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Accounting for intrablock structures at rockmass and laboratory specimen scales

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ABSTRACT
For deep excavations in heterogeneous complex rockmasses that contain hydrothermal veins and other types of intrablock structures, conventional field characterization and laboratory measurement protocols that were developed for numerical geotechnical design of homogeneous rockmasses are no longer adequate. In this paper, rockmass characterization methodologies in the field and laboratory for complex rockmasses are discussed, with particular emphasis on the importance of mineralogical investigation for both the matrix and vein materials. The opportunities for continuum and discontinuum numerical modelling are also discussed based on the availability of different field or laboratory data. Finally, a case study of unconfined compressive strength laboratory tests on three lithological units from the Legacy skarn deposit is presented to demonstrate both weakening and strengthening influences that intrablock structures can have on stiffness and peak strength properties.

RÉSUMÉ
Les protocoles classiques de caractérisation de terrain et de mesure en laboratoire développés pour la conception géotechnique numérique des massifs rocheux homogènes ne sont plus adéquats pour les excavations profondes dans des massifs rocheux complexes et hétérogènes qui contiennent des veines hydrothermales et d'autres types de structures intrablocs. Dans cet article, les méthodologies de caractérisation de terrain et en laboratoire pour les massifs rocheux complexes sont discutées, avec un accent particulier sur l'importance de l'enquête minéralogique tant pour les matériaux de la matrice et de la veine. Les possibilités de modélisation numérique en continu et discontinu sont également discutées en fonction de la disponibilité de différentes données de terrain ou de laboratoire. Enfin, une étude de cas d'essais de laboratoire de résistance à la compression non confinée sur trois unités lithologiques du gisement de skarn Legacy est présentée pour démontrer les influences d'affaiblissement et de renforcement que les structures intrablocs peuvent avoir sur les propriétés de rigidité et de résistance maximale.

1 INTRODUCTION

The mechanical properties of intact rock and parted discontinuities are key components that control rockmass behaviour in homogeneous lithologies, which are the basis of the vast majority of field characterization protocols and laboratory measurement approaches in rock mechanics. While effective in many cases of surface and underground excavations, these approaches are not adequate for particularly deep excavations in heterogeneous rockmasses, such as those with hydrothermal veins, stockwork or other types of intrablock structures.

Accounting for intrablock structures in rock engineering design has become critical for the safety and economic successes of excavations such as Andean base tunnels, deep geological repositories, deep open pit mines, and large underground sublevel and block cave mining operations. Inaccurate rockmass characterization that leads to inadequate ground support has been documented to increase worker safety risk related to ground failure. For example, from 2000-2014, 45 fatal injuries occurred in Ontario, of which 8 (18%) were caused by fall of rock (MOL 2015). While the number of injuries associated with rock falls has decreased since the mid-1900s with improvements to excavation and ground support, significant work remains to achieve a zero harm workplace.

In this paper, a methodology is presented to address the challenge of complex rockmass characterization, which incorporates the mechanical properties of intrablock structures at the rockmass (excavation) and laboratory specimen scales, before translating these observations into input parameters for geomechanical numerical models.

The rockmass scale approach begins with the Composite Geological Strength Index with validation from and application to tunnel and mine excavations (Day et al. 2019), which provides data that is suitable for continuum models where rockmass structures are represented implicitly through the constitutive models properties of the materials. Additional geometric and geomechanical data of rockmass structures may be collected in the field to provide some data for discontinuum models where rockmass structures are modelled explicitly or discretely; however, laboratory testing is necessary to collect all required data that captures the behaviour and geomechanical properties of natural fractures and intrablock structures. A case study of Unconfined Compressive Strength (UCS) laboratory tests on veined rocks from the Legacy skarn ore deposit in northwestern New Brunswick, Canada, is presented in this paper to illustrate several influences that hydrothermal veins have on homogeneous intact rock properties.

Intrablock structures that remain unbroken in diamond drill core can have, depending on mineralogy and structural character, either a weakening effect on overall rock block strength or can strengthen the rock as the structure acts to arrest propagating damage.

2 ROCKMASS CHARACTERIZATION FOR SITE INVESTIGATION AT THE EXCAVATION SCALE

Many conventional site investigation programs are designed to collect data through the lens of empirical classification parameters; however, this does not satisfy the input parameters needed for a sophisticated numerical approach. Particularly for block cave mining, the collection and use of high-quality geotechnical data and accurate prediction of fragmentation have recently been highlighted as two significant challenges in industry (Chitombo 2010). Improvements to numerical geotechnical design must begin with effective site investigation and field data collection programs.

This paper discusses multiple methods that are available to integrate intrablock rockmass structures into various stages of geotechnical design of deep excavations in complex rockmasses. These stages include (i) site investigation and field data collection from outcrops and drill core; (ii) laboratory testing for both mineralogy assessment at hand sample, millimeter-, and micrometer-scales, and geotechnical intact compressive, tensile, and discontinuity direct shear tests; and (iii) numerical modelling with options for continuous and discontinuous methods. A workflow is presented in Figure 1.

For site investigation, the Geological Strength Index (GSI) (Hoek et al. 2013) and the Generalized Hoek-Brown strength criterion (Hoek et al. 2002) continue to be effective methods to assess conventional rockmasses comprised of intact rock and interblock structures (traditional fractures such as joints and bedding) for continuum numerical models with implicit rockmass structure. GSI is designed to characterize and quantify rockmass quality, in terms of joint condition and amount of structure, during field observations at rock outcrops and excavation faces. To characterize complex rockmasses at the field rockmass scale, the Composite GSI (CGSI) methodology and new GSI chart by Day et al. (2019) that includes intrablock structures can be used to evaluate multiple suites of rockmass structure (any combination of interblock or intrablock structures). Adapting GSI to complex rockmasses retains the benefits of the system that enable calculation of parameters for the Hoek-Brown criterion that can be input directly into numerical models. It is also possible to collect GSI and CGSI data during geotechnical core logging (Day et al. 2015).

For more advanced discontinuum numerical models where rockmass structure is modelled discretely, additional rockmass properties must be considered during rockmass characterization: geometry of structures (e.g. orientation, spacing, and persistence) and mechanical properties (stiffness, strength, and post-peak dilation). Geometric properties are collected in the field, while mechanical properties can be estimated in the field or measured in the laboratory. For rockmass structures, the required mechanical parameters are normal stiffness, shear stiffness, shear strength (in Mohr-Coulomb or Barton-Bandis criteria parameters), and dilation. Friction angle (ϕ, part of shear strength) can be estimated using the relationship between Barton's joint roughness (J_r) and joint alteration (J_a) parameters, where $\phi = \tan^{-1}(J_r/J_a)$ (Barton et al. 1974). Many of the Barton-Bandis shear strength criterion parameters are based on matching field observations to standard charts, and using a Schmidt Hammer to measure rebound stiffness (and make correlations to fracture surface strength) (Barton and Choubey 1977), which is useful for field-based characterization of fractures and can be used in explicit and discrete numerical models (e.g. RocScience 2015, Itasca 2014). This, combined with direct shear testing of fractures to measure normal and shear stiffness, provides mechanical property information for modelling discrete or explicit structures.

3 ROCKMASS CHARACTERIZATION AT THE LABORATORY SCALE

When considering veins and other intrablock structures individually, field characterization using the Barton-Bandis criterion is not suitable since the criterion does not allow for nonzero cohesion or tensile strength. At this time, laboratory direct shear testing of intrablock structures is a relatively new area of interest (e.g. Day et al. 2017, de los Santoz Valderrama 2011, and current research by the first author) to meet the demand for mechanical properties of these features that is necessary for discrete or explicit modelling.

An alternative solution to laboratory measurement of intrablock structures in direct shear is to target these features in intact laboratory tests, including UCS, axisymmetric triaxial, and tensile tests. Stiffness properties and strength envelopes can then be defined and fit to constitutive models, such as the Generalized Hoek-Brown criterion (Hoek et al. 2002) in numerical models.

Several studies have explored effects of intrablock structures on laboratory tests, including UCS (Bewick et al. 2015), axisymmetric triaxial (Turichshev and Hadjigeorgiou 2016), and direct tensile (Jacobsson et al. 2012). These results focus on conventional parameters for deformation and strength (peak and residual) but provide limited interpretations regarding influences of mineralogy and alteration. Ghazvinian (2015) highlights the importance of high-quality and consistent laboratory protocols for intact rock with variable results from homogeneous rocks tested at several labs, which emphasizes the need for rigorous evaluation and implementation of high testing standards for the heterogeneous and anisotropic rocks. It is important to select and test samples with varying amounts of intact mineral grain matrix and intrablock structures (at various orientations) to define the full stiffness and strength variability. This intact test data from UCS, triaxial, and tensile tests of complex rocks can then be sorted by failure mode, through the intact rock matrix versus structural failure through veins, and generate distinct failure envelopes (Figure 2). These appropriately sorted failure envelopes and associated Hoek-Brown criterion properties can then be used for both continuum and discontinuum numerical modelling approaches.

3.1 Case Study: UCS Tests on Legacy Skarn Deposit

The case study of the Legacy skarn deposit presented in this paper presents some results of mineralogical analyses and UCS tests of homogeneous (matrix-type) and veined (vein-type) specimens from three different lithological units. The mineralogy analyses provide key insight into the behaviours of the veined rocks compared to their matrix-type counterparts.

The Legacy copper-silver skarn ore deposit is located in northwestern New Brunswick, Canada. Its lithological units are Devonian to Ordovician in age and are part of the Matapedia Group and the McKenzie Gulch Porphyries (Derosiers 2012). The Matapedia Group hosts the center of the skarn deposit and includes altered and stockwork veined limestone skarn, as well as calcareous mudstone, which are both discussed in this study. The McKenzie

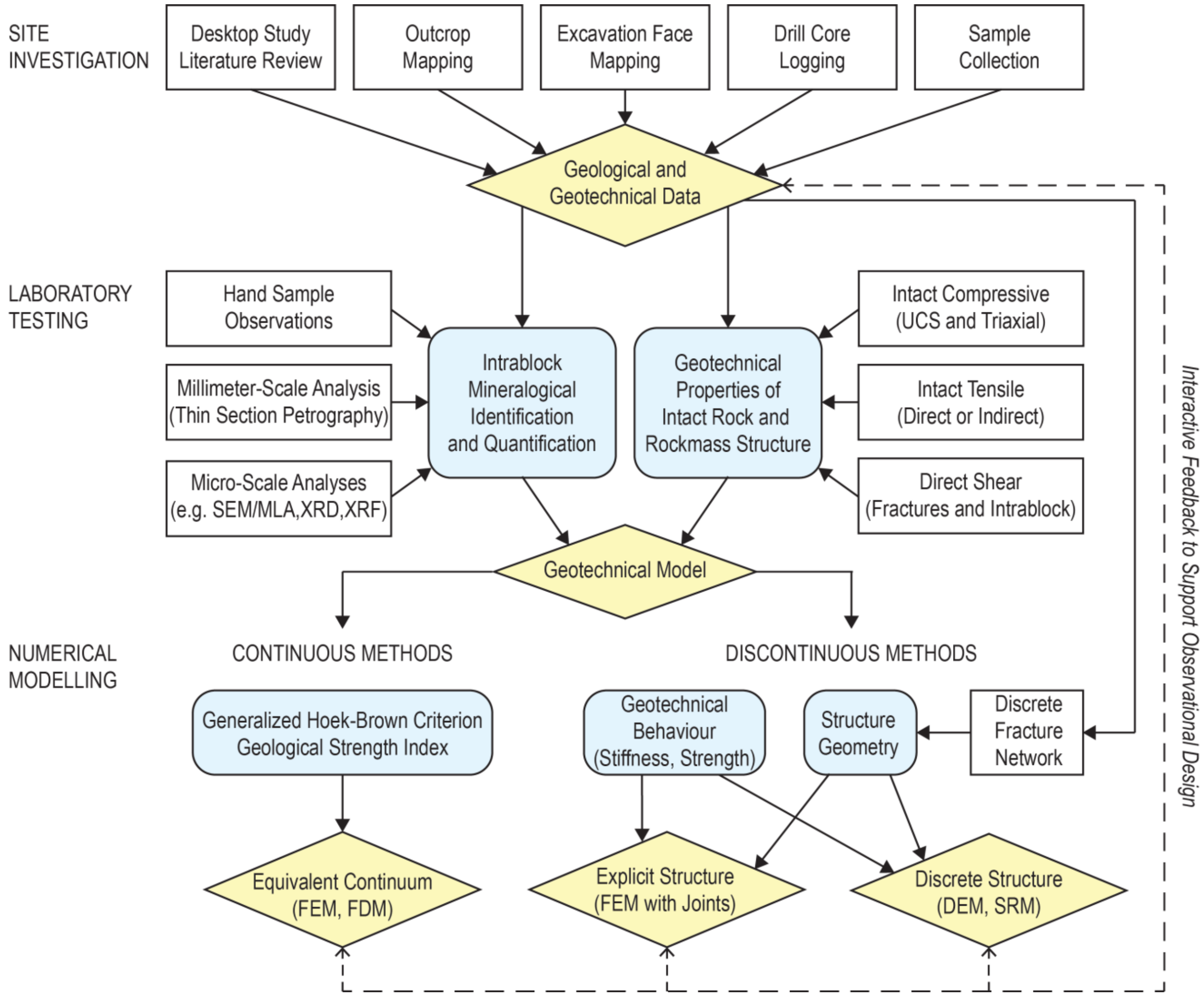


Figure 1. Workflow of data collection and analyses for numerical geotechnical design of excavations in complex rockmasses

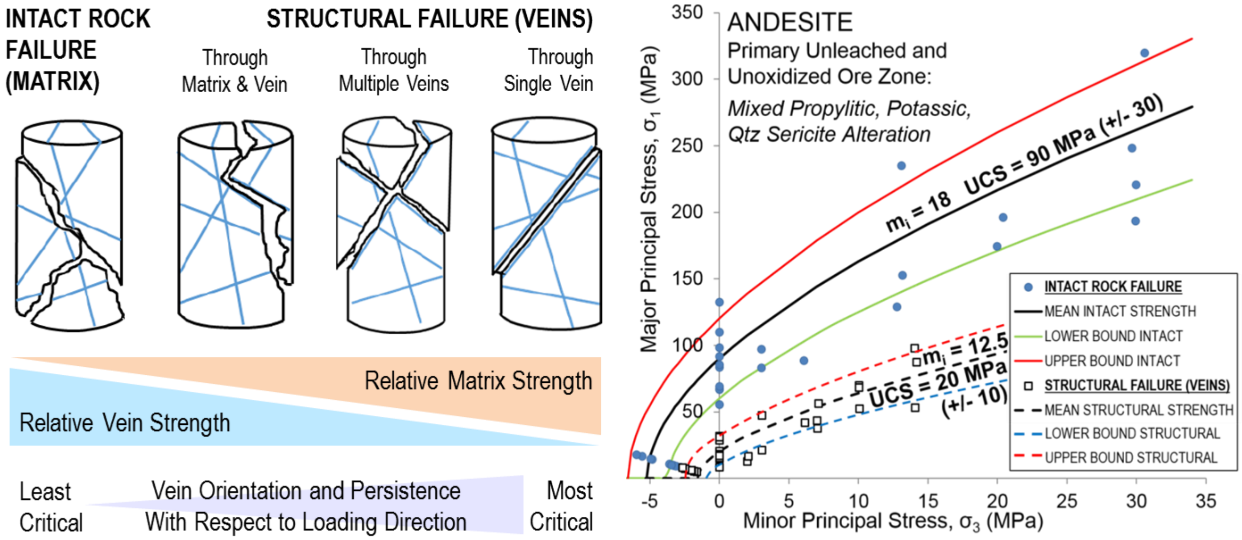


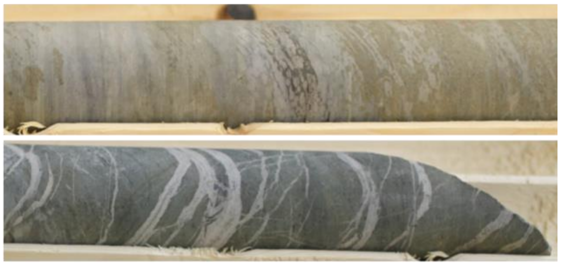
Figure 2. (left) Range of failure modes in UCS tests of veined rock specimens; (right) Hoek-Brown strength criterion envelopes for a hydrothermally altered andesite, with failures sorted through intact rock (solid lines) or weakening hydrothermal vein-type intrablock structure (dashed lines)

Gulch Porphyries host multiple granodiorite units with different zones of alteration. The quartz-plagioclase granodiorite in a zone of potassic alteration is also discussed in this study. Example drill core samples of these three lithological units are shown in Figure 3.

The mineralogical investigation used hand sample observations, thin section petrography, micro-X-Ray Fluorescence (µXRF) and powdered X-Ray Diffraction (XRD). The matrix and vein mineralogies are discussed in the following section.

The UCS tests were performed using a servo-controlled, hydraulic MTS 815 Rock Mechanics Testing System, and strains were measured using a set of three axial extensometers (axial strain) and one circumferential chain extensometer (lateral strain), and following the ASTM D7012 standard (ASTM 2014). The loading rates of the specimens were initially controlled by the axial extensometers up to 67% of the peak strength, and then switched to circumferential strain control. The UCS specimens are NQ size drill core (47.6 mm diameter) with a height to width ratio of 2.5:1. Stiffness (Young's Modulus) and peak strength of select specimens are discussed in the following section.

a. Skarn & Stockwork



b. Granodiorite

c. Calcareous Mudstone

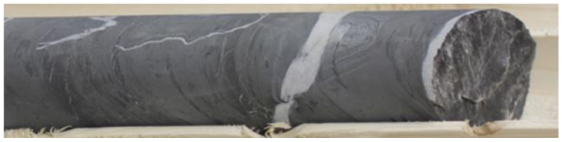


Figure 3. Drill core (NQ, 47.6 mm diameter) examples of rock units in this study from the Legacy skarn deposit

3.1.1 Mineralogy Investigation

The matrix of the garnet-pyroxene skarn unit contains almandine, diopside, and albite. Stockwork veining is abundant and is composed of quartz with minor sulphide mineralization (2-10 mm thick). The granodiorite unit matrix contains orthoclase and quartz with minor amounts of biotite. In this paper, only the results of the red granodiorite (dominated by potassic alteration) are shown and discussed; UCS test results of three alteration phases of the granodiorite are presented by Clark et al. (2019a). The veins within the granodiorite unit display little geometric variability (often single veins, 1-2 mm thick) and are composed primarily of calcite. Lastly, the calcareous mudstone unit matrix contains an abundance of clay minerals with calcite. The veins in this unit display the greatest geometric variability, ranging from single to multiple calcite veins (5-25 mm thick).

XRD results of the crystallographic mineralogy of the red granodiorite matrix and vein components are shown in Figure 4. Petrographic analysis of thin sections and µXRF elemental map data (not shown) agree with the XRD results (Clark et al. 2019b). The photographs and thin sections in cross-polarized light of the calcareous mudstone and skarn units in Figure 5 show calcite and quartz are the dominant vein minerals in these units, respectively. This is supported by the accompanying µXRF elemental maps that highlight high calcium content in the calcareous mudstone veins, and high silicon content in the skarn stockwork veins.

3.1.2 UCS Test Results

The UCS test results for all three units demonstrate the significant influence that veins can have on stiffness and strength compared to matrix-type specimens. Example stress-strain test results for one matrix-type and one vein-type specimen for each unit are shown in Figure 6, accompanied by photographs of the corresponding specimens after the tests. Young's Modulus and peak strength values are listed in Table 1.

In all cases, the vein-type specimens exhibited a softer response in terms of axial strain, which correspond to lower Young's Modulus values. This is attributed to contrasts in stiffness between matrix and vein materials; during loading, additional axial strain can be accommodated by the vein material itself or the contact zone between the matrix and vein materials during pre-peak deformation (which is captured in the Young's Modulus calculation). In these tests, the largest difference in Young's Modulus between matrix and vein type specimens occurs in the granodiorite unit, which also has the greatest contrast in mineral hardness and strength.

Regarding peak strength, veins are conventionally considered to weaken rocks. However, only the granodiorite was weakened in these tests, while veins actually strengthened the peak strength of the calcareous mudstone and skarn units. The veined granodiorite specimen failure occurred primarily along a critically oriented vein of weaker infill minerals (primarily calcite), which are clear factors that would weaken a specimen.

The vein material in the calcareous mudstone specimen is also calcite; however, the matrix material is substantially weaker than the granodiorite. This comparison demonstrates that weak (and soft) vein infill mineralogy such as calcite does not necessarily mean veins will have a weakening effect on the overall rock strength—comparing vein to wall rock strength is critical.

In the skarn stockwork specimen, the failure occurred primarily along a critically oriented vein, similar to the veined granodiorite specimen. However, in this case, the veined skarn specimen was nearly 70 MPa stronger than the matrix specimen. This difference in behaviour is primarily attributed to the stronger quartz-dominant vein mineralogy in the skarn, which dominates the expected weakening behaviour of a critically oriented vein.

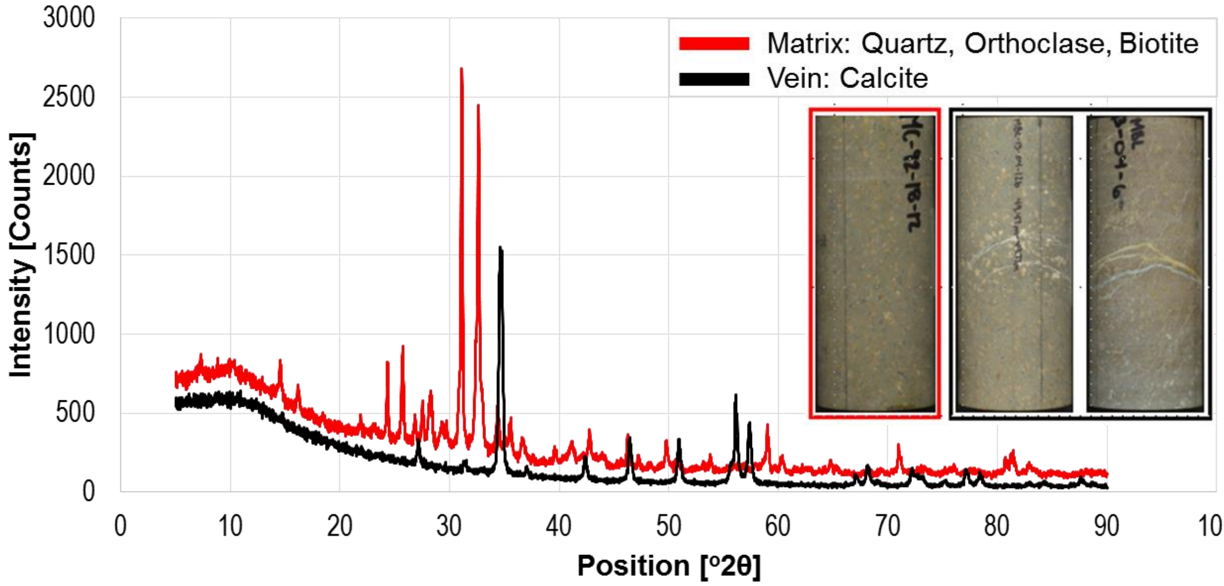


Figure 4. X-Ray Diffraction (XRD) results showing mineralogy of the red granodiorite matrix and veins

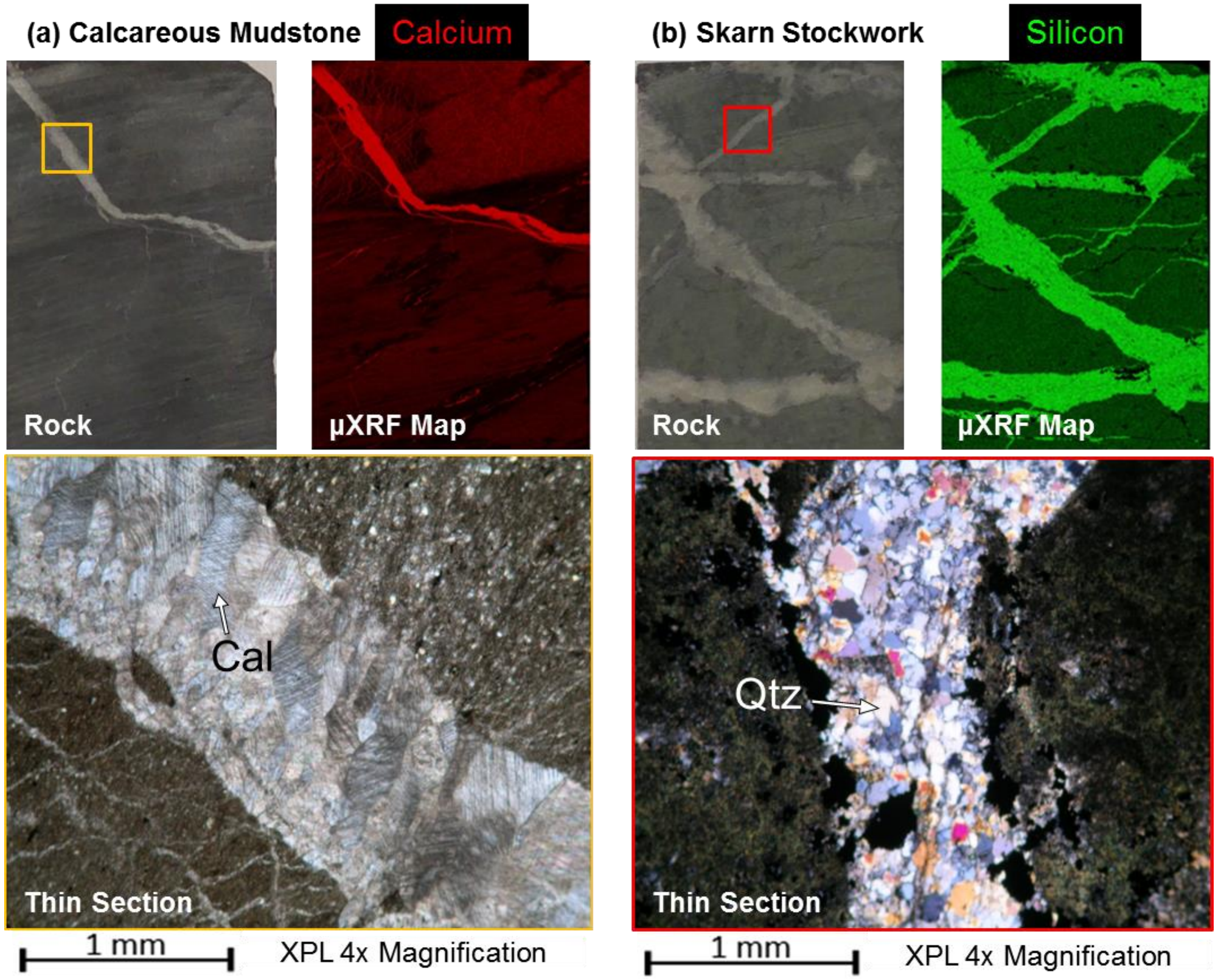


Figure 5. Thin sections in cross-polarized light (XPL) and micro-X-Ray Fluorescence (µXRF) maps highlighting dominant elemental compositions for veins in (a) calcareous mudstone and (b) skarn stockwork units

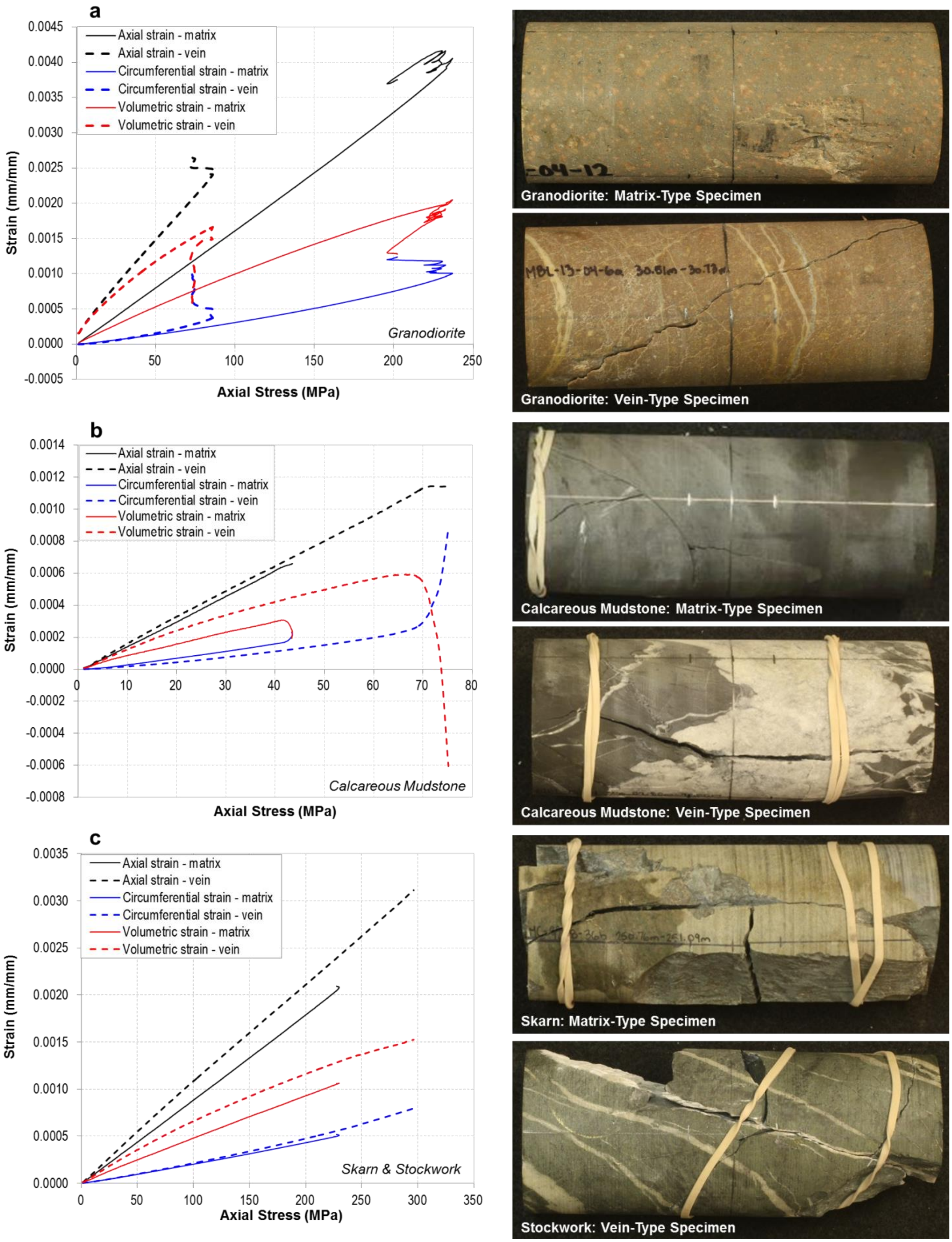


Figure 6. UCS test results for a matrix and a vein type specimen for each of (a) red granodiorite, (b) calcareous mudstone, and (c) skarn stockwork units, specifically showing the stress-strain extensometer measurements, and photographs of the corresponding specimens after testing

Table 1. Stiffness and peak strength of UCS specimens

Rock Unit	Young's Modulus (MPa)	Peak Strength (MPa)
Red Granodiorite, matrix	61,600	237
Red Granodiorite, vein	38,000	86
Calcareous mudstone, matrix	64,900	43
Calcareous mudstone, vein	62,400	75
Skarn, matrix	111,700	230
Skarn, stockwork vein	96,200	296

4 DISCUSSION

Laboratory testing of intact rock specimens that contain veins in addition to their homogeneous matrix-only counterparts for geotechnical characterization of complex rockmasses is a very important component of numerical based engineering design. Mineralogical analyses provide important context and aid in the interpretation of geomechanical behaviours on a geological basis. Overall, considering the geological model throughout geotechnical characterization will greatly improve the understanding of complex rockmasses and should result in more accurate stability and behaviour predictions of excavations in these environments.

For numerical engineering design, both strength modification approaches at rockmass and laboratory scales are possible with existing geomechanical numerical software and constitutive models. Field evaluation tools for complex rockmasses are available for continuum models. For discontinuum models, laboratory testing is currently needed to appropriately measure geomechanical properties of intrablock structures. Geometric properties of intrablock structures are also needed for discontinuum models, which can be measured in the field from excavations, outcrops, and to a limited extent from drill core.

For UCS testing in complex rockmasses, it is important to select and test specimens that are homogeneous (matrix-type) as well as heterogeneous (vein-type), when possible, to develop a more robust understanding of the behavioural variability between these materials. In this case, rockmass structure in models can be considered by either using the material constitutive model (from vein-type test results) or as discrete structural elements (from matrix-type results, where veins are considered at the rockmass scale). When matrix-type specimens are not available, laboratory testing protocols must adapt to test vein-type samples, and use these results in constitutive models. Veins can then be included as part of the intact material, while joints and other fractures can be modelled discretely.

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