CONTINUOUS CORE MEASUREMENTS: APPLICATIONS FOR OPTIMIZED PETROPHYSICAL AND GEOMECHANICAL MODELLING IN SNE FIELD, SENEGAL.

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ABSTRACT
An enhanced core analysis workflow, which integrates conventional core plug analysis with continuous direct core measurements and wireline log data, was developed to optimize petrophysical and geomechanical modeling of the reservoir intervals in the deep water SNE field, offshore Senegal. An extensive, continuous core scratch testing campaign was run on core from two wells. The scratch tests produced a continuous profile of Uniaxial Compressive Strength (UCS) and P-wave velocity values that were correlated with available core plug strength and porosity data. The sample site selection protocol based on the up-scaled scratch test data resulted in fewer plug sample failures during plug preparation for geomechanical testing. The Rock Mechanical Tests (RMT) results were also found to be in excellent agreement with the scratch strength profile. By integrating the scratch test results with core porosity and wireline logs, a centimeter-scale profile of estimated porosity was derived. The continuous rock property profiles created with the scratch test could be used to systematically check both Routine Core Analysis (RCA) and RMT plug results. The robust multivariate relationships established between the rock strength profile and selected wireline logs enabled reliable upscaling of plug rock properties to predict rock strength in non-cored intervals and wells. In comparison, rebound strength index tests run over the same core scratch interval produced limited and potentially misleading strength data. Plug sampling in thin bedded heterogeneous formations may lead to an irreducible bias in test results unless it is based on a-priori knowledge about the rock small scale heterogeneity. The heterogeneity assessment methodology based on the scratch test enables the selection of more representative plug site and more robust core property-log calibration at different length scales. This leads to a significant reduction in uncertainty in petrophysical and geomechanics models, and better decision making in well design and field management.

INTRODUCTION
Several cores were acquired from two wells in order to characterize the petrophysical and geomechanical properties of reservoirs in the deep water SNE field, offshore Senegal. A complex sequence of variable grain-size sandstones and thin-bedded heterolithics have created significant challenges in the acquisition of reliable and representative core data.
This paper presents the enhanced core analysis workflow applied on these cores and the improvements in the acquisition of reliable geomechanical and petrophysical properties.
In the first well, high resolution continuous profiles of rock properties from the scratch test were acquired on about 100 meters of fresh cores, prior to any other test. The existence of a good correlation was established between the scratch test strength profile and the porosity wireline log. As a result the scratch test could be used to map local heterogeneities of the rock porosity at the centimeter scale and to guide the selection of representative sample sites for SCAL and Rock Mechanics Tests (RMT) plugs. A robust multivariate empirical relationship was established between the sonic and gamma ray wireline logs. Once the results of the RMT conducted on plugs were received several months later, an excellent agreement with the strength profile of the scratch test was found. The proper upscaling of plug test results for porosity helped with the construction of a robust porosity predictor based on wireline logs, which enabled the calibrated prediction of porosity from wireline logs in the non-cored sections of the reservoir. In the second well, the same series of continuous high resolution tests was conducted on cores which had already been slabbed and plugged for Routine and Special Core Analysis (RCA, SCAL) and RMT. Extensive plug failure and misleading results characterized the RCA. However the continuous high resolution porosity profile built from an empirical relationship between the scratch strength profile and the neutron porosity log was found in excellent agreement with the validated RCA plug results. Finally, rebound tests (EQUOTIP) were conducted on the cores. The large dispersion of this test prevented a clear choice between Brinell or Leeb hardness on which of the two would be best suited to derive UCS values.

METHODOLOGY
Continuous High Resolution Core Data
Continuous high resolution profiles of rock strength profile and ultrasonic compressional velocity (Vp) profile were acquired on fresh cores. Details on the scratch tests can be found in [1], [2]. An adequate preservation of the core was maintained by taken them out of their liner for as short a time as possible (less than 40 minutes) and cutting only a narrow slit of 5cm width along the core length. The cores were immediately wrapped back in plastic film at the end of the test sequence. The first step of the scratch test consists in removing a few millimeters of core material from its surface using a sequence of accurately controlled displacements of a cutting tool. The evolution of the energy consumed during each cut at a given depth is monitored as an indicator of the superficial damage of the core material. Once the groove is perfectly flat, within 10 micron accuracy, measurements can be conducted such as high resolution core photography (30µm/px),

high resolution rock strength profile, ultrasonic P and S wave velocities, or surface roughness assessment.

Sampling Sites Recommendations

Several sources of uncertainties could affect the upscaling of laboratory measurements conducted on plugs with wireline logs:

- Measurements (Wireline or Lab) are never perfect;
- Downhole and laboratory environments are different;
- Core shifts are not always accurate and can vary along one core;
- Only a small fraction of the rock is tested discrete samples taken from cores;
- A difference in resolution exists between the wireline logs (50cm) and the plug samples (5cm)
- Rock heterogeneity includes centimetre length-scales.

Assuming strength is intrinsically correlated with the geomechanical and petrophysical properties to be measured on the plug samples, the most homogeneous sampling intervals of a set length (10cm) are identified from the dispersion of the strength profile around its means for each interval. Sampling intervals are ranked according to the values of this heterogeneity index $\boldsymbol{I}$. The distribution of $\boldsymbol{I}$ and its percentiles are then used to partition the cored interval into several categories:

1. Intervals where $0 < \boldsymbol{I} < P10$
2. Intervals where $P10 < \boldsymbol{I} < P20$
3. Intervals where $P20 < \boldsymbol{I} < P30$

Recommended sampling sites are visualized with color coded lines in the high resolution core pictures taken after the scratch test (Figure 1). A thick yellow line is use to highlight the intervals of the best category while a thin yellow line indicate the intervals in the intermediate category. The vertical position of these lines is fixed by the strength values at the center of the corresponding sampling intervals. This method is efficient to quickly visualize the most homogeneous sampling intervals. Twin plugs should be taken in homogeneous intervals where relevant rock properties are uniform at 10 cm scale. Mapping rock properties at the centimeter scale reveals anomalous features at the plug scale (Vugs, fractures, weak spots), which should be avoided to lower plug failure rates during preparation cycles.

Empirical Relationships between Strength and Petrophysical Properties

The high resolution rock strength profile and the porosity wireline log are combined to map petrophysical properties onto the strength profiles. If such a suitable empirical relationship is found, a similar heterogeneity study can be conducted with the constructed high resolution porosity profile to identify suitable homogeneous sampling sites for petrophysical tests. Once the RMT and RCA results are received several months later, they can be checked against high resolution profiles derived as detailed above.

APPLICATIONS

Well 1

RCA results

In this study, the selection of RCA sampling sites had not been based on prior core-based quantitative high resolution information about the rock heterogeneity. A three-stage benign plug preparation and repeat measurement sequence was devised to capture as much porosity and permeability data as possible before potential plug fracturing, and to ensure quality-controlled RCA data for petrophysical evaluation. RCA sample numbers are summarized for Well 1 in Table 1. More than a third of tentative plug locations did not yield samples suitable for porosity and permeability measurements at the end of the preparation cycles. Most failures were related to hairline fractures. The depths of intact plug samples remaining at the end of each preparation cycle is shown in Figure 2. For Well 1, plug failure happened predominantly in a core interval between X550 and X650m, regardless of the rock porosity.

Scratch Test Results

Full core recovery was achieved in the first tested well over an interval of around 110.m. Samples were preserved as full diameter core sections of 1 meter in length, most of them in good conditions except a few sections that were highly fractured. They were composed essentially of sandstones and shales. The shifted profiles of high resolution the strength and ultrasonic P-wave velocity are shown in Figure 3 and Figure 4.Originally, no core-log depth shift was reported but a slight core shift of -0.3m (*i.e.* cores moved up 0.3m to match log depth) was deemed necessary to improve the match between the strength profile and the compressional sonic transit time (DTCO) wireline, as seen in Figure 3
The very good correspondence existing between the wireline DTCO log (travel time of a compressional elastic wave) and the core based ultrasonic profile proves the consistency of the ultrasonic core based measurements (Figure 4).

Plug Sampling Sites Recommendations for Geomechanics

Based on the heterogeneity mapping provided by the scratch campaign, seven plugs were taken for uniaxial compressive strength testing and three for thick wall cylinder analysis. In Figure 5, the UCS and TWC test results are mapped onto the strength profile from the scratch test. The positions of the dots showing the UCS and TWC test results suggest that the scratch test strength profile is an excellent candidate to upscale those rock properties. Attempting a direct correlation of plug measurements with wireline as in Figure 6 usually does not result in a robust calibration of the wireline because of the following reasons: the measurement errors inherent to any test run on cores but mostly the existence of local heterogeneities that are not seen by the wireline but that affect nonetheless the plug measurements. Once the link between the plugs measurements and the continuous high resolution strength and velocity profiles from the scratch test has been established, one can use the continuous scratch test data to establish a robust upscaling law with the wireline logs. In the context of Well 1 it was easy to identify sonic velocity calculated from the DTC sonic log as the best wireline candidate to upscale the strength. The clay content derived from the gamma ray was found to be a valuable term to include in a more accurate proxy. The proxies developed from plug testing (taking into account 30 plugs over more than 5 wells) and from continuous core data profiles are compared with the scratch strength profile in Figure 7. The proxy derived from the continuous scratch test is much more appropriate to capture the low strength intervals. In the Well-1, high resolution continuous profiles of rock properties from scratch testing produced robust correlations with the wireline porosity log (see Figure 7), and were used to map heterogeneity length-scales to guide the selection of representative sample sites for SCAL and rock mechanics test (RMT) plugs.

Well 2

RCA results

The RCA plug sites selection was based on a “one plug every foot” criterion without the a-priori knowledge of rock heterogeneity. A summary of the RCA tests is given in terms of sample numbers for Well-2 in Table 2. More than one third of tentative plug locations did not yield samples suitable for testing at the end of the preparation cycles. Most failures were related to the presence of hairline fractures. The depth of intact plug samples remaining at the end of each preparation cycle is given in Figure 8. For Well 2, plug failure happened predominantly above and below a core depth interval between X550 and X600m, regardless of the rock porosity.

Scratch Test Results

In Well-2 the Scratch test was staged after plugging and slabbing. Figure 9 compares the UCS and the scratch strength. Only three UCS are in the same depth range than the scratched sections; they correlate well with the scratch strength. All UCS plugs have been taken in the low and middle strength sections of the cores, where rock mechanical tests (RMT) run on plug samples yielded UCS values less than 50 MPa. The scratch test indicates large sections of cores have a strength larger than 50 MPa: 30% of the scratched sections has a strength above 45MPa. These results underline the difficulty of capturing the full range of rock properties with only a handful of samples. A rock strength proxy was derived successfully for this well (Figure 10), with an equation almost similar than the one found for Well-1, which underlines the coherence of strength predictors base on properly calibrated wireline logs in this reservoir.

Rebound Tests

Rebound tests (Equotip) has been run in parallel (15 rebounds per location). Two proxies were established to derive the UCS from Rebound Tests, however the factor two between the strength predictions from these two models underlines their lack of reliability.

Link Between Geomechanical And Petrophysical Properties

The high resolution porosity profile shown in Figure 11 was calculated from the correlation found between the Total Porosity wireline and scratch strength. As deduced from the very good agreement between RCA porosity and the high resolution porosity profile, the latter could have been used a priori for SCAL selection and checking the RCA to detect hairline fractures. For instance, a question could be raised about the validity of the RCA results in the first 5 m of the cored interval, since the porosity measured on plugs seems to overestimate the high resolution porosity profile. A similar high resolution porosity profile built from the Rebound Test Results would have been impaired by the considerably larger scatter in the cross-plot as seen in Figure 12b.

CONCLUSION

The sample site selection protocol based on the up-scaled scratch test data resulted in fewer plug failures on plug preparation. The RMT results were also found to be in excellent agreement with the scratch strength profile. By integrating the scratch test results with core porosity and wireline logs, a centimeter-scale profile of estimated porosity was derived. The continuous rock property profiles created with the scratch test could be used to systematically check both RCA and RMT plug results. Robust multivariate relationships established between the rock strength profile and selected wireline logs enabled reliable upscaling of plug rock properties to predict rock strength in non-cored intervals and wells. In comparison, rebound strength index tests run over the same core scratch interval produced limited and potentially misleading strength data. The core testing technologies described in this paper are integrated in one compact and portable test bench enabling extensive sets of high quality rock property data to be obtained on fresh cores within a few days and before plugging. Plug sampling in thin bedded heterogeneous formations can be a haphazard process leading to understandable bias in sample selection. The heterogeneity assessment protocols from the scratch tests enable more representative plug site selection and more robust core property-log calibration at different length scales. This significant uncertainty reduction in petrophysical and geomechanics models leads to better decision making in well design and field management.

ACKNOWLEDGEMENTS

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[1] C. Germay, T. Richard, C. Lindsay and H. T. Woo, "SPE-174086-PA The Continuous Scratch Profile: A High Resolution Strength Log for Geo-Mechanical and Petro-Physical Characterization of Rocks," *SPE Reservoir Evaluation & Engineering-*

Formation Evaluation, publication pending.

[2] T. Richard, F. Dagrain, E. Poyol and E. Detournay, "Rock Strength determination from scratch tests," *Engineering Geology,* pp. 91-100, 2012.

Table 1: Summary of plug numbers in RCA programs for Well 1

	Well1					
Total	236					
	Intact	Vuggy	Failed	Fracture	NPP	Intact to total ratio
Cycle1 (Toluene)	139	97				59%
Cycle2 (Humidity Drying)	104	132				44%
Cycle3 (Hot Drying	101	135				43%

Table 2: Summary of plug numbers in RCA programs for Well 2

	Well2					
Total	425					
	Intact	Vuggy	Failed	Fracture	NPP	Intact to total ratio
Cycle1 (Toluene)	365	60				86%
Cycle2 (Humidity Drying)	281	144				66%
Cycle3 (Hot Drying	277	148				65%

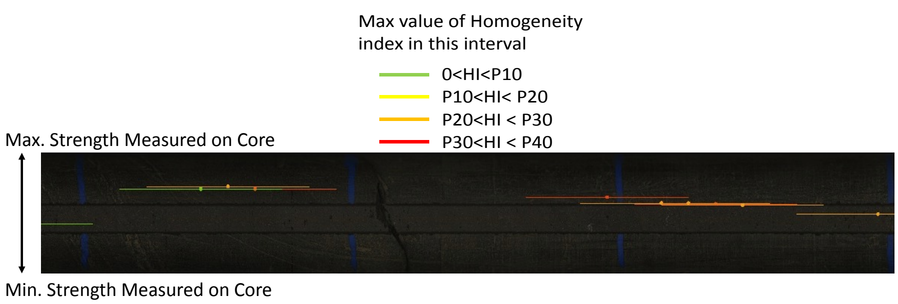

Figure 1: Visualization of recommended sampling sites

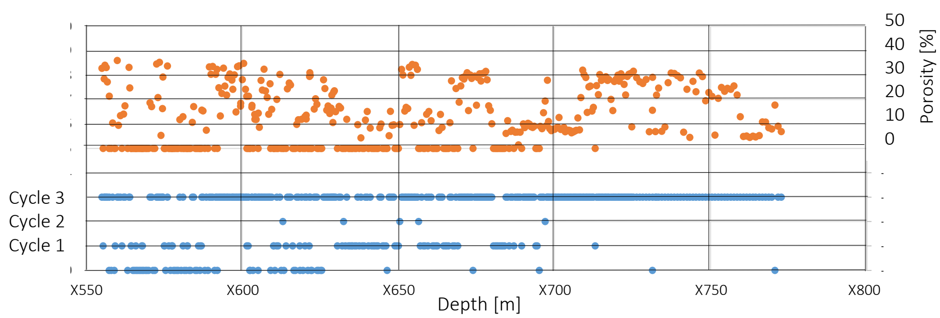

Figure 2: Depth and porosity of intact plugs at the end of each preparation cycle (as defined in Tables 1 and 2), Well 1. Blue dots on the horizontal axis for plugs failing ahead of cycle 1.

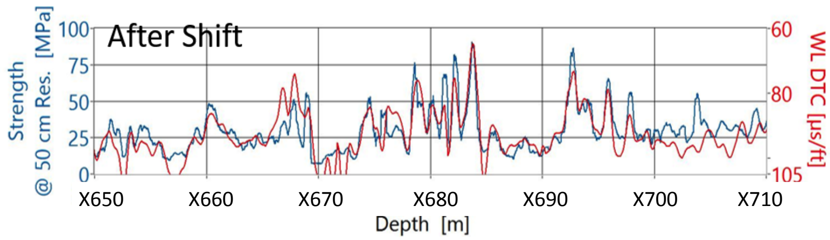

Figure 3: High resolution strength profile plotted against the sonic wireline log.

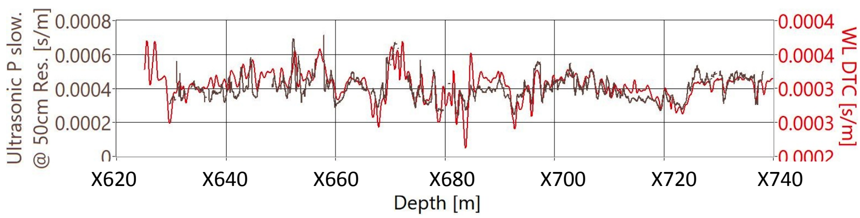

Figure 4: Ultrasonic P-wave Slowness plotted against the sonic wireline log.

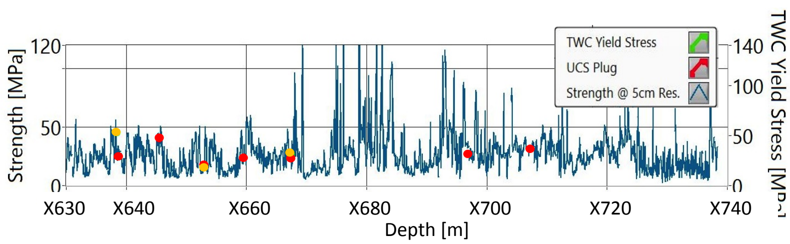

Figure 5: Chart exhibiting the excellent agreement between the scratch test and the plug UCS and TWC.

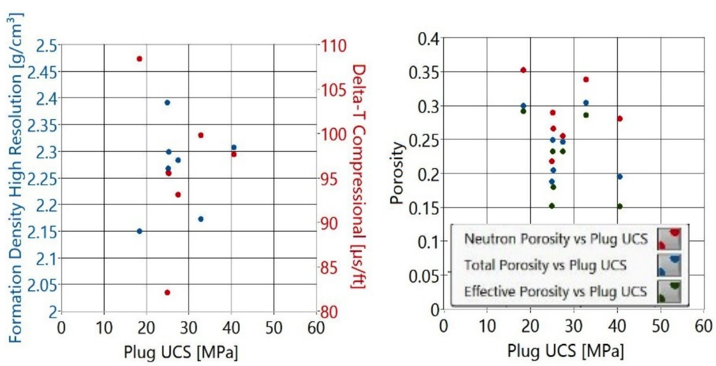

Figure 6: Direct correlation of plugs RMT *vs* wireline logs

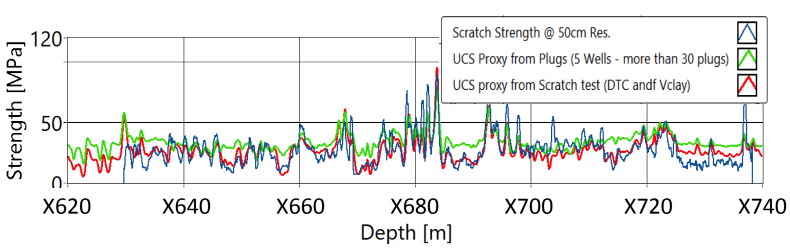

Figure 7: Comparison of strength proxies for Well-1

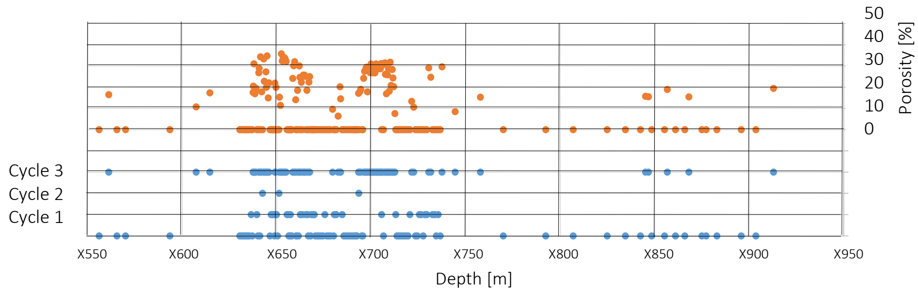

Figure 8: Depth and porosity of intact plugs for each preparation cycle (as defined in Tables 1 and 2), Well-2. Blue dots on the horizontal axis for plugs failing ahead of cycle 1.

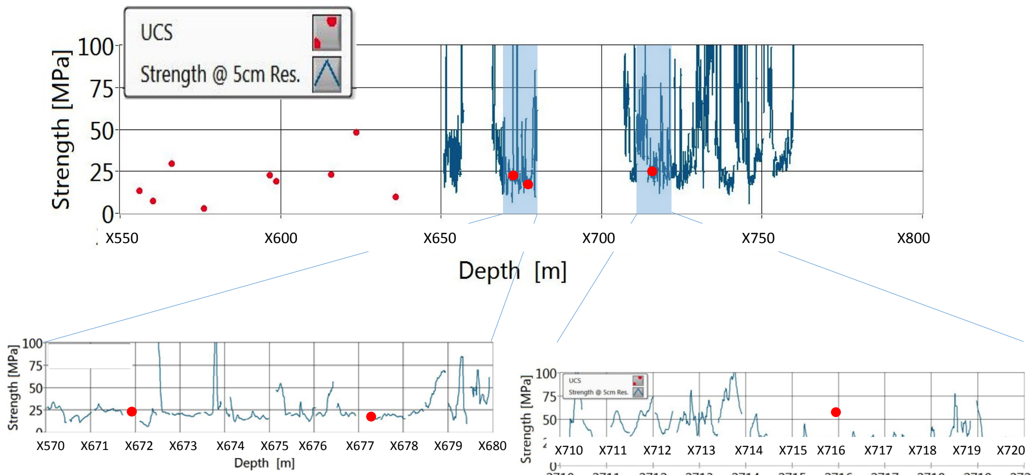

Figure 9: Comparison between Scratch Strength and UCS from plug tests, Well-2

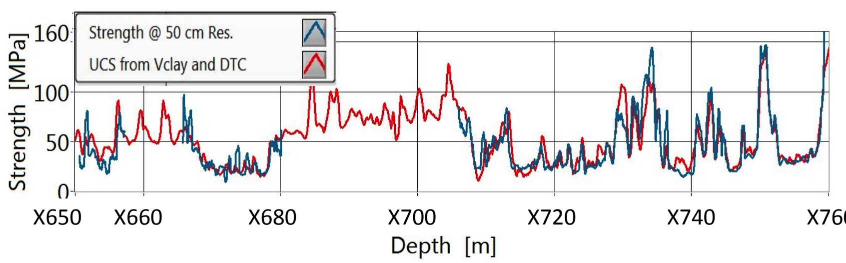

Figure 10: Strength proxy from wireline logs for Well-2.

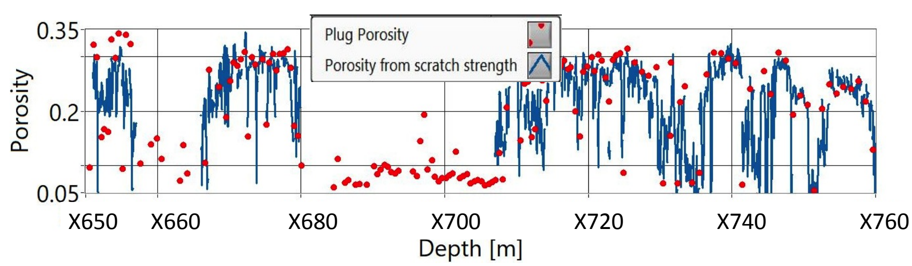

Figure 11: Comparison between RCA porosity and high resolution porosity profile.

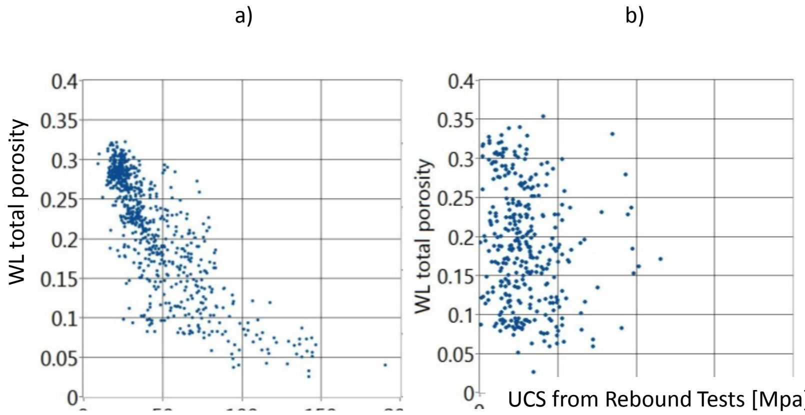

Figure 12: Wireline total porosity *vs* UCS derived from a) Scratch test b) Rebound tests