

# Impact of sample selection on unconfined compressive laboratory test results in hydrothermally veined rocks

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## ABSTRACT

Geotechnical properties measured by unconfined compressive strength (UCS) laboratory tests can be greatly influenced by sample selection practices, especially for heterogeneous, hydrothermally veined and altered rocks. This data is not captured by many site investigation programs since it is common practice to test homogeneous specimens but discard heterogeneous specimens. This may lead to erroneous assessments of rockmass strength and behaviour prediction for excavations. This paper first discusses industry sample selection practices and a case study of sample selection from the Bruce Deep Geological Repository project. Secondly, the effects of sample selection on UCS test properties of 39 UCS specimens from the Legacy skarn ore deposit are compared using four methods of sample selection for homogeneous and heterogeneous (veined) granodiorite and calcareous mudstone units. In all units there are significant differences in UCS properties between homogeneous and heterogeneous samples. Comparing the total UCS test suite to mixed subsets of each unit shows fairly similar results, but this may depend on how the subset selection method is implemented.

## RÉSUMÉ

Les propriétés géomécaniques mesurés par les tests au laboratoire de résistance à la compression non confinée (UCS) peuvent être influencés par les pratiques de sélection des spécimens, en particulier pour les roches hétérogènes avec les veines hydrothermales et avec altération. Souvent, les programmes d'étude de site ne capturent pas cette information, puisqu'il est commun de tester les roches homogènes mais d'écartier les roches hétérogènes. Ceci peut causer des évaluations erronées de la résistance et des prédictions incorrectes du comportement du massif rocheux pour les excavations. Cet article discute premièrement les pratiques de sélection des spécimens et présente un cas d'histoire de sélection des spécimens dans le projet de stockage en couches géologiques profondes à Bruce. Deuxièmement, les effets de la sélection des spécimens sur les résultats des tests UCS, de 39 spécimens du gisement de minerai Legacy Skarn, sont comparés avec quatre méthodes de la sélection des spécimens pour les roches homogènes et hétérogènes (avec veines) des unités granodiorite et mudstone calcaires. Il y a des différences importantes entre les roches homogènes et hétérogènes pour les propriétés UCS dans tout les unités. Les résultats sont similaires en comparant tout les résultats de UCS aux résultats des sous-ensembles de chaque unité, mais ça peut dépendre sur comment les méthodes de sélection des spécimens sont implémentés.

## 1 INTRODUCTION

As the demand for metals increases, mining excavations are being undertaken in increasingly complex, heterogeneous rockmasses at greater depths. Complex rockmasses contain healed intrablock structures (e.g. hydrothermal veins, stockwork, and others) within blocks of otherwise intact rock, which are bounded by joints and other fractures (interblock structures). Intrablock structures have been observed at the excavation scale to control additional or delayed development of ground failures (Day 2016). Healed intrablock structures influence rockmass deformability and strength (e.g. Brzovic & Villaescusa 2007; Day 2016), but are not sufficiently considered in conventional rockmass characterization and geotechnical design practice (Day 2016; Moss et al. 2018). Inadequate consideration of intrablock structures and other hydrothermal alteration in rockmass characterization for geotechnical design of underground excavations can lead to inaccurate design of ground support and erroneous predictions of rockmass behaviour, ultimately resulting in significant risk of economic loss in delayed production and a greater safety risk for workers. Therefore, accurately observing and measuring heterogeneous rockmass characteristics in the laboratory is essential to effectively understand and predict how the rockmass will behave when it is excavated. This should begin in the site investigation project stages while geological and geomechanical data are collected.

This paper first presents a discussion of modern methods of sample selection practices from the experiences of various industry professionals. A case study is presented to discuss geotechnical sample selection compared to drill core length and other information from the Bruce Deep Geological Repository (DGR) project in Ontario by Ontario Power Generation (OPG) and the Canadian Nuclear Waste Organization (NWMO).

Secondly, a study comparing the mechanical properties of unconfined compressive strength (UCS) laboratory test results based on one typical and three experimental sample selection practices is presented. The experimental selection practices proposed in this paper evaluate the implications of including heterogeneous samples and using a reduced amount of samples (a statistical subset) in reported test results. Specifically, the following sample selection practices are compared: (i) homogeneous samples only (typical), (ii) heterogeneous samples only, (iii) all homogeneous and heterogeneous samples, and (iv) a subset of all samples in each lithology. The UCS laboratory test results were measured during testing of 39 specimens (conducted by the authors), which were selected from borehole MBL-13-04 at the Legacy skarn ore deposit in northwestern New Brunswick. The following geomechanical properties were measured in each UCS test and are compared by sample selection practices in this study: deformation parameters (Young's modulus and Poisson's ratio), brittle damage thresholds (crack initiation and crack damage), and peak strength.

## 2 CURRENT SAMPLE SELECTION PRACTICES

Determining the geotechnical properties of a rockmass is an important aspect of any successful underground infrastructure project. These properties are acquired through observation, measurements, and testing of diamond drill core, which can be hundreds of meters long and often contain multiple geological units and structural domains. Due to time and financial constraints, testing the entire core is not realistic nor feasible. Therefore, representative samples of drill core from each lithology or geotechnical domain are selected and tested. These results are collectively meant to represent the geotechnical properties of the rockmass within the whole project area.

Four rock geotechnical engineering industry practitioners shared their experiences with sample selection practices for UCS tests with the authors. These practitioners have worked in the industries for Canadian, Chilean, and other international mining projects, Canadian tunnelling projects, and Canadian DGRs for nuclear waste storage. Collectively, the practitioners indicated that there are no standards for sample selection, nor are there a minimum number of tests required in a project. Instead, sample selection decisions are conducted using professional judgement and sometimes company guidelines (e.g. de la Vergne 2008). ASTM (2017) similarly states that sample selection decisions should be based on professional judgment. The main factors considered by these practitioners when making sample selection decisions are as follows:

- stage of the project (scoping, prefeasibility, feasibility and operation)
- geological setting
- variability of the rockmass
- existing material characterization
- project risk and uncertainty
- project budget

Two methods of selecting samples were discovered to be most common. The first method relies upon an agreement with the client on the number of tests, where a certain number of samples are selected from each geotechnical domain. The second method relies on selecting samples at predefined intervals. Since this method is somewhat based on random selection, additional core may be sampled to better capture the heterogeneity of the rockmass. Frequently, however, if the selected sample contains intrablock structures, the sample is discarded and replaced with the nearest intact homogeneous sample. Of course, the number of samples in a UCS test program also depends on the type of project, where a mining project would generally conduct fewer tests than a DGR project for nuclear waste storage.

### 2.1 Case Study: Bruce Deep Geological Repository Geotechnical Sampling and Testing Program

The Bruce DGR project is a proposed storage facility for low to intermediate nuclear waste by OPG and NWMO, located near Kincardine, Ontario. This facility will consist of access shafts and a network of tunnels at a depth of

680 m. It was vital for OPG to conduct a thorough site investigation to determine if the bedrock in this location is suitable to store the waste material for at least one million years. As part of the site investigation, eight boreholes were drilled (DGR 1-8) and core was recovered (Figure 1). This core was used for a variety of tests to investigate and characterize the geological, geochemical, and geotechnical properties of the bedrock (OPG 2011a).

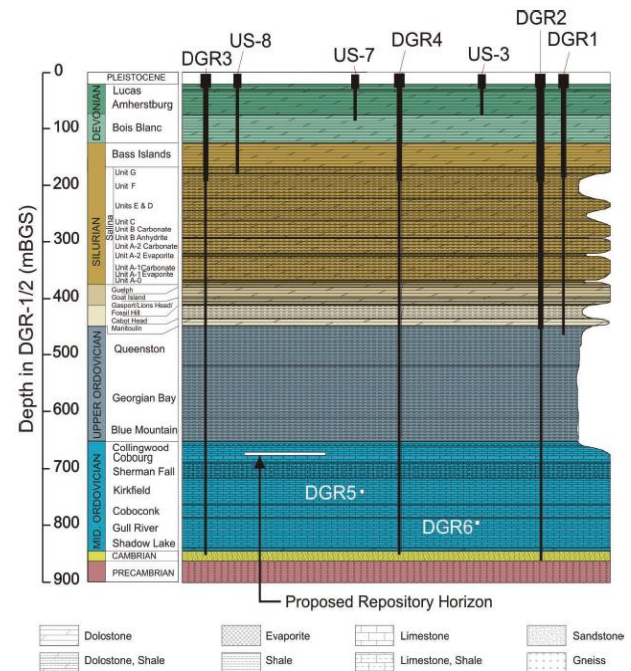


Figure 1. Cross-section of the Bruce DGR showing borehole locations, stratigraphy, and the proposed repository horizon (OPG 2011a)

In this paper, sample selection practices of OPG are investigated using the core logs of DGR-1, -2, -5 and -6 (OPG 2010; OPG 2011b) to determine the frequency and location of samples that were selected for UCS testing and axial point load (APL) testing. APL testing is an indirect, low cost, and faster method of estimating UCS peak strength (ASTM 1995). The OPG reports do not state how samples were selected. The numbers of UCS and APL tests in each Formation are illustrated in Figure 2.

UCS sample selection appears to have been thoughtful, not random. For instance, DGR-1 was the first exploratory borehole drilled for this project; samples were selected across the largest number of Formations and did not seem to specifically target any Formation. Sample selection in DGR-2 targeted the area near the Ordovician units including the proposed repository horizon in the Cobourg limestone and the immediately overlying shale units. In DGR-2, the number of UCS samples increased but APL samples decreased. The increase in UCS samples could be used to improve the accuracy of input properties for geomechanical numerical models of the repository excavations. In DGR-5 and DGR-6, sample selection even more specifically targeted the Cobourg-Collingwood and Cobourg Formations within and immediately above the proposed repository horizon.

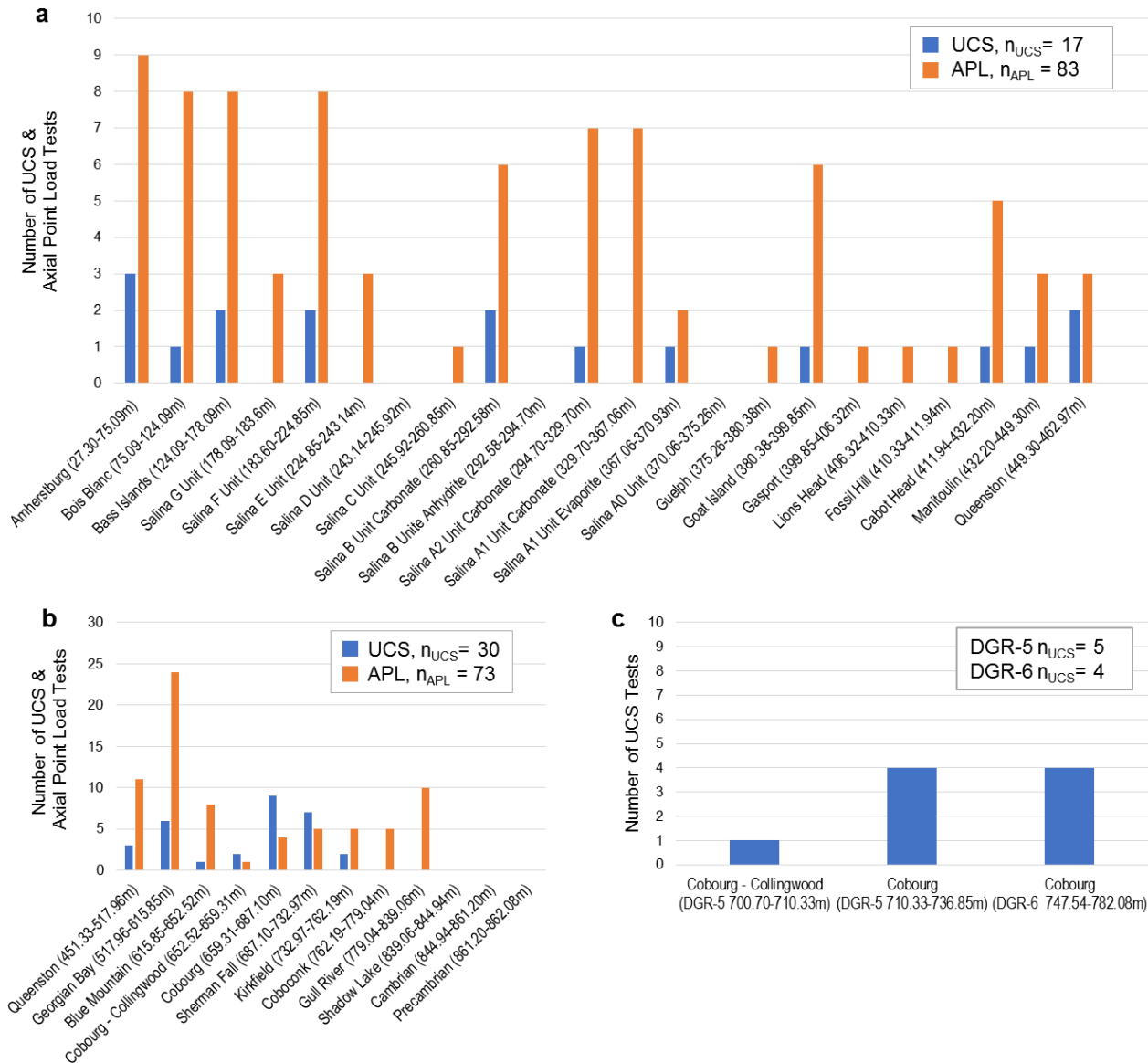


Figure 2. UCS and APL sample selection from each Formation at the Bruce DGR site from several boreholes: (a) DGR-1, (b) DGR-2 and (c) DGR-5 and DGR-6

The sample selection intervals for UCS and APL tests are summarized in Table 1. Interestingly, if you compare the average spacing for the samples selected in DGR-1 and DGR-2, the interval for UCS sample selection decreases by 53%, whereas the APL sample selection remains similar at 5.2 m and 5.6 m. The UCS sample selection intervals for DGR-5 and DGR-6 were significantly higher at 118.3 m and 170.6 m because by this point in the sample selection program, UCS testing was focused over a narrow range (Cobourg-Collingwood and Cobourg Formations) compared to the entire sample range. Finally, there was no APL interval for the last two holes (DGR-5 and DGR-6) since no samples were selected for this testing.

Table 1. Sample selection intervals for UCS and APL testing from Bruce DGR boreholes

| Borehole No. | Sampling Depth Range (m) | UCS Test Interval (m) | APL Test Interval (m) |
|--------------|--------------------------|-----------------------|-----------------------|
| DGR-1        | 27.3 - 463               | 25.6                  | 5.2                   |
| DGR-2        | 451.3 - 862.1            | 13.7                  | 5.6                   |
| DGR-5        | 215.2 - 806.6            | 118.3                 | N/A                   |
| DGR-6        | 219.7 - 901.9            | 170.6                 | N/A                   |

### 3 DESCRIPTION OF LEGACY DEPOSIT AND ROCK TYPES

The drill core samples selected for UCS testing and this study were obtained from borehole MBL-13-04 at the Legacy copper-silver skarn deposit located in northwestern New Brunswick, Canada (Figure 3). The lithologies associated with this deposit are Devonian to Ordovician in age, consisting of the Matapedia Group and the McKenzie Gulch Porphyries (Desrosiers 2012). The Matapedia Group hosts the skarn deposit and is characterized by dark grey calcareous mudstone, white limestone and well-laminated limestone in interbedded units 1-5 cm thick. The McKenzie Gulch Porphyries consist of a system of quartz-plagioclase granodiorites and plagioclase-hornblende granodiorites. The skarn deposits in this region are spatially related to faults trending northeast (Desrosiers 2012) which are also responsible for the granodiorite dykes and sills that occur throughout the deposit.



Figure 3. Map of eastern Canada with an inset of New Brunswick showing location of the Legacy skarn deposit

The calcareous mudstone and three granodiorite (black, red, and beige) units are considered in this study. Their geological descriptions are based on literature (Desrosiers 2012) and a micro-scale geological laboratory investigation (Clark et al. 2019b). Powdered X-Ray Diffraction was used to determine the mineralogical compositions of the matrix and vein components. Micro-X-Ray Fluorescence was conducted on thin sections to analyze the spatial distribution and concentration of

elements. Finally, petrographic analysis of the thin sections was conducted for verification (Clark et al. 2019b).

The calcareous mudstone matrix is dark grey, fine grained, and contains quartz, calcite, muscovite, and dolomite. It contains layers of mudstone (1-5 cm thick) interbedded with thin layers of limestone (Desrosiers 2012). The veins are composed of calcite and range from 3-40 mm thick (Figure 4). The beige quartz-plagioclase granodiorite matrix contains albite, quartz, biotite, calcite, muscovite, fine grained disseminated pyrite, and traces of chalcocopyrite. It is dominated by sericitic alteration and 1-3 mm thick calcite and ankerite veins. The red quartz-plagioclase granodiorite matrix contains orthoclase, quartz, biotite, calcite, fine grained pyrite, and traces of chalcocopyrite. It is dominated by potassic alteration with 1-3 mm thick calcite veins. The black quartz-plagioclase granodiorite matrix contains anorthite, quartz, biotite, calcite, chlorite, fine grained pyrite, and traces of chalcocopyrite. It is dominated by sausseritic alteration with 1-2 mm thick calcite veins (Figure 4). Note the granodiorites are grouped as one unit in the NI-43-101 core logs (Desrosiers 2012) but have been separated in this study based on the influence of the varied alterations on UCS test results (Clark et al. 2019a).

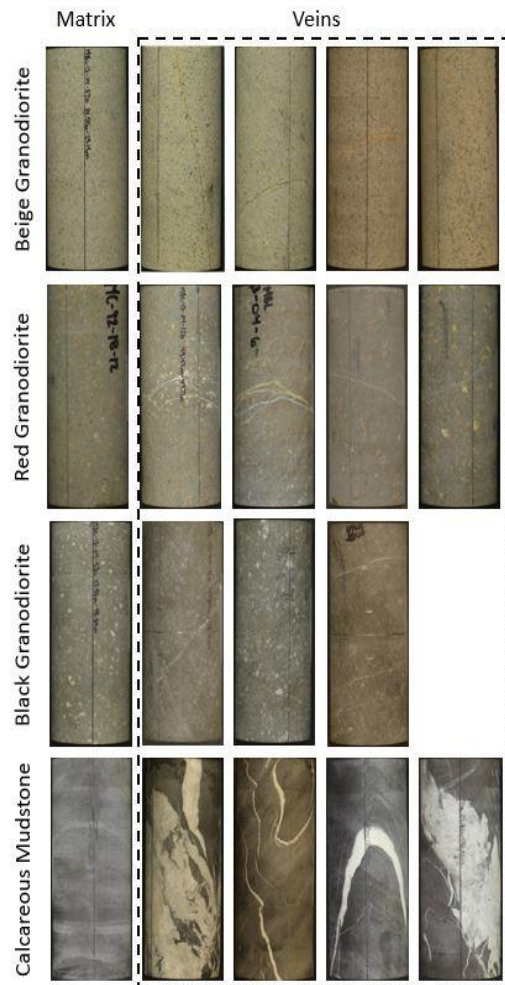


Figure 4. Examples of matrix-type and all vein-type UCS samples in this study from the Legacy skarn deposit (NQ drill core, 47.6 mm diameter)

#### 4 SAMPLE SELECTION OF LEGACY DEPOSIT CORE

The drill core from the Legacy deposit was obtained from the Department of Energy and Resource Development of the Government of New Brunswick. The primary objective of sample selection from borehole MBL-13-04 was to select similar quantities of homogeneous (matrix-type) and heterogeneous (vein-type) core belonging to each rock type in sufficient quantity for a rigorous laboratory testing program to examine the influence of veins on the geomechanical properties. The particularly large amount of core samples that were collected was driven by the:

- interest in testing veined rocks with a variety of vein mineralogy, thickness, persistence, and orientation;
- anticipation of potential losses from transportation and specimen preparation;
- uncertainty of the variability of geomechanical properties with different disseminated alterations observed within the granodiorite core (beige, red and black coloured alterations); and
- scoping of additional testing (e.g. Brazilian tensile and triaxial tests) for future studies.

The core samples were photographed and wrapped with dish foam or pipe insulation foam at the core storage facility near Bathurst, NB (Figure 5, top). They were subsequently transported by car in wood core boxes to the University of New Brunswick in Fredericton for some specimen preparation and geological analysis, and finally to Queen's University in Kingston, Ontario for final preparation and UCS testing. Three calcareous mudstone samples were fractured during transport. After transport, the core was unwrapped and sorted by rock type, homogeneous versus heterogeneous, and colour (granodiorites) to determine the impact of heterogeneity on UCS test results. While preparing specimens for UCS testing, two of the first four calcareous mudstone specimens fractured along laminations. To prevent additional failures, electrical tape was wrapped around the ends of the calcareous mudstone specimens during cutting and grinding (Figure 5, bottom) to provide confinement near the cutting and grinding surface. Once this technique was implemented, just one of the remaining nine calcareous mudstone specimens failed during preparation.

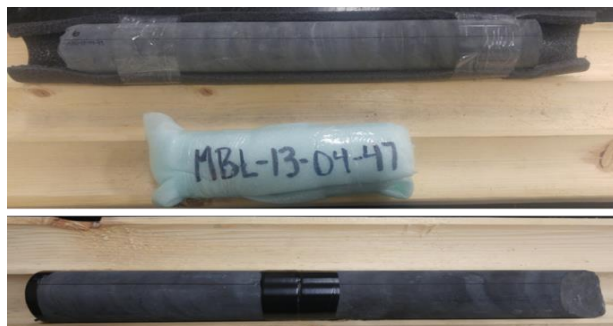


Figure 5. (Top) Core wrapping with foam to preserve samples during transportation; (bottom) calcareous mudstone core wrapped with electrical tape for saw cutting and grinding specimen preparation

Of all the samples collected from MBL-13-04 (all boxes in Figure 6), only 39 have been tested in UCS conditions to date (solid white boxes in Figure 6). A mixture of homogeneous samples that contain only the intact matrix material and heterogeneous samples that also contain veins were selected. Details of the UCS testing and data analyses are presented by Clark et al. (2019a). For this paper, the UCS test results are sorted by different subsets of sample selection: (i) homogeneous matrix-type core only, (ii) heterogeneous vein-type core only, (iii) all samples including matrix- and vein-types, and (iv) a subset of all samples, sorted by lithology, with a mixture of matrix-type and vein-type samples.

#### 5 IMPACT OF SAMPLE SELECTION ON UCS TEST RESULTS

The following UCS test parameters are compared in this study to examine the impact of sample selection: deformation parameters (Young's modulus and Poisson's ratio), brittle damage thresholds (crack initiation (CI) and crack damage (CD)), and peak strength. The test results, sorted by each method of sample selection, are all presented in Figure 7.

##### 5.1 Matrix-Type Core versus Vein-Type Core

The most common sample selection practice in geotechnical engineering is the selection of homogeneous matrix-type samples that are free from discontinuities (e.g. Bieniawski and Bernede 1979; Hoek and Brown 1988). Consequently, heterogeneous vein-type samples that contain intrablock structures are typically excluded. Some notable exceptions to this are at particularly large block cave mining operations such as El Teniente in Chile (e.g. Turichshev and Hadjigeorgiou 2015).

The data set for matrix core includes six specimens for each of the four rock types. The data set for veined core includes four beige granodiorite, four red granodiorite, three black granodiorite, and four calcareous mudstone specimens.

UCS test results of the calcareous mudstone samples reveal that Young's modulus and Poisson's ratio are higher in the homogeneous samples, whereas peak strength and brittle damage thresholds are higher in the heterogeneous samples. UCS test results of the beige and red granodiorite share similar trends with higher homogeneous test results for all parameters compared to the heterogeneous samples. Finally, for the black granodiorite, the homogeneous samples result in higher parameters for all parameters except Young's Modulus.

##### 5.2 All Tests versus Mixed Subsets

All 39 UCS tests along the 145 m section of the Legacy deposit borehole MBL-13-04 have an average specimen spacing of 3.7 m. Comparing these results to subsets of the four lithologies selected at a larger spacing is an important consideration for potential differences in the scope and budget of a testing program. Between three and five specimens per lithology was determined to be a suitable subset range for this study. To determine an

appropriate subset group of specimens, an objective, repeatable approach was developed. The first specimen was selected as the shallowest of each lithology. Subsequent specimens were selected by searching using an initial fixed spacing (by depth) between specimens of 2 m. If the next sample did not occur at 2 m spacing, the length of the interval was extended until the next occurring sample of the same lithology. This process resulted in a measured average specimen spacing of

24.2 m for the calcareous mudstone, 36.3 m for the red granodiorite and 48.3 m for both the beige and black granodiorite.

This sample selection practice illustrates the implications of selecting a subset of core for each lithology, including both the homogeneous and heterogeneous samples (mixed). This produced the most variable results of all methods but tended toward the homogeneous results due to there being a greater number of homogeneous samples. The distribution

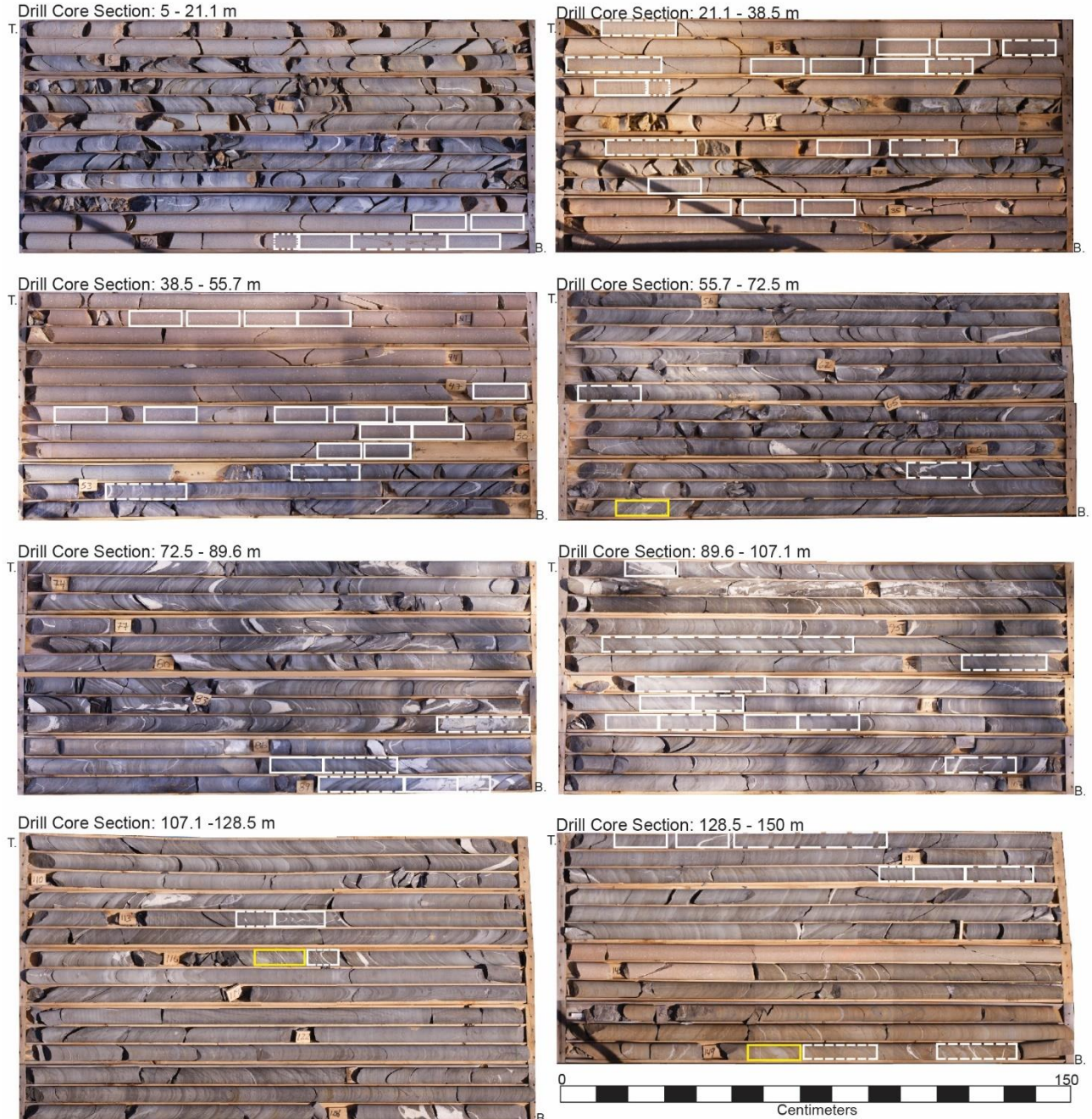


Figure 6. Core boxes containing NQ (47.6 mm) diameter core from the Legacy Deposit borehole MBL-13-04 from 5 m to a depth of 150m; solid white rectangles show core samples that were selected for UCS testing, white-dashed rectangles show samples that were collected but not tested, and solid yellow rectangles show core samples that failed during sample preparation

of lithologies was the main factor that determined the number of samples selected for each rock type. For instance, the granodiorite samples came from dykes and sills that intruded the calcareous mudstone. Therefore, the range over which granodiorite samples could be selected was smaller than that of the calcareous mudstone. This resulted in a sample selection distribution of 30% beige granodiorite, 40% red granodiorite, 30% black granodiorite and 60% calcareous mudstone. The mixed subset selection resulted in the highest UCS test properties for the calcareous mudstone samples. The beige granodiorite results show intermediate values between the homogeneous and heterogeneous methods for all parameters except for CI which has the highest average value. The red granodiorite has values that

are only higher than those from the heterogeneous selection method. Finally, the mixed subset selection for the black granodiorite has very similar Young's modulus and Poisson's ratio values to the other sample selection methods, and intermediate results for peak strength and brittle thresholds between the homogeneous and heterogeneous methods.

## 6 DISCUSSION AND CONCLUSIONS

Common practice of UCS laboratory testing is to avoid selecting heterogeneous samples or to discard test results affected by heterogeneity. However, where deep mining, tunnelling, and other excavations encounter complex rockmasses affected by hydrothermal alteration,

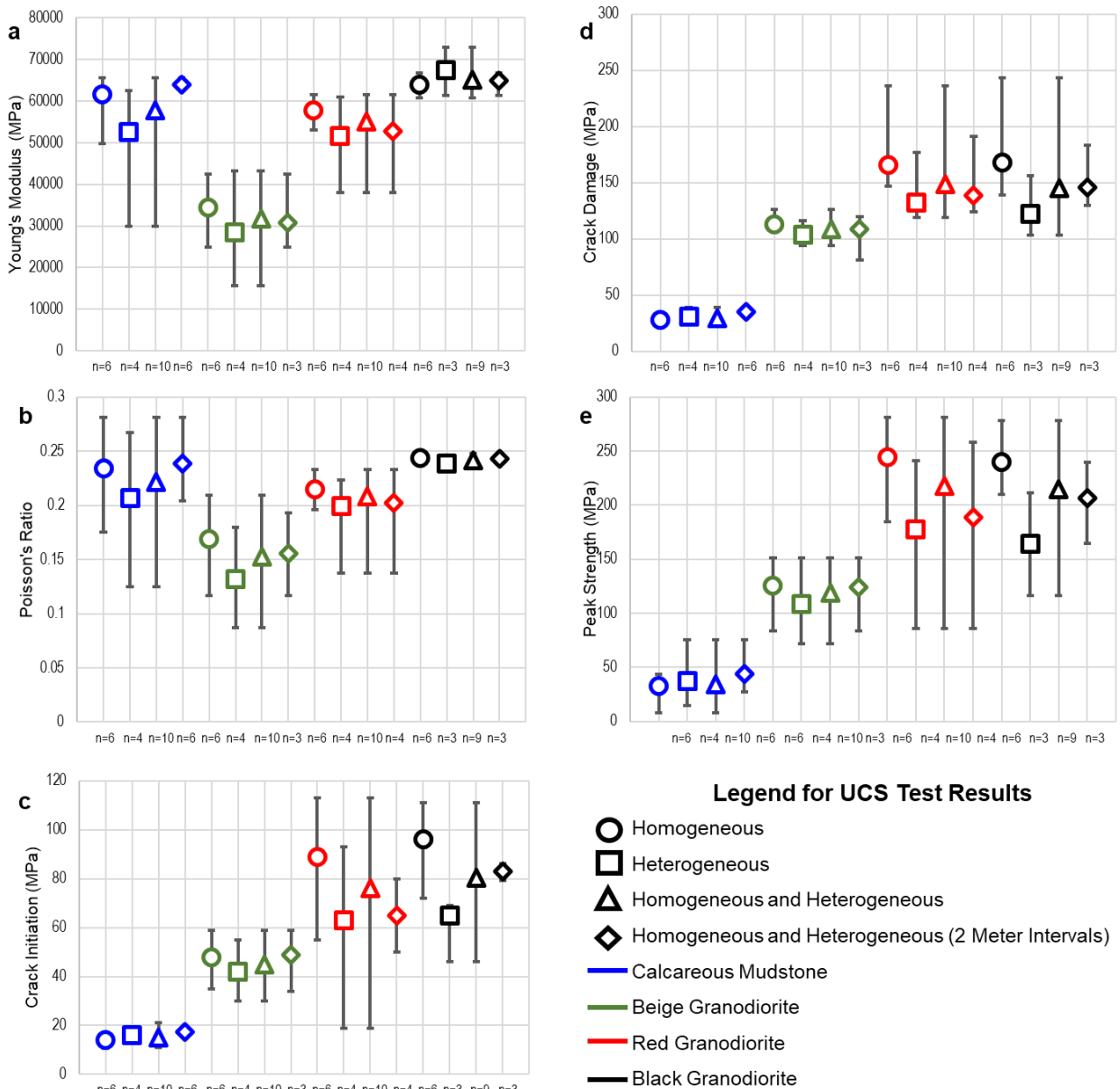


Figure 7. UCS test results for (a) Young's modulus, (b) Poisson's ratio, (c) crack initiation, (d) crack damage, and (e) peak strength for the Legacy skarn deposit calcareous mudstone, beige granodiorite, red granodiorite and black granodiorite rock units

heterogeneities such as vein-type intrablock structures have been observed to influence or control rockmass behaviour. The UCS test results from the Legacy skarn deposit presented in this study support these observations at the laboratory scale and demonstrate the importance of including heterogeneous samples in geotechnical testing programs.

This paper presented examples from the Legacy deposit of how alteration and intrablock structures such as veins can significantly affect the UCS test properties of a rock. While many of the tested homogeneous specimens show higher peak strength, deformation parameters, and brittle thresholds than their heterogeneous counterparts, this is not always the case. For multiple heterogeneous calcareous mudstone specimens, veins increased peak strength by interrupting failure through the laminated matrix component of a specimen.

When comparing the impact of sample selection between the total UCS test suite (9 or 10 per unit) and the selected mixed subsets of each (3 or 4 per unit), the UCS test parameters showed relatively similar values. A notable exception is in the calcareous mudstone unit, where the mixed subset Young's modulus average value was significantly higher than the total UCS test suite. The overall results of the comparison between the total test suite and subsets of each unit may depend on the subset sample selection procedure. Therefore, further investigation on this matter is warranted.

To improve sample selection practices for excavation projects in complex rockmasses, it is essential to consider geological settings, mineralogies, and alterations. This will lead to more effective rockmass characterization and ultimately contribute to improved geotechnical engineering designs.

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