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COMPARATIVE MEASUREMENTS BETWEEN A NEW LOGGING TOOL AND A REFERENCE INSTRUMENT

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Measurements were performed on reference samples (D_2O-H_2O mixtures) and on highly heterogeneous rocks (Vosges sandstone) with a new logging tool designed to give access to a high spatial resolution, below 1.5 cm on the vertical scale, for a toroidal sensitive volume of 20 cm^3. The results were compared to measurements obtained on a clinical magnetic resonance imaging (MRI) equipment working at the same frequency (4.3 MHz). T_2 differences as high as 30% were observed for the reference samples; the shortest values were obtained with the logging tool. Porosity profiles of the rock samples were also compared to reference profiles obtained with a conventional computed tomography (CT) scanner. Both nuclear magnetic resonance (NMR) measurements underevaluate porosity by 2–4% for short T_2 values (<10 ms).

Keywords: **Nuclear magnetic resonance logging tool; Magnetic resonance imaging; Porous media.**

INTRODUCTION

In the last years a new generation of nuclear magnetic resonance (NMR) logging tools for oil-well evaluation has appeared.[1,2] These tools combine two new features: permanent magnets for the generation of the static magnetic field, and use of multiple pulse techniques for faster and more sensitive measurements. Permanent magnets give access to higher magnetic field intensities and thus increase signal intensity. However, the achieved spatial resolution is obtained by compromising with acceptable sensitivity. Multiple-pulse techniques allow faster measurements of both signal amplitude and NMR relaxation times, in particular the Carr–Purcell–Meiloom–Gill (CPMG) technique is used for transverse relaxation measurement. However, multiple pulse sequences present a well-known sensitivity to inhomogeneities of both static magnetic field and radiofrequency (RF) field, particularly for the evaluation of transverse relaxation. Therefore, the comparison to a well-calibrated laboratory instrument is desirable.

Measurements were performed on reference samples and on highly heterogeneous rocks with a new logging tool designed to give access to a high spatial resolution, below 1.5 cm on the vertical scale. The results were compared to measurements obtained on a whole-body MR imaging equipment working at the same frequency (4.3 MHz). Porosity profiles of the rock samples were also compared to reference profiles obtained with a computed tomography (CT) scanner.

MATERIALS AND METHODS

References samples were prepared by diluting a paramagnetic aqueous solution by D_2O in the following H_2O/D_2O proportions: 3.25%, 10%, 25%, 50%, and 100%. The starting paramagnetic solution is $CuSO_4$ to a concentration of 2 g/liter in pure H_2O. Solutions of variable proton density and relaxation time were thus obtained.

Rock samples of high heterogeneity were chosen, so as to check the achievable resolution. Cores of 7-cm diameter and 80-cm length were bored from cubic blocks of 80-cm size. Each of these long bores was then cut into four 20-cm-long cylinders to be examined by the reference mea-

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surements. Four different Vosges sandstone blocks taken from the same quarry were thus examined saturated in water.

We have used a new logging tool for which the configuration has been optimized to achieve a resolution of about 1.5 cm in the vertical direction, along the well axis. The polarization field is created by a magnetic source[3] including a SmCo permanent magnet and polar pieces. The measurement volume approximately corresponds to a nearly square section (1.5×1.5 cm^2) of a torus of 11.5 cm intermediate diameter under a 110° angle, corresponding to a volume of about 20 cm^3 at 1 cm from the bore wall inside the formation. The B0-field intensity is of 0.1 T within better than 2% over the measurement volume. This volume corresponds to a local minima in the induction field, so as to prepolarize the spins before their arrival in the measurement zone. A CPMG sequence with an interpulse spacing that can be shortened down to 0.5 ms has been implemented with up to 255 echoes. Measurements have been made with samples fixed relative to the tool or at relative displacement speeds of 4 and 8 cm/s. Signal intensity is collected from the whole echo enveloppe by taking 400 samples/echo. The relaxation curve is then analyzed by one- or two-exponential fit. One profile along 80 cm is typically acquired in 10–20 s.

Comparative measurements were made with a whole-body 0.1 T NMR scanner (Magnetech, Orsay, France). The B0-field homogeneity is better than 5 ppm on the measurement volume. A special RF-coil was used, with a B1-field homogeneity better than 10% on a 10-cm cubic volume. Mo and T_2 profiles along the sample axis were obtained by a multiecho sequence at an interpulse spacing of 3.4 ms, which is the shortest achievable with the whole-body gradient coils installed on the scanner; it corresponds to a spatial resolution of 3.125 mm. A phase-alternated multiecho sequence[4] was used to avoid distortions due to gradient and RF imperfections. Typically up to 256 echoes were acquired, from which porosity profiles were computed after normalisation to a similar volume of pure water. The relaxation curve at a given spatial position was analysed as a monoexponential, stretched exponential or multi-exponential law. The multi-exponential fit was derived by standard minimization of the χ^2 function (Levenberg-Marquardt method), with a regularization term.

Bulk porosities were measured by the conventional method (water saturation after vacuum evacuation). We also performed x-ray tomography (CGR scanner CE12000) on dry and water-saturated cores to obtain porosity profiles at a resolution of 8 mm. The difference between the bulk porosity of a 20-cm-long core and its averaged "scanner porosity" was always lower than 1% in porosity units.

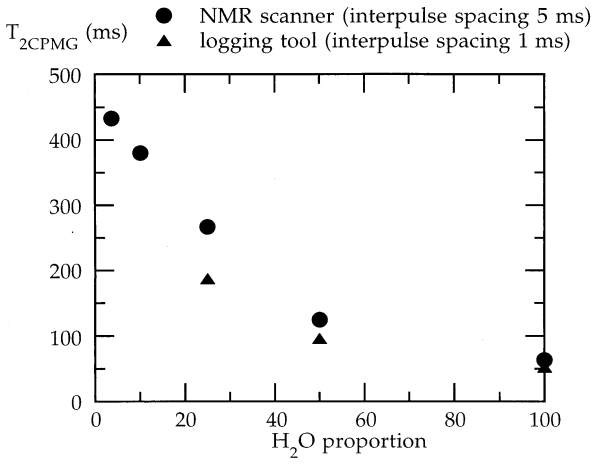

Fig. 1. Transverse relaxation times measured in the paramagnetic solutions as a function of the H_2O/D_2O proportion, either with the new logging tool at an interpulse spacing of 1 ms (triangles) or with the 0.1 T scanner at an interpulse spacing of 5 ms (circles). Both measurements were fitted by mono-exponential.

RESULTS AND DISCUSSION

For all measurements made with the paramagnetic solutions, the signal amplitude was found satisfactorily linear with H_2O proportions, and the relaxation curves were monoexponential. Figure 1 displays T_{2CPMG} of the paramagnetic solutions obtained with the new logging tool and with the NMR scanner. At lower H_2O proportions, the paramagnetic concentration is lower, and as expected, the relaxation time increases. However, the relaxation times are systematically lower when evaluated with the logging tool than with the NMR scanner, and the discrepancy is increased at decreasing concentration. For 30% H_2O, T_2 values differ by 30%, even though the interpulse spacing was 1 ms with the logging tool and 5 ms with the scanner. These deviations could be interpreted as due to the poorest homogeneity of the magnetic fields for the logging tool.

By contrast to the reference solutions, the NMR relaxation curves for water in the sandstone samples are strongly deviating from a monoexponential law. More extensive data were obtained with the NMR scanner; they are better described by either stretched exponentials with exponents in the range 0.4–0.7 or by multiexponential laws. The signal intensity derived by monoexponential fit is systematically underevaluated by up to 40–50%, while the stretched exponential fit gives results comparable to the multiexponential fit, but only under the condition $T_2 > 50$ ms. Here and below, T_2 is a representative value for the relaxation time spectrum obtained by the faster and more simple stretched exponential fit. So the most robust method to extract porosity

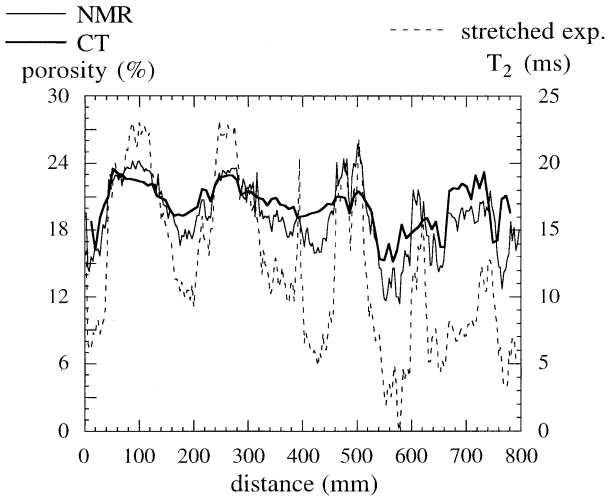

Fig. 2. Porosity profiles measured in the same sandstone cylindrical sample either by CT scan or with the NMR scanner, and T_2 profile obtained from the same NMR data. The T_2 data shown are representative values from a stretched exponential fit.

from the NMR data obtained with the 0.1 T scanner is the multiexponential fit, although the stretched exponential fit performs equally well for T_2 longer than 50 ms. Figure 2 compares porosity profiles obtained from the same sample with the CT scanner and with the NMR scanner by multiexponential fit; the T_2 profile is also shown. It should be noted that the T_2 values were the lowest in this sample compared with those in the other blocks. A

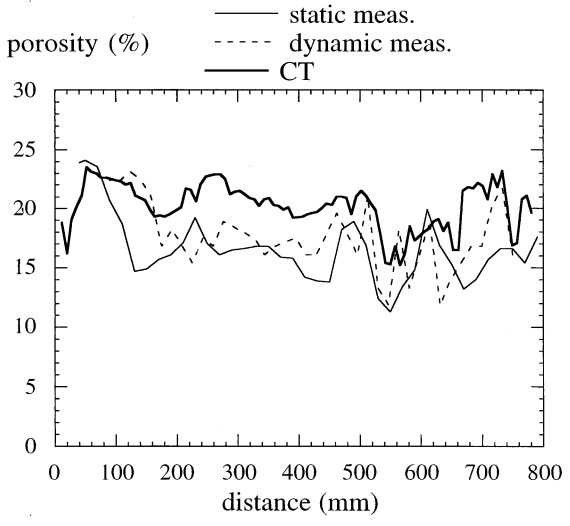

Fig. 3. Porosity profiles measured either by CT scan (same data as in Fig. 2) or with the NMR logging tool in sandstone samples from the same block; NMR data shown from static and dynamic measurements were not taken at the same location, illustrating sample heterogeneity.

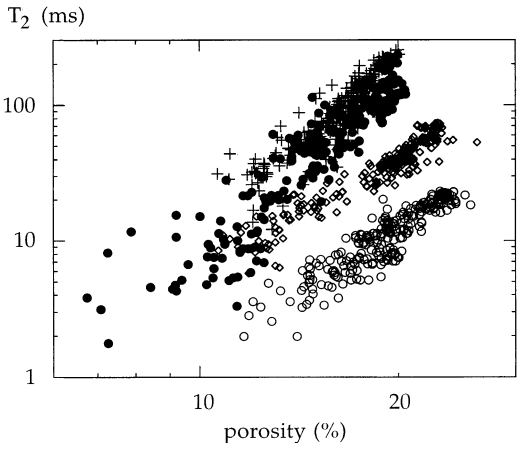

Fig. 4. T_2 as a function of porosity from the stretched exponential fit of the NMR scanner data for four different Vosges sandstone samples. Data in Figs. 2 and 3 correspond to the sample of shortest T_2 values (open circles).

porosity underevaluation by 2–4 in porosity units still remains when T_2 is below 10 ms.

Figure 3 compares porosity profiles obtained with the CT scanner and with the NMR logging tool from the same block. However, only the cylinders of 7-cm diameter were examined by CT, while the NMR data were taken along two directions from the cored block, either under static conditions or at a displacement speed of 7.6 cm/s. The porosity found by NMR is of the same order of magnitude as that observed by CT; however, it seems underevaluated by 2–4 porosity units. Moreover, noticeable differences between the CT and static NMR data, on the one hand, and between static and dynamic NMR data, on the other hand, are probably due to sample heterogeneity, since each measurement was performed at a different physical location from the other.

From the NMR scanner data, a fairly high correlation was found between T_2 and porosity ρ for each block (Figs. 2 and 4). Phenomenologically T_2 is proportional to ρ^{ε}, with $2.5 < \varepsilon < 4$. However, the same porosity could correspond to differences by two orders of magnitude in T_2 from one block to another, presumably because of differences in chemical composition between the blocks.

In these highly heterogeneous samples, the T_2 measurement alone is thus unpractical as a predictor of porosity, but porosity measurement within an accuracy of 2–4 porosity units is possible from a simple two-exponential analysis of the transverse relaxation curve obtained by a multiecho sequence.

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