Hydrogeological Characterisation of Sherwood Sandstone using BNMR and Geophysical Logs

Sodiq Oguntade[1] , Ulrich Ofterdinger[1] , Jean-Christophe Comte[2] , Ryan Gee[3] , Myles Kynaston[4] , and Robert Raine[5]

[1]School of the Natural and Built Environment, Queen's University Belfast, Belfast, United Kingdom (soguntade01@qub.ac.uk) [2]School of Geosciences, University of Aberdeen, Aberdeen, United Kingdom [3]NMRSA/Orica Ltd., Melbourne, Australia [4]European Geophysical Services Ltd, Shrewsbury, United Kingdom [5]The Geological Survey of Northern Ireland, Belfast, United Kingdom

Introduction

- The Aquifer thermal energy storage ATES system (figure 1) consists of two groundwater wells that operate in a seasonal mode. Water is extracted from one of the wells (cold storage well) during the summer and passes through a heat exchanger to cool a building or facility. The water is then injected into the second well (heat storage well).
- A detailed hydrogeological site characterisation is needed for ATES systems, as they are sensitive to groundwater flow and heterogeneities (Fleuchaus et al., 2018). The porosity of an aquifer is one of the hydrogeological properties that determines its suitability for ATES systems.

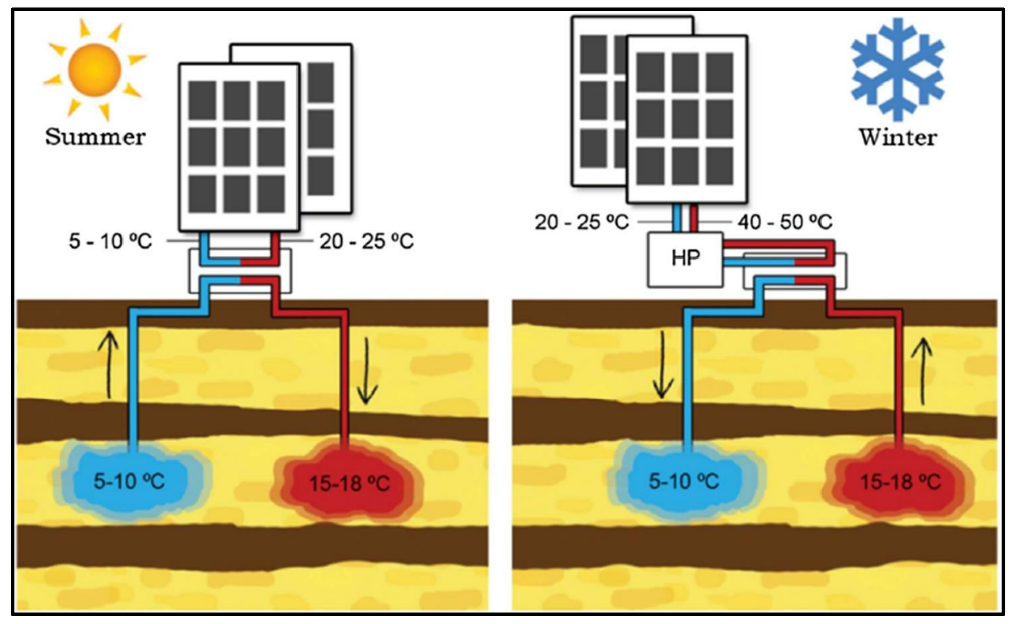

Fig. 1: Working principle of an ATES-doublet (Bloemendal and Olsthoorn, 2018)

- The Permo-Triassic Sherwood Sandstone is an essential aquifer in the UK with great potential for geothermal energy, including ATES systems (figure 2).
- The geothermal resource potential of the Sherwood Sandstone in Northern Ireland at a temperature of more than 20°C is about 523 Mtce (million tonnes of coal equivalent) (Downing & Gray, 1986).

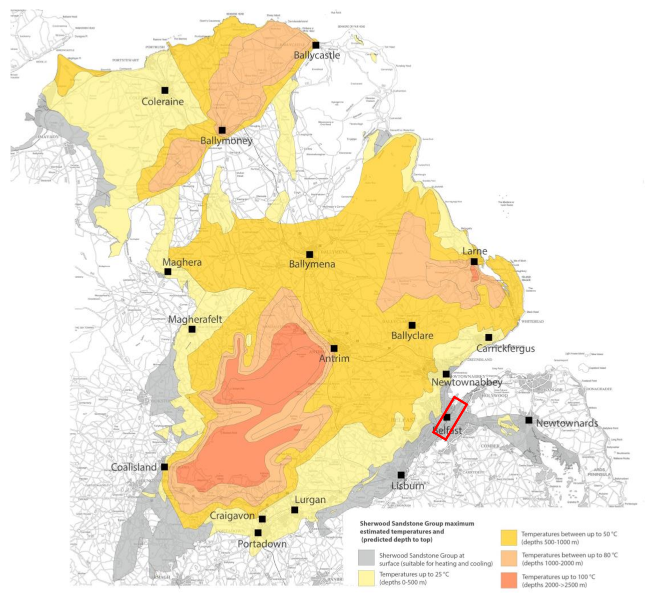

Fig. 2: Estimated temperatures and depth to the top of Sherwood Sandstone; indicated in red rectangle is the study area (after Raine et al. 2022)

Objectives

- This study investigates the porosities of the Sherwood Sandstone Aquifer as encountered in three boreholes completed on the Queen's University Belfast campus using borehole nuclear magnetic resonance (BNMR) and traditional geophysical logs.

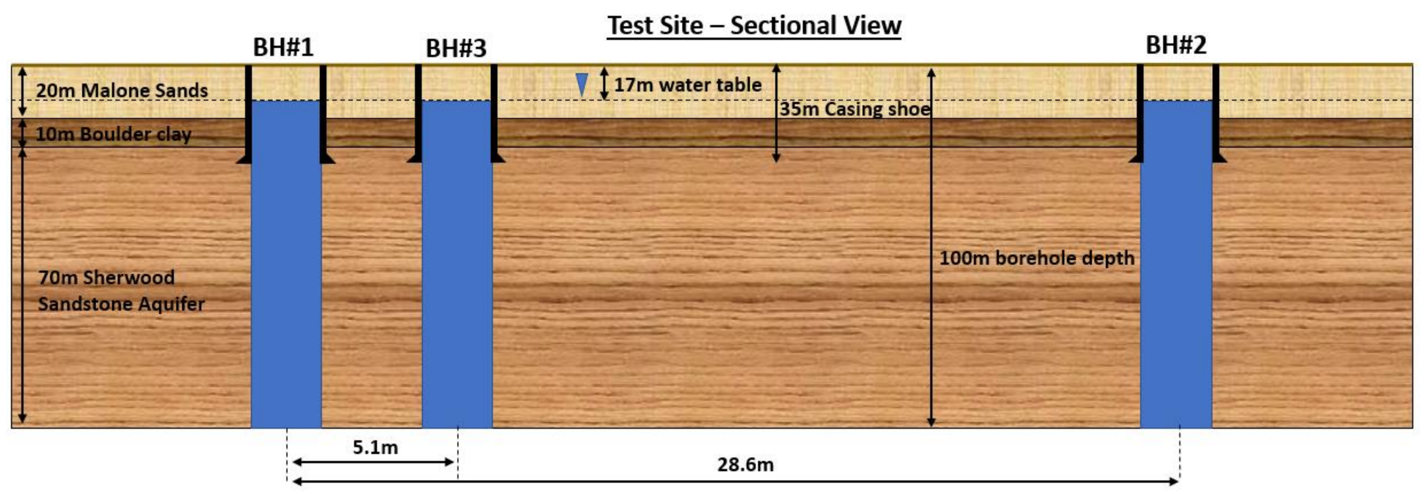

Fig. 3: Sectional view of the boreholes for this study

Methodology

- BNMR logging was completed at the 3 boreholes; the nominal borehole total depth of 100m.
- The most important output of BNMR data processing is the T_2 distribution (a Carr-Purcell-Meiboom-Gill pulse train), which gives the rock's total volume or porosity (Figure 4).

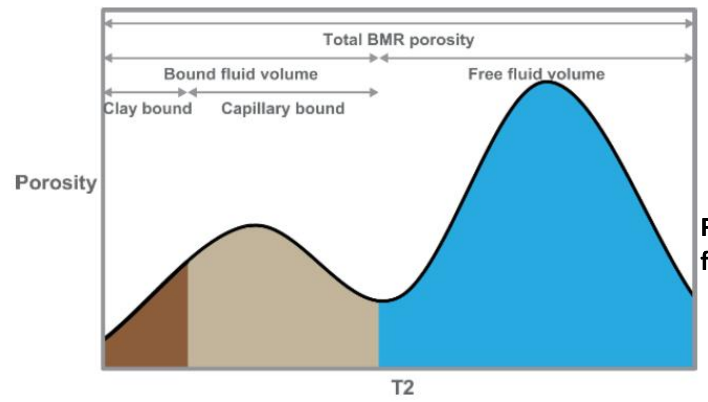

Fig. 4: The T_2 distribution reflects the volumes of fluid occupying different pore sizes.

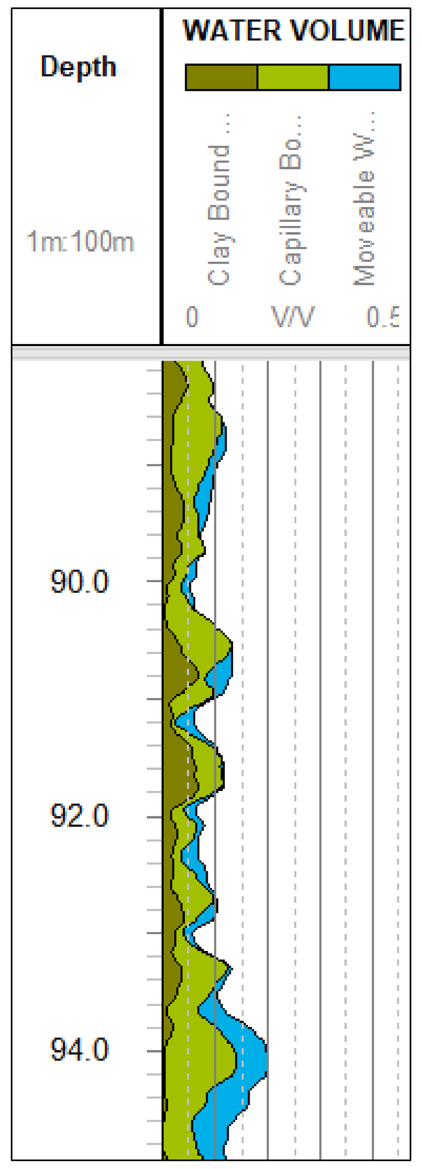

Fig. 5: Pore sizes in one of the boreholes

- This study also used Archie and Waxman-Smits petrophysical models to calculate porosity from geophysical logging data (resistivity, EC, temperature and natural gamma).
- Archie (1942) assumes that the rock is clay-free and a relationship exists between the formation factor (F) of a completely water-saturated sedimentary rock and its porosity (ϕ).

$$F = \frac{a}{\phi^{-m}}$$

Where m and a are the cementation and tortuosity factors, respectively

- Archie's method does not account for clay content in rocks, but the Sherwood Sandstone has some clay content. The Waxman-Smits (1968) petrophysical model incorporates it.

$$\sigma_o = \phi^{-m}(\sigma_w + BQ_v)$$

Where σ_o, σ_w, B and Q_v are the aquifer bulk conductivity, pore water conductivity, equivalent counterion mobility and excess charge per unit pore volume, respectively

- The mass fraction of clay in the rock was calculated from the gamma logs using the linear and Larionov (Larionov, 1969) equations:

$$I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$

Where the I_{GR}, GR_{log}, GR_{max} and GR_{min} are the gamma ray index, gamma ray log reading, maximum gamma ray value and minimum gamma ray value, respectively

$$\varphi_w = 0.33 \times (2^{IR} - 1)$$

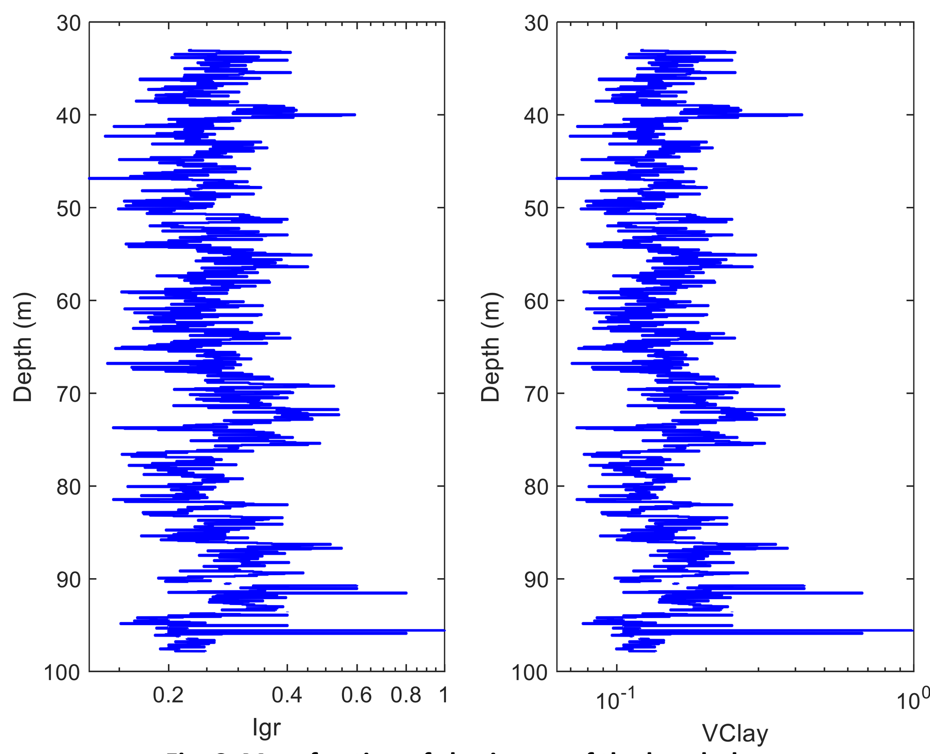

Fig. 6: Mass fraction of clay in one of the boreholes

- The relative fraction of each clay mineral in the rock was obtained from the Geological Survey of Northern Ireland's XRD analysis of clay minerals in the Sherwood Sandstone, which is located within the same geographic location.

Results

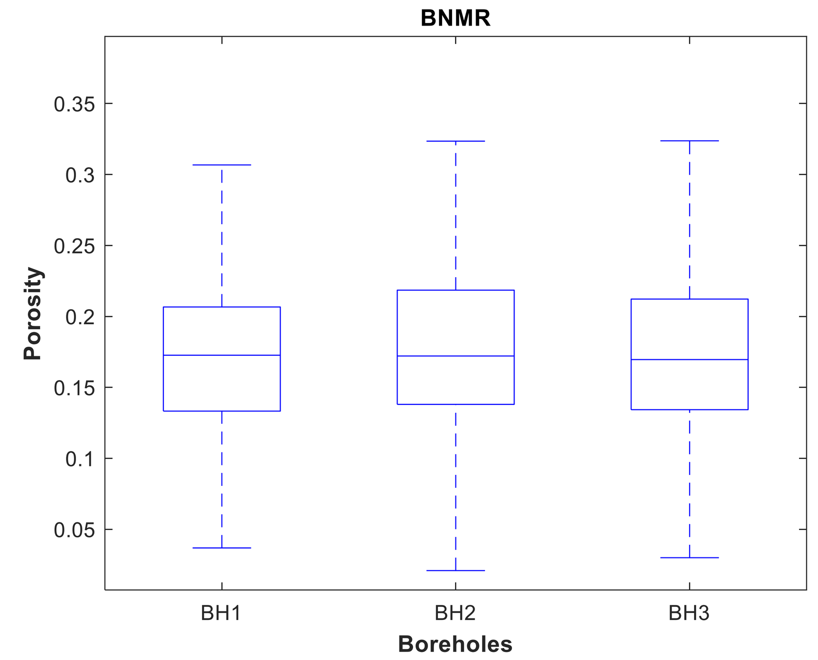

Fig. 7 (a): Porosity results from BNMR

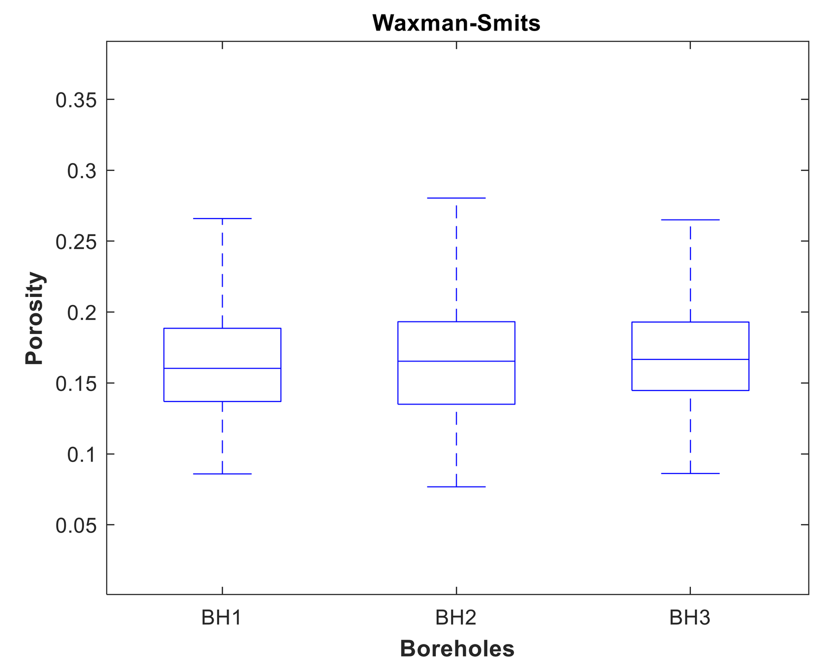

Fig. 7 (b): Porosity results from Waxman-Smits Model

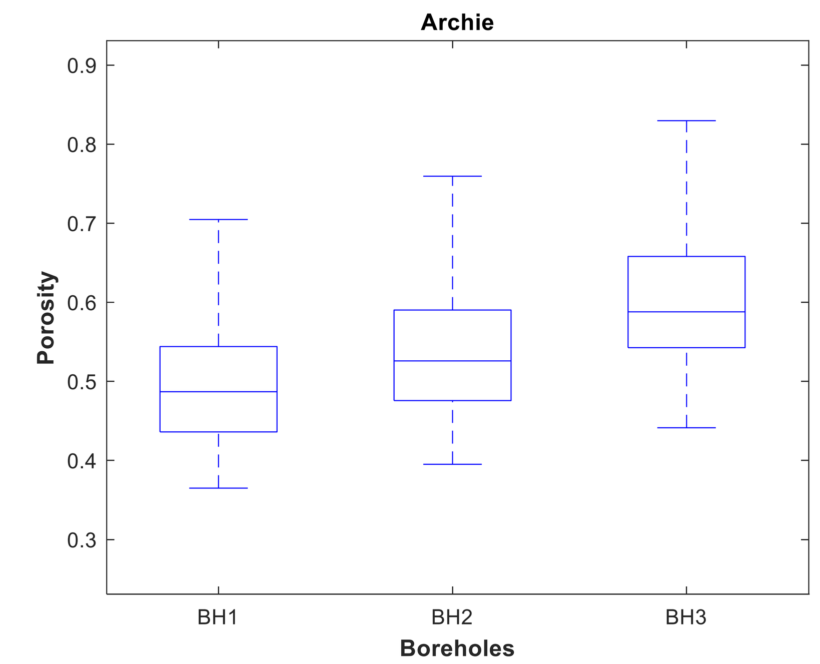

Fig. 7 (c): Porosity results from Archie Model

Conclusion and future work

- BNMR confirms the credibility of using the Waxman-Smits model instead of the Archie model to estimate porosity in the Sherwood Sandstone formation. The Archie model overestimates the porosity.
- The results demonstrate the relationship between BNMR and petrophysical-derived porosity and confirm the reliability of using BNMR in hydrogeological investigations similar to its widespread usage in the oil and gas industry.
- This study forms part of the broader research on the impact of subsurface heterogeneities on the performance of ATES systems in the Sherwood Sandstone of Northern Ireland.
- Further hydrogeologic characteristics such as hydraulic conductivity, transmissivity, and structure delineation will be carried out. Also, thermal injection testing and numerical heat transport modelling.

References:

Archie, G. E. (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. Transactions of the AIME, 146(01), 54-62.
Bloemendal, M. & Olsthoorn, T. 2018. ATES systems in aquifers with high ambient groundwater flow velocity. Geothermics, 75, 81-92
Downing, R. A., & Gray, D. A. (1986). Review of the geothermal potential of the UK. In R. A. a. G. Downing, D.A (Ed.), (pp. 152-161).
Fleuchaus, P., Godschalk, B., Stober, I., & Blum, P. (2018). Worldwide application of aquifer thermal energy storage – A review. Renewable and Sustainable Energy Reviews, 94, 861-876.
Larionov, M. (1969). Application of factor analysis to well logging data. Earth Science Journal, 1(1), 113-123.
Raine, R, Reay, DM, 2019, A review of geothermal reservoir properties of Triassic, Permian and Carboniferous sandstones in Northern Ireland, Geological Survey of Northern Ireland Internal Report, 19/00/01. 62pp
Waxman, M. H., & Smits, L. (1968). Electrical conductivities in oil-bearing shaly sands. Society of Petroleum Engineers Journal, 8(02), 107-122

This project receives financial support from the Natural Environment Research Council (NERC) through QUADRAT DTP.
Other supports are The Geological Survey of Northern Ireland (GSNI) and Advanced Logic Technology (ALT).