

MULTI-SENSOR LOGGING AND CONDUCTIVITY SCANNING LABORATORY MEASUREMENTS: ANALYSIS OF SPATIAL VARIABILITY IN PETROPHYSICAL PROPERTIES

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Abstract

Two laboratory petrophysical measurements techniques including the multi-sensor core logging (MSCL) and thermal conductivity scanning (TCS) methods were integrated in order to determine petrophysical properties and their spatial variations in a laboratory experiment. The objective was to investigate how the two techniques vary in the determination of the petrophysical properties and study their spatial variation. Two core samples (BS; sandstone and B6; metamorphic conglomerate), each cut in half, one fully saturated and one fully dried were used. Sensor-based devices of the MSCL equipment were used to determine the density, P-wave velocity, magnetic susceptibility and porosity, while the TCS technique estimated thermal conductivity and porosity. Results based on the MSCL for the BS shows change in the bulk density due to porosity and homogeneous factor, while B6 keeps constant bulk density. P-wave velocity in the BS dry sample shows higher velocity than the saturated sample, while in the B6 sample velocity curves depict irregular trend. Magnetic susceptibility for the BS sample shows zero magnetism, while for the B6 sample, curves indicate it is magnetic. The porosity values in the BS sandstone shows realistic and expected values from about 7 % to 11 %, confirming very homogeneous sandstone, while B6 sample has close to zero porosity, expected in hard rock specimen. Thermal conductivity for the BS sample shows very straight curves, confirming homogeneous sandstone. For the B6 sample, there is deviation, showing the effects of the rock inhomogeneity. Thus, MSCL and TCS laboratory techniques are reliable in the estimation of petrophysical properties and evaluation of their spatial variations.

Key Words: petrophysical laboratory; petrophysical properties, thermal conductivity, gamma-density, P-wave velocity and core samples

1. Introduction

This laboratory experiment utilized two different petrophysical methods including multiple sensors-based core logging and thermal conductivity scanning to measure a series of core samples in the laboratory, using Multi-sensor Core Logger (MSCL) and Thermal Conductivity Scanner (TCS) respectively^{1 2}. The objective was to investigate how these two techniques vary in the determination of certain petrophysical properties and study the spatial

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¹ Fullagar, P. K., Zhou, B., and Fallon, G. N., 1999, Automated interpretation of geophysical borehole logs for orebody delineation and grade estimation: Mineral Resources Engineering, 8, 269–284. doi: 10.1142/S095060989900027X.

² Fullagar, P. K., 2005, A review of meso-scale petrophysics at metalliferous mines: Fullagar Geophysics Pty Ltd Report AM01F–1.

variation^{3, 4} of these properties, which are important for production of fluids. The aims of these experiments were to:

- (1) Assess the application of the MSCL and TCS methods in the estimation of physical rock properties as density, seismic velocity, electric resistivity, magnetic susceptibility and thermal conductivity.
- (2) Evaluate the derivability of core petrophysical properties such as porosity and permeability, which are relevant for the exploration of hydrocarbon resources, hydrogeology and geothermics, using these techniques.
- (3) Compare porosity values achieved from different physical rock properties based on the two methods.
- (4) Evaluate the influence of heterogeneous distribution of petrophysical parameters and their spatial variations.

In this experiment, two rock core samples, each cut into halves, creating two half-cylindrical cores⁵. One half was completely saturated in water, and the other half was completely dried to measure the differences in the measurements. Each sample also had two small core-plugs taken, again one fully saturated and one fully dried. One interesting thing to consider in this case was the inhomogeneity, because some samples were far more homogeneous than others, meaning that a smaller sample might not be representative of the whole core. The results from each experimental technique are incorporated into a single database, and an interpretation on each sample was made.

2. Theoretical Background and Principles

The determination of rock physical properties⁶ such as density, seismic velocity, electric resistivity, magnetic susceptibility and thermal conductivity is of utmost importance in the success of exploration project for natural resources of the earth, for example, oil and gas, groundwater, and renewable energy such as geothermal energy. Petrophysical properties such as porosity and permeability are inferable from the use of such logging tools as gamma, density, sonic velocities, induced polarization, etc.

Gamma and density for example can be determined by logging the rock formation (cores) using multiples sensors (Figure 1). In this case, gamma rays (photons of high energy) interact with electrons and atomic cores through the absorption and scattering phenomena and processes such as Photo-effect, Compton-scattering and Coupling. The density delivered from a Gamma-Ray source device is a bulk density, from which the densities of the dry and saturated samples are derivable. Derivation of the Wave Velocity (P-wave) works based on the fact that logging tool measures the travel-time of an acoustic wave through the rock sample as well as the thickness of the sample. Here, the sample is positioned between a supersonic transmitter and receiver, from which travel-time between transmission and reception of the

³ Ren, L., D'Hose, T., Borra-Serrano, I., Lootens, P., Hanssens, D., De Smedt, P., Cornelis, W. M. and Ruysschaert G. (2022). Detecting spatial variability of soil compaction using soil apparent electrical conductivity and maize traits, British Society of Soil Science, First edition, April 2022: <https://doi.org/10.1111/sum.12812>

⁴ Frykman, Peter (2001). Spatial variability in petrophysical properties in Upper Maastrichtian chalk outcrops at Stevns Klint, Denmark, Marine and Petroleum Geology 18 (10): Pp. 1041-1062; DOI: [10.1016/S0264-8172\(01\)00043-5](https://doi.org/10.1016/S0264-8172(01)00043-5)

⁵ Vatandoost, A. Fullagar, P. K. and Michael Roach, M. (2008). Automated Multi-Sensor Petrophysical Core Logging, *ASEG Extended Abstracts* 39(3), DOI:[10.1071/EG08020](https://doi.org/10.1071/EG08020).

⁶ Tiab D. & Donaldson E. C. (2004), *Petrophysics* (2nd Edition), Elsevier

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pulse is measured. Porosity is then derived based on the empirical relationship between interval transit time and porosity formulated

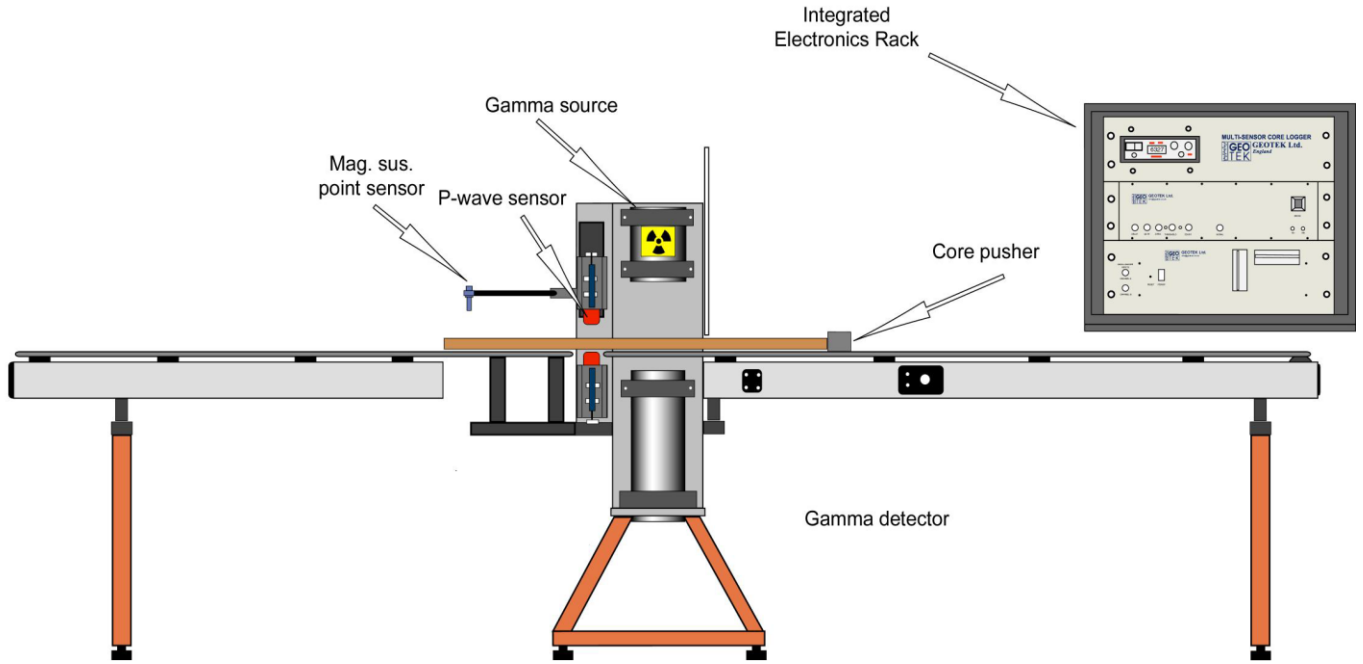


Figure 3: Schematic diagram of the MSCL logger

as Time average relationship after Wyllie et al.⁷, and Empirical equation by Raymer et al.⁸ for consolidated rocks, as shown in equations (1) and (2) respectively, based on numerous laboratory experiments and application of the sheet model to porous rocks:

$$\frac{1}{v} = \frac{1-\phi}{v_{ma}} + \frac{\phi}{v_{por}} \quad (1)$$

$$v = \phi v_{pore} + (1-\phi)^2 v_{matrix} \quad (2)$$

Determination of other important petrophysical properties such as thermal conductivity, λ , Temperature conductivity, a , and Specific thermal capacity, c , is important for geothermal investigations, which is needed for successful investigation earth's events such as plate Tectonism, seismicity, volcanism⁹. Other applications of thermal conductivity are in Mining, drilling techniques, application of geothermal exploration energy. In case of a purely

⁷ Wyllie, M. R. J., Gregory, A. R., Gardner, L. W., 1956. Elastic waves velocities in heterogeneous and porous media. *Geophysics* 21 1 (1956), pp. 4170.

⁸ Raymer, L. L., Hunt, E. R., Gardner, J. S., 1980. An improved sonic transit time-to-porosity transform. *SPWLA Trans., 21st Ann. Log. Symp., Paper P*, The Society of Professional Well Log Analyst (SPWLA), Tulsa, OK.

⁹ Börner, F., Schopper, J., Weller, A., 1996. Evaluation of transport and storage properties in the soil and groundwater zone from induced polarization measurements. *Geophysical Prospecting*, 44.

conductive regime, heat flux and geothermal gradient are connected via the petrophysical property "thermal conductivity λ , given as:

$$Q = -\lambda \cdot \text{grad}(T) \quad (3)$$

In one-dimensional case, we have:

$$Q = -\lambda \cdot \frac{\partial T}{\partial z} \quad (4)$$

For one-dimensional steady state temperature ($\partial T / \partial t = 0$), equation (4) becomes:

$$T(z) = T_0 + \frac{Q \cdot z^2}{\lambda} - \frac{A \cdot z^2}{2\lambda} \quad (5)$$

Where T_0 , Surface temperature; Q , Surface heat flux density; A , Heat production rate at the subsurface.

In the laboratory experiments, investigation is reduced to the spatial distribution, of λ , from which, porosities are determined. Thermal conductivity model includes simplest case (taking rock as sheet model), resulting in a series model and a parallel model (equations (6), (7) and Figure 2).

$$\lambda_{\text{parall}} = (1 - \phi) \cdot \lambda_{\text{ma}} + \phi \cdot \lambda_{\text{por}} \quad (6)$$

$$\lambda_{\text{vertical}} = \frac{(1 - \phi)}{\lambda_{\text{ma}}} + \frac{\phi}{\lambda_{\text{por}}} \quad (7)$$

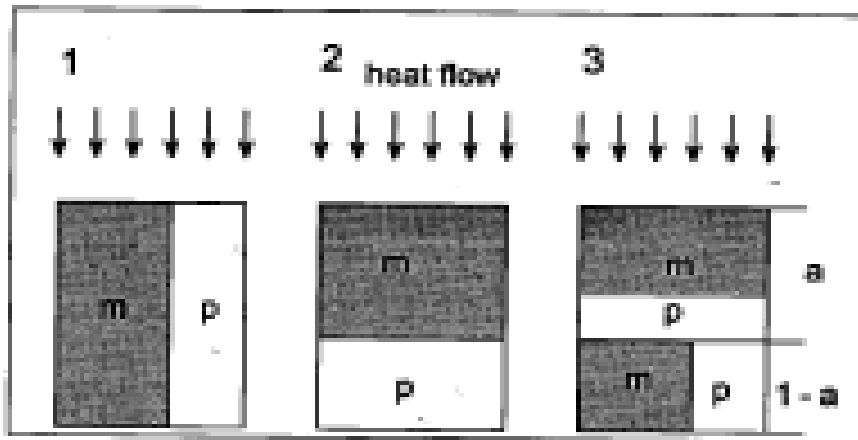


Figure 2: The family of sheet models for calculation of the thermal conductivity; 1: parallel model; 2: series model; 3: model after Krischer and Esdom¹⁰; m represents matrix and p represents pore fluid.

In the laboratory, the thermal Conductivity measurement principle^{11, 12} is based on scanning a sample surface with a focused, mobile and continuously operated constant heat source

¹⁰ Krischer, O, and Esdom, H. (1969). Thermal Conductivity Volume 1, Academic Press Inc, (London) LTD, Library of Congress Card Number: 68-24693.

¹¹ Popov Y, Pribnow D, Sass J, Williams C, Burkhardt H (1999). Characterization of rock thermal conductivity by high-resolution optical scanning. Geothermics 28: pp. 253-276

emitting visible and infrared light, while temperature is measured without contact by two infrared thermo sensors. The heat source and sensor move with the same speed relative to the sample and at a constant distance to each other (Figure 3). The temperature range displays the value of the maximum temperature rise, Θ , is determined by the relationship. From the spatial measurements, different rock specific parameters are determined using equations (8), (9) and (10).

$$\beta = \frac{\lambda_{\max} - \lambda_{\min}}{(\lambda)} \quad (8)$$

$$K = \frac{\lambda_{AN}}{\lambda_{\perp}} \quad (9)$$

$$\delta\lambda = \frac{\lambda_s - \lambda_d}{\lambda_d} \quad (10)$$

Where, in equation (8) to (10): β is the inhomogeneity factor; K represents anisotropy; $\delta\lambda$ term measure the influence of water saturation. For an anisotropic solid, the maximum temperature rise is determined by the relationship.

$$\Theta = \frac{Q}{2\pi \cdot x \cdot \sqrt{\lambda_A * \lambda_B * \cos^2(\gamma') + \lambda_A * \lambda_C * \cos^2(\beta') + \lambda_B * \lambda_C * \cos^2(\alpha')}} \quad (11)$$

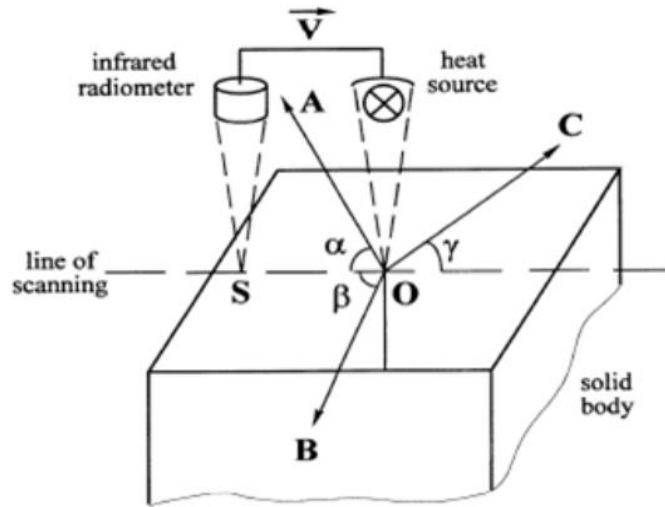


Figure 3: Principle of optical scanning method: velocity of scanning; O: area of the heat spot; S: detection area of the radiometer; A, B, C: main axes of thermal conductivity with angles α , β and γ to line of scanning, respectively.

3. Methodology

In this study, two petrophysical laboratory tools involving the multi-sensor core logging and thermal conductivity scanning are deployed to unravel the spatial variation in the

¹² Brigaud, F., Chapman, D. S., Le Douran, S. (1990). Estimating Thermal Conductivity in Sedimentary Basins Using Lithologic Data and Geophysical Well Logs. AAPG Bulletin, 74: Pp. 1459-1477.

petrophysical properties including density, P-wave velocity, magnetic susceptibility and the porosity of the rock samples.

For the purpose of adapting the core logging technique, Multi Sensor Core Logger (MSCL) was used. The MSCL is a multi-purpose tool that can utilize many different methods at once, streamlining the measurement process on a core sample. The samples range from 50mm to 150mm in thickness and up to 1.55m long and can be measured at intervals of a few millimeters if necessary. The equipment hooks up to the systems electronics rack, which then logs the data on a standard PC with the provided software. In this experiment the MSCL consists of three measuring devices (Figures 3 and 4), inclusive of gamma density, P-wave velocity and the magnetic susceptibility.

Two rock (core) samples, labeled BS (a red sandstone) and B6 (a metamorphic conglomerate of gray and black rock) were used for the analysis; with each cut into halves, creating two half-cylindrical cores. One half was completely saturated in water, and the other half was completely dried to measure the differences in the measurements, in order to create a clear difference in the pore spaces and measure those effects. This was to gain information on porosity and permeability as well as the rock fluid interactions inside the rock.

Each sample was set on the right side of the running track and systematically pushed along the rails, getting measured by each of the three devices at the same place, but various times. The three methods were combined to give information on the porosity or density of the sample.

3.1 Multi-sensor Core Logging (MSCL) Measurements

Gamma-Density: The first device the sample encountered was the gamma density sensor, which measures the number of gamma rays per second, which hit the sensor underneath the sample (Figure 4). Adsorption and scattering phenomena aid minimizing the number of gamma rays going through the sample. The Adsorption of the gamma rays by the sample is related to the bulk density of the sample. The relationship of number of gamma rays emitted from the source and the number that actually goes through the sample is given as:

$$I(x) = I_0 \cdot e^{-\mu \cdot x} \quad (12)$$

where the adsorption coefficient is related to the density by:

$$\mu' = \frac{\mu}{\rho} \quad (13)$$

and the bulk density given as:

$$\rho = -\frac{1}{\mu' d} \cdot \ln\left(\frac{I_0}{I}\right) \quad (14)$$



Figure 4: Actual laboratory picture of the MSCL logger

Where in equations (12) to (14); I_0 is the intensity before absorber; I_x is the intensity after absorber; x is the distance from the source of emission; μ is the absorption coefficient; μ' is the mass absorption coefficient; d is the absorption thickness.

Scattering of the gamma rays in the sample is a bit different from adsorption because the gamma rays can deflect off of the atoms, reducing their energy and resulting in change of direction. Eventually, some of these gamma particles with reduced energy get adsorbed, which is not included in the calculation of adsorption. Also, some of these detected particles never hit the measurement surface due to a Compton scattering effect, which describes the decay of energy in these deflected gamma particles.

In this study, our MSCL device used a Cesium ($^{137}/_{55}\text{Cs}$) source that emits x-rays with an emission energy of 0.6616MeV. This makes the dominant interaction process in the sample to be Compton scattering. The sensor underneath the sample captures each gamma ray that hits it and releases a small photon of light, which is then enhanced through a series of Photo-amplifications, and then turned into a current and measured. In order to calibrate the device, a measurement was made 15 times with a known input. The first calibration sample was zero, giving a known I_0 value. Each of the consecutive 14 calibration measurements added one aluminum plate sample so that the thickness of the scatterer increased linearly. In theory, the counts per second (cps) would decrease linearly on a log scale, but that was not the case in this experiment. The curved response was almost linear, but the fitting curve equation was

given as $y = -0.00019x^2 - 0.6341x + 10.20861$. At the end of all the measurements, the values from the fitting curve were used in the program as a correction factor.

After measuring both the dry and the wet samples, the ultimate goal was to calculate the porosity of the sample. Assuming the two core pieces have the same porosity and are homogeneous, we use the modified basic density equation (Wyllie et al. 1956) to calculate the porosity, and considering each fluid, we combine the equations as:

$$\phi = \frac{\rho_{sat} - \rho_{dry}}{\rho_{water} - \rho_{air}} \quad (15)$$

Where ρ_{sat} represents density of the fully saturated rock sample, ρ_{dry} represents density of the dry rock sample ρ_{water} represents density of the water fluid; ρ_{air} represents density of the air fluid. The porosity calculated based on model using the MSCL is then compared with that calculated based on the TCS method, allowing a realistic estimation to be made at the end.

P-Wave Velocity: The second device on the MSCL measured the travel time of acoustic waves through the sample as well as the sample thickness. After traveling through the gamma-ray device, the velocity measurement device encapsulates the sample, putting a transducer and a supersonic receiver above and below it. The total travel time is measured, which includes both the travel time in the equipment and in the sample, given as:

$$T_{total} = t_{sample} + t_{equipment} \quad (16)$$

where $t_{equipment}$ is a constant. The device also has a caliper-like quality that allows it to measure the thickness of the sample, thereby allowing the velocity to be calculated, using the relation:

$$V_p = d / t_{sample} \quad (17)$$

Because the interest is in the pore spaces, and therefore fluids in the samples, it is pertinent to look at the P-waves even though there are S-waves propagating as well¹³. The movement of the wave through the sample is understood simply by imaging the travel path as through the rock first, then through the pore space, allowing the sample travel time, t_{sample} , to be the sum of the travel time through the rock and the fluid (Figure 5). When measured with different fluids, this allows for the calculation of porosity in the sample. But the MSCL equipment also has a device for measuring P-wave velocity with a supersonic transducer on the top, which pushed down on the sample every time a measurement was made, and a rolling wheel receiver on the bottom. This allows the sample to roll directly into the measurement device, right after the gamma-density device.

There was a similar setup for calibrating this device as in the case of the gamma-density; here, where five measurements were taken with steel samples at 0cm, 2cm, 4cm, 6cm and 8cm. The no-sample measurement was specifically to find the $t_{equipment}$ value in equation (16), and the rest were used to create a linear plot, giving values for a correction factor for the software. The calibrating equation for this calibration is formulated as $y = 1.5662x + 14.385$.

¹³ Barton, N. (2007). Rock Quality, Seismic Velocity, Attenuation and Anisotropy, pp. 729, Balkema

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In this instance correction factor does not require the use of the $t_{\text{equipment}}$ measurement because it could be calculated.

For the calculation of velocity from porosity, the Wyllie time-average equation is adapted in the experiment by simply inverting all the time terms in the equation, resulting in equations (18) and (19) for generalized matrix porosity and for the case of saturated/dry sample respectively).

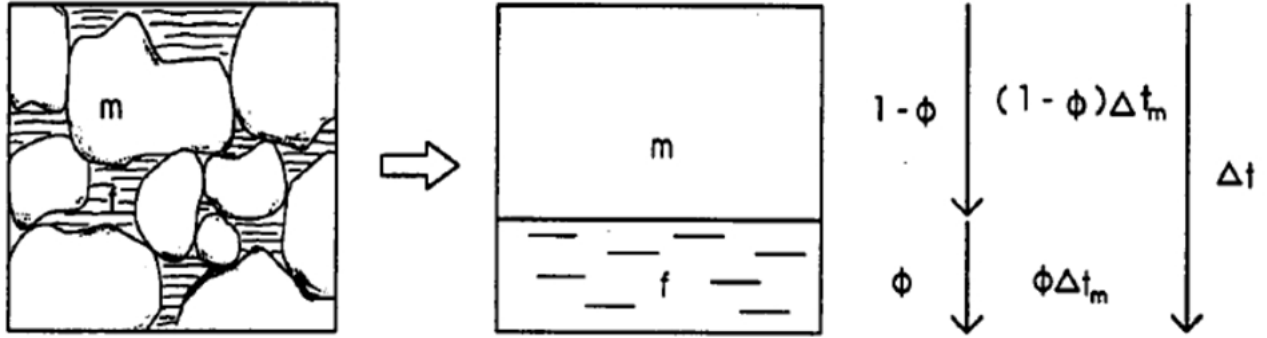


Figure 5: A rock sample with porosity can be broken to rock-space and pore-space, which is then easier to understand how much effect each part of the rock and fluid has on the total acoustic travel time through the entire system.

$$\phi = \frac{t - t_{ma}}{t_{por} - t_{ma}} = \frac{\frac{1}{v} - \frac{1}{v_{ma}}}{\frac{1}{v_{por}} - \frac{1}{v_{ma}}} \quad (18)$$

and

$$\phi = \frac{t_{dry} - t_{sat}}{t_{air} - t_{H_2O}} = \frac{\frac{1}{v_{dry}} - \frac{1}{v_{sat}}}{\frac{1}{v_{air}} - \frac{1}{v_{H_2O}}} \quad (19)$$

where $v_{air} = 343$ m/s and $v_{H_2O} = 1484$ m/s (sea water), which is assumed to be a good

estimation for fluids in this experiment.

Magnetic Susceptibility: The magnetic susceptibility of a material describes how magnetized it gets when an external magnetic field is applied (Auduson, 2018). The sample can either strengthen, weaken or does not affect the external magnetic field, and each response tells some properties of the rock. When the field is strengthened by the sample, the sample is paramagnetic, ferromagnetic or ferrimagnetic. When the field is weakened in the presence of the sample, the sample is diamagnetic. This makes description of the rock's magnetism simple and is shown as a unitless number either positive or negative, with a range from about -17 for quartz to about 6,000,000 for magnetite. Water has a magnetic susceptibility of 9.

The magnetic susceptibility measurement device component of the MSCL equipment is a Barrington point sensor (MS2E) and was attached to the P-wave sensor, such that it goes up and down during each measurement. The device only takes information from a 1cm radius, making the device not suitable for whole core samples, but perfect for these half core samples, in our experimental case. There was also a large effect on the measurement from temperature changes, such that the samples would have to be stabilized prior to measurement. Thus, the samples were saturated for a week to meet desired saturations requirement.

The sensor creates a magnetic field by sending a low intensity signal at a frequency of about 2 kHz into the device. Any material with a magnetic susceptibility within the range of the device would change that frequency, and then measured by the MS2E.

3.2 Thermal Conductivity Scanner (TCS) Measurements

The theoretical model of the optical scanning method is based on scanning a sample surface with a focused, mobile and continuously operated constant heat source in combination with a temperature sensor (Popov et al, 1999). In our experiment, the samples with a reference standard and known conductivity, λ_R , were aligned along the scanning direction, thermal conductivity of each sample being determined from the ratio of electric signals, U , to that of the known sample U_R , which are proportional to θ and θ_R .

The heat source and sensor move with the same speed relative to the sample and at a constant distance to each other. The temperature range displays the value of the maximum temperature rise, θ , is determined by the relationship:

$$\theta = \frac{Q}{2\pi \cdot x \cdot \lambda} \quad (20)$$

Thermal conductivity measurements were conducted using optical scanner (figure 6) to indicate the spatial distribution of thermal conductivity, λ , which was used to determine porosity.

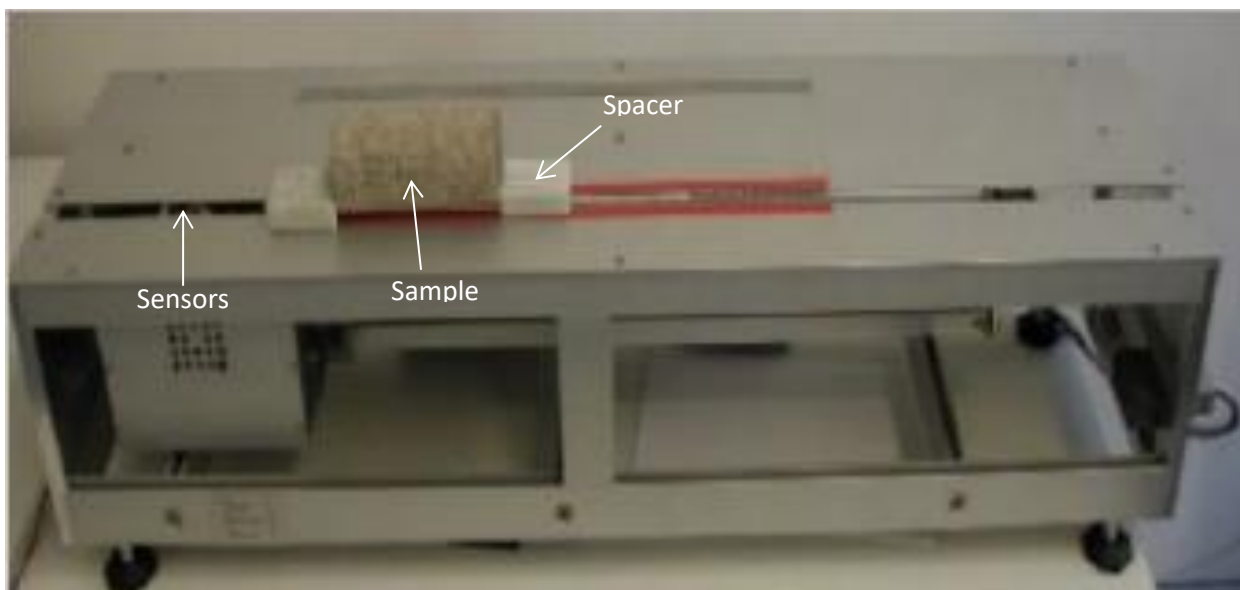


Figure 6: Thermal Conductivity Scanner (capable of measuring up to 60 samples per hour and has accuracy of $\pm 3\%$).

4. Results and interpretation

Based on the MSCL experiment, the two samples (BS; sandstone and B6; metamorphic conglomerate, in Figures 7 and 8 respectively), shows interesting results. The first track in each of the Figures 7 and 8 is the bulk density as obtained from the gamma ray log. For the BS sandstone sample (Figure 7), the bulk density had a regular and visible increase at every part of the core for the saturated sample. This is informative because it shows a great deal of change due to porosity and the fact that the sample is quite homogeneous. The metamorphic B6 (Figure 8) sample keeps the same bulk density measurements in each of the dry and saturated samples, but actually shows a higher bulk density in the dry sample.

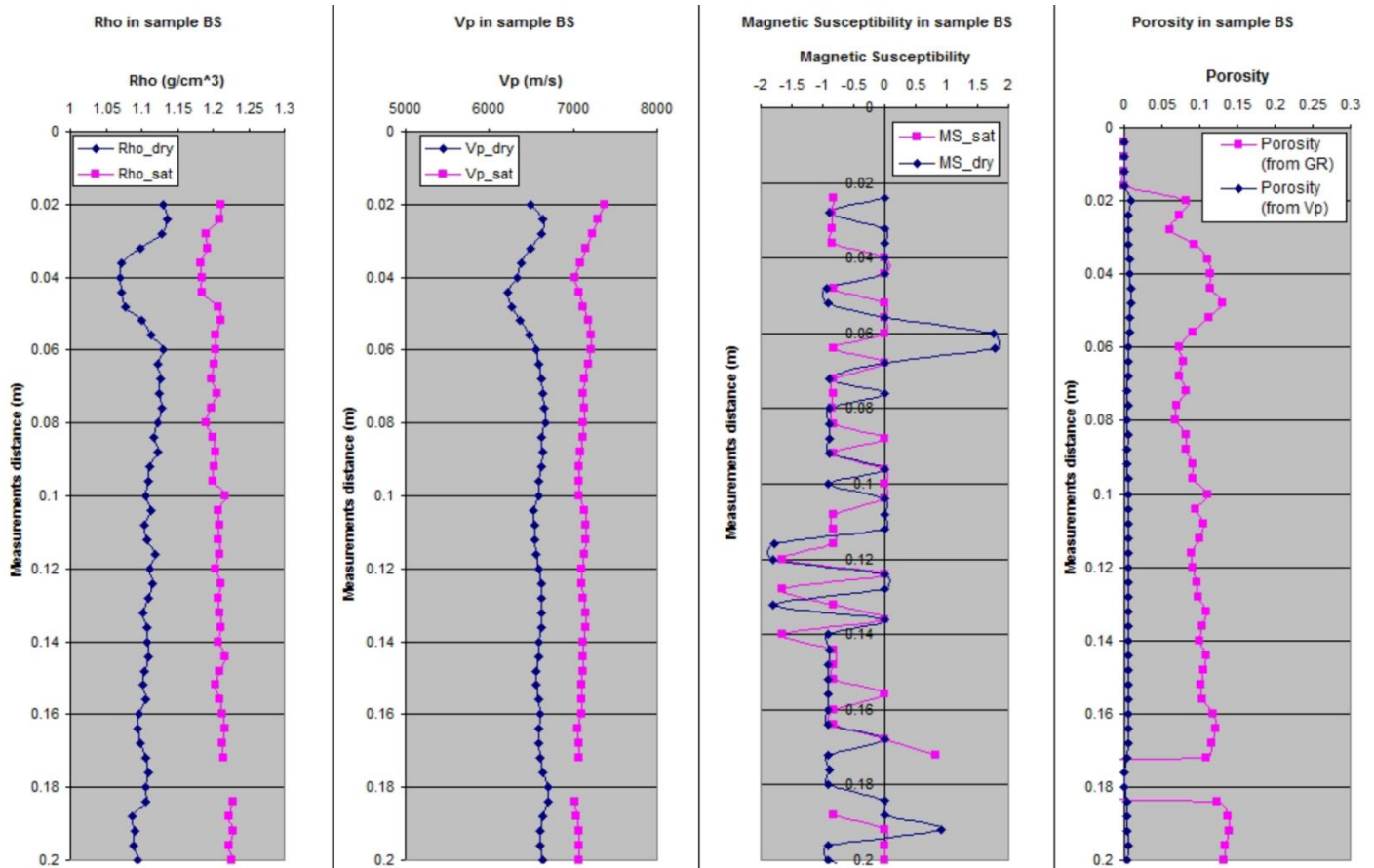


Figure 7: Measured and calculated logs from the dry and saturated half-core BS samples (red sandstone). From the left to right tracks are track 1: bulk density; 1: track 2: P-wave velocity; track 3: magnetic susceptibility; track 4: porosity (pink curve is porosity calculated using gamma-density, while black curve is porosity calculated using Vp, based on the [Wyllie et al¹⁴](#) equation).

The second track shows the P-wave velocity (Vp) curve of each saturated core half. In Figure 7 (BS sandstone sample) the dry sample shows a slower Vp than the saturated. This follows the assumption shown in Figure 5, because water has a much faster velocity than air. Again, the curves are similar and equally separated along the entire core. Conversely, in Figure 8 (metamorphic B6 sample), the curves are not similar at all, and do not show a general trend.

¹⁴ Wyllie, M. R. J., Gregory, A. R., Gardner, L. W. Op. Cit

The third track in both Figures shows the magnetic susceptibility curves. In Figure 7 (BS sample) the range is from -1.8 to 1.8, but mostly on the negative or zero-line. This indicates that, even with the water introduced in the saturated sample, the BS sample is very mildly diamagnetic, if magnetic at all. Since the values are so insignificant compared to the total range of magnetic susceptibilities, it is negligible and therefore, the value for BS is taken as zero.

The B6 sample, on the other hand is much more interesting and shows a regular increase in magnetic susceptibility when water was added.

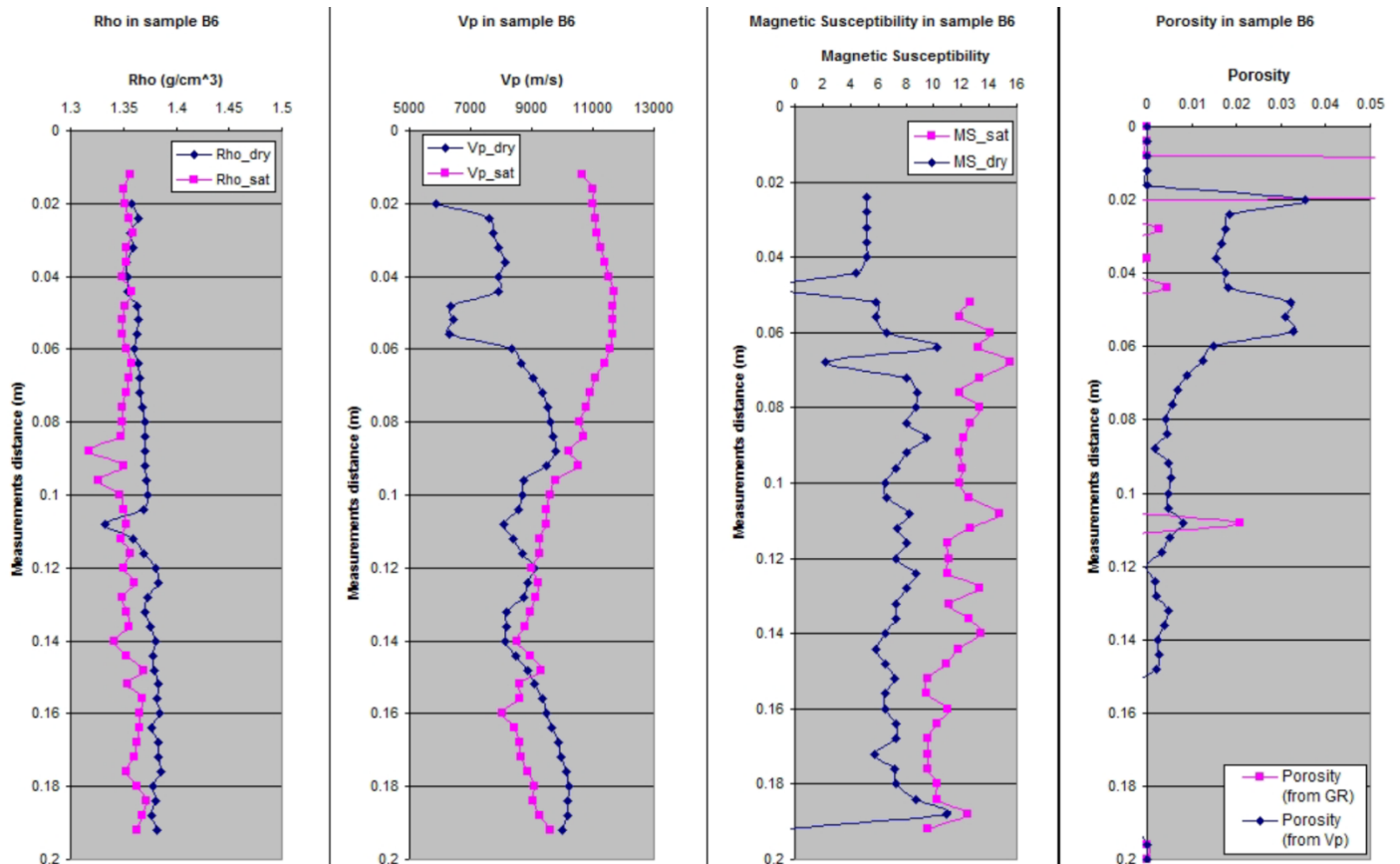


Figure 8: Measured and calculated logs from the dry and saturated half-core B6 samples (metamorphic conglomerate). From the left to right tracks are track 1: bulk density; track 2: P-wave velocity; track 3: magnetic susceptibility; track 4: porosity (pink curve is porosity calculated using gamma-density, while black curve is porosity calculated using Vp, based on the Wyllie et al¹⁵ equation).

The last track in both Figures 7 and 8 shows the calculated porosity. In Figure 7 (BS, sandstone sample), the porosity from the gamma-density shows realistic and expected values from about 7% to 14%. There is not much deviation from this range, again confirming that the sample is very homogeneous. The porosity calculated from the Vp, however, shows entirely zero porosity. This makes sense when looking at equation 19, since the separation of the velocities between the dry and saturated samples is nearly equal. However, in Figure 8 (B6, metamorphic sample) has close to zero porosity, probably because it is expectedly heavily cemented and pressurized. This is perfectly shown by calculation for porosity from

¹⁵ Wyllie, M. R. J., Gregory, A. R., Gardner, L. W. Op. Cit

gamma density model. Even though there are quite a few negative values, they are remarkably close to zero porosity.

Figure 9 shows the P-wave velocity, V_p , cross-plotted with the porosity, ϕ , for all samples in both experimental methods. There is a clear delineation in the samples showing the P-wave velocity decreasing as porosity increases, both for the dry and saturated samples. This is easily explained by the fact that both air and water have slower P-wave velocities than any rock sample. Using the assumption in Figure 5, which states that the total velocity can be shown as high, going through the solid rock, then lower in the fluid; the decrease in velocity with increasing porosity is corroborated. This also shows that there were quite a few samples that had exceptionally low porosity, meaning they probably were not sandstones.

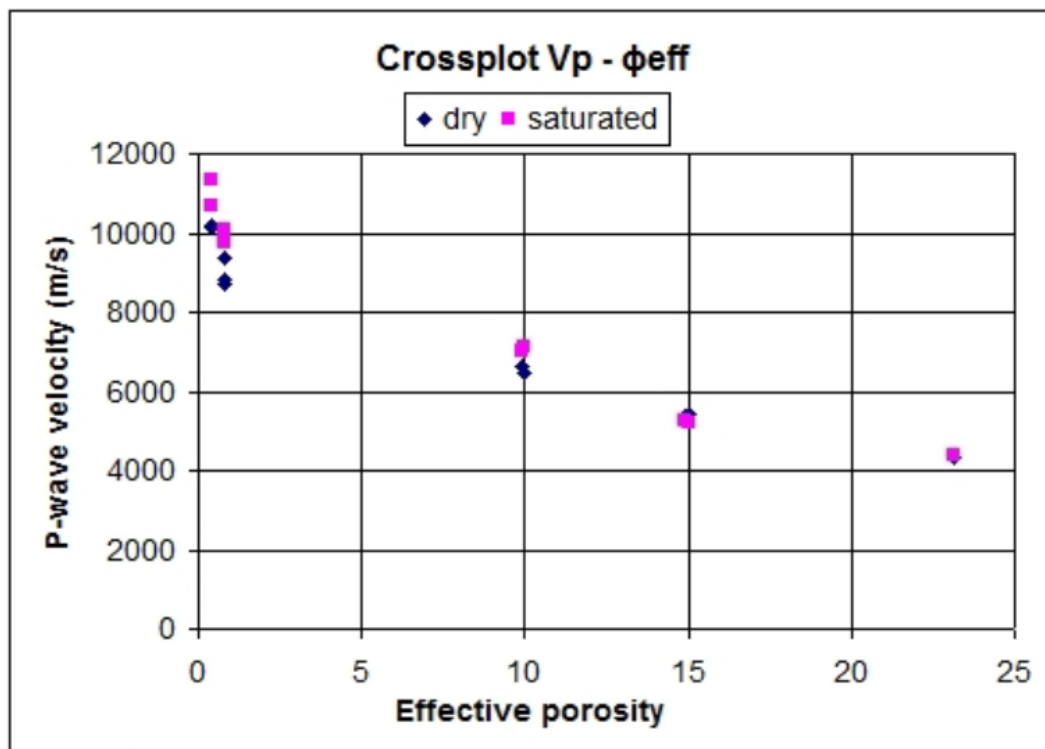
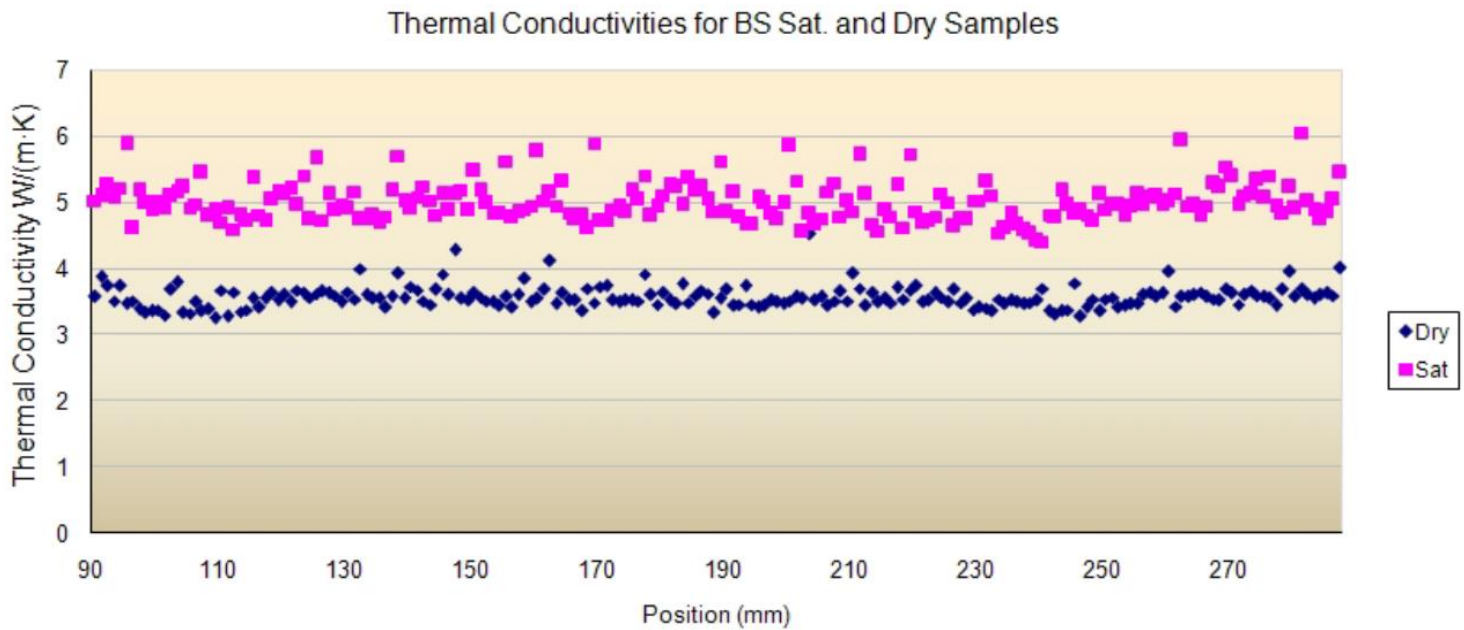


Figure 9: Cross-plot of the P-wave velocity versus porosity for all samples in the experiment based on the two methods.

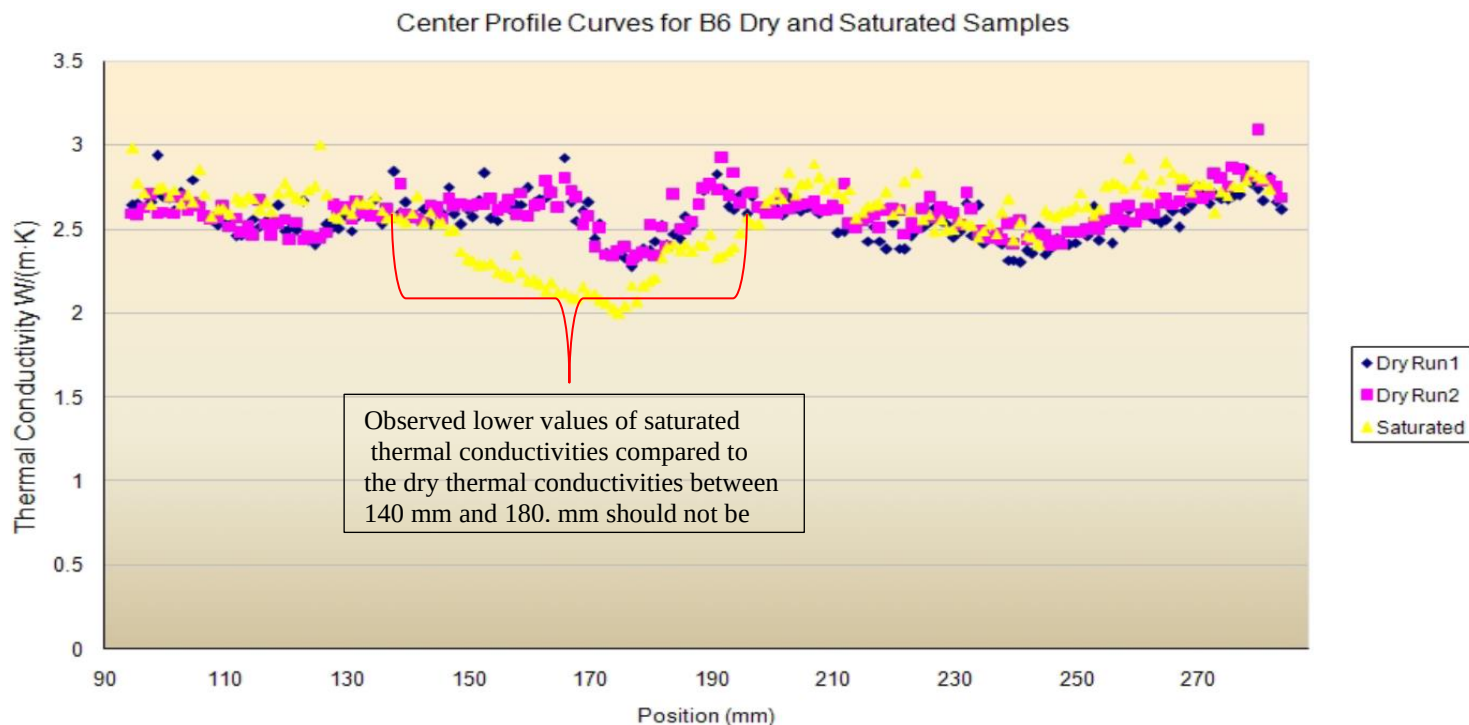
Based on the thermal conductivity experiment, each of the samples measured a profile of the measured thermal conductivity, λ , which are plotted (Figures 10, 11 and 12). In Figure 10, the BS sample curves are very straight and uniform separation between the dry and saturated curves. This is good, since the BS sample is homogeneous sandstone with a large porosity, causing the water to have a large effect on the sample thermal conductivity.

Conversely, the B6 curves, both dry and saturated (Figure 11), there is deviation in the dry curve, showing the effects of the rock inhomogeneity. The saturated sample shows mostly that the water has no effect on the thermal conductivity except in the middle, where there is the most inhomogeneity in the dry curve. This could be due to two reasons: first, anisotropy in porosity, and second anisotropy in mineralogy. Since the rock has no porosity, it is due to

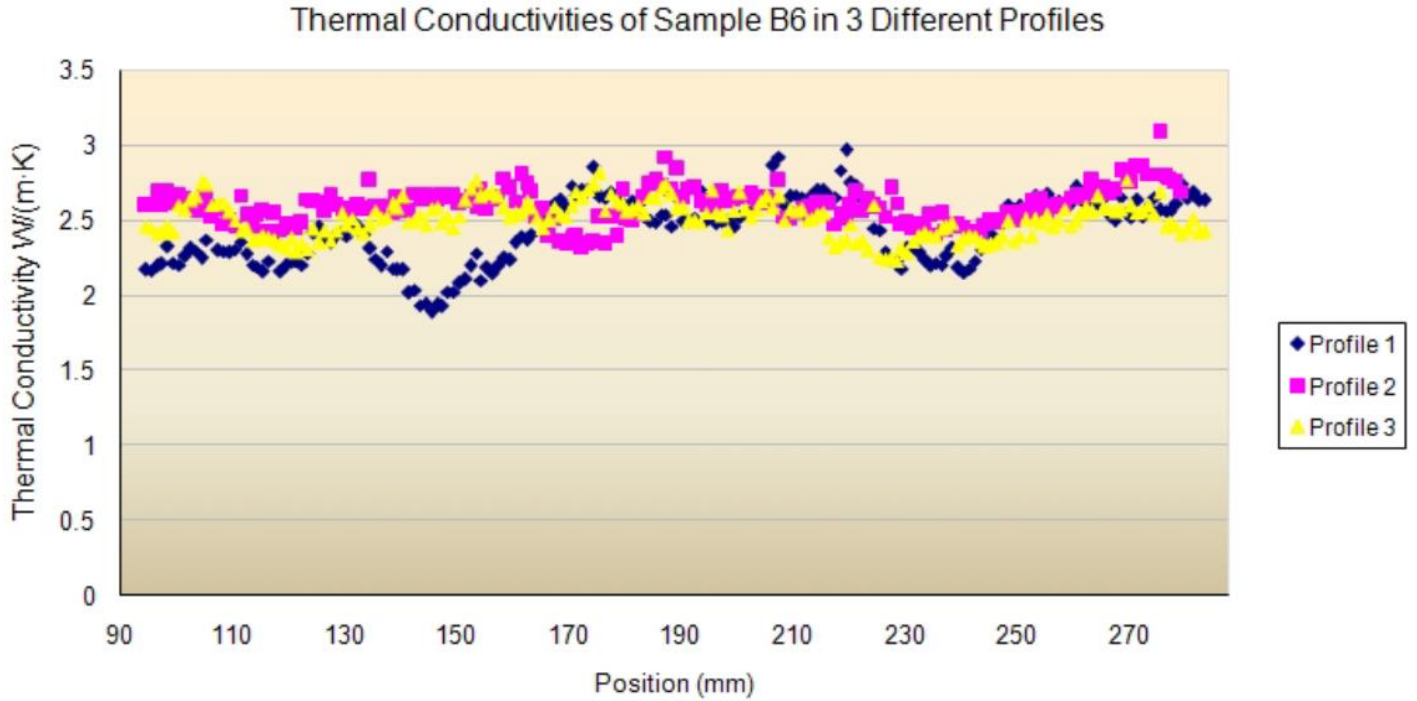
anisotropy in the mineralogy. Figure 12, inhomogeneity is more explicitly demonstrated by plotting the curves of three different measurements at different points of the same B6 sample.



In Figure 10: Result of thermal conductivities curves for the BS sample (red sandstone), both dry and saturated.



In Figure 11: Result of thermal conductivities for the B6 (metamorphic conglomerate) sample, both dry and saturated; (b) B6 sample, both dry and saturated; (c) the three dry B6 sample profiles.



In Figure 12: Result of thermal conductivities for the B6 (metamorphic conglomerate) sample, in three dry B6 sample profiles.

It is interesting to note in Figure 11 that between 140 mm and 180 mm, the dry thermal conductivities are consistently more than those of the saturated sample. The simulation was run a second time (pink curve) and to confirm the results; thus, this is the reality of the rock. To calculate the porosity of the samples from thermal conductivity measurements, equation (22) was adapted:

$$\lambda = \lambda_{ma}^{1-\phi} \cdot \lambda_{fluid}^{\phi} \quad (21)$$

This was reformulated as:

$$\phi = \log\left(\frac{\lambda_{dry}}{\lambda_{sat}}\right) \cdot \left(\frac{1}{\log\frac{\lambda_{air}}{\lambda_{water}}}\right) \quad (22)$$

where the values for λ are taken from the rocks mean value. With the porosity known, the thermal conductivity of the matrix, λ_{mat} , were calculated, using equation (23):

$$\lambda_{mat} = \exp\frac{\ln(\lambda_{dry}) - \phi \ln(\lambda_{air})}{1 - \phi} \quad (23)$$

However, there are some discrepancies in the porosity which, in this case, could lead to different values of thermal conductivity. Therefore, the results have also been calculated with the porosity results from MSCL's measurements. Fortunately, there is not much difference in the results, as shown in Table 1, meaning that the calculation of porosity from the TCS is a reliable technique and it consistent with results obtained based on the MSCL method.

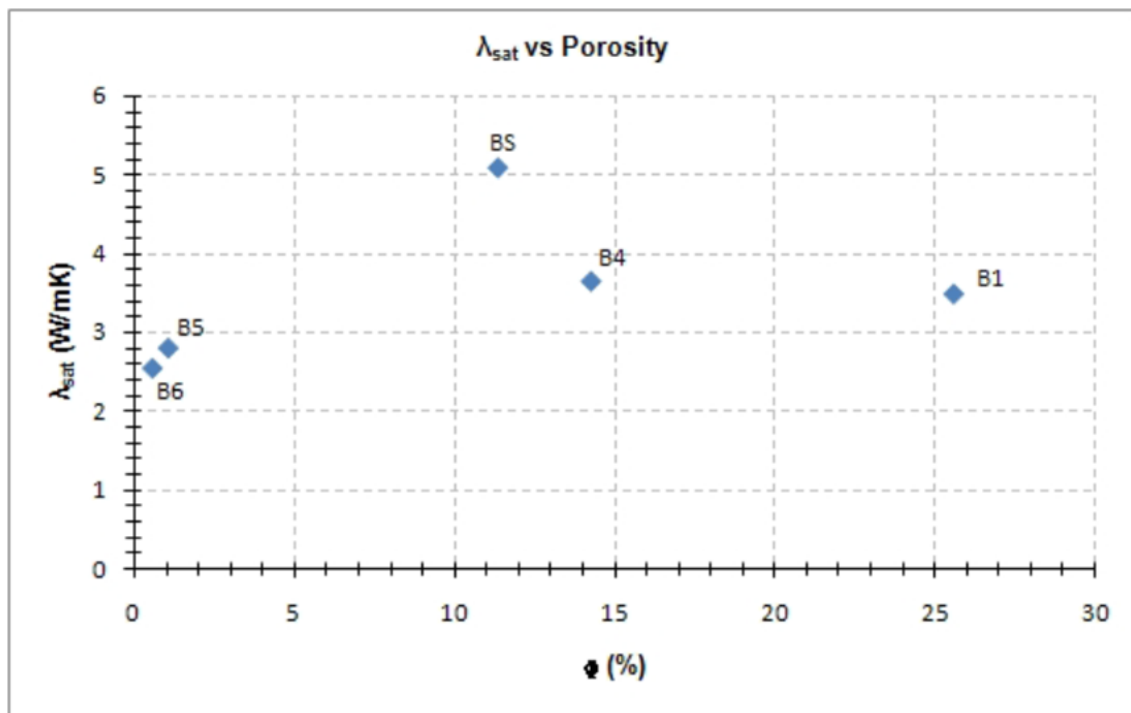
Table 1: Calculated porosity values based on the TCS technique

Sample label	λ_{Sat_mean}	λ_{dry_mean}	ϕ	λ_{mat_TCS}	λ_{mat_MSCL}
BS	4.992	3.583	10.4	6.412	6.249
B6-1	2.562	2.435	1.6	2.624	2.551
B6-2	2.562	2.560	0	2.554	2.705
B6-3	2.562	2.505	0.7	2.589	2.625

Plotting the mean λ -values of all TCS measurements against porosity from all measured samples (Table 2 and Figure 13) shows that all samples, regardless of their type, yield a larger thermal conductivity with higher porosity. However, this trend is not visible on the curves for each individual rock. This is because thermal conductivity is not only a function of porosity. There is not a fixed relationship between porosity and thermal conductivity because pore sizes and pore size distribution generated during compaction of the rocks differs in different physical and chemical environments.

Table 2: TCS results for all samples

Sample label	λ_{Sat_mean}	λ_{dry_mean}	ϕ	λ_{mat_TCS}
BS	3.583	3.4.992	10.4	6.412
B6-1	3.494	1.547	25.6	5.998
B6-2	3.653	2.320	14.3	4.021
B6-3	2.809	2.717	1.04	2.826
B6-4	2.562	2.505	0.55	2.603

Figure 13: Cross-plot showing the thermal conductivity (λ) versus porosity (ϕ) for all samples.

4.1 Discussion

The density, P-wave velocity, magnetic susceptibility and porosity were uniquely estimated using the MSCL equipment, while the thermal conductivity scanning technique estimated thermal conductivity and porosity. But there exists a limitation of the MSCL equipment, which also has a device for measuring P-wave velocity with a supersonic transducer on its top, designed to push down on the sample every time a measurement is made. This allows the sample to roll directly into the measurement device, right after the gamma-density device. This is because the device was designed for whole cores and to have a rolling transducer on the top. But this experiment, two half-cylindrical cores were used in order to create a clear difference in the pore spaces and gain information on porosity, as well as the rock fluid interactions inside the rock. In view of this, the top transducer was modified for half-cores, to cater for our sample geometry, which introduced some errors in the measurement. To circumvent this limitation, at each measurement, human interaction was adapted to keep the sample stable as the machine moved and to keep the sample settled in the rails correctly. This resulted in reliable values for most measurements of the thickness variation and the P-wave velocity.

4.2 Distribution of petrophysical parameters and their spatial variations:

The sandstone core sample displaying bulk density with regular and visible increase at every point in the sample, as well as P-wave curves with similar and equally separated along the entire core (tracks 1 and 2 in Figure 7) shows that that the sample is quite homogeneous. Also, the porosity calculated from the gamma-density showing realistic values between 7 % and 14% (track 4 in Figure 7), confirms the homogeneous nature of the sample. The metamorphic core sample with the same bulk density measurements in each of the dry and saturated samples, but actually shows a higher bulk density in the dry sample (Track 1 in Figure 8). As illogical as it sounds at first, this shows that the rock is quite inhomogeneous; even within the small core sample there are large enough differences in the measured density. P-wave curves in the metamorphic core sample (track 2 in Figure 8) show dissimilar trends. This is because the pore space that would be filled in this sample is mostly fracture space, causing different acoustic behaviour than a regularly porous sample. In the dry sample around 0.05 m, there is a large dip which is due to measurement error; this is ignored, because it might also be due to an inhomogeneous component of the rock which was not visible.

Heterogeneous attribute of the metamorphic rock sample is further confirmed by regular increase in magnetic susceptibility when water was added. This could be because the water dissolves a bit of the sample and carries some ions that are attracted to and/or repelled from the sensor. One interesting thing to note is at about 0.07 meters the sample spikes in the saturated form and drops in the dry form. This interesting phenomenon could be from a larger fracture space that was filled with the water and ions. This sample would be considered paramagnetic. The porosity calculated from the Vp in the sandstone core sample (track 2 in Figure 7), showing entirely zero values (track 4 in Figure 7) implies a main limitation of the [Wyllie et al¹⁶](#) equation. For the metamorphic sample, the calculated porosity with expectedly zero values is characterized with quite a few negative values (track 4, Figure 8). Again, a failure with the Wyllie equation is depicted here because the differences in the velocity of the dry and saturated samples are not heavily dependent on the fluid. The anomalous motif at about 0.05 m in the case of P-wave calculation (tract 2, Figure 8) shows up again, this time in a reversed trend, leading to nearly 4% porosity value, which just cannot be in this kind of

¹⁶ Wyllie, M. R. J., Gregory, A. R., Gardner, L. W. Op. Cit

rock sample. The Wyllie equation fails here, because the different minerals in the rock affect the velocity much more than the fluid it is saturated with.

The results of the TCS experiments (Figure 11) further corroborate the inhomogeneous nature of the metamorphic core sample. It is interesting to note in Figure 11 that between 140 mm and 180 mm, the dry thermal conductivities are consistently more than those of the saturated sample. The simulation was run a second time (pink curve) and to confirm the results; thus, this is the reality of the rock. Results of thermal conductivity values were recalculated with the porosity value from that MSCL method, due to some discrepancies in the porosity calculated based on the TCS method. It is observed that there is not much difference in the results (Table 1), meaning that the TCS is a technique is reliable and it consistent with the MSCL method.

5. Summary and Conclusion

Two petrophysical laboratory measurements techniques including the multi-sensor core logging and thermal conductivity methods were integrated in order to determine certain petrophysical properties and their spatial variations. Multi-sensor core logging technique uniquely estimated density, P-wave velocity, magnetic susceptibility and porosity using the MSCL equipment, while the thermal conductivity scanning technique estimated thermal conductivity and porosity, and therefore matrix type.

Results of the experiment on the MSCL experiment on both (BS; sandstone and B6; metamorphic conglomerate), shows interesting results for bulk density, P-wave velocity, magnetic susceptibility and porosity. For the BS sandstone sample, the bulk density had a regular and visible increase at every part of the core for the saturated sample, which is highly informative because it shows a great deal of change due to porosity and the fact that the sample is quite homogeneous. The metamorphic B6 sample on the other hand keeps the same bulk density measurements in each of the dry and saturated samples, but actually shows a higher bulk density in the dry sample. For P-wave velocity, the BS sandstone dry sample showed higher velocity than the saturated sample. The metamorphic B6 sample velocity curves depict irregular trend probably because fracture space, causing different acoustic behaviour than a regularly porous sample and the possibility of an invisible inhomogeneous component of the rock.

Magnetic susceptibility curves for the BS sample shows values mostly on the negative or zero-line, indicating very mild or zero magnetism, while for the B6 sample, curves values indicating regular increase in magnetic susceptibility. The porosity values in the BS sandstone sample shows realistic and expected values from about 7 % to 11 %, confirming that the sample is very homogeneous. The porosity calculated from the v_p , however, shows almost entirely 0 %, an unexpected value in a homogenous porous rock, indicating a major limitation of the Wyllie equation of 1956. However, the B6 metamorphic sample has close to zero porosity, indicated almost perfectly by gamma density calculation, as expected in hard rock specimen. Again, there exists some anomalous value (about 4 % porosity), unexpected in this kind of rock sample caused by failure of the Wyllie equation here because the differences in the velocity of the dry and saturated samples are probably not heavily dependent on the fluid.

Results of thermal conductivity for the BS sample show very straight curves, as well as very uniform separation between the dry and saturated curves, confirming homogeneous sandstone

with a large porosity. For the B6 sample (dry and saturated curves), there is deviation in the dry curve, showing the effects of the rock inhomogeneity, most like due to anisotropy in mineralogy.

Therefore, on the basis of this results, measurement with the MSCL and TCS techniques are reliable in the estimation of physical rock properties such as density, seismic velocity, magnetic susceptibility and thermal conductivity, as well as porosity, as derivative calculation. Also, the techniques have proven especially useful in evaluating the influence of heterogeneous distribution of petrophysical parameters and their spatial variations. Furthermore, comparative analysis of porosity values based on the two methods proves that even though there are some discrepancies in the porosity values obtained in the TCS, the results from the TCS method are consistent with results obtained based on the MSCL method, meaning that both methods are dependable in estimating petrophysical parameters.

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