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Statistical analysis of pulsed-neutron well logs in monitoring injected carbon dioxide

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ABSTRACT

Pulsed-neutron well logs (PNLs) were acquired to monitor CO_2 storage associated with enhanced oil recovery. This work quantifies the precision of repeat PNLs using data from four wells and 15 repeat PNLs. Root-mean-square (RMS) precision for the repeat PNLs was less than 3%, indicating good agreement between the baseline and repeat PNLs. Evaluations of scaled relative difference (Scaled-D) showed variation in precision among individual wells and formations. Analysis of false-positive rates (FPRs) across the entire data set showed that a Scaled-D threshold in sandstone formations of approximately ± 8% resulted in a 1% FPR. These Scaled-D precision thresholds were used to estimate the value of CO_2 saturation able to be confidently distinguished from baseline. The detection limit for CO_2 is lowest for high-porosity formations filled with saline water and is highest for low-porosity formations filled with fresh water. Thus, detection of vertical out-of-zone CO_2 migration using repeat PNLs is a function of instrument precision, petrophysical properties, and hydrology, all of which must be taken into account as part of the monitoring program. The results of this work provide insight into how PNLs may be included within monitoring plans to detect vertical out-of-zone CO_2 migration along a wellbore or instances of wellbore failure and provide a quantitative basis for establishing detection limits of repeat PNLs to distinguish change from baseline conditions.

1. Introduction

The Energy & Environmental Research Center (EERC), through the efforts related to the Plains CO_2 Reduction (PCOR) Partnership, is developing practices and technologies that will allow future commercial-scale CO_2 storage projects to make informed decisions regarding site selection, injection programs, operations, and monitoring strategies that improve storage efficiency and effective storage resource potential in geologic formations. As part of the PCOR Partnership's subsurface monitoring activities, pulsed-neutron well logs (PNLs) were acquired with Schlumberger's Reservoir Saturation Tool (RST) in monitoring CO_2 storage associated with enhanced oil recovery (EOR). These PNLs were acquired from 45 wells, including water-alternating-gas (WAG) injection wells and oil production wells. Baseline PNL acquisition for all wells began prior to initiation of CO_2 injection and continued intermittently during injection operations for a period of approximately 5 years, with a total of 96 PNLs acquired and some wells having as many as five repeat PNLs. This data set has proven valuable in evaluation of the utility of PNLs as a commercially viable technology for monitoring subsurface injection of CO_2. The specific location of the study area is not included to avoid operational sensitivities but is unimportant for the discussion of this investigation. The focus of this work is on the ability of repeat PNLs to detect change from baseline conditions along a wellbore, which is broadly applicable to CO_2 storage sites.

The RST logging theory is thoroughly discussed in existing literature, including Svor and Globe (1982), Adolph et al. (1994), Albertin et al. (1996), and Ellis and Singer (2008). Therefore, only a brief discussion of the logging theory and interpretation is included here. The RST sigma log, which involves measurement of the rate of thermal neutron capture, was used in this analysis. The sigma log is produced as a result of neutron emission by the tool and measurement of the rate of decay (τ) of gamma ray counts (gamma rays produced as neutrons generated by the tool are "captured" by rock and formation fluids). The neutron capture cross section (Σ), which is inversely proportional to τ, is then calculated, providing important information about the injection horizon and overlying strata (Svor and Globe, 1982). Specifically, this process enables: 1) baseline characterization data (lithology/mineralogy, porosity, and water and oil saturations) and 2) monitoring for

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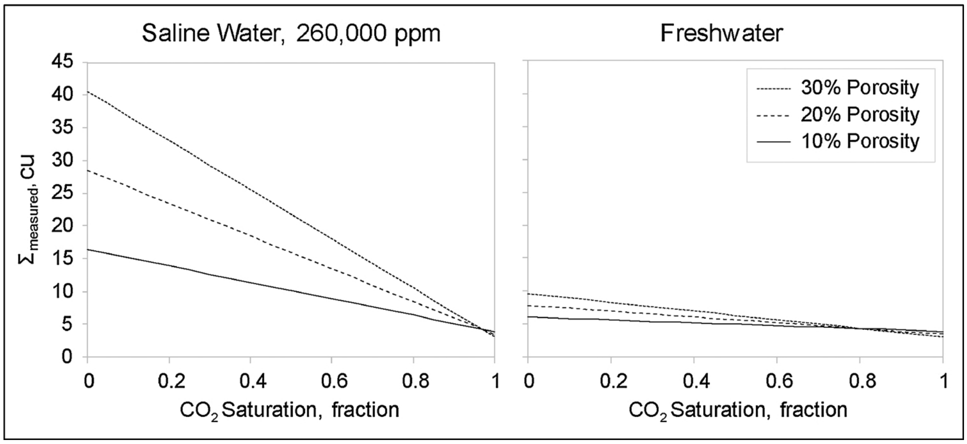

Fig. 1. Predicted $\Sigma_{measured}$ (*y*-axis) as a function of CO_2 saturation (*x*-axis) according to Eq. (2) and assuming porosity of 10%, 20%, or 30%, and thermal neutron capture cross sections of Σ_{ma} (quartz sandstone) = 4.3 cu, Σ_{CO2} = 0.03cu, and Σ_w = 125 cu and 22 cu for saline water (left) and fresh water (right), respectively.

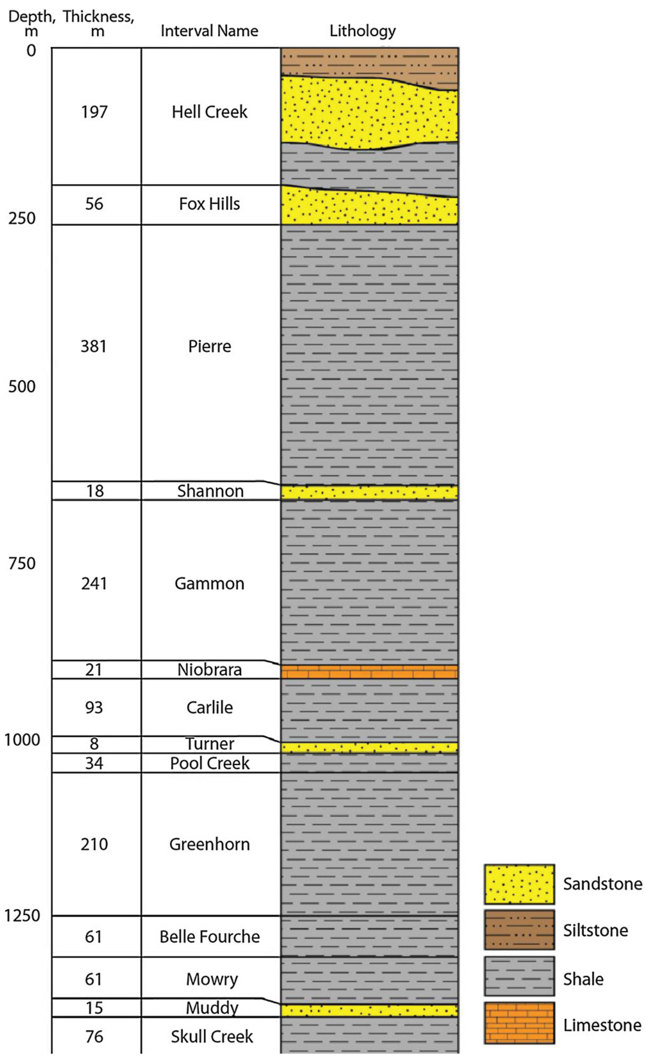

Fig. 2. Local stratigraphy of the wells studied (Bosshart et al., 2015).

time-lapse changes in fluid saturations (water, oil, and CO_2) (Albertin et al., 1996; Ellis and Singer, 2008). Additionally, porosity and fluid saturation data from baseline PNLs may provide direct inputs to geologic models. Repeat PNLs may be compared with numerical simulation results to improve history matching, thereby increasing the accuracy of the simulated fluid behavior. These multiple applications of PNLs highlight the value these measurements provide in managing and understanding subsurface injection of CO_2.

Another application of PNLs, and the focus of this investigation, is detection of vertical, out-of-zone migration of injected CO_2 from the target storage unit into overlying strata along a wellbore and/or detection of wellbore failure resulting in unintended CO_2 saturation, which are relevant to long-term monitoring of geologic CO_2 storage. The depth of investigation for the PNL is generally less than 20 centimeters (Ellis and Singer, 2008; Mimoun et al., 2011); therefore, the application of this technology is for diagnosing saturation changes in the near-wellbore environment. The PNL measurement of Σ follows a volumetric mixing law of rock (mineral) matrix and fluid components. In the case of monitoring subsurface CO_2 injection associated with EOR, the reservoir contains oil, water, and CO_2 fluid components. However, the overlying geology should contain only rock and water. The environmental effects associated with well-specific factors such as casing size, cement type, and borehole fluids, can be reasonably assumed to remain constant for all measurements in the same well and for the same depth interval/formation. Therefore, while the PNL measurement is sensitive to these factors, for the purposes of evaluating the ability of repeat PNLs to distinguish change from baseline measurements within a single well, these effects can be disregarded. For a rock matrix with a porosity that is filled with only water, excluding other potential logging environmental effects, the RST Σ measurement will be (Ellis and Singer, 2008; Svor and Globe, 1982):

$$\Sigma_{measured} = (1 - \phi)\Sigma_{ma} + \phi\Sigma_w \tag{1}$$

Where:

$\Sigma_{measured}$ = measured thermal neutron absorption cross section, capture units (cu)

ϕ = formation porosity, fraction

Σ_{ma} = thermal neutron absorption cross section of the mineral matrix, cu

Σ_w = thermal neutron absorption cross section of water, cu

The thermal neutron absorption cross section of the mineral matrix (Σ_{ma}) ranges from approximately 4.3 cu for quartz sandstone to 7.3 cu for limestone and is generally less than 10 cu for most rocks. The thermal neutron capture cross section of water (Σ_w) is approximately 22 cu for fresh water and 125 cu for highly saline water (26 wt% sodium chloride [NaCl]) (Ellis and Singer, 2008). Under a scenario of vertical out-of-zone migration, the water-filled pore space of the rock matrix will be displaced with increasing amounts of CO_2. For a rock matrix with a porosity that is filled with both water and CO_2, again excluding other potential logging environmental effects, the RST Σ measurement will reflect the saturation of the pore space filled with either water or CO_2 (Ellis and Singer, 2008; Svor and Globe, 1982):