MAGNETIC RESONANCE IMAGING OF POROSITY HETEROGENEITY IN BIOTURBATED SANDSTONE FROM THE WHITE ROSE RESERVOIR, ATLANTIC CANADA

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ABSTRACT

The determination of porosity heterogeneity within hydrocarbon reservoirs is important because cost-effective, efficient production of hydrocarbons depends on accurate knowledge of reserve estimates, and hydrocarbon distribution. A new magnetic resonance imaging (MRI) technique, based on the conical SPRITE (Single-Point Ramped Imaging with T_1 Enhancement) MRI method is capable of revealing the three-dimensional geometry of porosity distribution in core samples taken from reservoir rocks.

Porosity heterogeneity at the core scale is difficult to assess by conventional petrophysical methods. Conventional MRI methods also fail because of complications associated with the multi-exponential nature of spin-spin relaxation time decay and restrictions on the minimal echo time. The SPRITE MRI technique allows direct quantitative measurements of porosity and imaging of samples with short MR signal lifetimes. We illustrate the application of this method to two core samples from the White Rose reservoir: one containing shell fragments and the other fine grained and massive in texture.

The data presented in this paper show the potential of the conical SPRITE MRI technique as a tool for porosity heterogeneity evaluation by application of the method to core plugs taken from sandstone reservoir rocks of the White Rose oilfield, located in offshore Newfoundland. The results show that the MRI technique can significantly enhance petrophysical studies on reservoir rocks by providing: 1) direct and non-destructive visualization of three-dimensional data required to model the porous network; 2) spatially resolved porosity throughout the core sample, which allow reveals the porosity heterogeneity and will result in better understanding of reservoir quality.

INTRODUCTION

It is well known that NMR is a valuable technique for evaluating different reservoir properties both downhole and in the laboratory. NMR laboratory measurements have also been used to calibrate NMR logging tools to get reliable estimates on porosity and permeability. X-ray computerized tomography (CT) in rocks mainly visualizes the rock matrix, while MRI visualizes only fluids and the interactions of these fluids with the confining surfaces of the pores. The purpose of this paper is to illustrate a new MRI laboratory method for estimation of porosity heterogeneity. This study applies the conical SPRITE MRI technique [1] to quantitatively assess porosity heterogeneity in sandstone core samples from the White Rose reservoir of Atlantic Canada.

The White Rose oilfield is located on the eastern margin of the Jeanne d'Arc Basin, approximately 350 km east of St. John's, Newfoundland, and 50 km from the Hibernia field. The Ben Nevis - Avalon reservoir, of early Cretaceous age, is characterized by low to medium permeabilities because of the very fine-grained nature of the reservoir, and pore throat size reduction due to physical compaction and quartz overgrowths. The Ben Nevis - Avalon reservoir consists of sandstone, siltstone, shale, and calcite concretions. The sandstones exhibit porosities ranging from 10 to 22 percent, averaging approximately 16 percent. Sandstone fabrics range from predominantly massive to cryptically bioturbated to finely laminated. The formation also includes beds rich in shell fragments and calcite concretion zones where calcite cement has occluded the pore space. Calcite concretions take up approximately 8 percent of the reservoir volume. Both carbonate and silica cements are presented in the sandstone reservoir rocks [2].

METHOD

Porosity heterogeneity at the core scale is difficult to assess by conventional methods. Standard spin-echo MRI methods generally fail when applied to realistic porous media due to multi-exponential spin-spin relaxation time T_2 decay and restrictions on the minimal echo time [3]. The conical SPRITE MRI technique [4] for local porosity measurements in fluid-saturated porous media was recently developed by Marica et al. [5]. Conical SPRITE is a modified version of the single-point imaging (SPI) method [6] and provides a robust and flexible method for the study of different fluid-saturated sandstones. The SPRITE MRI technique allows direct quantitative measurements of porosity in a range of porous media. This MRI technique involves a pure phase encoding of the magnetization and thus allows the quantitative imaging of samples with short signal lifetimes. The conical SPRITE MRI technique employs ramped phase-encoding magnetic field gradients, with a radio frequency (RF) pulse applied at each gradient step [7].

Conical SPRITE is a fast MRI method, characterized by a simplified image contrast and reduced gradient duty cycle, appropriate for overcoming the problems caused by the short signal lifetimes of realistic porous systems [1]. The local image intensity is related to proton (water) density by Equation 1,

$$S = \rho_0 \cdot e^{-t_p / T_2^*} \cdot \sin\theta \qquad (1)$$

where ρ_o is the proton density, t_p is the time from RF pulse excitation to signal detection, T_2^* is the effective spin-spin relaxation time and θ is the RF pulse flip angle. T_2^* governs the exponential decay of the MR signal following an RF pulse. The local image intensity may be calibrated by using a reference standard of known porosity that is imaged with the sample.

The single exponential T_2^* decay of fluid in rocks is essential to the quantitative nature of this experiment. True spin density imaging for samples with short T_2^* is achieved by acquiring a series of 16 centric scan SPRITE images with different t_p parameters and fitting the resulting data, pixel by pixel to the equation 1. The reference standard with known signal intensity and porosity was imaged with samples. This was used in calculation of the samples' porosity at each point.

EXPERIMENTAL DETAILS

The samples were fully saturated with water under vacuum conditions. The experiment was performed on a 7 Tesla 16 cm horizontal bore Magnex magnet using a Resonance Instruments Maran-DRX console. The 62 mm inside diameter Magnex gradient set driven by Techron amplifiers had a maximum gradient strength of 40 G/cm, the RF amplifier was a CPC 1kW model 7T 1000S. A conical trajectory data acquisition was used with 39 cones. The repetition time was 2ms and the delay between scans was 1s. The image data matrix has 64^3 data points, acquired with 2 signal averages. The image field of view was 128mm along z, x and y directions. The nominal resolution was 2 mm/pixel in the z, x and y directions. The resolution does not depend on the pore type or lithology, however can be adjusted depending on core sample size (i.e. the MRI field of view). All data processing was performed using routines developed in the UNB MRI Centre written with Interactive Data Language.

ROCK STUDIED

This paper focuses on the porosity heterogeneity of two core samples taken from well # L-08, White Rose oilfield. The core plugs are from the Ben Nevis - Avalon reservoir and have bulk porosities of 13.7 and 18.8 percent as measured with porosimeter. The bioclastic sandstone consists of medium- to very coarse-grained shell hash that includes numerous coarser bioclasts and other pebbles, set in a matrix of very fine-grained quartzose sandstone. Bioclasts include oysters, belemite guards and serpulid worm tubes. Burrows are common [2]. The fractured carbonate cemented sandstones are comprised of very fine-grained, moderately silty sandstone. The facies is cryptically to visibly bioturbated and forms much thicker homogeneous units without the laminated sandstones [8].

RESULTS AND DISCUSSION

The samples were selected for their reservoir characteristics and present different geological facies: a bioclastic quartz arenite, and fractured carbonate cemented quartz arenite. Figs. 1B and 2B shows the acquired images at different encoding times, which were 55μs for core plug #11 and 90μs for core plug #160. Local maps of effective spin-spin relaxation time T_2^* (Figs. 1C, 2C) are also produced by the fitting procedure.

Core plug #160 is fine grained and massive in texture. The fracture through the rock (Fig.1A) can be seen on the resulting porosity map as a dark area through the sample due to the calcite cemented fracture zone (Fig.1D). The other part of the sample looks homogeneous because of the uniform saturation with the fluid. The histogram shows that 75% of the pixels in this image exhibit porosity in the range of 15 to 25%, which is in good agreement with the bulk porosity of 18.8% determined by porosimeter. Porosity values lower than 10% within the object, in some cases, will be the result of poor fits to Equation 1.

By contrast, the second core plug #11 contains numerous bioclasts and shell fragments seen on the rock's surface (Fig.2A) and is visibly heterogeneous. Selected slices through the image showed a high degree of porosity heterogeneity within the sample (Fig.2D). Bright spots in the image are related to higher porosity. Shell fragments can be seen as dark areas on MRI images as they contain calcite and have little or no porosity. The histogram (Fig.2E) shows that porosity within the pixels of the 2D slice lie dominantly in the range of 0% to 35%, with average spatially resolved porosity equal to bulk porosity. This high porosity heterogeneity is caused by shell hash that includes numerous coarser bioclasts such as oysters, belemite guards and serpulid worm tubes, set in a matrix of very fine-grained sandstone. The shortest t_p images of this sample reveal relatively little structure in the image due to the fact that residual water in the shell fragments contribute to the image intensity.

Imaging of rocks can also be undertaken with x-ray CT. The critical difference between x-ray CT and MRI is that with x-rays one observes an image based on the rock matrix density and effective atomic number. With MRI one directly visualizes the ^{1}H content associated with fluid of interest, H_2O in the first instance. Both methods are non-destructive and have become very useful in petrophysical studies with x-ray CT far better known. CT uses an x-ray source that rotates around the sample to obtain one-dimensional projections of x-ray attenuation at different angles followed by reconstruction of a three-dimensional image from sequential cross-sectional slices. The disadvantage of CT scan method is that only density map is acquired, thus porosity estimation is not as accurate as in MRI method. The main advantage of this SPRITE MRI method is imaging of fluid in the pore and providing a spatially resolved porosity map. The acquisition time for both imaging techniques requires from seconds to minutes, with spatial resolution on the millimeter and submillimeter scale.

CONCLUSIONS

In this paper, we applied a recently developed conical SPRITE MRI technique for local porosity measurements to quantitatively assess porosity heterogeneity in 1.5 in. core plugs taken from sandstone reservoir rocks from the White Rose oilfield. A comparison of porosity images from two samples shows that heterogeneity can be assessed quantitatively in three dimensions and in a way that is not possible with conventional methods of core analysis. The presented results show that the MRI technique can improve petrophysical studies on reservoir rocks by providing spatially resolved porosity at the core scale and imaging bioclasts, fractures and other features non-destructively.

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FIGURES

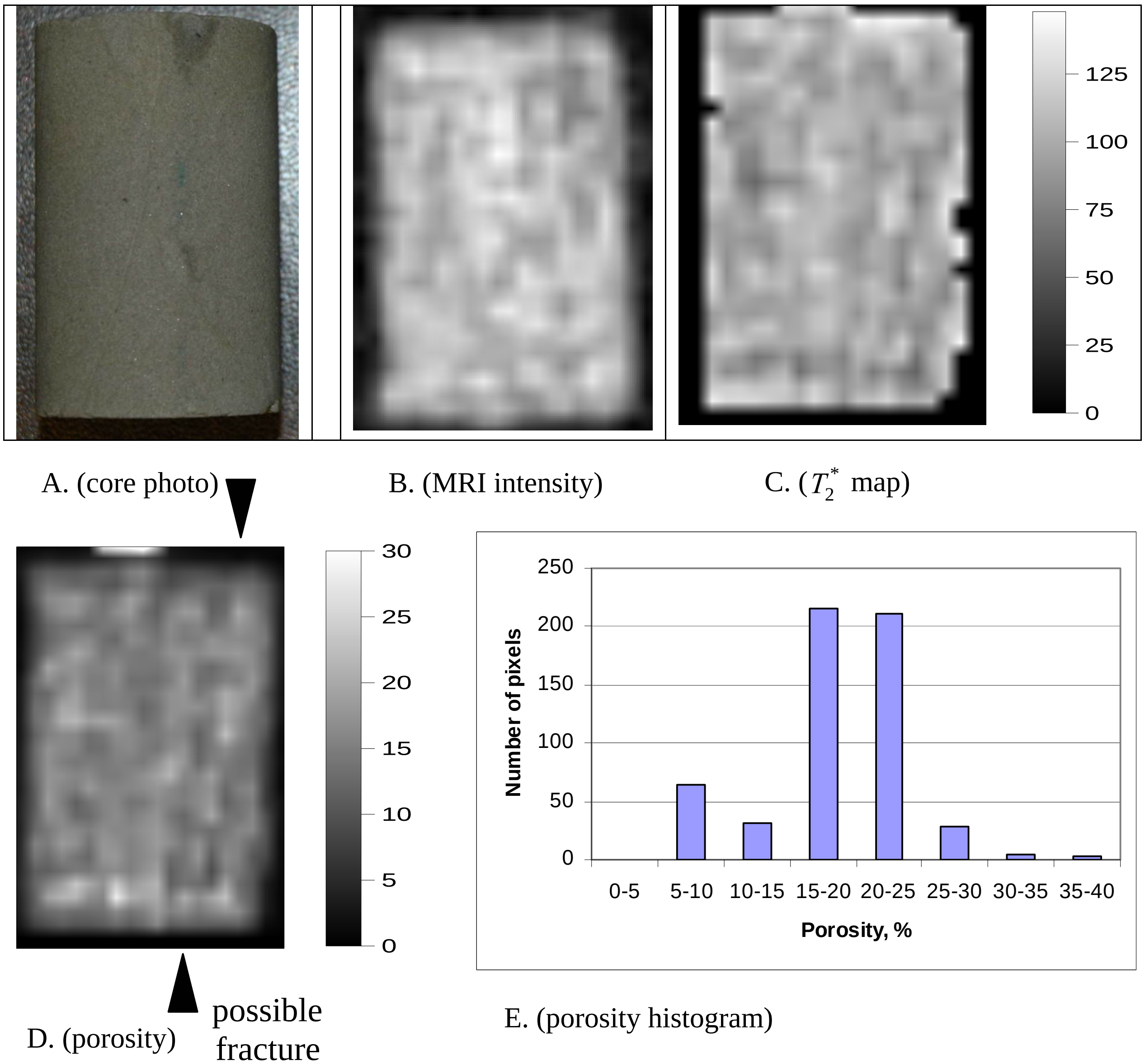

Figure 1. Various images of core plug #160 from White Rose well L-08, have a diameter of 37mm and a length 59.5mm. **A.** Photograph of the sample, showing fractured massive carbonate cemented sandstone. **B.** A 2D slice from a 3D image dataset acquired at the encoding time of 90 μs for the #160 sandstone core, using the Conical SPRITE sequence. In this image, the bright zones represent a high MRI signal, but not necessarily a high porosity, due to T_2^* variation. **C.** The 2D T_2^* map corresponding to the same slice of the #160 sandstone in (b). The scale bar is calibrated in units of microseconds. **D.** The r esulting 2D porosity map for the same slice of the #160 sandstone in (b). The scale bar is calibrated in units of percent. **E.** Histogram of porosity distribution within the 2D slice shown for core plug #160. The images are cropped.

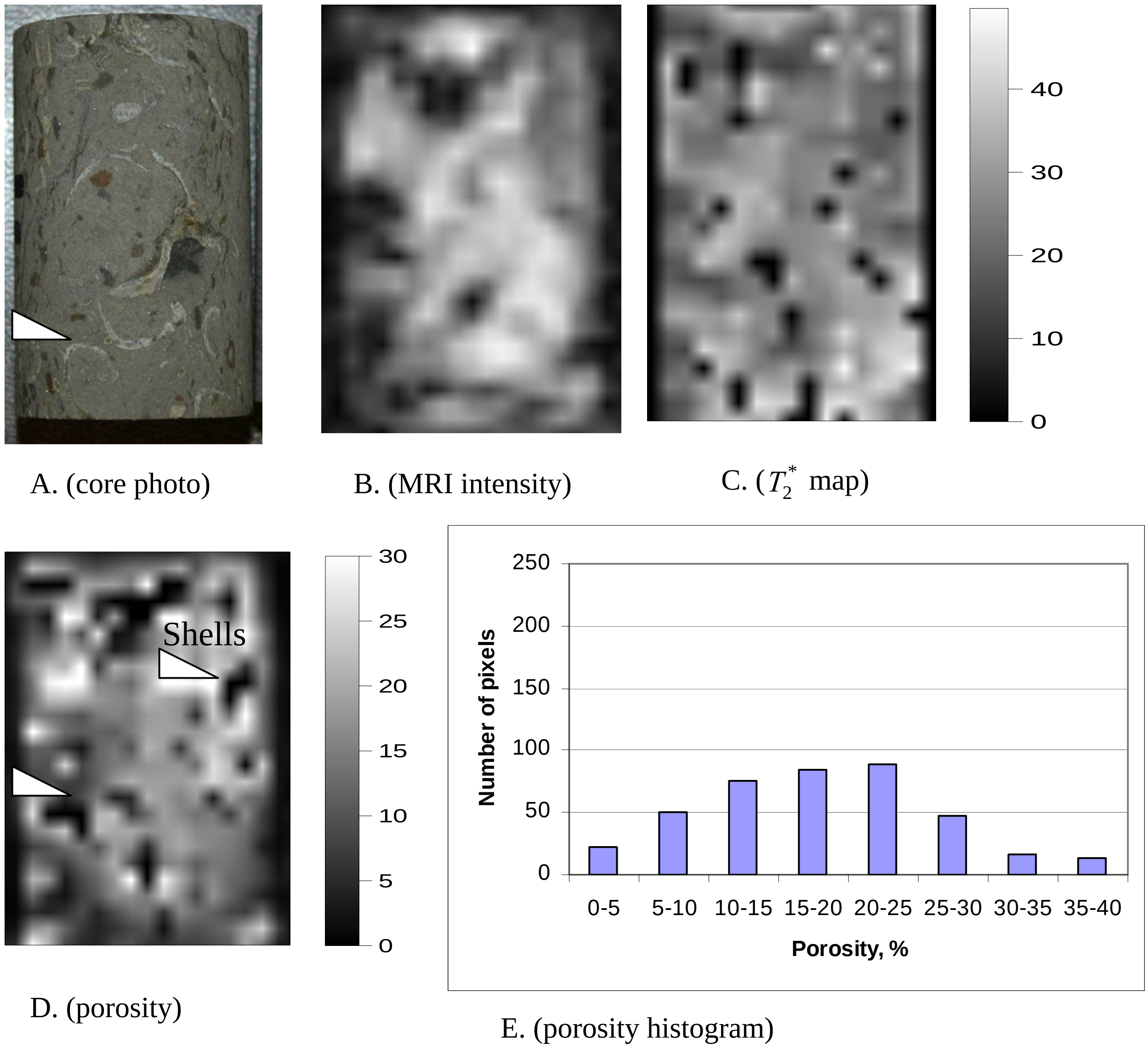

Figure 2. Various images of core plug #11 from White Rose well L-08, have a diameter of 37mm and a length 61mm. **A.** Photograph of the sample, showing numerous bioclasts. **B.** A 2D slice from a 3D image dataset acquired at the encoding time of 55 μs for the #11 sandstone core, using the Conical SPRITE sequence. In this image, the bright zones represent a high MRI signal, but not necessarily a high porosity, due to T_2^* variation. **C.** The 2D T_2^* map corresponding to the same slice of the #11 sandstone in (b). The scale bar is calibrated in units of microseconds. **D.** The resulting 2D porosity map for the same slice of the #11 sandstone in (b). The scale bar is calibrated in units of percent. **E.** Histogram of porosity distribution within the 2D slice shown for core plug #11. The images are blurry due to resolution of the technique.