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A study to apply nuclear magnetic resonance porosity measurements to seabed sediments

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Abstract

The method of Nuclear-Magnetic-Resonance (NMR) Quantitative-Relaxation-Tomography (QRT) of ^{1}H nuclei is proposed for cores of ocean bottom sediments in order to determine porosity as functions of position within a core without disturbing the material. This information, with cm or mm resolution, is relevant to the understanding of acoustic properties of ocean bottom sediments, which affect sonar and echo sounding. The feasibility of the method is shown by QRT on samples up to 8 cm in diameter of glass beads ranging from 0.3 to 16 mm in diameter and also of small 2 mm plastic cylinders. All samples were fully saturated with water. Three kinds of maps are produced for each section, with 0.73×0.73 mm pixel size and 5 mm slice thickness: Proton Density map, and two relaxation times (T_1 and T_2) maps, where T_1 and T_2 are the time constants for the return to the equilibrium of the longitudinal and transverse components of the nuclear magnetization, respectively. For each voxel the relaxation data are fitted to single exponential functions, giving values of T_1, T_2 and also of extrapolated signal, giving voxel porosity. Since the tomograph has a minimum echo time of 10 ms, any part of the signal having $T_2 < 10$ ms is not seen. In the systems tested, the NMR porosity Φ_{NMR} is, for this reason, approximately 3 percentage porosity units less than the porosity Φ measured destructively by wet and dry weight differences.

Keywords: nuclear-magnetic-resonance (NMR); porous media; quantitative-relaxation-tomography (QRT); non-destructive analysis; ocean sediments; echo sounding

1. Introduction

The acoustic response measured by echo-sounding technologies, and used to define sea bottom classifications, essentially depends on the reflectivity of the water-sediment interface, especially when using high frequency sound sources (Akal, 1972; Hamilton and Bachman, 1982; Urick, 1983; Pouliquen and Lyons, 2002). Any interpretative model used in these investigations, needs a detailed physical description of the sea bottom and shallow surface up to centimeter resolution, depending on the source frequency. Therefore, it is very important to obtain undisturbed core samples of the first meter of sediment and perform non-destructive measurements: for this reason the NATO Undersea Research Center (NURC) is utilizing the "SW 104" corer, originally designed and eventually improved by ISMAR (CNR) of Bologna (Magagnoli and Mengoli, 2000).

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The corer can extract an undisturbed sediment sample 10.4 cm in diameter with a maximum length of 135 cm, including a minimum of a 10 cm layer of saltwater, which is used for calibration of seawater density and *P* wave velocity. On these cores, parameters such as density, speed of sound and magnetic susceptibility are usually obtained without disturbing the samples using a Multi-Sensor Core Logger (GEOTEK MSCL, Manual). This paper proposes a method based on Nuclear-Magnetic-Resonance (NMR) for measuring porosity, namely the ratio between the volumes occupied by the pore space and the total sample, without destroying the sample. NMR is a well-established technique in many fields for analyzing porous samples both in laboratory and in situ (Bergman et al., 2002; Fantazzini et al., 2005). It is therefore a very attractive tool for non-destructive analysis of core samples saturated with hydrogen-bearing fluids (water, oil, etc.). Moreover, if the structure of the pore space is heterogeneous, tomographic methods such as Magnetic Resonance Imaging (MRI) are extremely useful in calculating local porosity defined in this case as the ratio between the volume of pore space in one Region of Interest (ROI) and the total volume of the same ROI (Borgia et al., 1997). In the case of a highly heterogeneous system, the determination of the local porosity can be made exclusively with tomographic methods, whereby ROI of variable dimensions can be analyzed from virtually any selected sediment layer. Clearly, the porosity distribution is not in itself sufficient to characterize the structure of the pore space. In fact, two samples could have the same porosity, but different spatial distributions of pore sizes. In this circumstance, non-invasive measurements based on QRT–Nuclear-Magnetic-Resonance (QRT–NMR) can help to discriminate the difference to the millimeter by providing not only the local porosity but also the distribution of parameters related to the local Surface/Volume (*S*/*V*) ratio (Borgia et al., 2001).

Experiments using NMR to investigate pore structure are usually performed on samples saturated with water, thereby exploiting the ^{1}H nuclide of the water molecule, characterized by the gyromagnetic ratio $\gamma/2\pi = 42.6$ MHz/T. The saturated sample is exposed to a magnetic field B_0 that induces a nuclear magnetization of ^{1}H along the direction of the magnetic field. A sequence of radio frequency pulses of resonant frequency ν, such that $2\pi\nu = \gamma B_0$, reorients the magnetization so that it is no longer in its equilibrium state. The phenomenon of return to equilibrium, which can be quantitatively measured, is called the relaxation. The signals acquired during relaxation contain information on the density of nuclei ^{1}H (from which the porosity can be obtained) and also on the properties of the pore space, which can be extracted from the time constants T_1 (the relaxation time of the magnetization component in the direction of the magnetic field) and T_2 (the relaxation time of the magnetization component perpendicular to the magnetic field). Among the numerous NMR techniques employed in the study of porous materials, the most widely used are Magnetic Resonance Relaxometry, dedicated to the computation of relaxation parameters, and Magnetic Resonance Tomography or Imaging (MRI), providing internal images of the pore system without damaging the sample. These techniques allow for the representation of the pore space from the "perspective" of a water molecule, by visualizing its accessible or its non-accessible spaces on a scale given by relaxometry that can vary from hundreds of Å to hundreds of μm. Utilizing MRI, images of the inner sections of saturated porous bodies can be obtained non-destructively, thereby gathering complementary information on the absorption kinetics of water within the pore space.

QRT combines the advantages of both the previously mentioned techniques. It can quantify a classic parameter such as porosity on several scales, from the entire sample to the voxel (elementary volume). The greatest potential of this method is in describing the porosity distribution among voxels as a function of relaxation times. Given that the local *S*/*V* ratio can be deduced from relaxation times, it is possible to study how the voxel-mean porosity varies with different pore space dimensions. This information is extremely significant, as it allows distinguishing voxels having the same porosity but different local *S*/*V* values. In this paper, the use of QRT measurements is extended to samples from the sea floor. Fig. 1 displays the image obtained from the MRI of a sample core collected close to Marettimo Island.

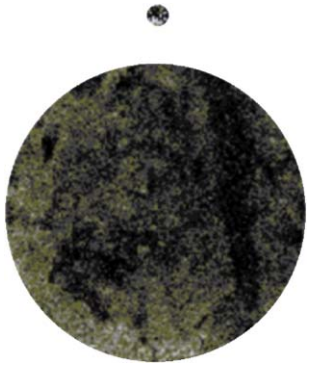

Fig. 1. Spin-Echo image of an inner 5 mm section of the sample Marettimo Herman.