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Utilising Equotip Leeb hardness testing for rock strength estimation and geotechnical domain definition

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Abstract

Rock strength estimation plays a fundamental role in geotechnical engineering and mining. Incorporating additional sources of data to reduce uncertainty in estimates will therefore lead to improved confidence in site characterisation and subsequent design. Equotip Leeb hardness testing has emerged as a widely accepted technique for estimating the hardness of rocks. Its practicability, non-destructive nature, and repeatability make it an excellent tool to obtain strength information which complements other tests such as point load tests (PLT), laboratory strength tests, and field hardness estimates. This study presents a methodology used to process Equotip Leeb hardness measurements and a methodology to evaluate how these results can be used to identify trends and patterns within the rock mass, helping define geotechnical domains.

This paper outlines the approach used for the analysis of Leeb hardness measurements collected on core samples. The authors will discuss the data collection process and pre-processing techniques, as well as the statistical analysis used to establish correlation factors between the Leeb hardness measurements, PLT, and uniaxial compressive strength (UCS) results. The paper will present the findings from this analysis and discuss how the results were utilised to inform the geotechnical domains.

Lastly, the authors will discuss the potential for use of Equotip datasets in other applications, such as resource estimation or identification of weak zones where additional ground support would be required. This source of additional data can provide valuable insight into the overall understanding of a site's geological characteristics within the mining area and assist with design refinement prior to construction phases.

Keywords: *Leeb hardness, Equotip, intact strength, UCS, characterisation, domaining*

1 Introduction

Accurate estimation of rock strength remains a challenge in geotechnical engineering and mining. Laboratory tests on core specimens, such as uniaxial compressive strength (UCS) and triaxial compressive strength tests combined with direct tensile strength estimates are the most accurate way to determine the strength properties of the rock; however, those tests are expensive and subject to bias in the sample collection as it is difficult to sample weak core specimens. The use of point load tests (PLT) is a good additional source of information. While a larger quantity of data can be collected with PLT, this technique is also subject to sampling bias and results are largely influenced by the operators of the loading apparatus. Lastly, field strength estimated with a rock hammer during geotechnical core logging (Brown 1981) is a very simple qualitative test that can provide a large amount of information; however, the strength estimates heavily rely on the user’s expertise and judgment. PLT, UCS, and field strength estimates samples all have a minimum sample size; usually at least 10–15 cm length of intact core. This sample size requirement inherently biases sample selection towards stronger rock and rock that is less defected (veins, bedding, etc.).

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Using non-destructive testing methods such as the Equotip Leeb hardness can provide insight into rock strength without requiring core samples and give measurements that remain unaffected by user bias.

Although the Equotip probe offers practical, non-destructive, and repeatability, the Equotip Leeb hardness measurements (HLS) should be supplemented with the tests, outlined previously, to establish correlation factors and associate the HLS to a known industry measure of intact strength. As listed in Corkum et al. (2017), several authors have developed and published correlations between HLS and UCS. Corkum et al. (2017) and Nasir & Powell (2023) also investigated how various factor such as the effect of inclination of the probe, the moisture conditions of the core (wet or dry), the core diameter, the number of impacts readings, the support of the core (plastic or steel) and the rock types can influence HLS. Both studies indicated stronger correlations when the measurements were processed by rock unit. Bruning et al. (2022) used core logging data collected at Northparkes mine to understand the spatial distribution of weak rocks and structures which aligns with the work presented in this paper, where an assessment of the statistical distributions of all Equotip data assisted with the development of geotechnical domains.

This paper presents a case study where HLS were collected on core during a geotechnical drilling program and discusses how these measurements were subsequently correlated with the UCS and PLT results collected from specimens on the same core. The paper also presents how the results were used to support the definition of geotechnical domains.

2 Project overview

The current project consists of a geotechnical drilling investigation followed by geotechnical characterisation for the design of a portal and decline for underground access. The rock mass of focus consists of sedimentary lithologies that comprises predominantly chert and graphitic, calcareous, and silicified shales along with sandstone, mudstone, and conglomerates forming distinct geological formations (i.e. groups of lithologies with distinct characteristics, typically grouped by deposition time). Geological features include pronounced foliation, cleavage, and bedding within the shale units, with a dominant trend of folding and thrust faults, as well as extensional faults.

The underground development will be excavated within three formations, Unit A, Unit B and Unit C. The percentage of each formations expected to be intersected by the development is presented in Table 1**Error! Reference source not found.**.

Table 1 Percentage of decline intersected by formation

Formation	% along decline alignment
Unit A	63
Unit B	35
Unit C	3

The logging data collected in boreholes were used to understand the lithology distributions within each of the formations near the intersection with the decline. The review indicated that Unit A is expected to comprise mainly of undifferentiated shale, Unit B to contain siliceous shale and undifferentiated shale, and Unit C to predominantly feature chert and undifferentiated shale. Although not directly intersected by the chosen development, sandstone and mudstone lithologies are also present within the project site. Examples of core photographs of the different lithologies are shown in Figure 1.

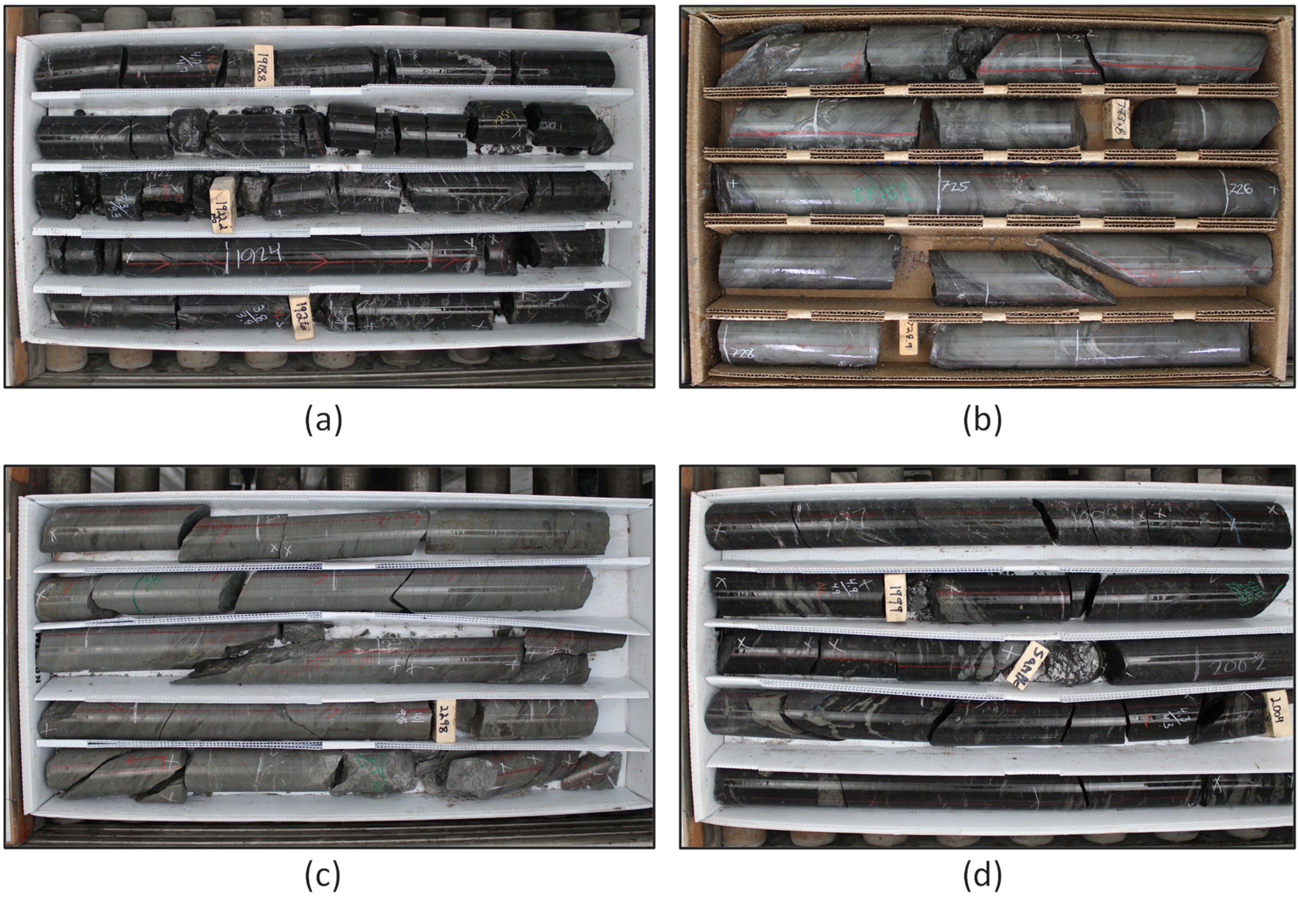


Figure 1 Core photograph examples of lithologies: (a) Chert; (b) Siliceous shale; (c) Indifferentiated shale; (d) Mudstone

3 Data collection

The Equotip 550 Type S was used to test the Leeb impact hardness of the surface of the rock core recovered from the geotechnical drilling program. The Equotip hardness tester employs a concept first demonstrated in 1948 in the Schmidt hammer (Schmidt 1951). The device measures the impact and rebound velocity of an impact tip against the rock surface. This allows non-destructive testwork to be conducted. The Leeb hardness is then calculated using Equation 1 presented by Proceq SA (2016):

$$\mathrm{HLS} = (\mathrm{V_r}/\mathrm{V_i}) \times 1{,}000 \tag{1}$$

where:

HLS = Leeb hardness

V_i = impact velocity

V_r = rebound velocity.

The Equotip apparatus is a battery-operated, spring-loaded impact device. It comprises a 3 mm diameter spherical tungsten carbide test tip that is spring mounted in an impact body (Figure 2). During a hardness test, the tungsten carbide test tip impacts under spring force against the test surface and then rebounds. The measurement is obtained by a permanent magnet built into the impact body which passes through a wire coil. During movement of the magnet through the coil, an electrical voltage is generated that is proportional to the velocity of the impact tip. The Equotip 550 includes a touchscreen interface that logs and stores the data collected from the probe.

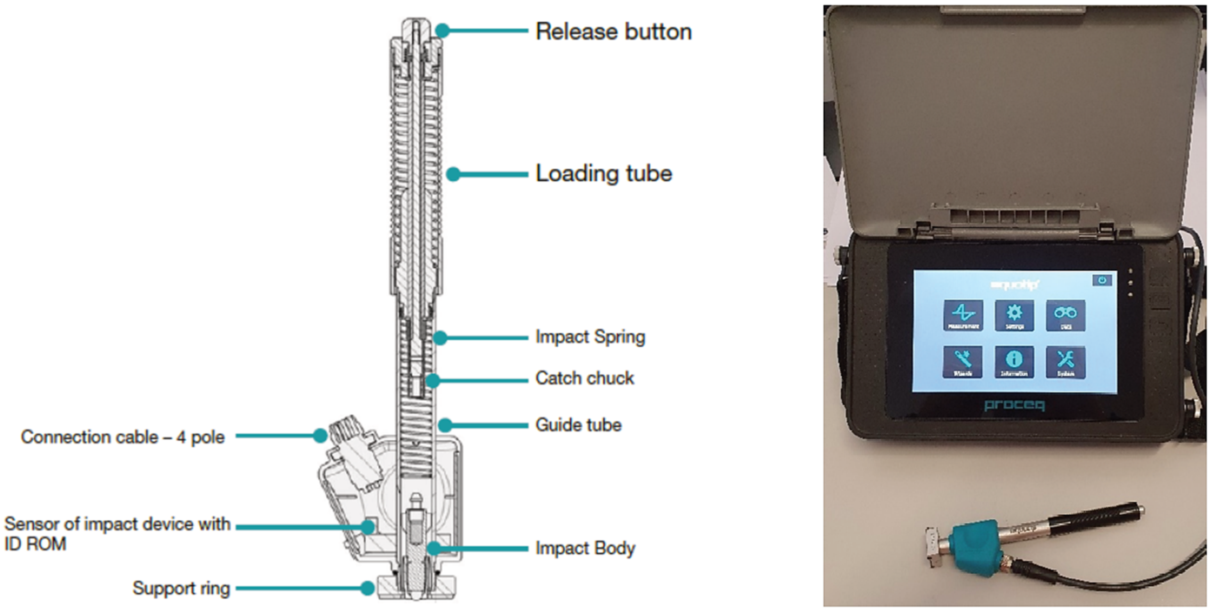


Figure 2 Equotip probe and touchscreen interface

Three Equotip readings were collected on a single depth marker. The measurements were then averaged to reduce statistical uncertainty. As mentioned above, Corkum et al. (2017) investigated the increased accuracy associated with a greater number of impacts and concluded that the choice of three readings was considered sufficient, where tests pieces are comparatively homogeneous in hardness (Proceq SA 2016). In areas where it was not possible to take a reading exactly on the depth marker, an arbitrary reading was collected on a wood drill run block to represent a weak material. Comments were included in the log to indicate that this was a null measurement.

4 Post processing

Although HLS can provide an understanding of the variability in intact strength of the core material (identifying weaker versus stronger areas), obtaining an actual strength value in MPa requires correlating these measurements with PLT and UCS data obtained through field and laboratory testing. While authors (Bruning et al. 2022; Corkum et al. 2017) have published relationships between UCS and HLS, this study opted to establish a distinct correlation for better accuracy. The comparison between the various correlations is not discussed in this present paper.

4.1 Correlation with PLT results

To explore the relationship with the PLT Index (Is_{50}), various factors were assessed. This involved examining how the number of HLS measurements correlated with a single Is_{50} result, the type of PLT test (axial or diametral), and the defined failure types outlined below:

- homogeneous failure type (sample failed through the homogeneous rock matrix)
- combined (sample failed through a combination of homogeneous rock matrix and discrete structures) or defect network (sample failed along multiples veins or defects) failure types.

In this study, PLT tests were conducted at intervals of 3 m, and the average Equotip HLS values were determined within a range of 1.0, 1.5, and 3.0 m above or below the location of each PLT test. These findings were then plotted on a log-log graph, correlating PLT Is_{50} with HLS values. Figure 3 provides visual representation of this sensitivity.

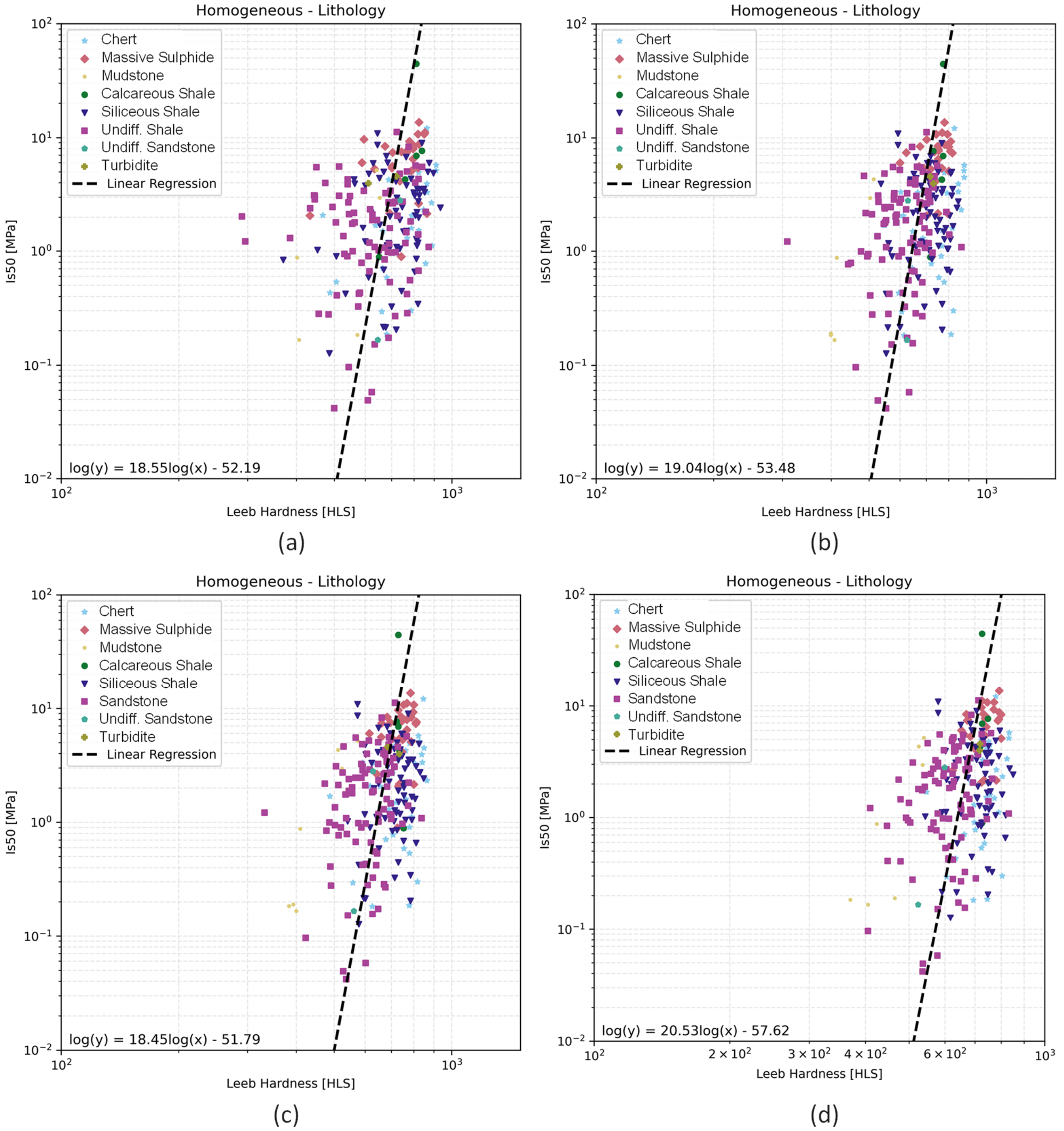
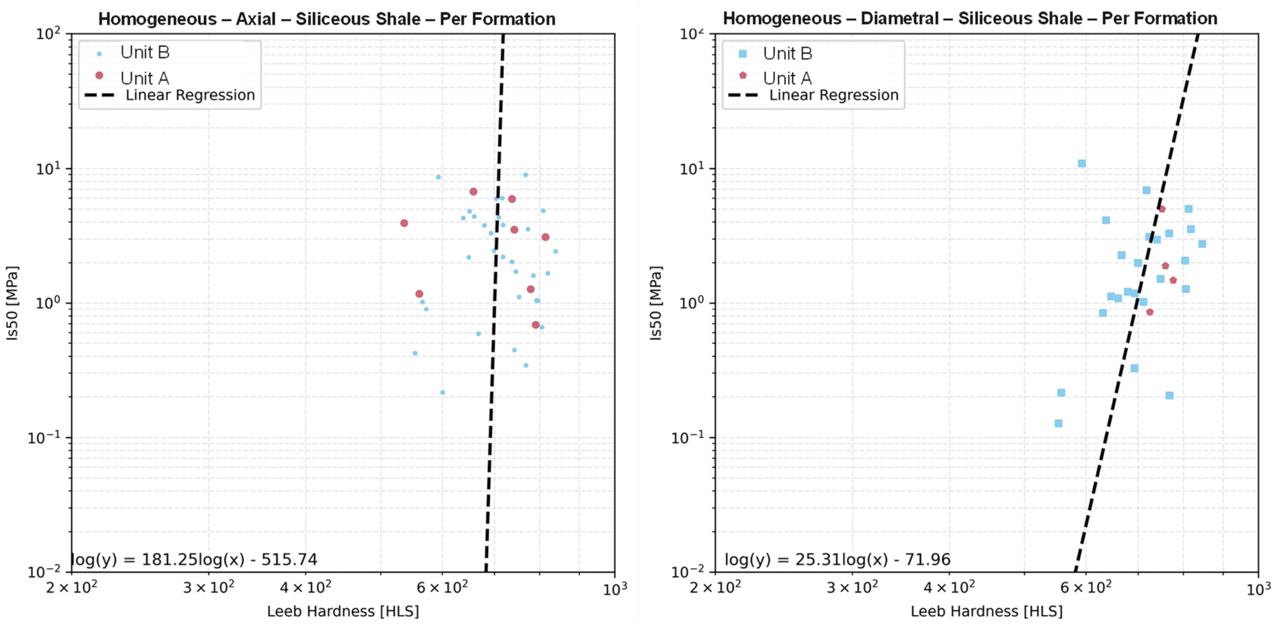


Figure 3 Sensitivities on the averaging intervals using the point load tests and Leeb hardness data (a) to the closest depth marker; (b) within 1 m above and below; (c) within 1.5 m above and below; (d) within 3 m above and below

The findings indicate that when solely relying on PLT results at the nearest depth marker, the data points exhibit greater dispersion. However, no significant variance is observed with averaging intervals of 1.0, 1.5, and 3.0 m.

A secondary analysis was conducted to compare the correlation between HLS data and the diametral and axial results from the PLT dataset. This comparison is illustrated in Figure 4.

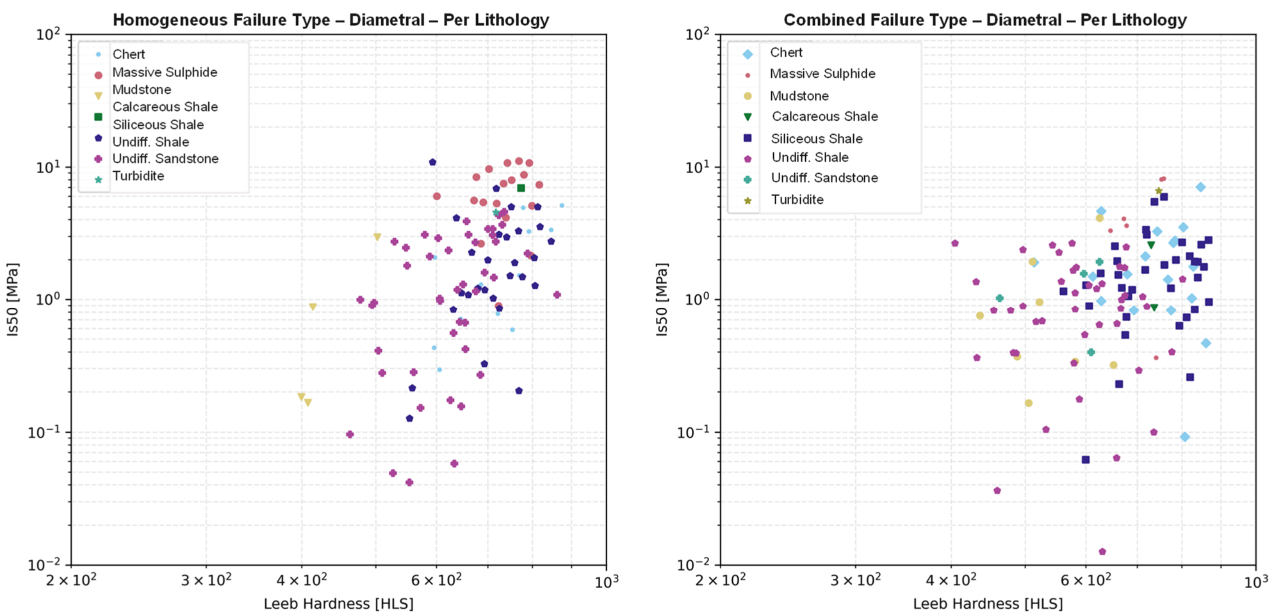
The findings of the study revealed that axial tests exhibited little correlation with HLS data, leading to the decision to exclusively utilise diametral tests. Diametral tests are conducted perpendicular to the core axis (the direction the core is drilled), while axial tests are conducted parallel to the core axis. Since the Equotip tests were completed perpendicular to the core axis, it is reasonable to assume that the diametral tests would provide a better correlation.



(a) (b)

Figure 4 Linear regressions between Leeb hardness and point load tests (PLT) Is50 for (a) axial PLT tests and (b) diametral PLT tests

The influence of the failure type of the PLT tests on the correlation with HLS was also reviewed. The comparison is presented in Figure 5.



(a) (b)

Figure 5 Linear regressions between Leeb hardness and (a) PLT Is_{50} results for specimens failing with a homogeneous failure type; (b) PLT Is_{50} results for specimens failing with a combined failure type

The comparison indicates that the distribution of HLS using PLT Is_{50} results failing with a combined failure type, is much more scattered than the distribution of HLS using PLT Is_{50} results for failing with a homogeneous failure type. The scatter is explained by more limited data for the combined dataset and for better accuracy, the PLT Is_{50} results from specimens failing with a homogenous failure type were used.

Based on the observations discussed, a correlation between the HLS and PLT Is_{50} was developed, using PLT diametral results from specimens failing with a homogeneous failure type. Figure 6 presents the HLS and PLT Is_{50} correlation using the available data points.

Generally, there seems to be a correlation between HLS and PLT, although there is significant scatter in the PLT dataset. Additionally, it was observed that using linear regression on the log-log plot and fitting data in the Y-direction (reducing X residuals) results in a much more reliable fit, however, it tends to overestimate Is_{50} at high HLS. Figure 6 also highlights the influence of lithology on strength (mudstone versus siliceous shale) which will be discussed later in this paper.

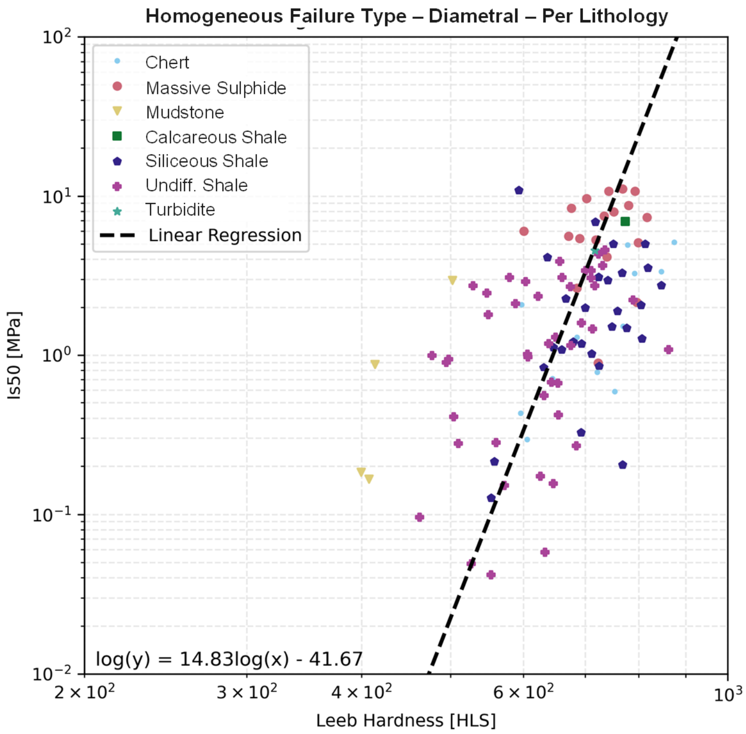


Figure 6 Linear regression between point load tests Is_{50} (diametral tests with a homogeneous failure type) and Leeb hardness, plotted per lithology

4.2 Correlation with UCS results

The dataset available for correlation with UCS is more constrained compared to the one used for the correlation to PLT. Only 22 UCS datapoints were correlated with HLS measurements at corresponding locations. Figure 7 illustrates the correlation based on failure type and lithology. In contrast to the PLT data, the UCS data were aligned with HLS using a fitting approach in the X direction to minimize Y residuals.

There is no clear distinction apparent when looking at the data per failure type and therefore all failure types were considered to allow for more data availability. Additionally, Figure 7b suggests weaker lithology control on strength in comparison to the findings from the PLT dataset, likely due to the smaller dataset available.

Despite the limited dataset, the UCS to Equotip correlation is strong enough to be confident in predictions of UCS strength from Equotip data points. Using the correlation presented in Figure 7, UCS was predicted using a rolling average of the HLS measurements over 1.5 m intervals. A total of 18,906 UCS predictions were generated across the site and distributions of intact strength were generated within each formation/lithology. Figure 8 presents the predicted UCS distribution for four lithologies.

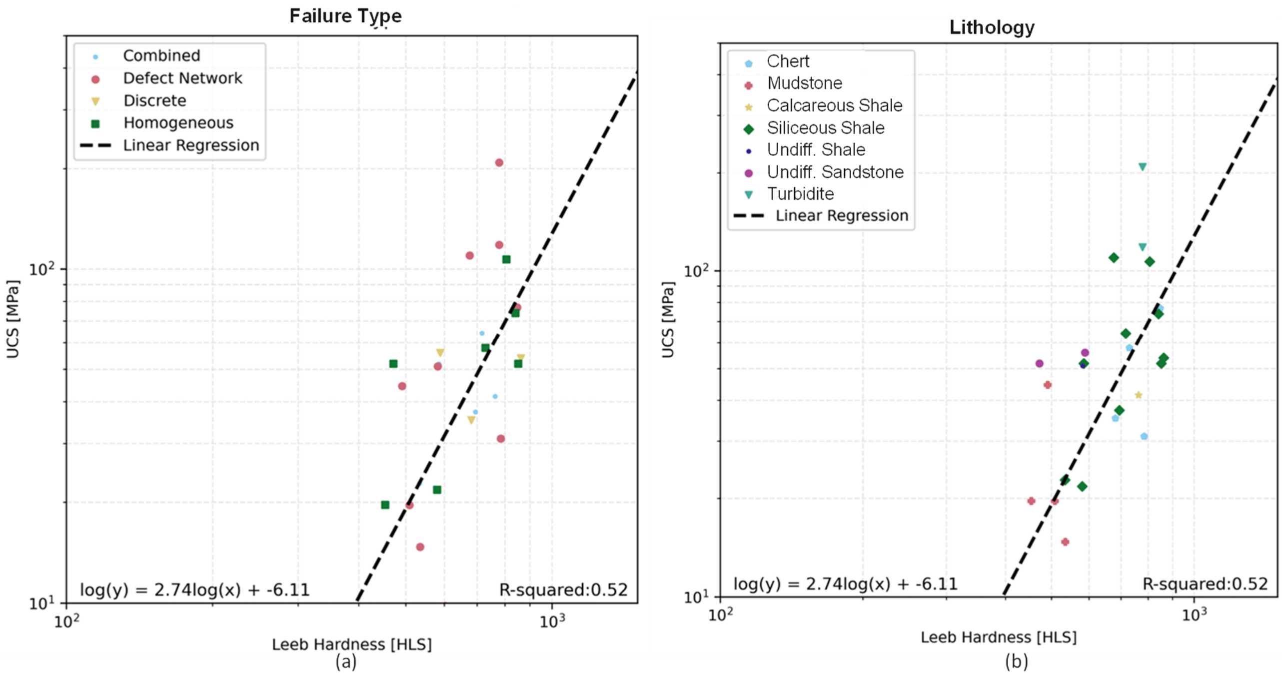
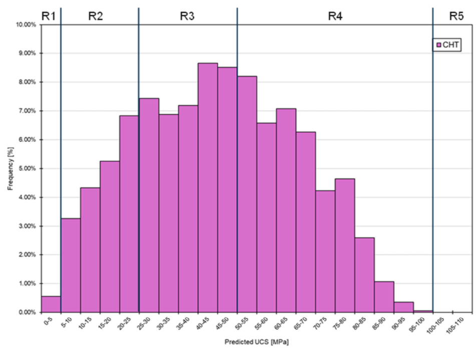
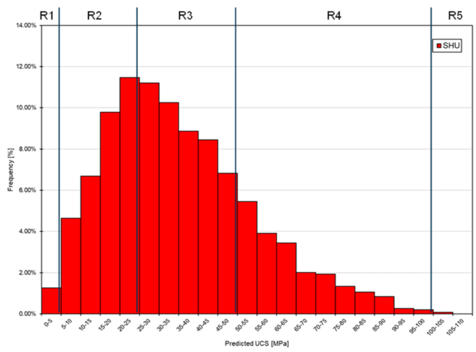


Figure 7 Uniaxial compressive strength and Leeb hardness correlation: (a) Plotted per failure type; (b) Plotted per lithology



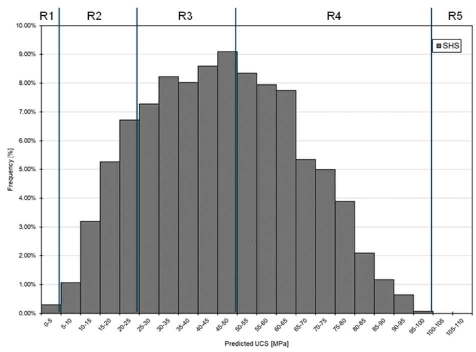
Count	1962
Mean UCS	45 MPa

(a)



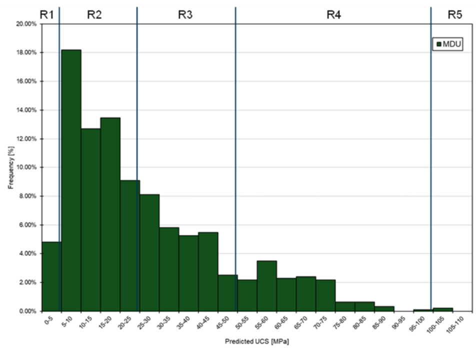
Count	5623
Mean UCS	35 MPa

(b)



Count	4013
Mean UCS	46 MPa

(c)



Count	913
Mean UCS	27 MPa

(d)

Figure 8 Uniaxial compressive strength prediction from Leeb hardness data for: (a) Chert; (b) Mudstone; (c) Siliceous shale; (d) Sandstone

A comparison of the average UCS and estimated sigma c_i from the laboratory testing for the same units is shown on Table 2. Note that because of the limited dataset, the confidence level isn't high enough yet to utilise these estimated UCS values for developing Hoek–Brown intact strength curves (Hoek et al. 2002), or for design purposes.

Table 2 Average predicted uniaxial compressive strength (UCS) and average UCS and sigma c_i from laboratory testing per lithology

Lithology	Average predicted UCS (MPa)	UCS homogeneous failure type		
		Count of tests	Average UCS (MPa)	Sigma c_i (MPa)
Chert	45	5	46	31
Undifferentiated shale	35	37	50	43
Siliceous shale	46	17	69	114
Mudstone	27	44	30	29

The predicted UCS distributions highlights differences among the various lithologies. The mudstone lithology being the weakest. Both the siliceous shale and the chert indicates stronger data. The average predicted UCS values between the different lithologies are similar, as most of the HLS values are between 600 and 800. This is explained by the limited dataset and additional Equotip, and UCS data would likely reduce the uncertainty and increase the resolution of the prediction between HLS and UCS.

Additionally, the average projected UCS value remains relatively low for each lithology, typically ranging from 25–50 MPa. The comparison of the distributions illustrated in Figure 8 indicates that weaker units (mudstone, for example) show a more right-skewed distribution, with high outlier values bringing the average closer to the average of the lithologies with more normally distributed predictions. This presents a case for using percentiles for geotechnical design rather than averages; however, that is a topic that deserves a separate and more detailed discussion.

5 Geotechnical domaining

The logged field strength PLT Is_{50} estimates, the HLS and UCS from laboratory testing were reviewed to evaluate the relative difference in strength between the formations and lithologies. As briefly discussed, it appears that the lithologies and their corresponding formations have an influence in the correlations between the HLS and UCS, as well HLS with PLT Is_{50}. This influence is also observed when looking at the downhole HLS data with depth. Examples for two boreholes are shown on Figure 9 and Figure 10.

The downhole plots of HLS with depth indicate some notable observations. One significant finding is that the mudstone lithology appears consistently weaker than the other lithologies regardless of the formations it's situated within. Another finding is that within Unit B, the siliceous shale demonstrates greater strength compared to the undifferentiated shale, suggesting that intact rock strength appears to be controlled by lithology rather than by formation. Unit C encompasses weaker lithologies like chert and undifferentiated shale with the chert lithology showing similar HLS estimates regardless of the formation it's situated within.

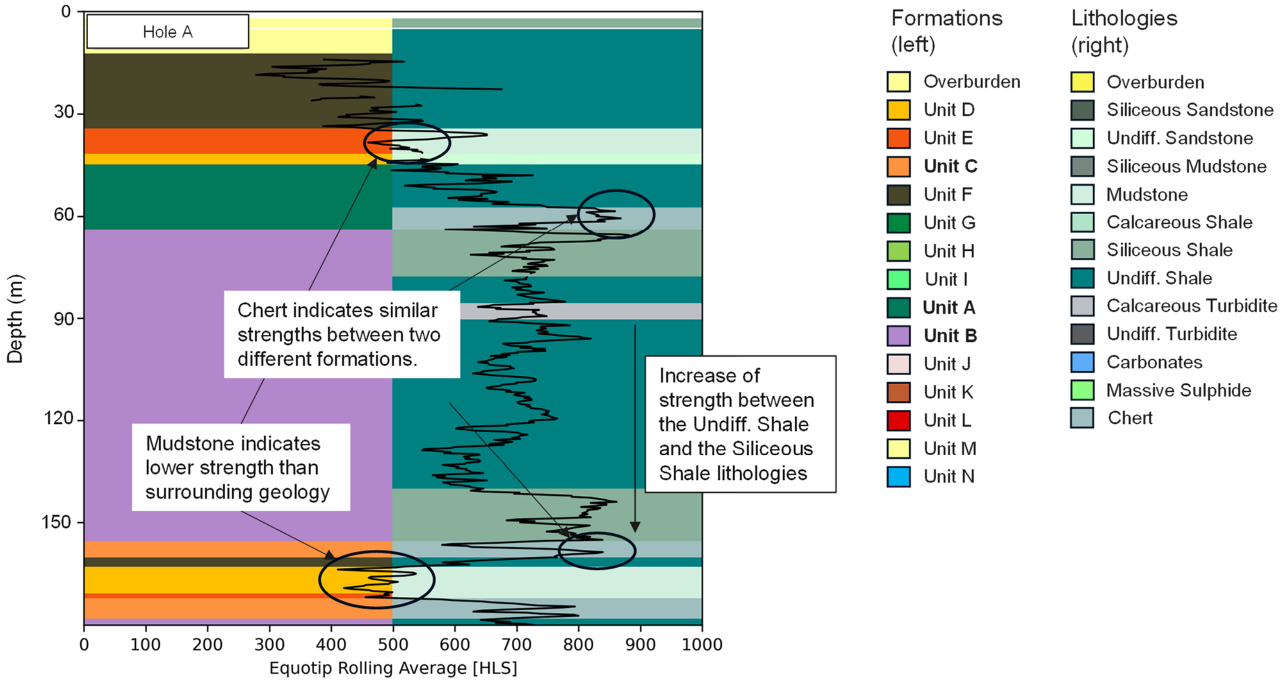


Figure 9 Downhole plot of Leeb hardness data, example 1

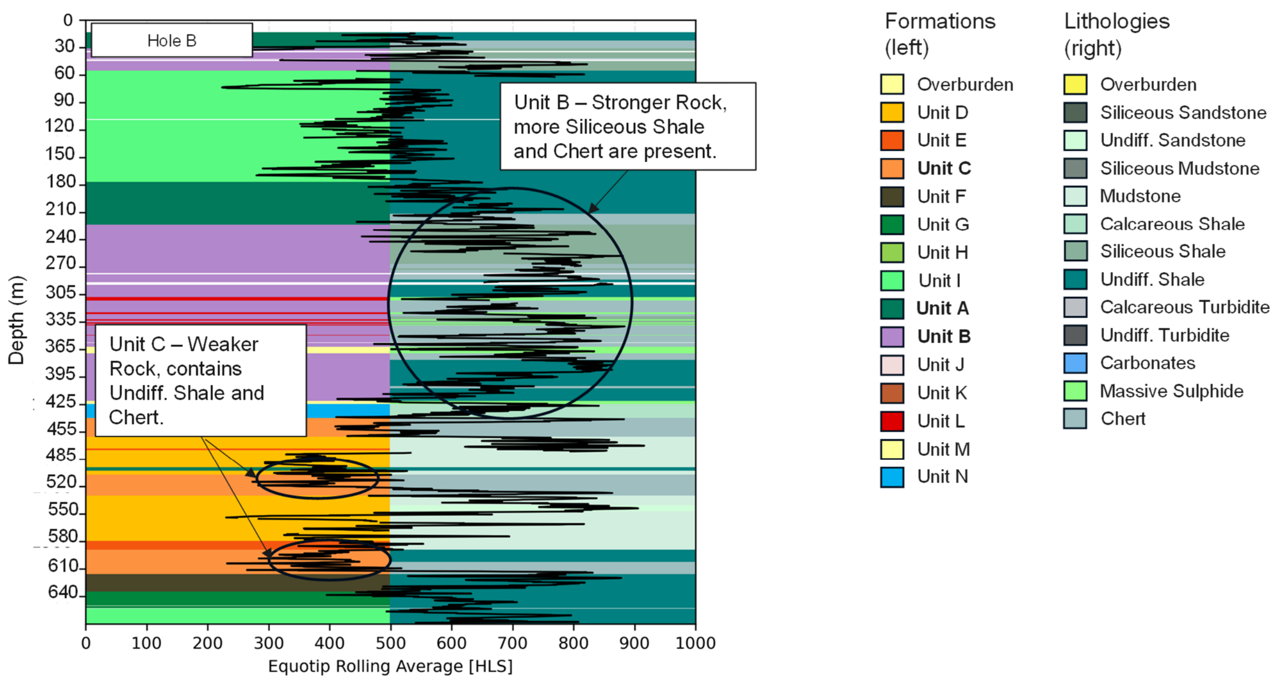


Figure 10 Downhole plot of Leeb hardness data, example 2

HLS from the Equotip appear to be partially controlled by formation and primally per lithology. This observation is consistent with the previous correlation analyses conducted using the PLT data. When correlations between PLT and Leeb hardness were developed, there were only small deviations around the best fit when split by lithology. However, when split by formation, there were larger deviations, and the data points appear to be clustered by lithology. This comparison is shown on Figure 11. This observation was not seen in the UCS versus Leeb hardness correlations, however, there is less data available for this correlation.

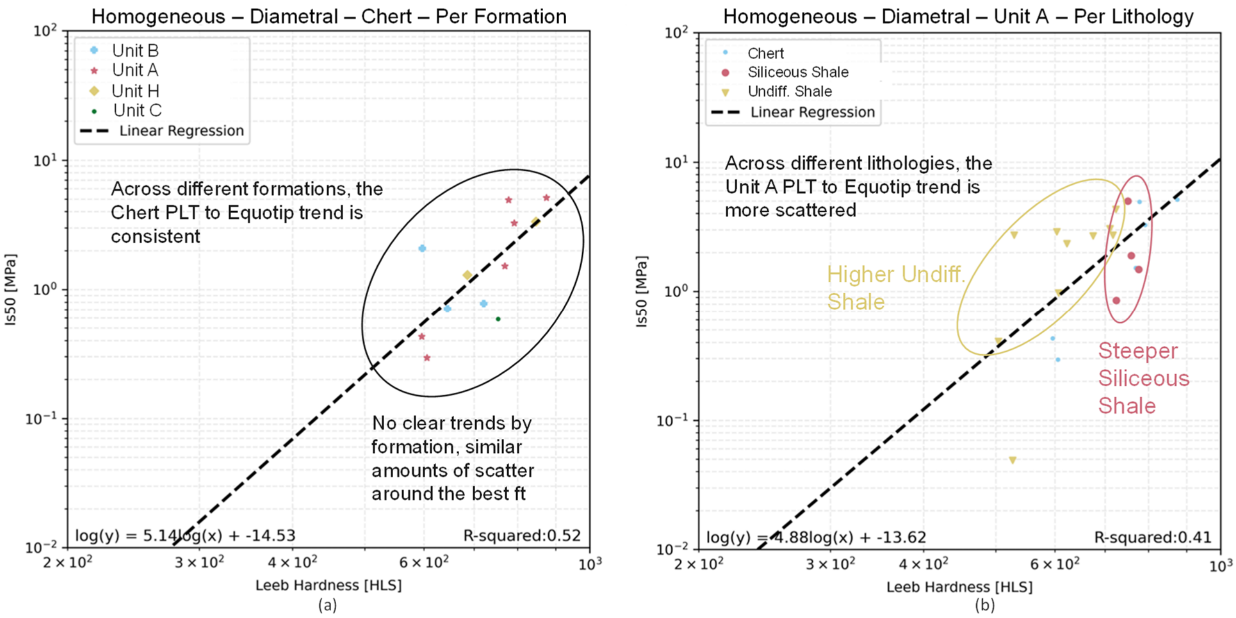


Figure 11 Comparison of point load tests to Leeb hardness correlations per (a) formation and (b) lithology

Based on these observations, the intact strength expected along the decline was observed to be largely lithology-dependent and therefore both the units A and B were combined for the development of geotechnical domains. Domains where developed based on the lithologies, which included siliceous shale, chert and undifferentiated shale.

6 Conclusion

In this study, HLS measurements were collected on core samples, along with PLT and UCS laboratory tests to assist with the rock mass characterisation for the design of a portal and decline for underground access. Analysis of intact strength estimates categorised by lithology revealed consistent trends across all data sources. Correlations developed between the HLS and PLT Is_{50} show that the Equotip data appears to be corelated to the PLT Is_{50}, although the PLT dataset showed considerable scatter. The study revealed that axial tests exhibited little correlation with HLS data, leading to the decision to exclusively utilise diametral tests. While not discussed in this study, incorporating data such as RQD, field strength estimates, and defect intensity using machine learning algorithms could likely enhance correlations.

The strong correlation between UCS and Equotip instils confidence in predicting UCS for each Equotip data point. UCS predictions were generated across the site to obtain distributions of intact strength for each formation/lithology. However, while this correlation is robust, the confidence level isn't yet sufficient to utilise these estimated UCS values for design purposes. Additional Equotip and UCS data would likely reduce the uncertainty and increase the resolution of the prediction between HLS and UCS. Equotip testing on laboratory samples with several Equotip measurements would also provide better correlations.

In addition of helping with reducing uncertainties on the intact strength estimates, the review of the Equotip Leeb hardness also assisted with the development of geotechnical domains and confirmed that the intact strength expected along the decline was observed to be largely lithology-dependent with some weaker lithology units (mudstone and chert) and stronger unit (siliceous shale).

While not discussed in this study, with refined correlations, both Is_{50} and UCS estimated from HLS could be block modelled assisting in delineating spatial domains of weaker units or understanding strength variability. Additionally, comparing statistical distributions of all Equotip data, with Equotip data specifically for geotechnical samples (PLT, UCS) should allow the quantification of sample selection bias. While this was not undertaken as part of this study, the understanding of this aspect would provide more robust adjustments to laboratory sample intact strength testing, ensuring a more justified approach.

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