CONTINUOUS PERMEABILITY PROFILES IN CORES INTEGRATING PROBE PERMEAMETRY AND PLUG MEASUREMENTS – COMPARISON WITH BOREHOLE NMR LOGS IN BRAZILIAN RESERVOIRS

Cristiano L. Sombra, Marcelo C. Monteiro, Carlos R. O. Rodrigues, Gustavo C. Pinho, Gilvan P. Hamsi, Alexandre J. M. Figueiras, Ricardo J. O. Queiroz and Fernando S. Rodrigues

PETROBRAS S/A, BRAZIL

ABSTRACT

This paper presents a methodology of integrating probe permeametry and plug permeabilities, generating fast, relatively accurate and densely sampled permeability profiles in cores, and how to transfer these data to the scale of vertical resolution of borehole logs. These upscaled core data allow further comparison and calibration of borehole log results. Cores were described and petrographic image analysis was used to characterize pore size distribution of the main reservoir facies.

Several reservoirs logged with NMR (nuclear magnetic resonance) tools along Brazilian basins were analyzed with this methodology. Borehole NMR permeability estimates presented very good correlation with these upscaled core data, but they were pessimistic in front of some specific facies with larger pore sizes. Either logging speed was not slow enough to allow complete relaxation of hydrogen protons from these larger pores or the equations used to estimate permeability did not consider properly the effect of larger pores. Knowing the facies where this problem occurs will conduce to a better planning of parameters for estimating permeability. The best criteria for facies definition for this purpose must take into account pore size distribution, pore throat distribution and minimum vertical resolution of logs.

INTRODUCTION

Some problems do not allow the direct comparison of permeability measurements taken from cores with those from logs. The volume of a plug is very small if compared to the volume investigated by borehole logs – which is known as the support effect problem (for details, see Isaaks & Srivastava, 1989). Although average properties may be similar, the variance of core measurements is high, since borehole logs tend to average properties due to the greater volume investigated. Another critical problem is that plug sampling is biased - plugs are usually taken in reservoir rocks, but not in non-reservoir rocks. This bias shifts average properties between plugs and borehole logs. To shortcut these problems, closely spaced probe (mini) permeametry measurements become an alternative to complement Hassler cell plug permeabilities. This paper describes (i) how probe permeametry can be calibrated with plug results, corrected and smoothed (upscaled) to the vertical resolution of borehole logs, and (ii) it compares upscaled cored permeability profiles with borehole NMR (nuclear magnetic resonance) permeability estimates from some oil charged reservoirs from Brazilian basins. Core descriptions and pore size distribution obtained from petrographic image analysis complement the conclusions obtained initially with this comparison.

CORE PLUG PERMEABILITY

Absolute permeability is routinely measured in Hassler cells flowing air through cylindrical core plugs, using Darcy's equation of linear flow. Although the values obtained are considered precise and accurate, plug measurements are relatively expensive and time-consuming. Only a small number of plugs are taken from the cores (usually three plugs at every one meter core box, representing less than 5% of the core volume). In heterogeneous reservoirs, most of the heterogeneities in permeability are not captured by such a small sampling. Another characteristic of plug sampling is that only reservoir rocks are plugged routinely, for obvious reasons. Non-reservoir lithologies, such as shales and siltstones, are almost never plugged. Therefore, plug sampling is biased, representing only the reservoir portion of the rock.

PROBE (OR "MINI") PERMEAMETRY

Probe permeametry in consolidated slabbed cores is an alternative to measure permeability between plugs in a fast, cheap, non-destructive way, obtaining a quasi-continuous permeability profile and sampling with close spacing both reservoir and non-reservoir rocks. The high sampling density can capture the real variability of permeability. Profiles generated in such a manner, after calibrated with plug results and filtered to a suitable vertical resolution, can be comparable to wire-line logs. A pressure-decay probe permeameter (Jones, 1992) was used to measure permeability between plugs in slabbed cores. Air is injected through a thin probe in the slabbed rock surface, and pressure decay is measured along time. Measurement time varies from about 2 to 35 seconds. In highly permeable rocks, measurements are faster. The spacing between measurements was kept very close, about 3 cm.

Probe permeametry has been used at PETROBRAS for a few years and the experience has shown that the data have good quality and correlate well with plug measurements, although they are not very accurate for obvious reasons:

- the cores are not clean, that is, are fluid impregnated, and fluid saturations vary along the cores;
- argillaceous rocks may develop almost invisible microfractures due to clay dehydration, and gas leakage along microfractures can result in relatively higher permeabilities;
- irregularities in slabbed surface may result in gas leakage between probe and slabbed surface of the rock, usually in very coarse grained lithologies;
- probe permeametry in poorly consolidated cores are excessively optimistic and, in most situations, they are non-realistic due to decompression and pore expanison;

These problems deviate probe permeability measurements from plug permeabilities, but results from these two techniques in consolidated rocks use to present correlation coefficients from the order of 0,80 to 0,90, encouraging correction of probe permeametry results by calibrating them with plug results. This calibration minimizes the relatively low accuracy of probe permeametry, resulting in a good quality, quasi-continuous permeability profile.

PROBE PERMEAMETRY CALIBRATION, CORRECTION AND UPSCALING

One possible method for calibrating probe permeametry with plug permeability is to measure permeability in plugs with both techniques and perform regression analysis. Problems with this methodology are: (i) after regression equation is applied to correct probe permeametry results, they do not honor plug permeabilities, and (ii) the variance of the data is reduced. Kriging with external drift would honor plug data but cannot be used in this case because the secondary or soft variable (probe permeametry) has greater variance than the primary or hard variable (plug permeability). Other geostatistical techniques are being tested, but results are still being evaluated.

The procedure used to correct probe permeametry measurements was (i) to measure, at every plug, the difference or residue between logarithms of probe permeametry and plug permeability, (ii) interpolate linearly this residue between two consecutive plugs at every depth where probe permeametry has been measured and (iii) add this interpolated value to the logarithms of the probe permeametry measurement. The resulting permeability profile, which will be referred as plug-calibrated probe permeability profile, honors plug data, has the approximate shape and keeps the approximate variance of probe permeability profile.

Before comparing high frequency plug-calibrated probe permeametry profiles with relatively low-frequency borehole logs, it is necessary to correct core depth to log depth and then smooth probe permeametry curve. To smooth probe permeametry curve, unweighted geometric moving averages were tentatively tested with different windows, from 10 cm up to 130 cm. Depth corrected curves were then correlated with NMR borehole logs, and optimum correlation coefficients were obtained with windows around 70 cm, which is close to the vertical resolution of NMR logs. The curve smoothed with this optimum window will be referred as upscaled core permeability profile.

PERMEABILITY ESTIMATES FROM BOREHOLE NMR (NUCLEAR MAGNETIC RESONANCE) LOGS

An important characteristic of NMR logging tools is that the signal comes from the fluid in the pore space rather than from formation matrix, which yields a porosity measurement independent of matrix or mineralogy (Cherry, 1997). The received signal decays exponentially from initial amplitude that is proportional to the number of hydrogen protons in pore fluids. Therefore, this initial amplitude is proportional to the formation's porosity. The signal's rate of decay is described by a time constant called T_2. The area under the T_2 curve represents the porosity and the area under each peak the amount of pore space occupied by the fluids in each pore size group. The shape of the T_2 curve strongly reflects the pore size distribution (but not pore throat distribution). The distribution of T_2 peaks may also indicate distribution of clay bound water (clay pore sizes), capillary bound water (silt pore sizes) and free fluids.

By combining the magnitude of the porosity with the shape of T_2 distribution it is possible to estimate permeability, since pore throats control the permeability of a formation and, in most situations, they are presumed to be related to pore size distribution. A review of some methods of estimating permeability from T_2 distribution is presented by Singer *et al*. (1997). Many of the methodologies presented seem to fail in some situations. Limiting factors may be related to different constraints such as wettability, type of T_2 distribution, lithology, etc. These limitations point to the need of calibration of permeability estimates with direct measurements in core data. One must keep in mind that (i) NMR permeability is not a direct measurement of permeability, since there is no fluid flow involved in the process, (ii) permeability estimates use T_2 distribution, which may be strongly related to pore size distribution, but not to pore throat distribution in some situations: thin clay coatings, for example, may reduce considerably pore throats without reducing so much pore sizes.

COMPARING UPSCALED CORE PERMEABILITY PROFILES AND BOREHOLE NMR PERMEABILITY LOGS

Upscaled core permeability profiles were generated for some oil charged sandstones and carbonates along Brazilian Basins: (i) cretaceous, distal alluvial fan sandstone deposits of the Sergipe-Alagoas Basin; (ii) Paleozoic, eolian and fluvial sandstones of the Solimões Basin; (iii) cretaceous, fluvial sandstones of the Potiguar Basin; (iv) cretaceous fluvio-deltaic sandstones of the Espírito Santo Basin; (v) tertiary turbiditic sandstones of Campos Basin and (vi) cretaceous carbonates of Campos Basin. Petrographic analysis of mineral constituents and quantification of pore size distribution through petrographic image analysis was already concluded in some of these reservoirs (i, and ii).

Preliminary analysis has shown that borehole NMR permeability estimates are very well correlated with upscaled core permeability profiles, in all of the cases mentioned above. Pearson's correlation coefficients vary between 0,65 and 0,90. The magnitude of NMR permeability estimates, however, may be either quite similar or quite different from the magnitude of permeability in upscaled core permeability profiles, independently of the equation used in permeability estimates.

Up to now, sandstones of the Sergipe-Alagoas Basin have been studied in more detail (figure 1). Reservoirs are clean sandstones (91% of reservoir facies) to conglomeratic sandstones and conglomerates (9% of reservoir facies), with 21%

average porosity (average plug porosity and average NMR porosity are similar). Three main sandstone facies have been described: C_1 (coarse to very coarse grained sandstones, performing 30% of reservoir facies), C_2 (medium grained sandstones, performing 22% of reservoir facies) and C_3 (fine to very fine grained sandstones, performing 39% of reservoir facies). NMR tool was the CMR*. Permeability was estimated with the Timur/Coates equation, using T_2 *cutoff* of 10 msec. Pearson's correlation coefficient between CMR permeability and upscaled core permeability is 0,79. The magnitude of CMR permeabilities is similar to that of upscaled cored permeability in the intervals where predominate C_2/C_3 facies, but pessimistic in intervals dominated by C_1 facies. C_1 facies, the more coarse grained sandstone facies, has higher core permeabilities and larger pores as quantified from petrographic image analysis. It is possible that logging speed was not slow enough to allow complete relaxation of hydrogen protons from greater pores.
Fluvio-eolian sandstones of the Solimões Basin have also been analyzed in detail (figure 2). The cored interval analyzed is composed of 5 meters of fine to very fine grained eolian sandstones with 17% average plug porosity, over a sequence of 12 meters of fine to coarse grained fluvial sandstones with 8% average plug porosity. Fluvial facies is more coarse grained and, despite the lower porosity, presents some larger isolated pores. Quartz cementation was responsible for porosity reduction in fluvial facies. Eolian sediments are fine to medium sand, poorly consolidated, with smaller pores but well connected pore system. Clay content is very low in both facies. Average plug porosity and average NMR porosity are almost similar in both sequences. The NMR tool was the CMR and permeability was estimated with both SDR and Timur/Coates equations, using T_2 *cutoff* of 33 msec. Pearson's correlation coefficient of upscaled core permeability logarithms is 0,77 with SDR estimate, and 0,66 with Timur/Coates estimate. When facies are analyzed separately, correlation coefficients rise to 0,80 (SDR) and 0,88 (Timur/Coates) in eolian facies, and to 0,90 (SDR) and 0,89 (Timur/Coates) in fluvial facies. Despite the excellent correlation presented, the permeability estimates are pessimistic in fluvial facies with both equations, while in eolian facies, SDR estimate is close to upscaled core permeability and Timur/Coates is optimistic. Therefore, CMR permeabilities are pessimistic in the more coarse grained sandstones of the fluvial facies, which are less porous than eolian facies but have greater pores. Eolian sediments have no pores larger than 0,25 mm, in opposition to fluvial sediments, that have pores larger than that value.

CONCLUSIONS

Densely sampled probe (mini) permeametry in slabbed cores generated quasi-continuous permeability profiles. After calibrated with plug measurements in Hassler cells and smoothed (upscaled) to the vertical resolution of borehole logs, these profiles were used as a reference to analyze the accuracy of borehole permeability logs. To smooth high-frequency probe permeametry curves, geometric moving averages were tested with different windows, and smoothed curves that presented the best correlation coefficients with borehole logs were chosen.
Upscaled core permeability profiles were generated with such methodology in cores from several wells along Brazilian basins where NMR logs had been run, in oil charged reservoirs. Regression analysis between borehole NMR permeability estimates and upscaled core permeability profiles presented high correlation coefficients (0,66 to 0,90), demonstrating that NMR permeability estimates may be very good indicators of relative changes in permeability, being excellent tools for estimating permeability in poorly known basins or wildcat areas. Despite the good correlation coefficients, NMR permeability estimates were shifted from core data in some facies. In two reservoirs studied in more detail, estimates were pessimistic in facies with larger pores, as observed in pore size distribution from petrographic image analysis. Either logging speed was not slow enough to allow complete relaxation of hydrogen protons from these larger pores or the equations used to estimate permealbility did not consider properly the effect of larger pores. Knowing the facies where this problem occurs will conduce to a better planning of logging parameters for estimating permeability. The best criteria for facies definition for this purpose must include, besides conventional criteria such as lithology, texture and diagenesis, other important parameters related to pore size and pore throat distribution and minimum vertical resolution of logs.

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* Combinable Magnetic Resonance tool, Mark of Schlumberger

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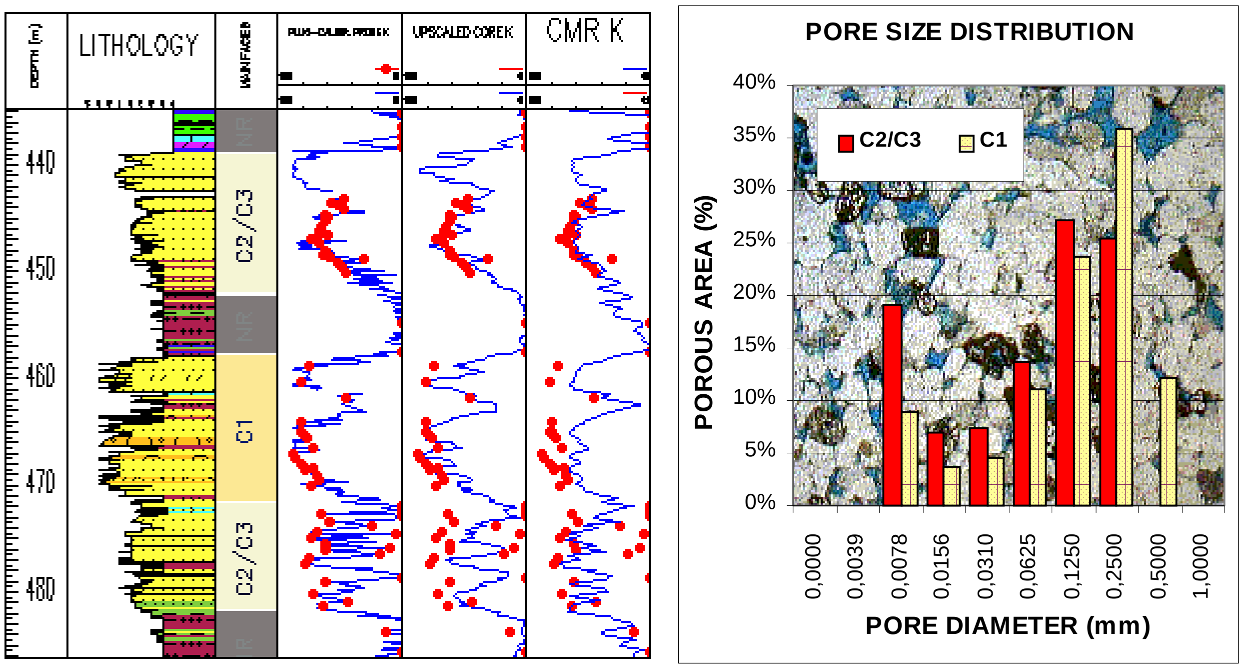

Figure 1. Core analysis and pore size distribution from Sergipe-Alagoas basin deposits. NMR permeability (estimated with the Timur/Coates equation) presents very good correlation with upscaled core permeability, but absolute values are smaller when compared to core measurements in facies where large pores predominate (C1 facies). Permeabilities increase from right to left.

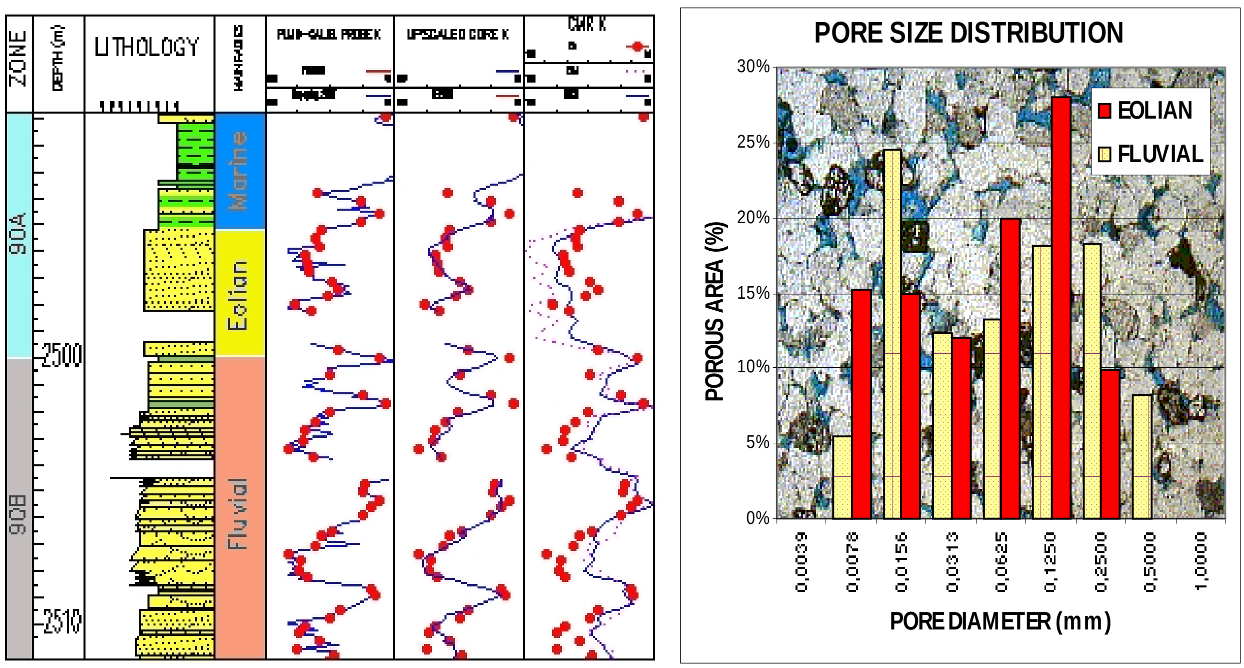

Figure 2. Core analysis and pore size distribution from Solimões basin sandstones. NMR permeability (estimated with the SDR equation) presents very good correlation with upscaled core permeability, but absolute values are smaller when compared to core measurements in facies where large pores predominate (Fluvial facies). Permeabilities increase from right to left.