

Field-dependence of relaxation time distributions in rock samples



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INTRODUCTION

¹H-NMR relaxation times of water-saturated rock samples are widely employed to characterize the architecture of pore space and to estimate petrophysical properties, such as permeability and irreducible water saturation. These parameters are used both in laboratory studies and in well logging (NML).

So far, such NMR studies were always carried out at a fixed frequency (typically 10 or 20 MHz in laboratory and 2 MHz in NML). It is well known [1] that NMR relaxation rates are inherently field-dependent, a fact which might represent a complicating factor in the above mentioned applications. Mono-exponential analyses of so far published longitudinal relaxation dispersion profiles of rocks [2] indicates that a modest field dependence in fact exists. However, it has been amply demonstrated [3,4] that the mono-exponential hypothesis is rarely applicable to natural rocks, where one usually observes a wide distributions of relaxation rates, due to the wide distributions of pore sizes and their physical and chemical properties.

In this study, we have investigated the relaxation rate distributions in several sandstones and carbonates at a number of relaxation field values, ranging from 10 kHz to 30 MHz (field values are henceforth expressed in terms of proton Larmor frequency).

EXPERIMENTAL

Cylindrical rock samples (8 mm in diameter and 11 mm in height) were saturated by water under vacuum. Their longitudinal relaxation curves were measured at a number of relaxation field values, using the Fast Field Cycling NMR Relaxometer produced by Stelar Srl. Pre-polarized (PP/S) and non-polarized (NP/S) acquisition sequences have been used with the following parameters:

* 128 logarithmically distributed τ values (times in the relaxation field) ranging from 0.1 ms up to 4 s,

* polarization field of 25 MHz,

* polarization time of 2.5 s.

Continuous distribution analysis of the curves was performed by UPEN [3,4].

Figure 1 exemplifies the resulting T_1 distributions for Pietra Serena (a sandstone) where one sees an unmistakable and systematic dependence on the relaxation field value. In other rocks (such as the carbonate Miratoio), the effect was less evident, indicating that it depends upon the nature of the sample.

For each relaxation decay curve, we have also estimated the initial decay rate R_{1i} (corresponding to the arithmetic average of the decay rates of the various sample components), the geometric mean R_{1g} of decay rates and the tailing (final) decay rate R_{1f} obtained by mono-exponential fits of the tailing portions of the relaxation curves (this corresponds to water in the largest sample pores). These values are plotted in Fig. 2. One can see that:

(a) The geometric mean R_{1g} and the arithmetic mean R_{1i} unmistakably depend on the relaxation field (though the dependence is relatively weak). The relaxation dispersion profiles of all the measured rock samples, when plotted on a log-log scale, were approximately linear and their slopes did not exceed -0.1. In the case of Pietra Serena, for example, $d\log\langle R_{1g}\rangle/d\log(B) = -0.07$.

(b) No dependence on the NMR measurement frequency can be detected for the longest relaxation rates R_{1f} .

It therefore appears that (i) different components of the sample exhibit different field dependencies and (ii) such dependencies tend to be steeper for the components with high relaxation rates (short T_1 's) and practically null for components with low relaxation rates (long T_1 's).

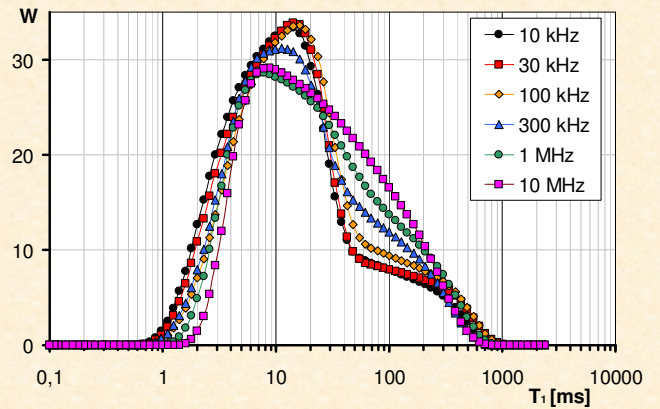


Figure 1. Field dependence of T_1 distributions for the Pietra Serena sandstone

The T_1 distributions were calculated from NMR relaxation decay curves measured at a number of relaxation field values. W is the probability density expressed in percent per Neper (the distributions are normalized to have the integral area of 100%). Relaxation field values are expressed by means of the corresponding proton Larmor frequencies.

THEORETICAL MODEL

Ideally, the T_1 distributions should reflect only the distribution of pore sizes which, of course, does not depend upon the relaxation field. However, we have encountered samples in which such a relaxation field dependence is appreciable. This means that, despite common beliefs, the T_1 distribution curves do not always *directly* reflect the distribution of pore sizes.

In a forthcoming paper [5] we propose a mathematical model which makes it possible to merge the distinct distribution curves obtained at different relaxation field values into a single, field-independent distribution which is more likely to reflect the distribution of pore sizes in the sample as perceived by NMR.

The model is based on two simple assumptions:

(1) For every component a of the sample, the field-dependence of its relaxation rate can be approximated by the empirically confirmed power law $R_{1a}(\omega) \sim \rho\omega^p$, where c is the bulk-water correction (about 0.3) and p , v are field-independent constants. Qualitatively, p corresponds to a relaxation rate measured at some reference field (large R_1 implying large p) and v corresponds to the negative log-log slope of the dispersion profile of the considered component.

(2) There is a correlation between v and p which can be formally encoded by means of a functional dependence $v \equiv v(p)$.

Knowing $v(p)$, the model allows one to 'correct' an experimental T_1 or R_1 distribution curve for the unequal field-dependencies of individual sample components and to calculate a sample-components distribution in terms of the field-independent parameter p (the p -distribution). Vice versa, given a set of two or more relaxation rate distribution curves, one can in principle determine the function $v(p)$ which provides for a best 'collapse' of all of them into a unique, field-independent p -distribution.

CONCLUSIONS

In some rocks, the T_1 distributions exhibit an apparent dependence on the relaxation field value. We have analyzed the problem and developed a mathematical method which makes it possible to correct for such effects (mathematical details of the method are about to be published [5]). Further study of the implications of these findings for the validity of NMR porosity-assessment techniques is under way.

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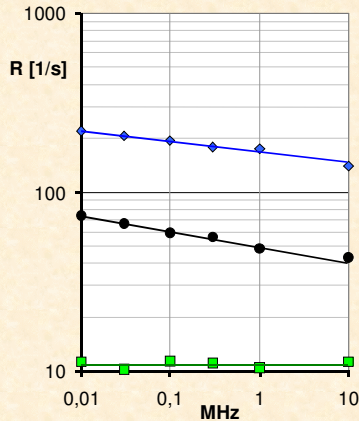


Figure 2. Decay rates rates in Pietra Serena

Relaxation field dependence of the initial decay rates (blue diamonds), the tailing decay rates (green squares) and the geometric means of decay rates (black disks).