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Use of Schmidt Hammer for Strength Heterogeneity Characterization, and a Way to Overcome the Lack of Mechanical Data

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ABSTRACT

Preliminary feasibility assessments for Eavor-Loop™ projects are often challenged by limited subsurface data, particularly when targeting deep formations without existing research or offset wells. From a geomechanical perspective, developing a preliminary wellbore stability model is highly sensitive to uncertainties in rock properties, with unconfined compressive strength (UCS) being a key parameter. The high cost of laboratory testing further complicates efforts to capture rock heterogeneity and assess wellbore stability. To address this, Eavor has implemented extensive Schmidt Hammer testing on outcrops of target formations, using a limited number of core plugs for UCS testing to calibrate rebound values. This approach enables the creation of comprehensive UCS datasets, offering insight into spatial variability and heterogeneity of rock strength including in basement rocks, critical to deviated Eavor-Loop™ designs but rarely characterized in literature. By refining UCS estimates and capturing heterogeneity, this method reduces uncertainty, improves early-stage geomechanical modelling, and provides a practical solution to the lack of subsurface mechanical data in unexplored locations.

1 INTRODUCTION

An Eavor-Loop™ is a multilateral closed-loop geothermal system constituted by two parallel multilateral wells intersected at the toe of each leg, therefore creating a closed, radiator-like system. One of the most critical sections of an Eavor-Loop™ is the multilateral section; each one of the legs will be left open hole, so heat can be extracted directly from the rock into the working fluid via conduction. Depending on the Eavor-Loop™ design, the open-hole, multilateral section will be either horizontal or deviated. Given the considerable length of the laterals, even if they are drilled within the same formation, variations in the rock mechanical properties of the rock mass being drilled through should be expected. As well, when the Eavor-Loop™ targets deep formations, these are usually unexplored, lacking any type of offset well data. These aspects represent a challenge when trying to characterize the rock mechanical properties to be used as inputs to create a geomechanical model. Developing a preliminary wellbore stability model is highly sensitive to uncertainties in rock properties, with unconfined compressive strength (UCS) being a key parameter. To overcome these challenges during preliminary feasibility assessments, outcrop sampling and testing campaigns can help to establish and narrow down uncertainty ranges for each one of the required rock mechanical properties.

Uniaxial and triaxial compression tests are two common ways to measure the UCS of a rock. Uniaxial tests directly measure UCS by applying only an axial load to the sample until reaching its peak strength. On the other hand, triaxial tests apply both axial and confining pressures, therefore providing the rock's peak strength at specific confining pressures. By using multiple peak strength values at different confining pressures, a Mohr-Coulomb failure envelope can be created, which can be used to indirectly calculate the UCS. Although an unconfined state of stress is not representative of the subsurface, the existence of a wellbore will disturb the stress state near the borehole. In this case, UCS can be helpful to describe the strength of the rock material conforming the wellbore wall, and the potential for breakouts.

One of the advantages of uniaxial compression tests, as compared to triaxial tests, is the cost. As well, uniaxial compression tests are more time efficient due to having a less complex setup and testing procedure. However, triaxial tests can provide more reliable results and a lower premature failure rate due to the application of confining pressure, resulting in a reduced influence of internal unconformities. Although these tests effectively provide strength characterization, their applicability in testing campaigns can be considerably constrained by factors such as budget and material availability, reducing the number of specimens tested. This leads to selecting limited samples, representing a minority of the rock mass of interest, and therefore introducing significant uncertainty and limiting the ability to characterize spatial variability and strength heterogeneity.

The Schmidt hammer is a tool which helps to characterize hardness, based on the measurement of energy loss of a body which impacts (and consequently rebounds) the material to be tested. Originally created for concrete hardness measurement, the Schmidt hammer has been adopted for rock testing due to its versatility, applicability and relative non-destructive nature. The research community has focused on studying the potential of this tool for rock strength characterization, resulting in empirical correlations being derived to correlate the hardness derived from Schmidt hammer rebound measurements (SHR) with unconfined compressive strength (UCS). This has made this tool a useful and easy option to obtain estimations of UCS in the field directly from outcrop rocks, or in the laboratory on extracted block or core specimens. This method can overcome challenges such as limited mechanical testing due to budget, material availability, or local restrictions on rock collection. This has facilitated the characterization of the strength of formations of interest or strength heterogeneity within a specific formation.

Eavor has adopted this technique during early-stage field exploration by conducting extensive Schmidt Hammer testing on outcrops of the target formations (Figure 1). A limited number of core plugs are then extracted and tested for UCS, which enables the calibration of UCS predictions derived from Schmidt Hammer rebound values and the development of comprehensive UCS datasets. To do this, correlation equations (UCS - SHR) have been derived internally at Eavor, using various UCS - SHR datasets from public research articles. This method not only facilitates preliminary UCS estimation but also provides insight into the spatial variability and heterogeneity of rock strength throughout a formation. Additionally, it supports the study of the mechanical properties of basement rocks, which are critical targets in deviated Eavor-Loop™ designs, yet rarely characterized in existing literature.



Figure 1: Examples of Schmidt Hammer implementation for field characterization of rock strength.

Although guidelines and best practices for Schmidt Hammer use are beyond the scope of this paper, Eavor recognizes the impact of user error and sample surface conditions on the accuracy of SHR measurements. Therefore, efforts are focused on ensuring consistency in the applied measurement techniques and continuously improving them (while adhering to existing guidelines), along with the refinement of selected outcrop suitability. All of this is to minimize the impact of user and sample implications in the SHR measurements, therefore achieving the highest possible reliability and accuracy.

Below, Section 2 will describe the process followed to derive the UCS - SHR correlation equations used at Eavor. Then, Section 3 will provide UCS and SHR measurements taken as part of different projects, along with the respective SHR-based UCS predictions. Section 4 will assess two cases of study to verify the validity of the SHR-based predictions, followed by the application of the approach presented in this paper to assess strength heterogeneity.

2 EQUATION DEVELOPMENT

The correlation between Schmidt hammer hardness or rebound measurements and unconfined compressive strength has been widely studied in the literature, targeting various lithologies from different regions in the world. Although some of these correlations achieve reasonable levels of confidence, usually their accuracy will be limited to the region or lithology of the rocks used as calibration points. In efforts to obtain equations which could provide a reasonable UCS estimate for any rock sample, several equations from the literature with high coefficient of determination (R^2) were analysed. The objective of this was to find an equation format and parameter range which could be used for generalized rock types.

Once these two factors had been determined, two comprehensive UCS - SHR datasets from the public domain (Demirdag et al., 2018; Karaman & Kesimal, 2015; 106 datapoints in total) including all rock types (i.e. sedimentary, igneous and metamorphic) were used to calibrate the equation parameters and therefore find the correlations with the lowest error between measured and predicted UCS values (Figure 2 and Figure 3).

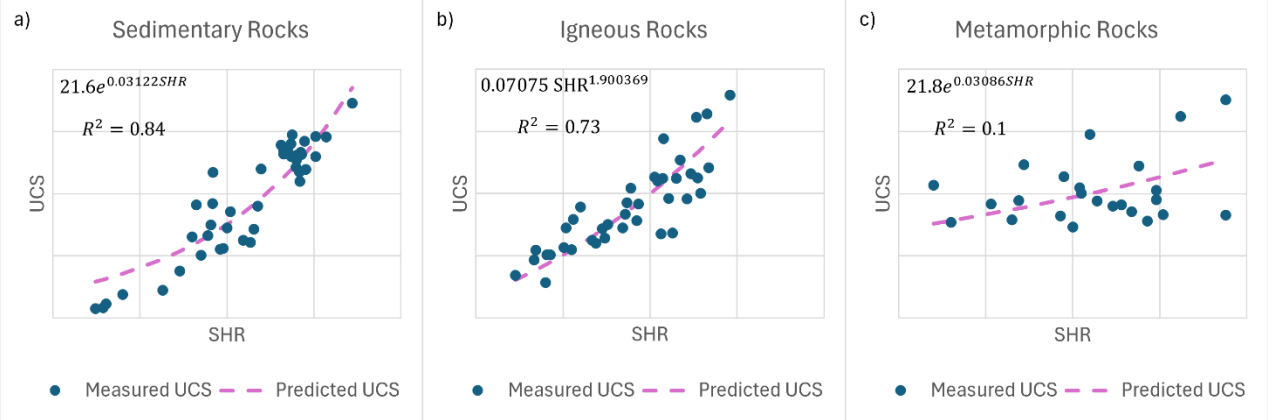


Figure 2: Resulting UCS - SHR correlations for a) sedimentary, b) igneous and c) metamorphic rocks. The measured UCS values come from the literature datasets mentioned before.

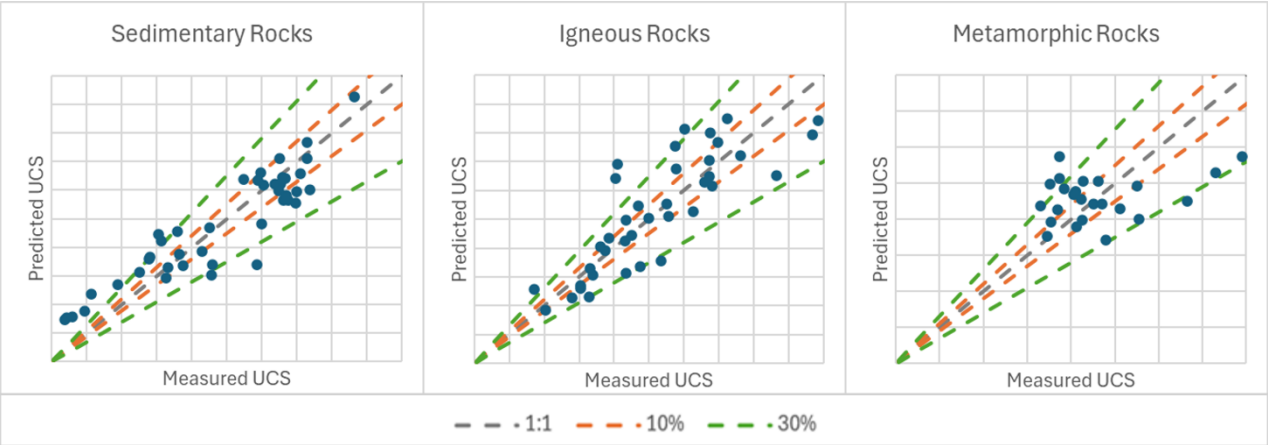


Figure 3: Comparison between measured and predicted UCS values, using the data from the calibration datasets. The percentages, represented by the colored dotted lines, show the error ranges for the predicted values.

3 PROJECT DATA

As mentioned before, Eavor has implemented the collection of Schmidt hammer measurements directly on outcrop rock representative of the target formation, along with sampling and testing of core samples for compressive strength. This practice has been used for both early- and advanced-stage projects, with major focus on the former where project-specific data tends to be scarcer.

In this section, data collected from some of Eavor's projects including Schmidt hammer rebound measurements, UCS from compressive strength tests, and UCS values derived with the equations shown in Section 2 will be presented and further discussed.

Four projects where both Schmidt hammer and UCS data (either from uniaxial or triaxial compression tests) were collected were selected for the purpose of this comparison. The samples used in these projects include sedimentary, igneous and metamorphic rocks (Table 1).

Table 1: SHR and UCS data from the four projects selected for this analysis.

Project	Sample	Rock Type	SHR	UCS (MPa)
A	A1	Metamorphic	62.50	124.43
	A2	Metamorphic	54.30	104.29
	A3	Metamorphic	66.00	238.15
	A4	Metamorphic	64.30	188.20
	A5	Igneous	67.50	200.16
	A6	Metamorphic	70.50	141.94
	A7	Sedimentary	71.50	236.38
	A8	Metamorphic	71.12	173.84
	A9	Metamorphic	65.80	103.56
	A10	Sedimentary	74.50	236.38
	A11	Metamorphic	62.00	204.97
	A12	Metamorphic	73.80	173.84
B	B1	Igneous	71.70	294.14
	B2	Igneous	67.25	166.93
	B3	Metamorphic	62.80	106.36
	B4	Igneous	69.50	157.17
	B5	Igneous	75.65	237.46
	B6	Igneous	72.30	157.67
	B7	Igneous	76.80	262.01
	B8	Metamorphic	78.40	213.93
C	C1	Sedimentary	67.50	141.29
	C2	Sedimentary	52.80	98.95
	C3	Sedimentary	67.70	103.84
D	D1	Sedimentary	58.22	52.00
	D2	Sedimentary	65.58	143.00
	D3	Sedimentary	66.33	323.00
	D4	Sedimentary	55.11	122.00

Using the SHR values from Table 1 and the equations presented in Figure 2, UCS predictions were calculated and then compared with the respective UCS values measured through compressive strength tests (Figure 4).

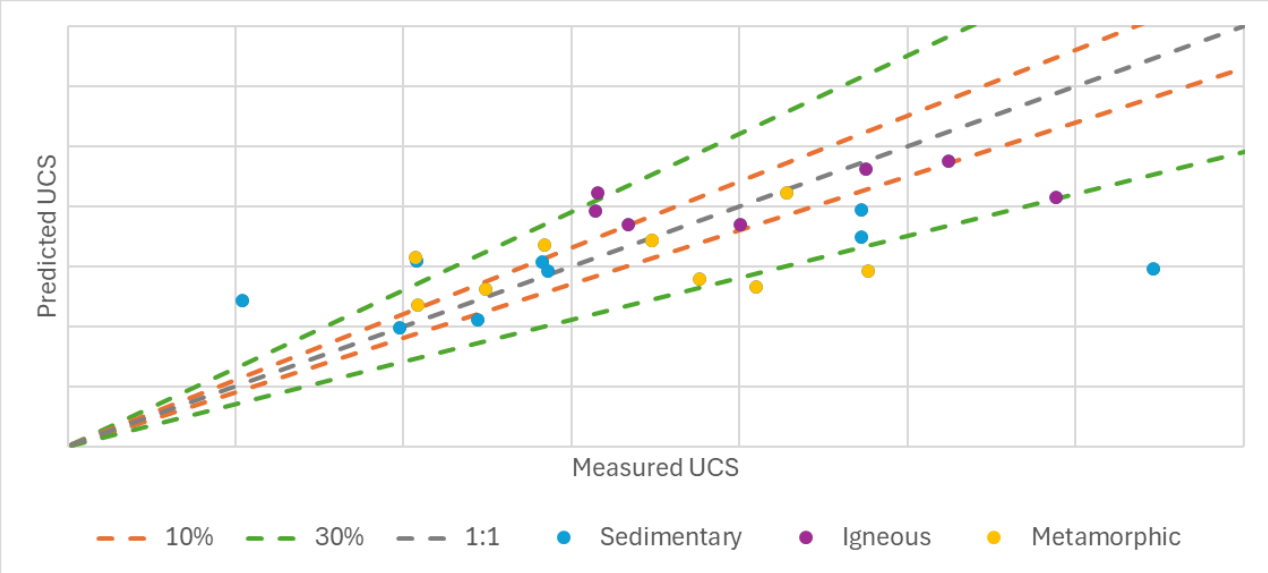


Figure 4: Comparison between measured and predicted UCS values, using the data from the four selected projects. The percentages, represented by the colored dotted lines, show the error ranges for the predicted values.

The average error from the UCS predictions on sedimentary samples is 34%. For the case of igneous samples, the average error is 17%, and for metamorphic samples it is 19%. Table 2 below shows the error distribution in the predictions for each rock type.

Table 2: Error distribution in the predictions for each rock type from the projects used in this report.

	Percentage of Samples		
Error	Sedimentary	Igneous	Metamorphic
<10%	33%	43%	40%
10-30%	33%	43%	30%
>30%	33%	14%	30%

4 VERIFICATION

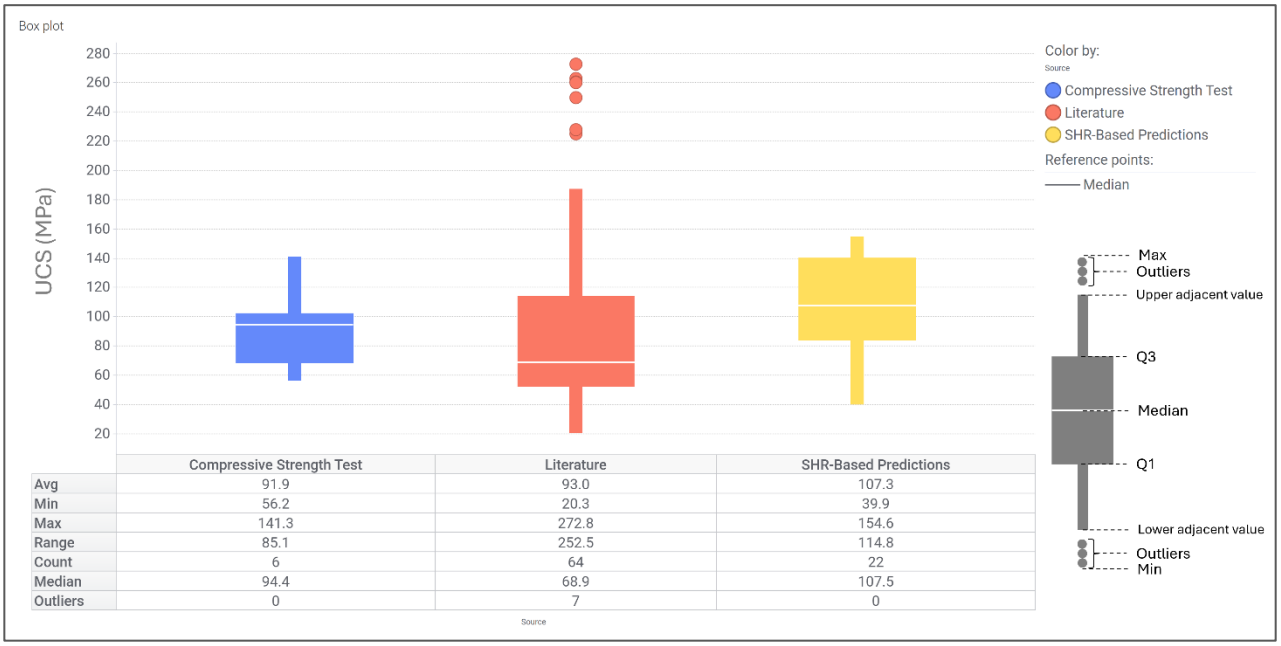
4.1 Case Study: Strength Prediction in Data Scarce Projects

In terms of wellbore stability modeling, we recognize that these differences between the predicted and 'in-situ' UCS will have significant impacts on the analysis. However, as mentioned at the beginning of this paper, the focus here is on trying to characterize rock strength, and to reduce uncertainty in early-stage exploration projects where rock strength data is either scarce or non-existent.

Usually, for this type of project where no reference data is available, rock property ranges are established based on values reported in the literature for rock analogues, which can introduce considerable uncertainty in preliminary wellbore stability analysis. The approach discussed in this paper could help reduce this uncertainty and therefore improve the reliability of early-stage geomechanical modelling, compared with using rock strength ranges extracted from the literature. To analyse this potential improvement, Project C (Table 1) will be used as an example to compare the UCS values measured through mechanical compressive strength tests, SHR-based UCS predictions using the equations presented in Figure 2, and a UCS range based on results from research articles on rock analogues.

Project C involved the design of a potential future Eavor-Loop™, where the lithology of the target formation (i.e. where the open-hole, multilateral section would be hosted) was characterized as a Triassic aged limestone. As part of the early-stage exploration, a testing campaign was conducted using outcrop samples collected from a

quarry where the available material was concluded to be representative of the target formation. As part of this testing campaign, 22 sets of SHR measurements were taken on outcrop rocks. From the same location where some of the SHR measurements were taken, 3 hand samples were collected for further core extraction and compressive strength testing. Table 3 and Figure 5 below show the UCS range obtained from compressive strength tests performed on specimens extracted from the mentioned hand samples, the range of UCS predictions based on the 22 SHR measurements, and a range based on UCS values found in some research articles (Attewell & Farmer, 1976; Cheshomi & Sheshde, 2013; Li et al., 2021; Nazir et al., 2013; Swamy et al., 2025) focused on limestone samples. As well, this table shows the increase in the uncertainty range of the SHR-based and literature-derived UCS ranges with respect to the range obtained from laboratory tests.



	Compressive Strength Test	Literature	SHR-Based Predictions
Avg	91.9	93.0	107.3
Min	56.2	20.3	39.9
Max	141.3	272.8	154.6
Range	85.1	252.5	114.8
Count	6	64	22
Median	94.4	68.9	107.5
Outliers	0	7	0

Figure 5: Comparison between the UCS ranges for Project C, including UCS values obtained from compressive strength tests, SHR-based predictions, and the literature.

Table 3: Comparison between measured and predicted UCS ranges for Project C. The uncertainty range is defined as the maximum value minus the minimum value from each UCS range, and the increase in uncertainty range is defined as the range increase (%) with respect to the uncertainty range derived from compressive strength tests.

Source	Minimum UCS (MPa)	Maximum UCS (MPa)	UCS Range (MPa)	Increase in Uncertainty Range
Compressive Strength Tests	56	141	85	-
SHR-based predictions	39	154	115	35%
Literature	20	272	252	196%

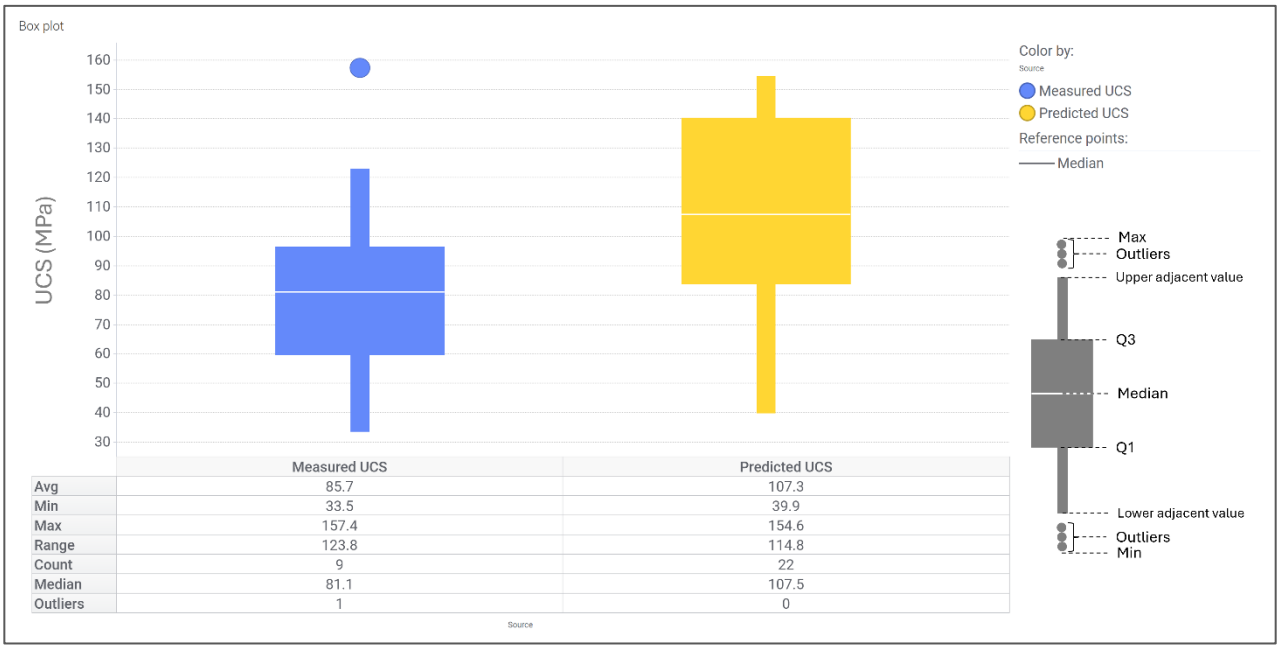
We can observe in Table 3 and Figure 5 that there is a significant difference in the uncertainty range when comparing the UCS range obtained from research articles, and the range obtained from SHR-based predictions. Using the UCS range derived from compressive strength tests as a reference, for this project, there is a reduction of 161% in the uncertainty range when using SHR-based predictions compared with using the range extracted from research articles.

4.2 Case Study: Characterizing Strength Range

As mentioned at the beginning of this paper, another objective of implementing the Schmidt Hammer in the field is the characterization of strength heterogeneity within a specific formation.

Given that the open-hole section of the Eavor-Loop™ consists of several laterals of considerable length, it is expected that the wellbore will encounter variability in the mechanical properties of the formation of interest throughout the trajectory of the well. However, laboratory testing is usually limited to a few rock samples, which are unlikely to represent the full range of uncertainty expected. The versatility of the Schmidt Hammer makes it possible to take several measurements at multiple locations within an outcrop in a matter of minutes, therefore enabling the creation of a comprehensive SHR database that captures the spatial variation of rock hardness within a specific formation, which can later be transformed into UCS.

A second testing campaign was performed in Project C, which focused on characterizing strength heterogeneity within the target formation. Several specimens were extracted at different depths (within the same formation) from a core collected in an offset well. This data was then compared with the range predicted from the SHR measurements taken in the first campaign, with the objective of assessing the ability to capture the strength heterogeneity observed in laboratory results from collected core using SHR-based UCS predictions obtained in the field (Figure 6).



	Measured UCS	Predicted UCS
Avg	85.7	107.3
Min	33.5	39.9
Max	157.4	154.6
Range	123.8	114.8
Count	9	22
Median	81.1	107.5
Outliers	1	0

Figure 6: Comparison between the UCS range measured with compressive strength tests performed on core specimens (second campaign), and the range predicted from SHR measurements taken in the field.

It can be observed that although the core sample and the SHR measurements did not originate from the same location or rock mass, the SHR-based UCS range closely reflects the strength heterogeneity observed in the compressive strength test results from the offset well core sample. The SHR-based predictions tend to estimate higher UCS values, resulting in a higher mean compared to the laboratory results. However, the predicted minimum and maximum values are notably close to those measured, therefore providing a very similar range.

5 APPLICATION TO STRENGTH HETEROGENEITY CHARACTERIZATION

As mentioned before, the first sampling and testing campaign in Project C targeted a quarry, where outcrop samples were collected for further compressive strength testing, and 22 SHR measurements were taken at different locations and depths where the target formation was exposed.

Previous sections focused on verifying the expected accuracy of the SHR-based UCS predictions, comparing them to strength ranges derived from analogues in the literature, and comparing predicted strength ranges from outcrop samples with actual laboratory-measured strength from offset well cores. Now, this section will focus on putting into practice the correlations shown in this paper to describe the expected heterogeneity within the target formation. Figure 7 and Figure 8 below show different SHR measurement points at two locations in the quarry, selected to calculate their respective SHR-based UCS predictions, and to characterize vertical and horizontal strength heterogeneity,

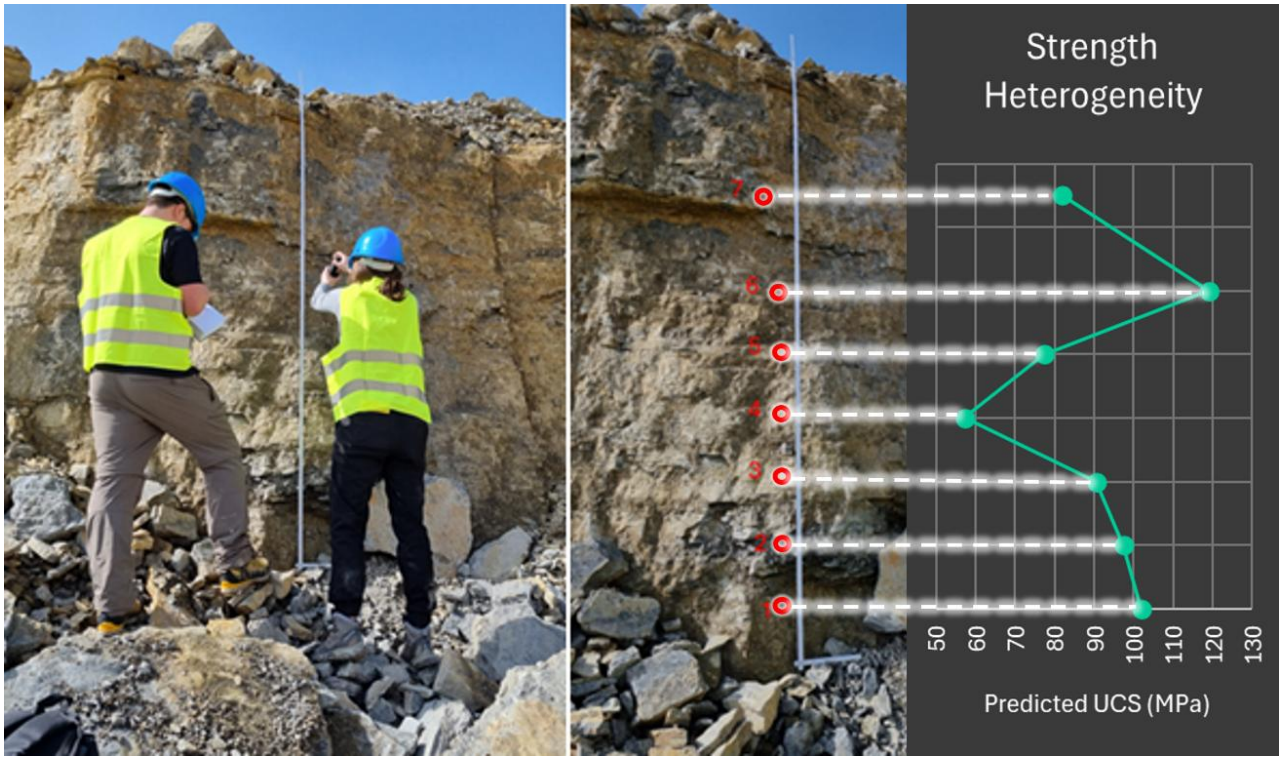


Figure 7: Use of Schmidt Hammer to characterize strength heterogeneity at Location 1. The picture in the middle shows the locations where SHR measurements were taken, representing different depths of the target formation. The plot on the right shows the respective UCS predictions.

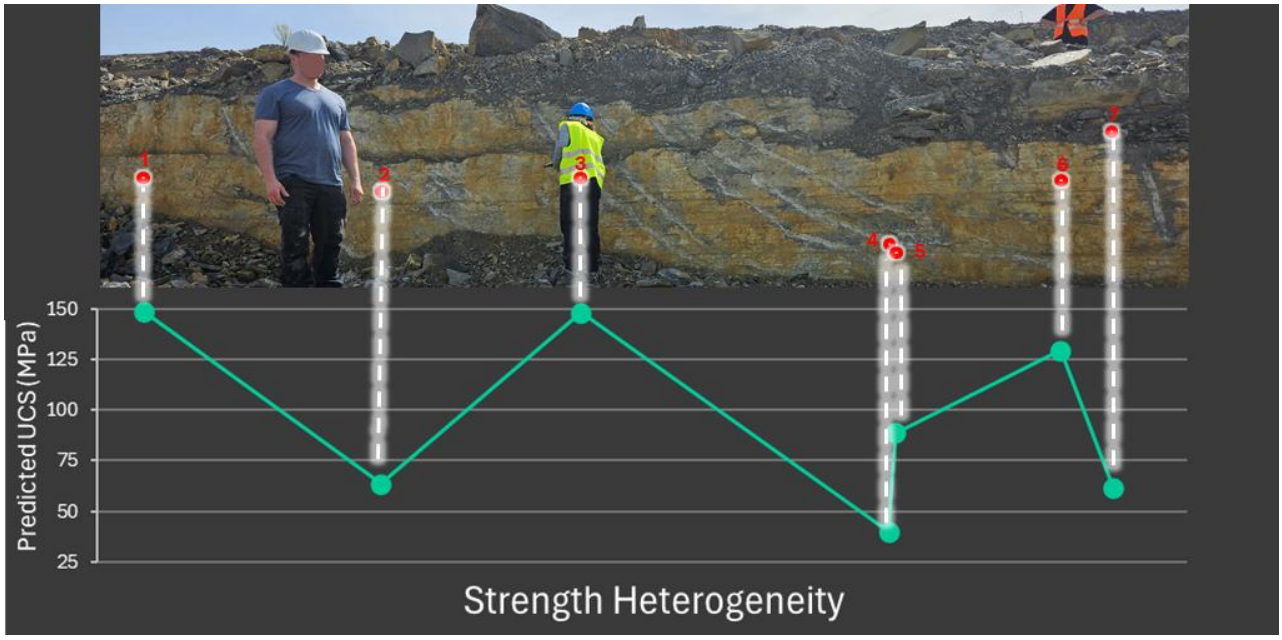


Figure 8: Use of Schmidt Hammer to characterize strength heterogeneity at Location 2. The picture shows the locations where SHR measurements were taken, representing mainly horizontal variability within the target formation. The plot shows the respective UCS predictions.

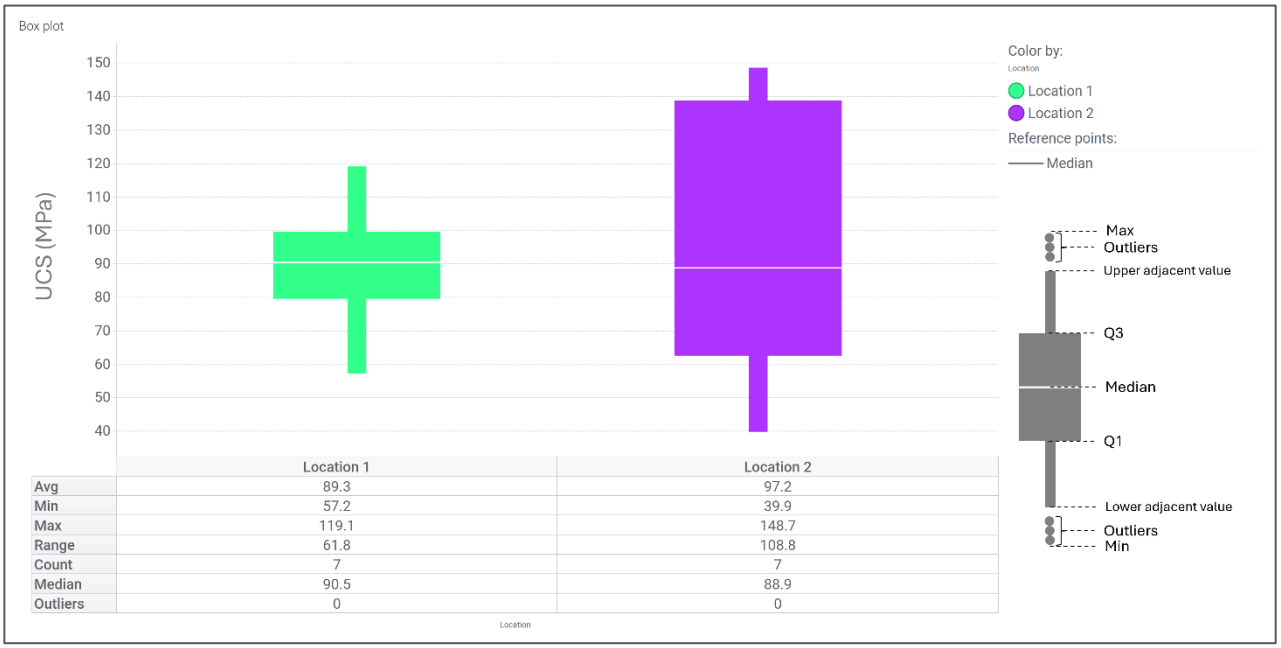


Figure 9: SHR-based UCS predictions from Location 1 and 2, describing vertical and horizontal variability, respectively.

We can observe that strength heterogeneity should be expected both vertically and horizontally in the target formation. According to the SHR-based predictions, both locations exhibit a similar UCS average. However, in Location 2, where the focus was horizontal variability, we can observe a wider UCS range than in Location 1, where the focus was vertical variability. These learnings can be further used to, for example, be able to build strength ranges specifically for the upper or lower multilateral sections, using the observed vertical variability. On the other hand, the expected strength variability for each one of the laterals throughout their total length can also be characterized by the observed horizontal variability.

Although, as shown in Section 3, we should expect some error in the predicted UCS values, horizontal and vertical strength variability have been effectively captured with this approach. These ranges will be helpful to build the rock strength range to be used as input in wellbore stability modeling and therefore build more reliable preliminary models.

6 CONCLUSIONS

Schmidt Hammer rebound measurements combined with SHR-UCS correlation equations offer a practical and cost-effective alternative for the estimation of rock strength in early-stage field exploration. By using this approach, Eavor has successfully generated comprehensive UCS datasets that capture spatial variability and heterogeneity, and that are able to characterize rock strength even in data-scarce locations and unexplored formations.

Although the predictions resulting from this method present some error compared with laboratory-derived values, this approach significantly reduces uncertainty compared to relying solely on analogues from the literature. The case study from Project C illustrates that UCS ranges derived from SHR measurements are notably closer to the range obtained from compressive strength tests than those extracted from research articles, narrowing the uncertainty range by over 160%. As well, it was observed that the SHR-based UCS predictions were able to capture the strength range observed in the laboratory test results. Furthermore, this approach has been able to effectively characterize vertical and horizontal strength heterogeneity within the target formation.

Ultimately, the use of this approach in early-stage geomechanical workflows enhances the reliability of preliminary models, supports informed decision-making, and provides a scalable solution for characterizing rock strength and overcoming laboratory testing limitations due to factors such as budget and material availability.

7 FUTURE WORK

At this stage, the validity and applicability of the presented equations and workflow have been verified against real project data, corroborating the benefits of this approach. Next steps will focus on creating project-specific equations, where the data used to build the correlations will come from specific project locations and lithologies; the accuracy of these new equations will then be compared with the ones presented in this paper. For this it will be required to ensure that in the sampling campaigns, the number and type of samples are adequate for the development of UCS - SHR correlations.

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