites. The reference line shown on each correlation represents the case where permeabilities to air and liquid are equal. The fit line is the result of a least squares regression of the data. The fit equations are shown on each figure.

DISCUSSION

Specific permeabilities to air and oil are compared graphically in Figure 1 for 1868 samples over a permeability range from 0.1 to 10,000 md. The lithologies included 1117 sandstones, 422 dolomites and 329 limestones. The two parameters show a close relationship, with permeabilities to oil being slightly lower than the equivalent air permeabilities. This difference is assumed to be primarily due to the Klinkenberg effect. The relationship of the specific oil and air permeabilities is similar to the empirical Klinkenberg corrections for air permeability measurements that are widely used throughout the industry (Core Laboratories, 1984).

Figure 2 shows equivalent data for 895 pairs of specific brine and air permeabilities for both sandstone and carbonate formations. These parameters also provide a good correlation. The fit line for brine permeability is lower than for oil permeability, which is attributed to the interaction of water with the rock surfaces or clays. The ratio of brine to air permeability is about 0.5 over a permeability range from 0.1 to 10,000 md.

Specific brine versus air permeabilities were first examined separately for different rock types: 578 sandstones (Figure 3), 111 limestones (Figure 4), and 206 dolomites (Figure 5). Deviations from the reference line were similar for all rock types and, therefore, the composite correlation of air versus brine permeability was developed that includes all rock types (Figure 1).

The overall results show a strong correlation between specific permeabilities and that standard core analysis air permeabilities are of value in approximating reservoir liquid permeabilities. The differences between air and liquid permeabilities were not large, and the differences between air and brine permeabilities were consistent over a wide permeability range. The data show that air permeabilities can be used to approximate reservoir liquid permeabilities for many reservoirs and are valuable in the characterization of reservoir quality.

A technique has been developed which includes the use of standard air permeability measurements to obtain reservoir descriptions to aid in the design of EOR projects (Chopra et al., 1989). The technique for obtaining a realistic reservoir description incorporates the reservoir performance during primary and secondary processes with geological, petrophysical, and pressure-transient data. The term petrophysical includes permeability and porosity data determined from standard core analyses. Geological and petrophysical data can be used together to develop a realistic layering from well to well which is important in the prediction of pressure maintenance.

Another technique involves permeability/porosity plots versus depth along with gamma ray data and connate water saturation data to identify reservoir layers. Core data are usually the source for permeability and porosity. The permeability/porosity dictates the speed at which fluid flows through the various layers. The initial estimate of the reservoir description is used in a simulator with appropriate rock and fluid property data to predict primary and secondary performance. The layer kh's (permeability x height) are changed in a trial-and-error manner until good matches between the predicted and actual performance of individual wells are obtained.

Significantly larger differences between measured air and brine permeabilities may occur for reservoirs with high concentrations of active clays. Formations with at least 5-10% total swelling clays have been considered as having high clay content (Bush and Jenkins, 1970). With a high degree of water sensitivity, specific permeabilities to brine could be considerably lower than the actual reservoir permeability. In most reservoirs, and particularly clayey formations, effective permeabilities to oil in the presence of a reservoir connate water saturation would more accurately define reservoir flow characteristics.

A second application for the use of air permeabilities in reservoir evaluations is presented for a clayey reservoir. Clay minerals present in the formation averaged (1) smectite 16%, (2) chlorite 4% and (3) kaolinite 3%. The standard core analysis study included effective permeabilities to oil for 71 out of a total of 282 samples that were analyzed. Standard air permeabilities were measured on the same 71 plugs after they were cleaned and dried. Effective oil permeabilities plotted versus air permeabilities for the 71 samples are shown in Figure 6.

The effective permeabilities to oil versus the air permeabilities show a close correlation over a wide permeability range. The ratio of effective oil permeability to air permeability is approximately 1.0 at 10,000 md but decreases with decreasing permeability. The ratio is 0.53 when air permeability equals 1000 md but decreases to only 0.12 for an air permeability of 1.0 md. This relationship was used to estimate effective oil permeabilities for the remaining 211 samples on which only air permeability had been measured. Core analysis costs are minimized by determining oil permeabilities for only about 25% of the samples. The correlation was successfully used for predicting effective oil permeabilities from standard air permeabilities measured on cores throughout the field.

CONCLUSIONS

1. Comparisons of liquid and air permeabilities show a strong correlation supporting the use of air permeabilities in evaluating reservoir quality and in the development of reservoir descriptions.

2. Air permeabilities are useful in describing many reservoirs.

3. A cost effective method is to obtain effective oil permeabilities on selected samples and develop a correlation with air permeabilities for use in estimating reservoir oil permeabilities.

ACKNOWLEDGMENT

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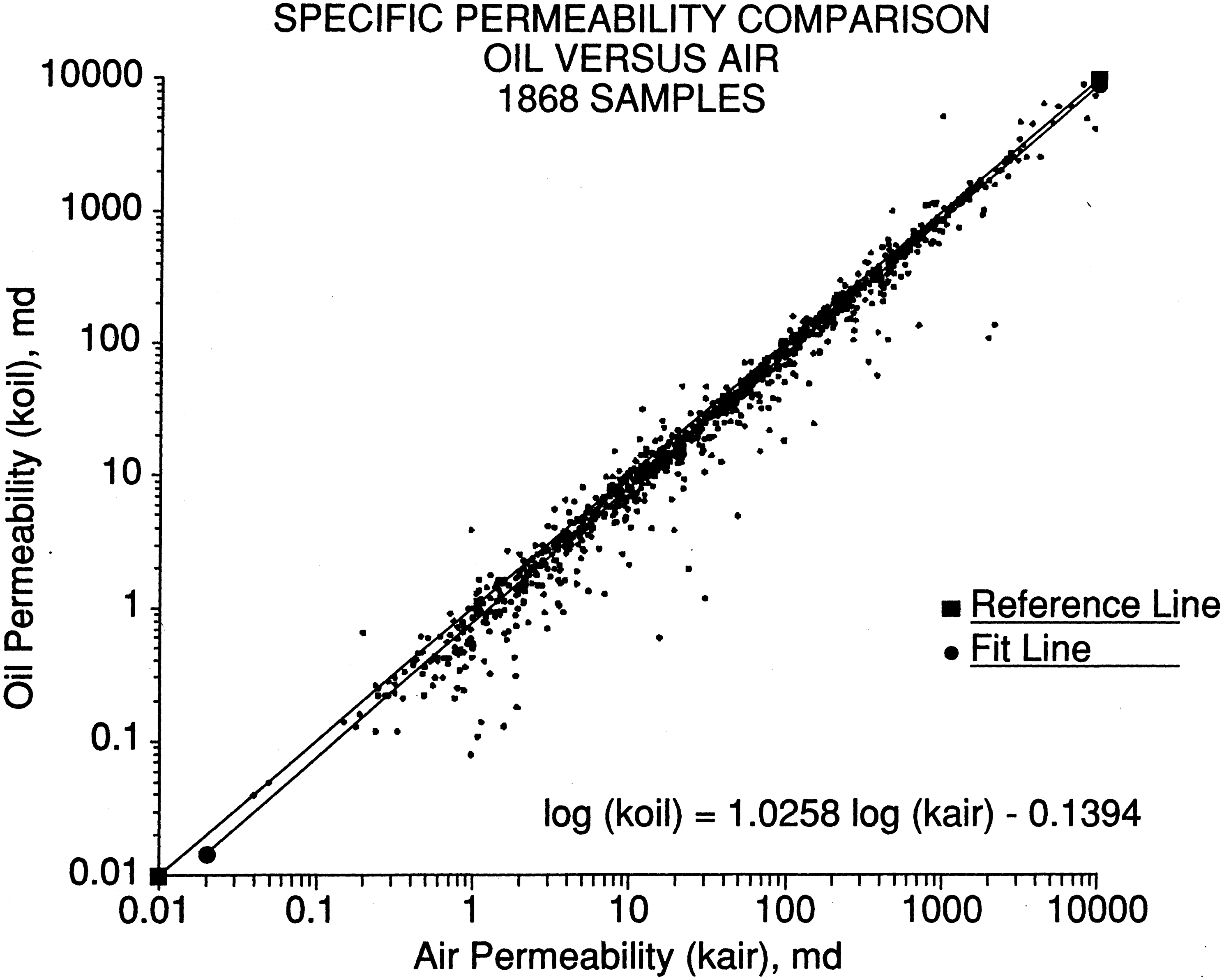


Figure 2

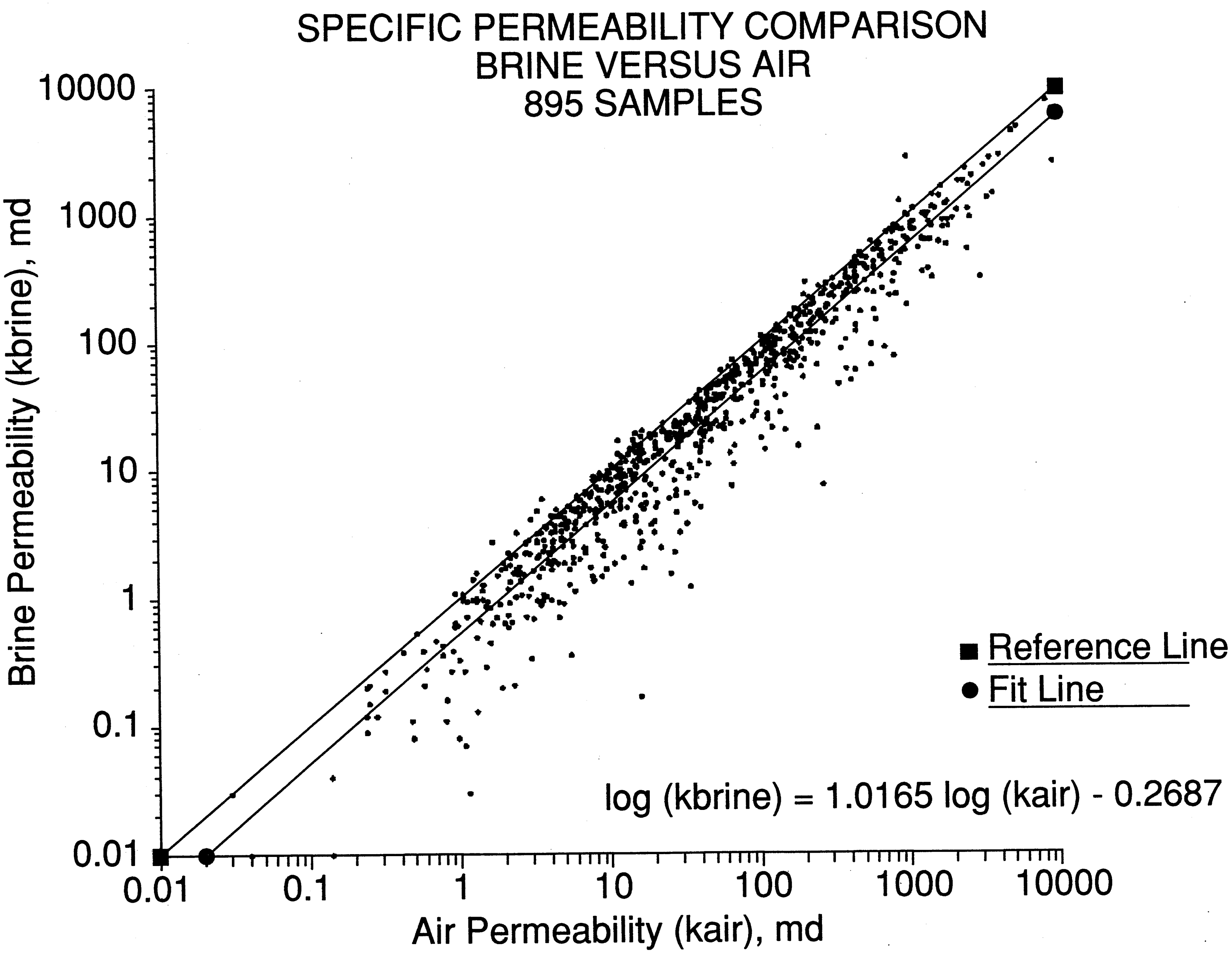

SPECIFIC PERMEABILITY COMPARISON
BRINE VERSUS AIR
895 SAMPLES

Figure 3

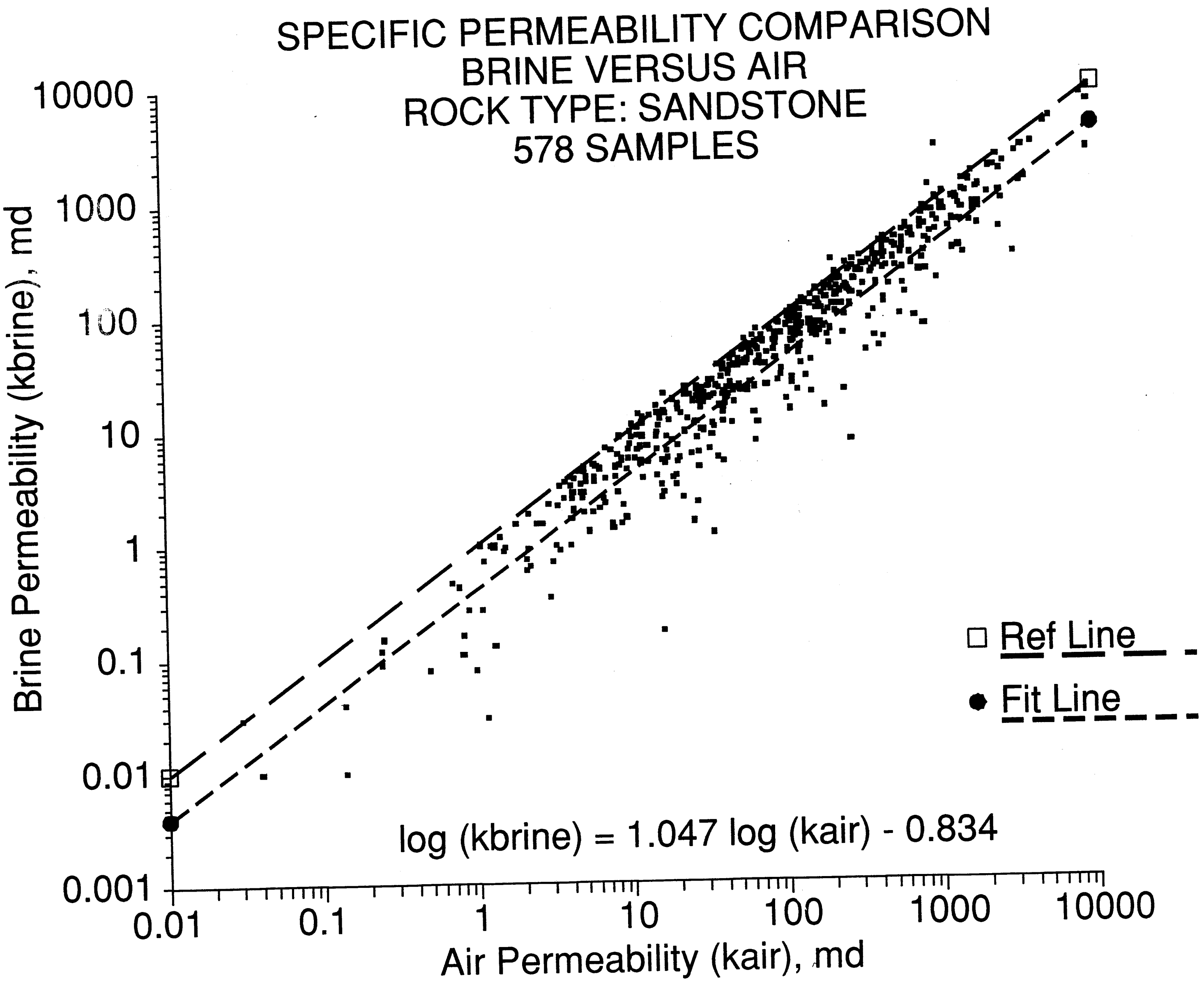

SPECIFIC PERMEABILITY COMPARISON
BRINE VERSUS AIR
ROCK TYPE: SANDSTONE
578 SAMPLES
Brine Permeability (kbrine), md
10000
1000
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
1000
10000
Air Permeability (kair), md
□ Ref Line
● Fit Line
log (kbrine) = 1.047 log (kair) - 0.834

Figure 4

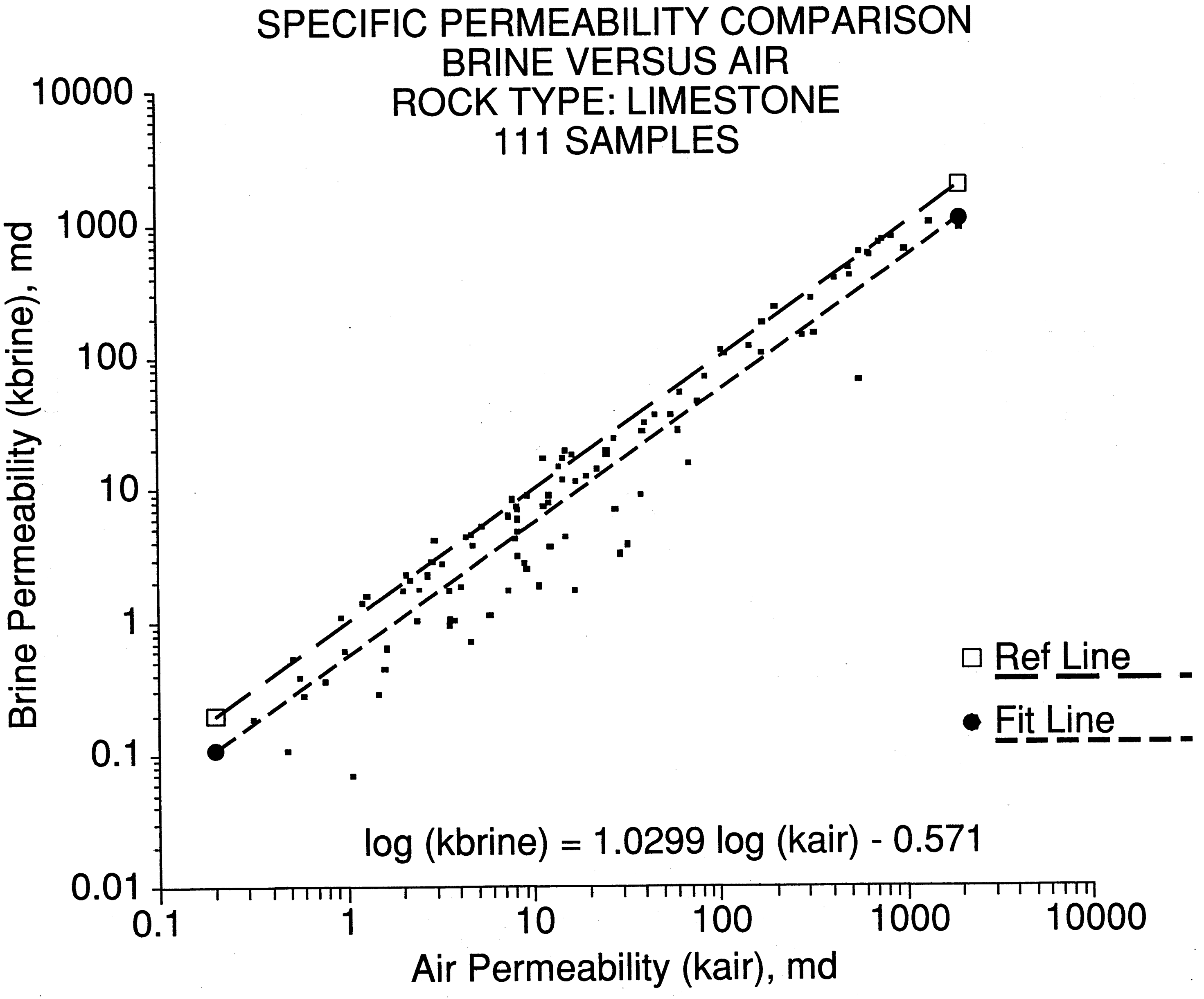

SPECIFIC PERMEABILITY COMPARISON
BRINE VERSUS AIR
ROCK TYPE: LIMESTONE
111 SAMPLES
Brine Permeability (kbrine), md
10000
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
10000
Air Permeability (kair), md
□ Ref Line
● Fit Line
log (kbrine) = 1.0299 log (kair) - 0.571

Figure 5

SPECIFIC PERMEABILITY COMPARISON
BRINE VERSUS AIR
ROCK TYPE: DOLOMITE
206 SAMPLES

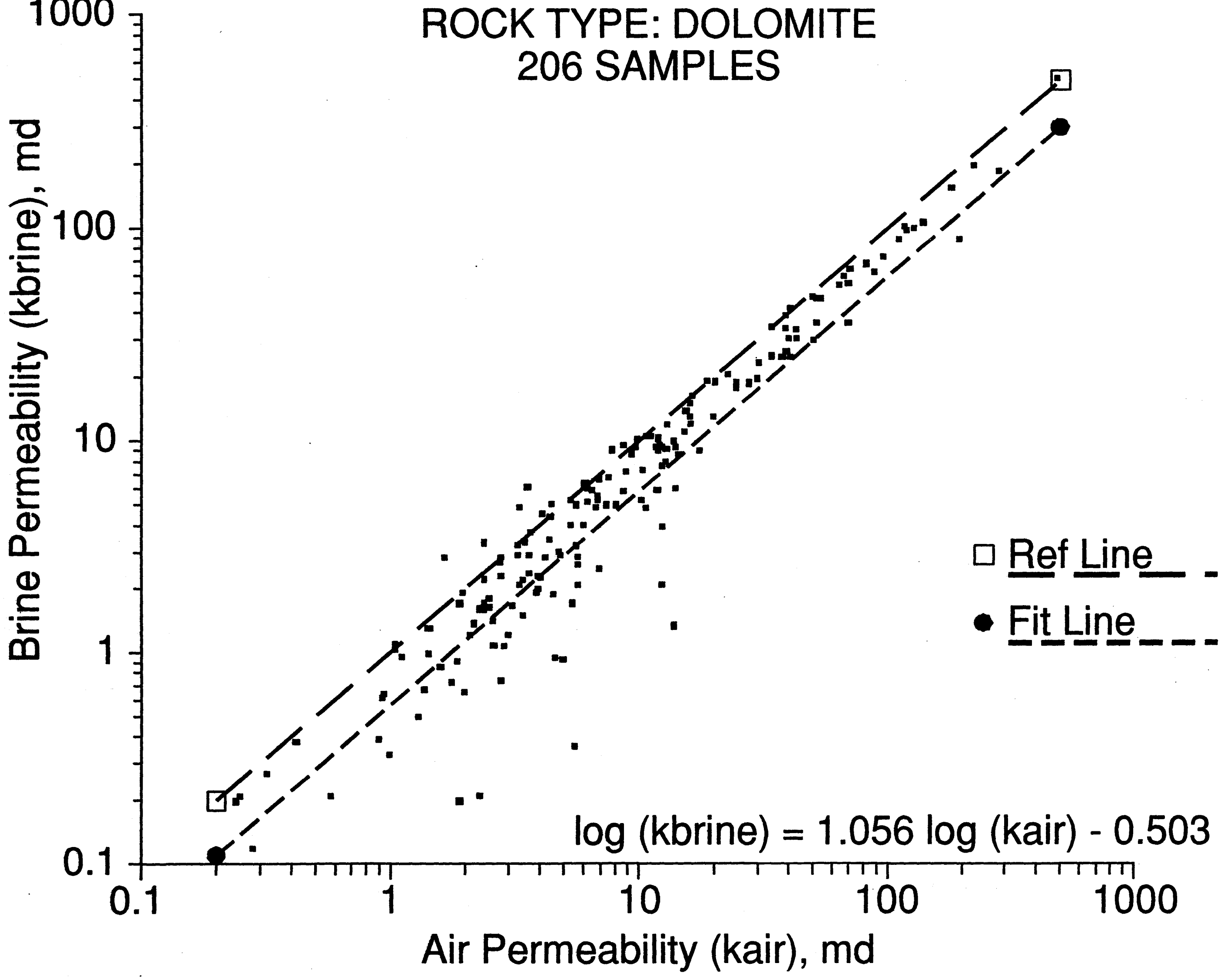
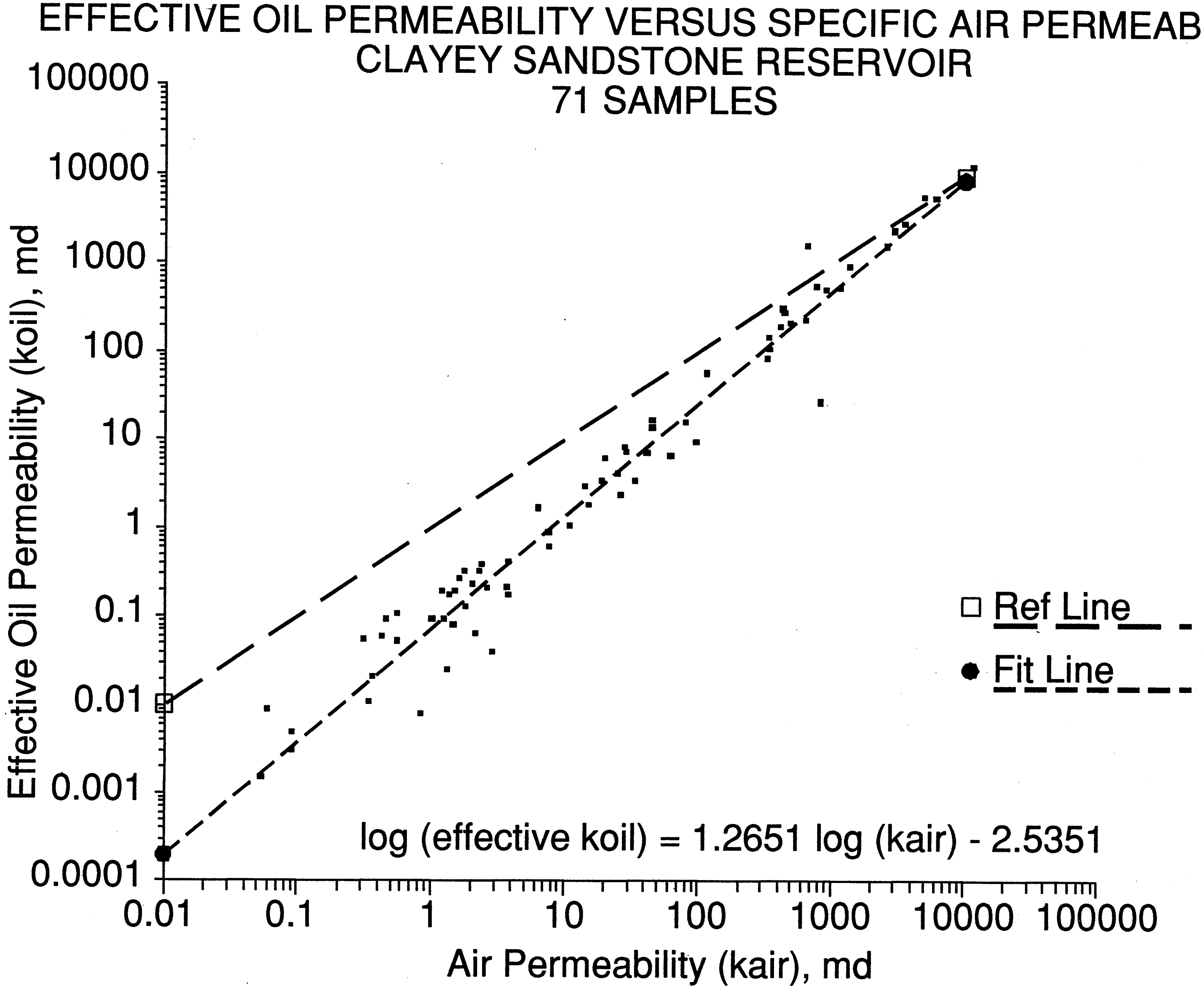


Figure 6


EFFECTIVE OIL PERMEABILITY VERSUS SPECIFIC AIR PERMEABILITY
CLAYEY SANDSTONE RESERVOIR
71 SAMPLES
Effective Oil Permeability (koil), md
100000
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
100
1000
10000
100000
Air Permeability (kair), md
Ref Line
Fit Line
log (effective koil) = 1.2651 log (kair) - 2.5351