Application of Systematic Point Load Testing to Characterization of Massive, Veined Orebodies

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Outline

- Introduction to block caving
- Practical objectives
- Geomechanical setting and workflow
- Systematic point load testing
- Block model development
- Application of advanced tools

Introduction to Block Caving

- See introductory video at this link

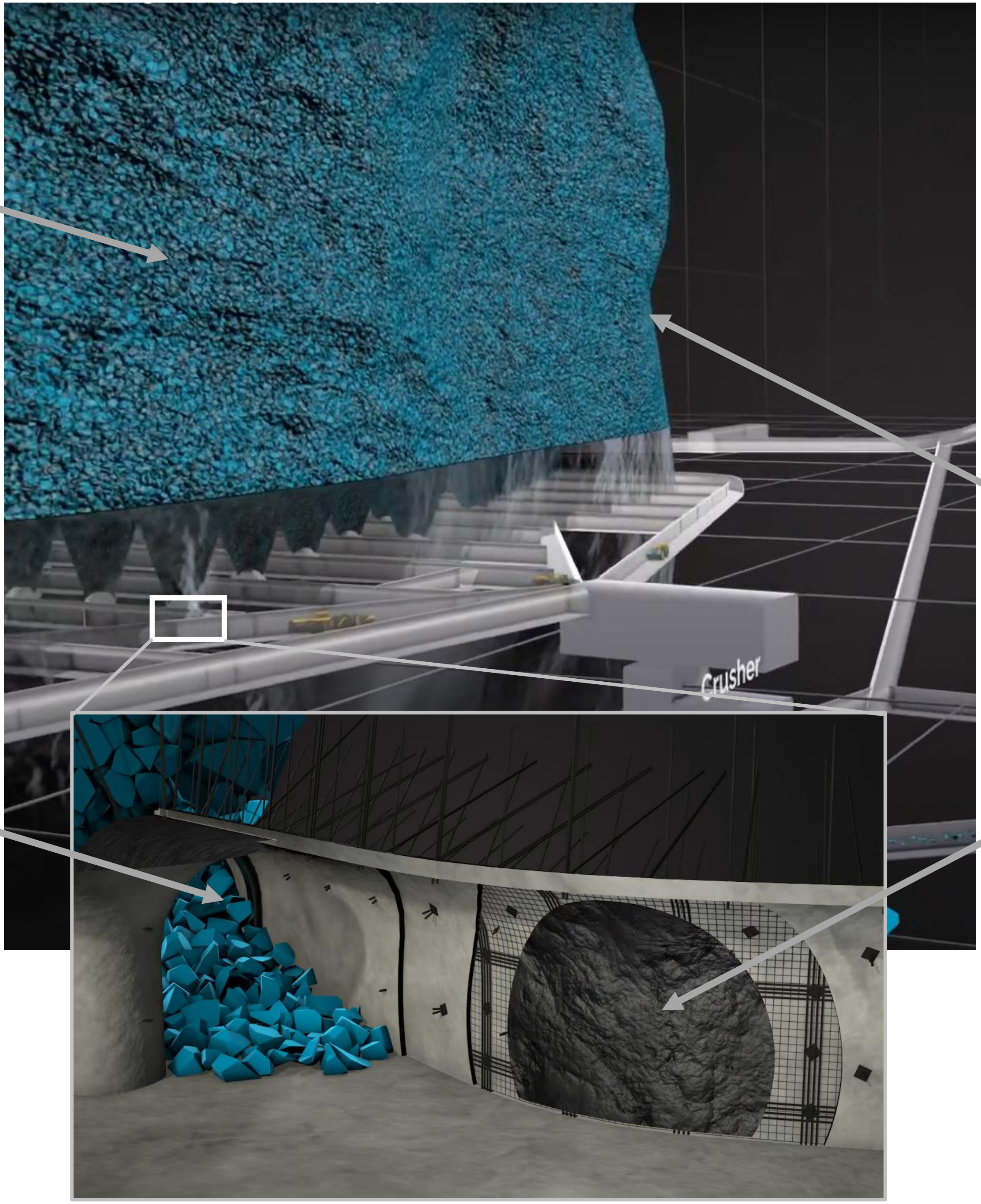
https://youtu.be/MWqMD85MVO4?si=aLVvv6xp4vLf_X6J

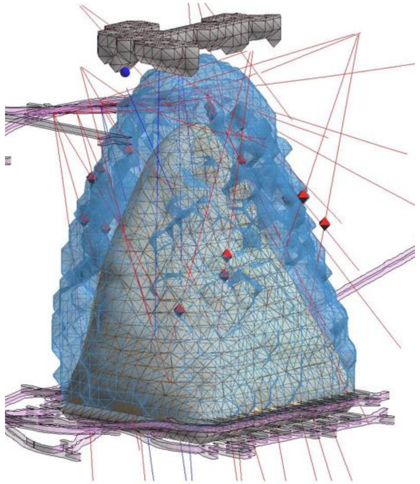
Practical Objectives

- Forecasting of cave mine performance and associated hazards:
  - Cave growth
    - Stalling
    - Deviation, necking and overhangs
  - Fragmentation
    - Fines generation and inrush
    - Coarse fragmentation and hangups
  - Footprint stability
    - Excessive spalling
    - Strainbursting

Inrushes of fines related to attrition of locally weak rock during drawdown

Drawpoint hangups related to locally strong rock and coarse fragmentation





Deviation of cave shape from vertical related to locally strong rock and low caveability

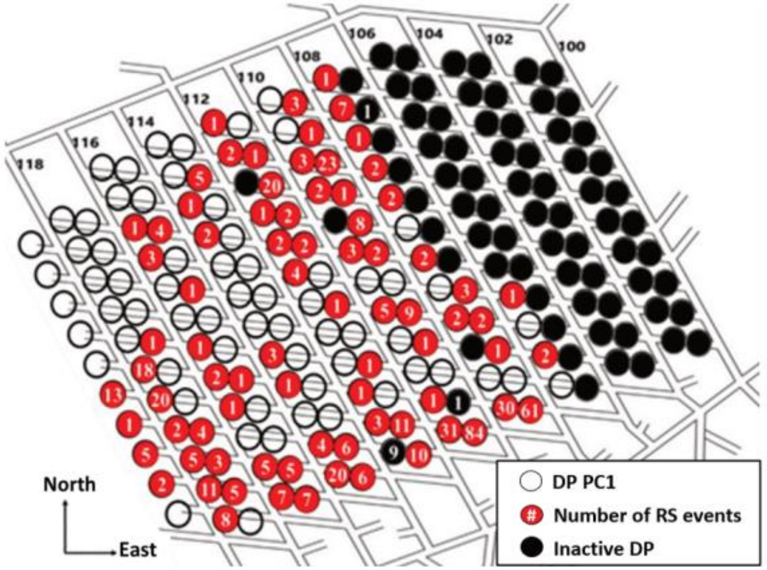
Spalling of extraction level related to locally weak rock in abutment stress zone

Practical Objectives

- We know that cave performance is strongly controlled by presence of locally weak or strong rock
- *Can we quantify strength heterogeneity at a higher resolution than lithology + alteration domain scale to improve forecasting?*

Inrush Forecasting Example

- Fines production and inrush risk is usually highest where pockets of weak rock exist near the outer perimeter of a cave
  - Examples: Cadia East PC1, Palabora Mine, Grasberg Block Cave, Argyle Mine
- This is because shearing is concentrated at the cave perimeter, where rock fragments grind past the static cave boundary and produce rock flour
  - Shearing also occurs internal to cave, especially if draw highly non-uniform (Pierce, 2010)
- Spatio-temporal trends in fines production and inrush potential have been successfully forecast at Cadia East and Grasberg Block Cave by combining:
  - Is50 block model
  - Flow simulation
  - Shear attrition model of Bridgwater et al (2003)



Cadia PC1 dry inrush event counts (Lett et al, 2022). The weakest rock is above the southern boundary.

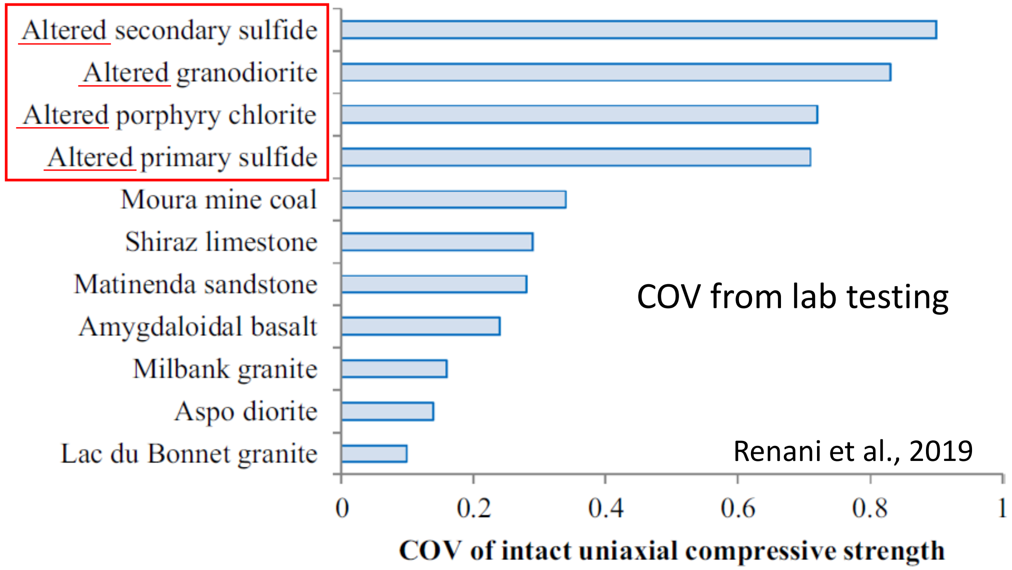
Geomechanical Setting and Workflow

Geomechanical Setting

- Deep, large porphyries commonly exploited by cave mining are generally massive and veined, with few open joints
- Strength cannot be estimated via traditional GSI/Hoek-Brown approach
- Spalling required in the cave back to achieve caving and fragmentation -> stress caving conditions
- Very large volumes to be characterized
- Role of veins must be carefully considered (in addition to joints and faults)

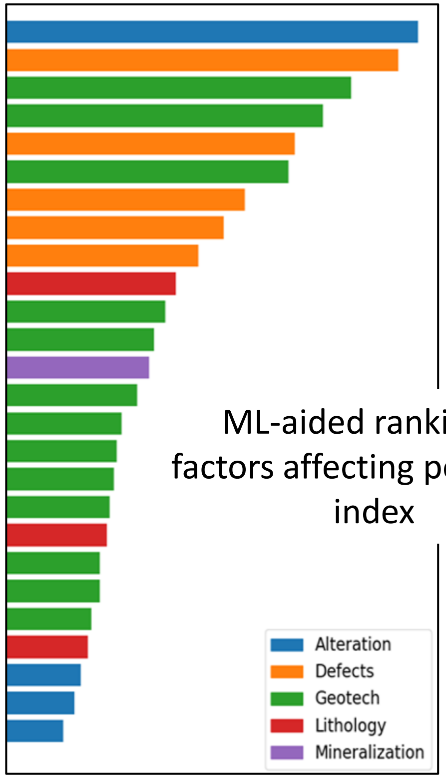
Geomechanical Setting

- Significant variability associated with hydrothermal alteration
  - Intensity of mineral replacement
  - Strength/intensity of veining
- Multiple factors simultaneously impacting strength: alteration, defects, lithology, mineralization
- Difficult to find correlations between individual logged quantities and intact strength
- Difficult to collect enough data to define the spatial variability over very large volume of interest



COV from lab testing

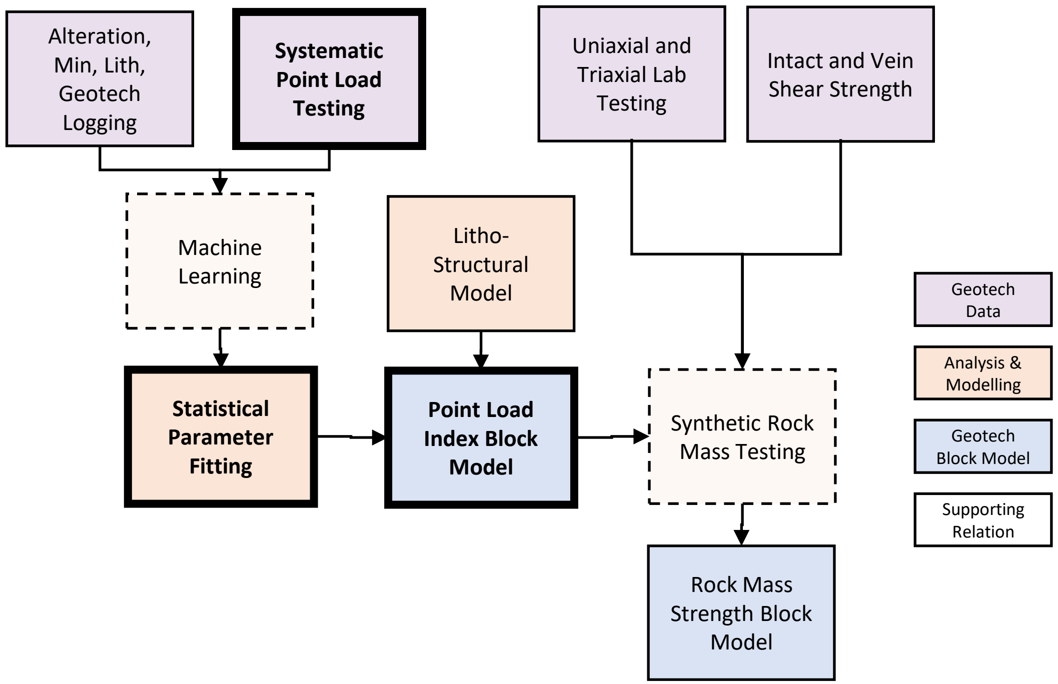
Renani et al., 2019



ML-aided ranking of factors affecting point load index

Workflow

- Main components
  - Systematic point load testing
  - Statistical parameter fitting
  - Block modeling of Is50
- Advanced components
  - Machine learning
    - To estimate Is50 in non-tested core
    - To better understand controls on intact strength
  - Synthetic Rock Mass Testing
    - To aid in production of rock mass strength block model
- Illustrated by application to Cadia East Mine (New South Wales, Australia)



Systematic Point Load Testing

Point Load Testing

- Point load testing offers a relatively quick and inexpensive means to indirectly measure the tensile strength of the rock
- Ubiquitous and well-known but suffers from a reputation of being imprecise and unsuitable for use in design
- In my experience, a reproducible and accurate point load data set can be obtained *if*:
  - Care is taken in sampling (effective, representative and systematic)
  - Test equipment is appropriately maintained, especially testing points
  - Testing practices follow the published standards (ISRM, 1989)

Systematic Point Load Testing

- Goal is to quantify strength in an unbiased manner over the widest possible area as opposed to precisely at a smaller number of discrete locations
- The procedures were first developed and applied to the study of rock strength variability at Niobec Mine (Pierce, 2014; Garza-Cruz and Pierce, 2016)
- Have since been applied to several orebodies, including Cadia East (Pierce et al, 2022), Red Chris, Ghaghoo, Renard, Henderson, Eleonore, Hermosa and Westwood (Bouzeran et al, 2019).

Systematic PLT: Procedures

Cadia East PLT Shed

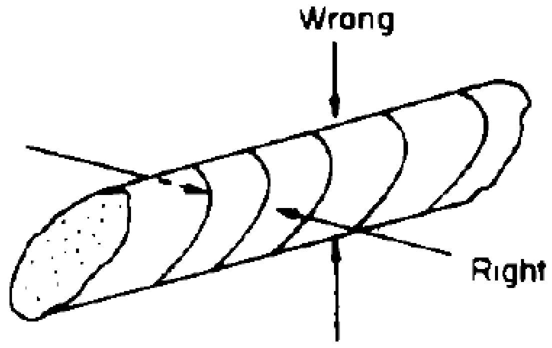
- ISRM standards followed
- Systematic testing involves the following additional steps:
  - Tests are conducted at regular, short intervals (typically 1-2m) rather than clustered around UCS tests for the purposes of correlation
    - Cadia East Mine conducted testing on 19 holes, resulting in 5,247 valid tests
  - Testing locations are marked on the core at strict, regular intervals, using a sleeve to mark the circumference of the core.
  - A single diametral test is conducted at each test location, with axial tests conducted periodically to check for anisotropy in strength.
  - Special consideration of healed structure and pre-existing breaks

Systematic PLT: Sample Selection Bias

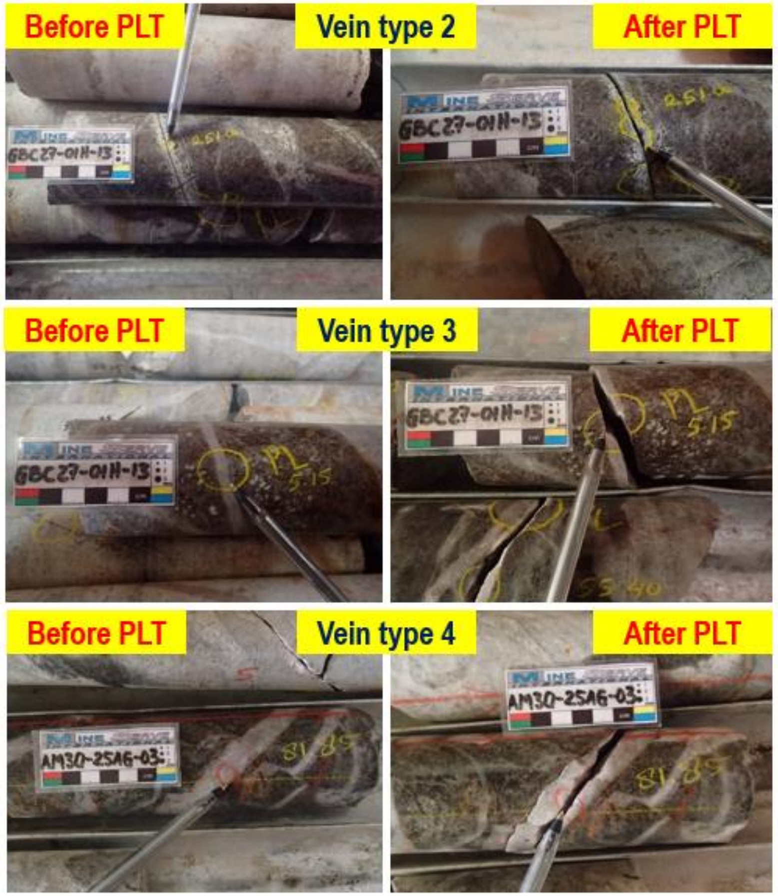
- Traditional sample selection campaigns (e.g. for lab testing) are often biased towards stronger, less defected rock due to
  - Ease of extraction
  - Difficulty in obtaining and successfully transporting adequately-sized samples
  - Classification schemes demanding “intact rock strength”
- Bias can also be introduced through what are referred to as ‘judgement samples’ where samples are deliberately selected based on their being representative of the lot (Lohr, 2019).
- Systematic point load testing aims to minimize sample selection bias through the use of regular, strict test spacings

Systematic PLT: Healed structure

- Healed structure (veins and other defects) often have lower tensile strength than the intact rock
- Are tested and characterized where present to quantify their impact on overall rock strength
- Requires alignment of the test platens to test the strength of the defect itself, as per ISRM standard



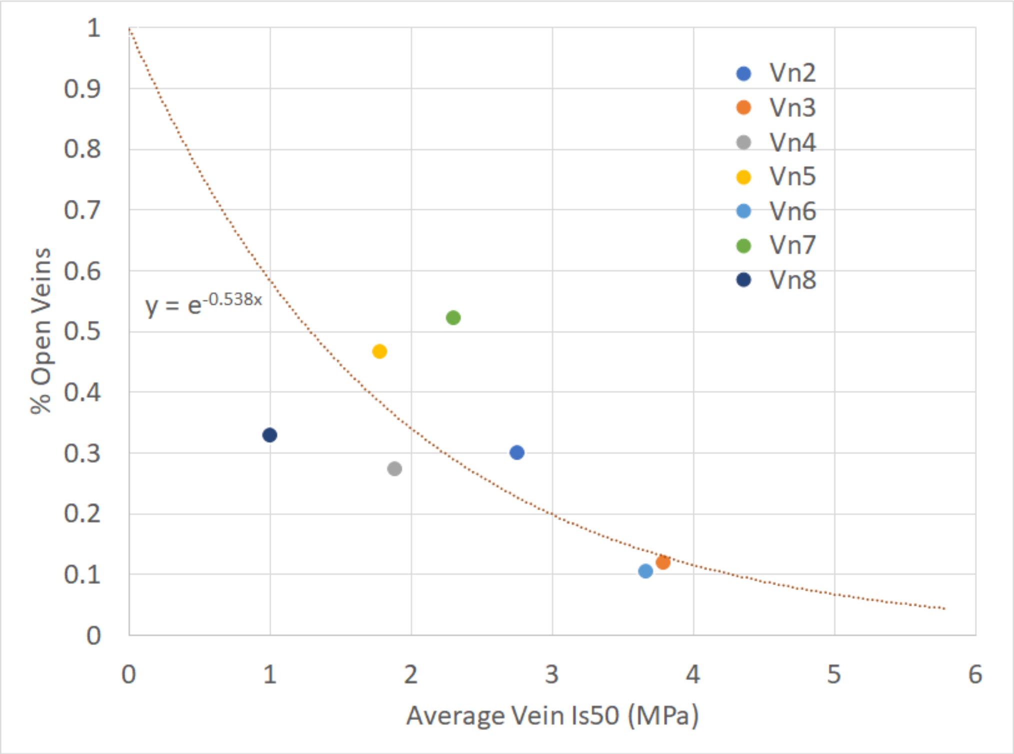
ISRM (1989)



Point load tests on veins

Systematic PLT: Pre-existing Breaks

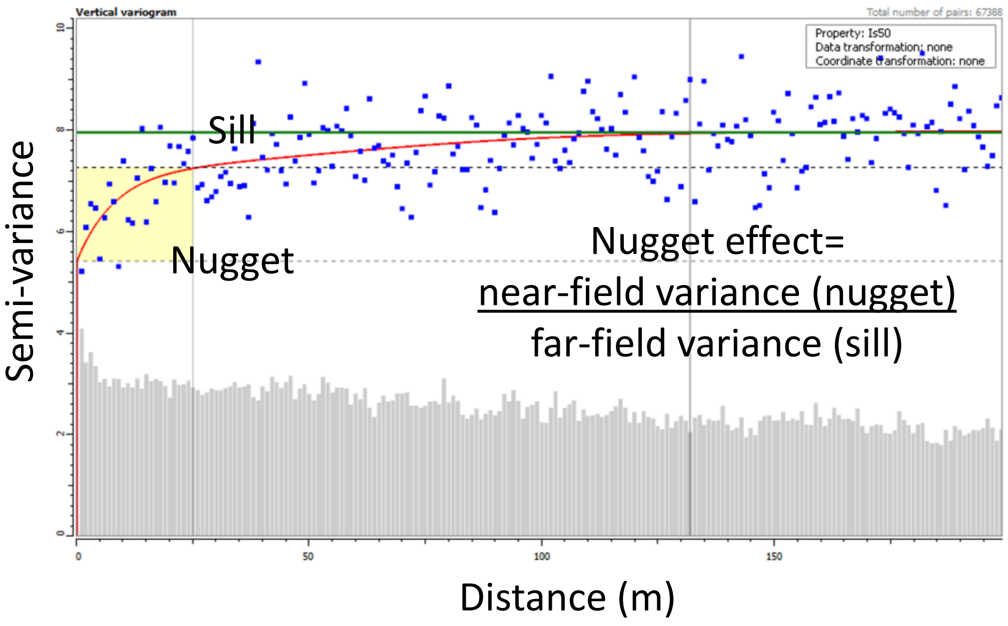
- Pre-existing breaks may be result of:
  - Natural open structure
  - Breaks induced by drilling and handling
  - Purposefully induced and marked breaks (e.g., at the end of a core run or to fit core into the box)
- Purposefully induced breaks ignored
- Breaks induced by drilling or handling are an indicator of low strength
  - Is50 should be estimated for these pre-existing breaks, e.g. based on interval logging of % open veins by mineralogy

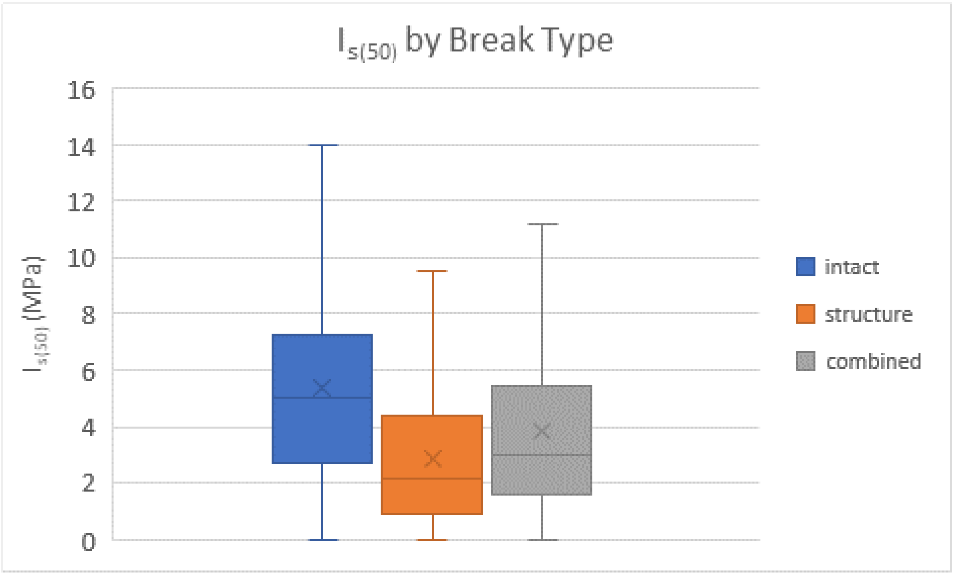


Correlation of vein vulnerability to drilling/handling-induced opening based on vein type (mineralogy) and average vein Is50 (from structural breaks) from a massive, veined copper-gold deposit.

Systematic PLT: Variability

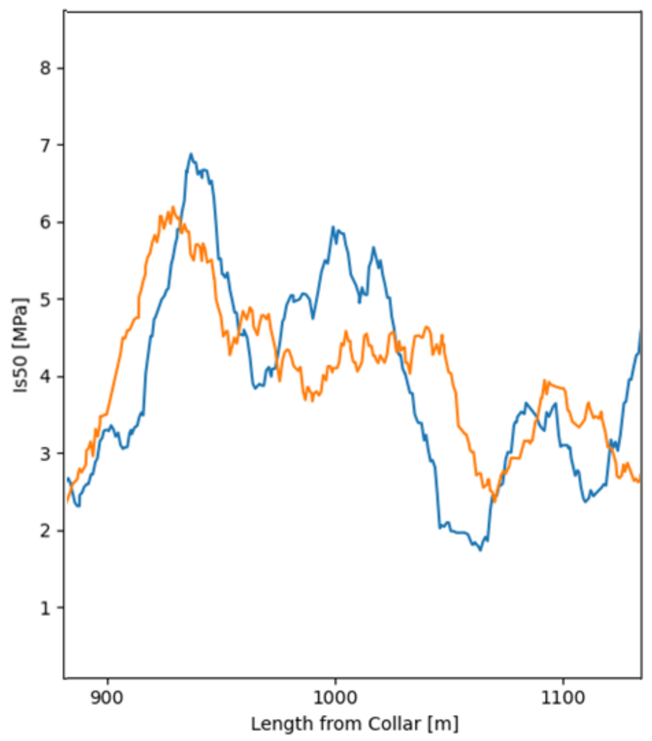
- Variogram analysis of point load indices reveals a strong nugget effect on the order of 60%
    - Nugget effect for gold grade commonly 30-50%, as high as 100% in some coarse gold and alluvial deposits
- Analysis of failure modes reveals that much of it can be attributed to the weak nature of veins and defects relative to intact rock
- Some of the nugget effect can be attributed to imprecision associated to the test method…



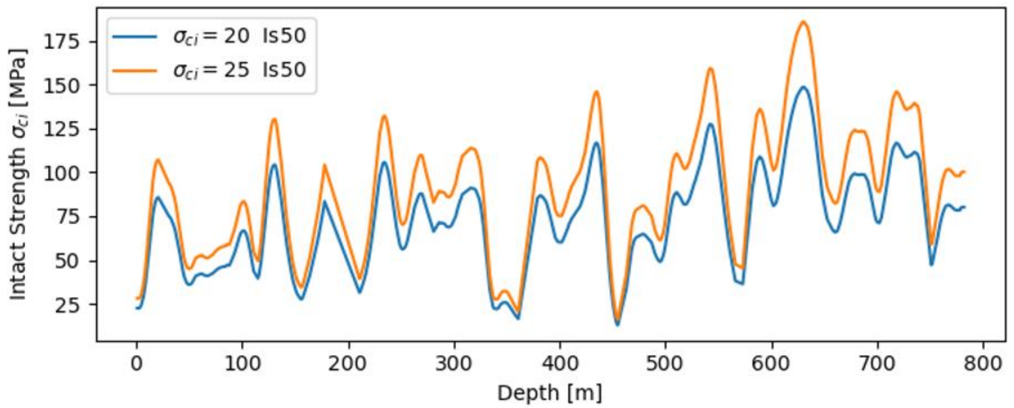


Systematic PLT: Precision and Accuracy

- Due to the high variability in tensile strength in altered rock it is not feasible to quantify precision through use of duplicates (e.g. as is done in grade sampling)
- There are other opportunities to quantify precision and accuracy of point load tests:
  - Perform tests along sub-parallel drill holes and comparing the trends in Is50
  - Convert downhole moving averages to UCS (e.g. using the typical conversion factor range of 20-25) and comparing these to lab tests
  - Testing of reference materials with a small, known variability in strength



Comparison of moving average point load indices from systematic testing of subparallel wedge holes.



Example of downhole variability in UCS estimated from a rolling average of systematic point load indices from testing at Cadia East (Pierce et al, 2022).

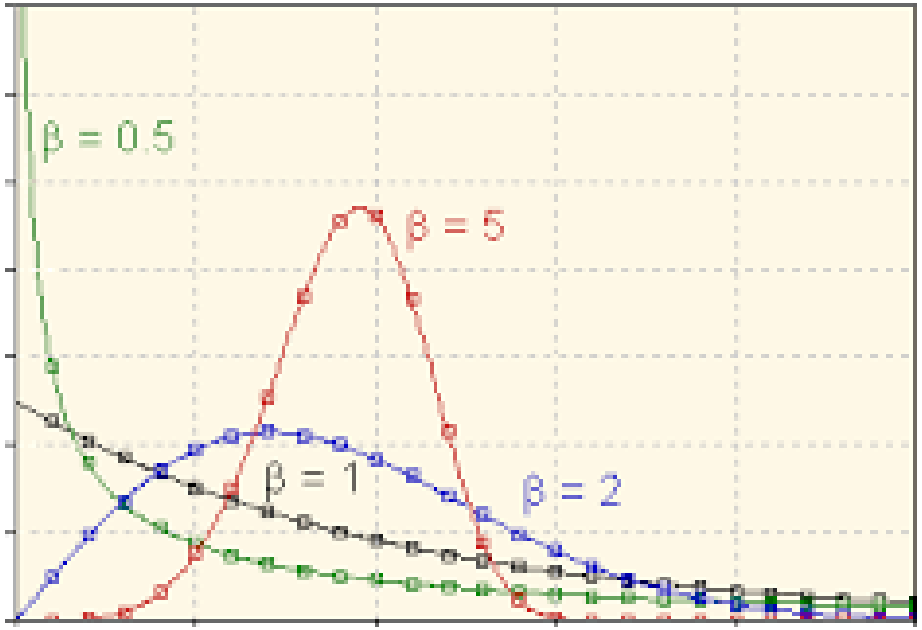
Systematic PLT: Statistical Parameter Fitting

- The Weibull distribution is used to describe the distribution of point load indices due to its versatility and flexibility.:

$$\text{PDF: } F(x)= (\beta/(\eta^{\beta}))\ (x^{(\beta-1)})\ (\exp(-((x/\eta)^{\beta}))$$

$$\text{CDF: } F(x)=1-\exp(-((x/\eta)^{\beta}))$$

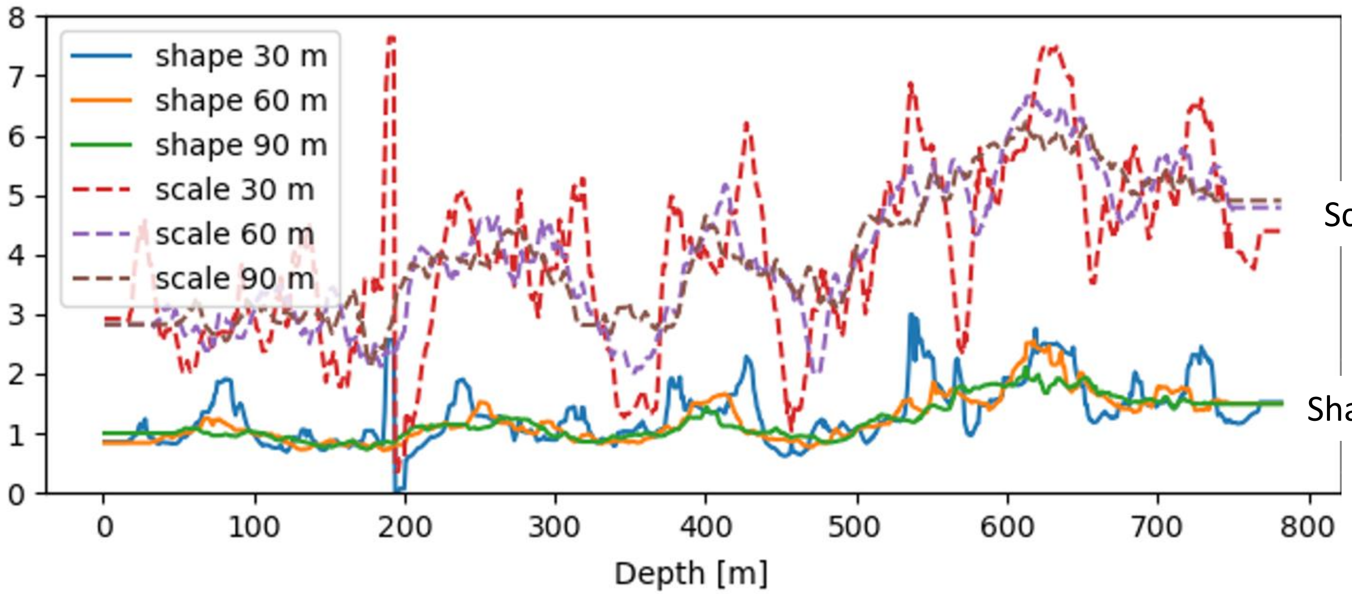
- The scale parameter η corresponds to the 63.2 percentile of the data
- The shape parameter β controls the skewness of the distribution and is sensitive to the level of defecting
    - A low shape parameter (<1-2) skews to the left and is typical of heavily defected rock
    - A high shape parameter (>3) is symmetric and is typical of non-defected rock



Weibull shape factor

Systematic PLT: Statistical Parameter Fitting

- Weibull distributions are fit to moving windows of point load index (30, 60, 90m)
  - A significant variability in 63rd percentile (scale factor) is commonly observed
    - Varies from ~1-8 MPa in Cadia East example below
  - Significant variability in distribution skewness (shape factor) is also typical
    - Ranges from 1 (exponential distribution) to 3 (normal distribution) in example below
- Weibull parameters are defined at 1m spacing down every drillhole for use in block modelling

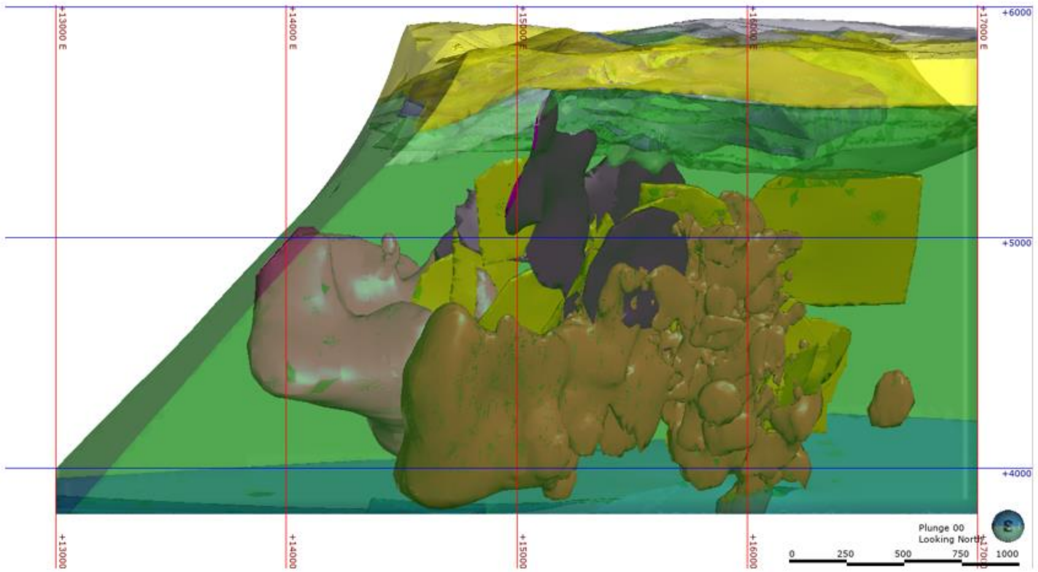


Scale factor (63rd percentile Is50, MPa)

Shape factor (defining skewness, >3 symmetric)

Block Modelling of Strength

- The Cadia East litho-structural model comprises 9 fault blocks and 13 recognized lithological domains
  - Formed a basis for statistical analysis of the Is50 Weibull parameters
  - Resulted in 10 sub-domains being selected for the Is50 block model
- The Cadia East deposit displays a strong sigmoidal-shaped trend along its length that is evident in both oriented structural (joints, faults) and mineralogical (veins) data
  - Used to control the orientation of the search ellipsoid
  - Further structural trends were defined to control the orientation of the search ellipsoids in applicable sub-domains
- Both Weibull scale and shape factor modelled to define distribution of Is50 in each block



Long-section view of color-coded sub-domains used for the point load index block model

Point Load Index Block Model (Mean Is50)

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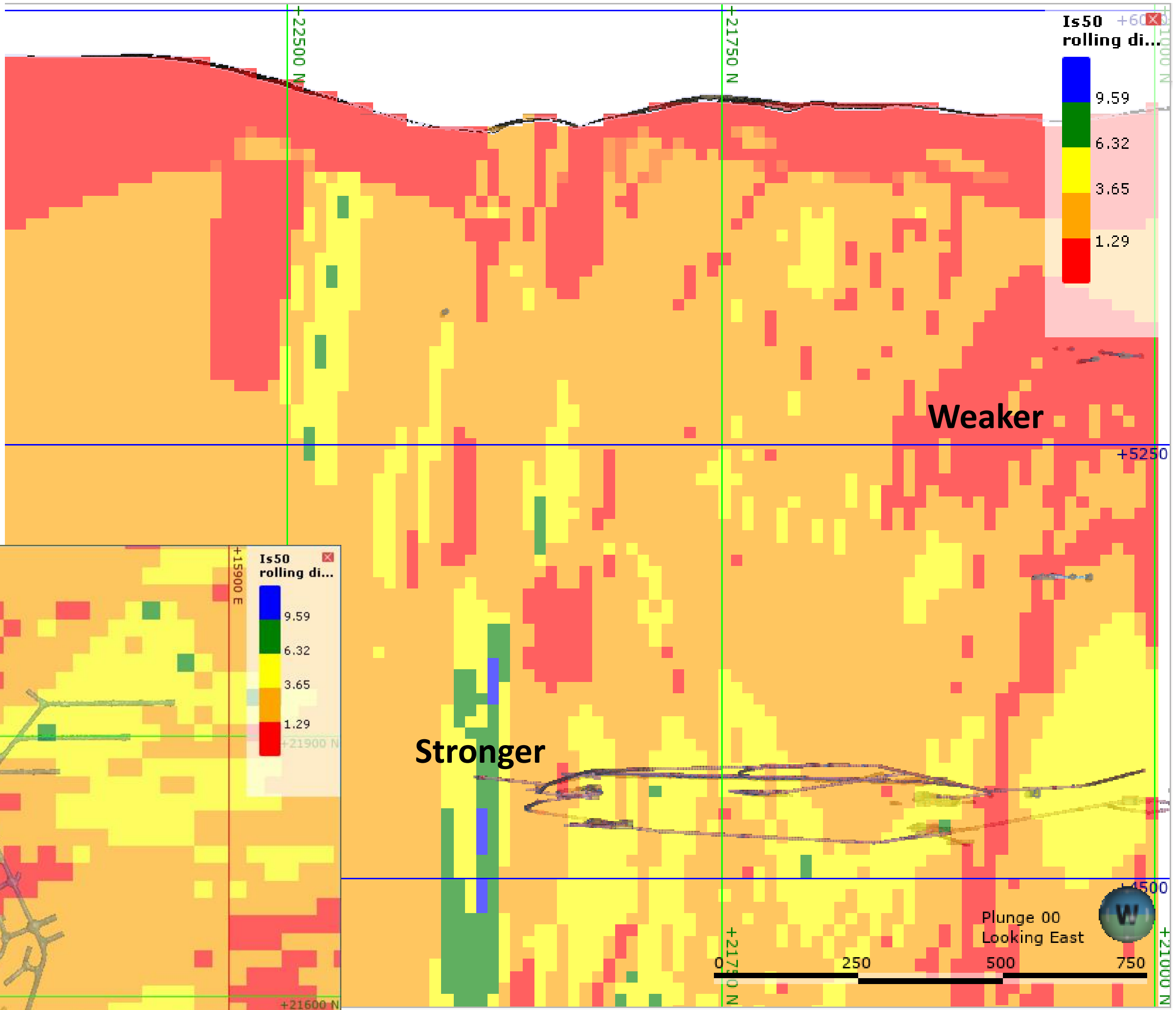

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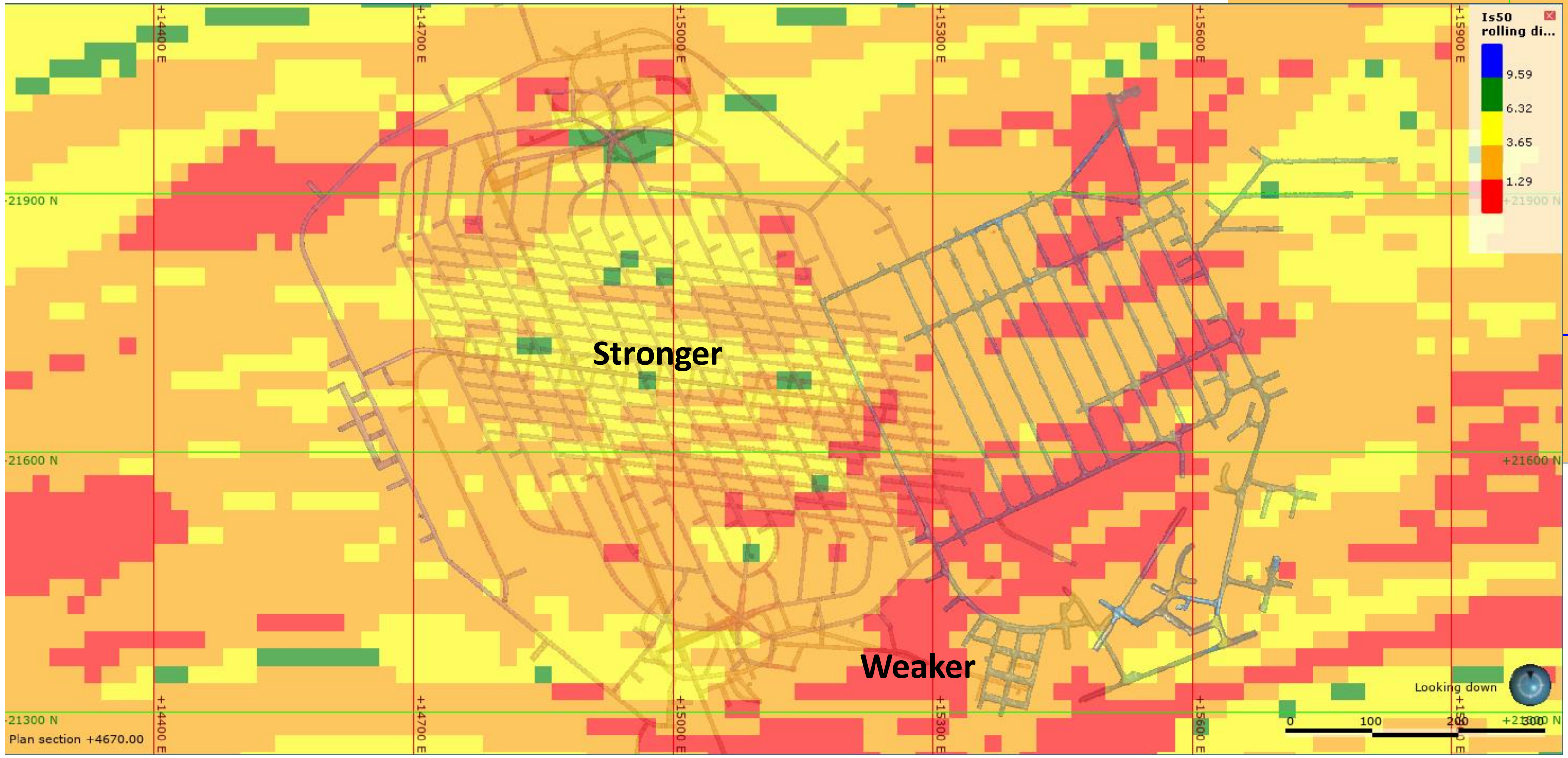

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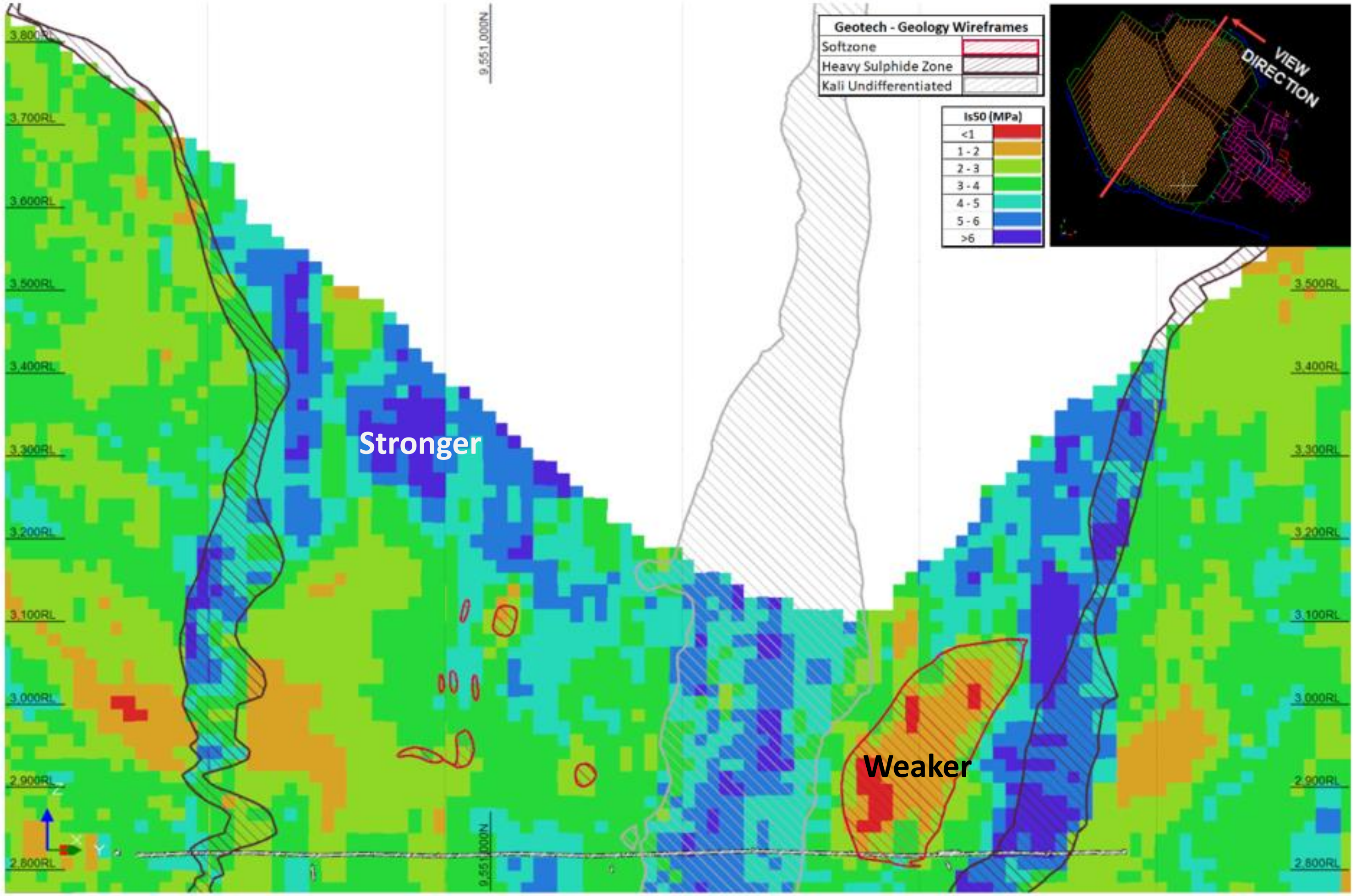
Other Examples: Grasberg Block Cave

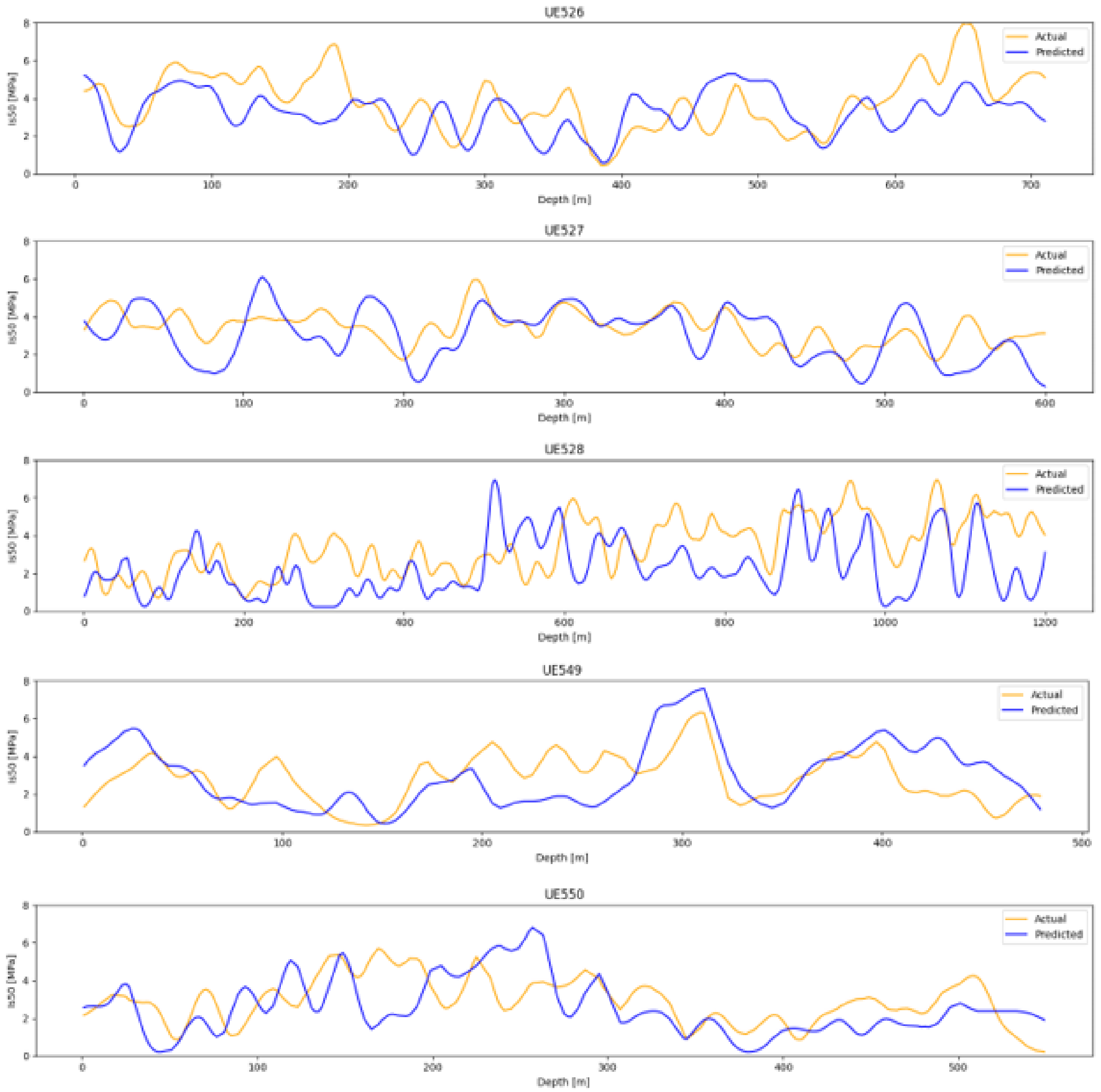
- Point load block model is an integral part of fragmentation forecasting workflow (FragPro; Pierce et al, 2022)
- Variability in Is50 results in high spatio-temporal variability in hangup frequency and fines production
- Is50 mixed along with grade as part of production simulations; exploring use in mill performance forecasting



Application of Machine Learning

Machine Learning

- Systematic PLT data collection covers only 1.3% of the 590 km of hole logged at Cadia East
- A random forest classifier was applied to predict point load index (Is50) along untested core (Thielsen et al, 2022; Pierce et al, 2022)
- The random forest model predicts the rolling average Is50 value within 1 MPa 48% of the time
- The model also gives insights into which core logging quantities have the strongest controls on rock strength
  - Top features were fracture frequency, RQD, density, alteration, mineralization, defect frequency



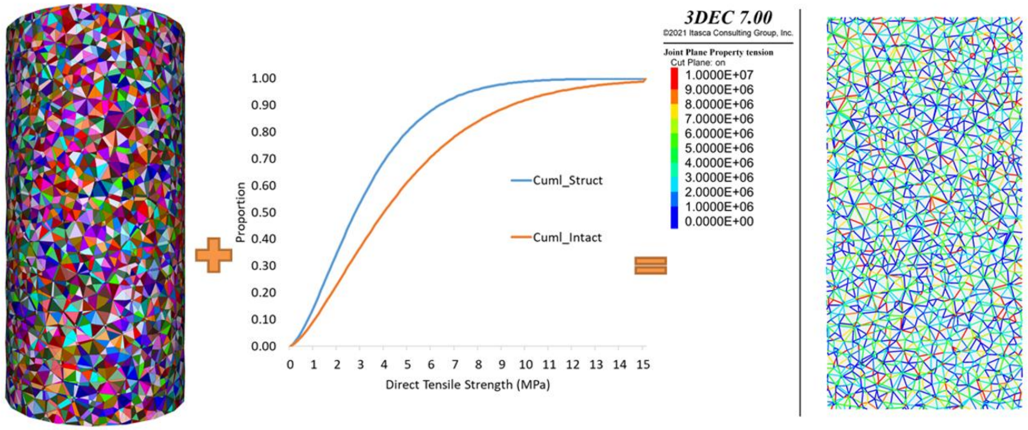
Machine Learning: Key Learnings

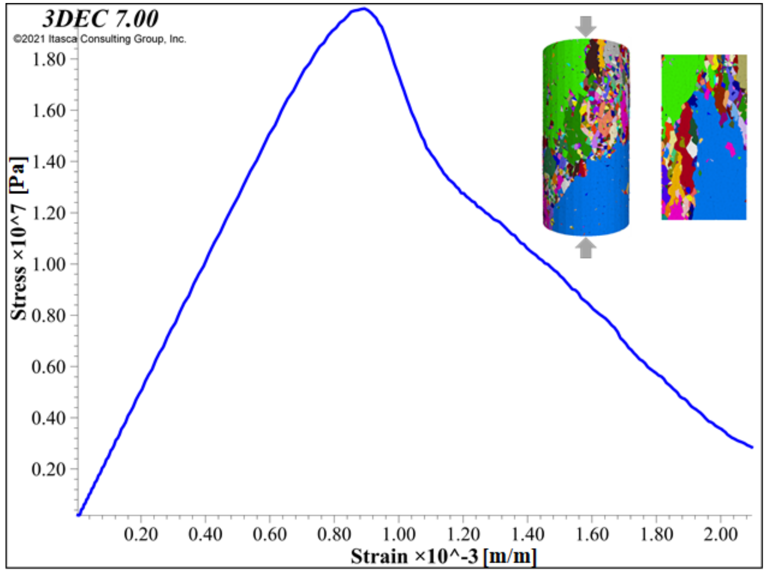
- Engineering of new features from the logged features is essential to creating a useful and accurate predictive model
  - For example, Alteration Strength Index defined as function of logged, intensity, order, and mineral types (Wyering et al, 2015)
- Effort is 90% data manipulation and homogenization and 10% machine learning training and evaluation
- Must seek to understand what controls prediction, not just use as a black-box
  - Can be challenging with random forest classification
  - Permutation feature importance (Altmann et al., 2010) provides opportunity to rank controls

Application of Synthetic Rock Mass Testing

Synthetic Rock Mass Testing

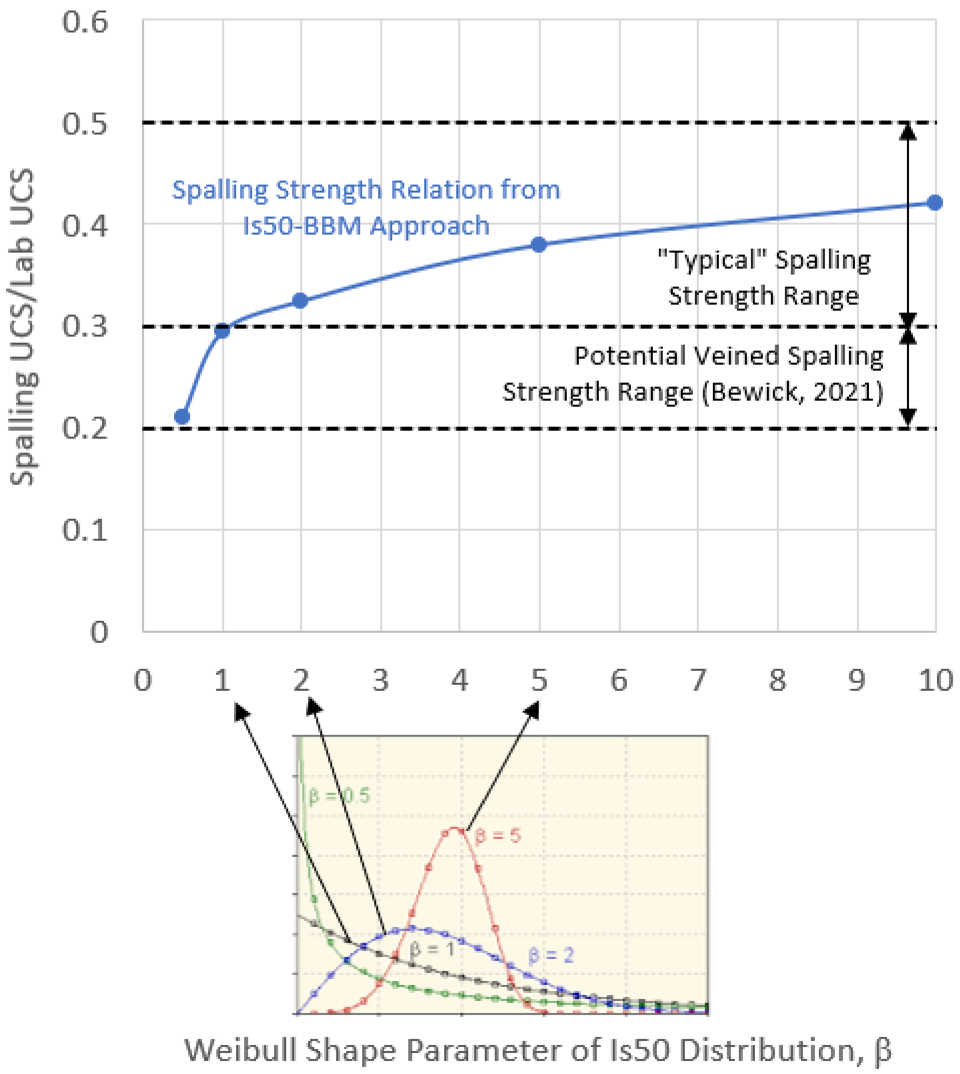
- Synthetic Rock Mass (SRM) testing can be used to estimate rock mass spalling strength
- Bonded Block Modelling (BBM) approach of Garza-Cruz and Pierce (2014) generally used
  - Rock is represented as an assembly of tetrahedral-shaped elastic blocks
  - High variance in contact tensile strength informed by point load strength Weibull distribution
  - Shear strength informed by triaxial testing
  - SRM samples tested in uniaxial compression





Spalling Strengths from SRM

- The spalling strengths derived from SRM testing are directly related to the shape factor (skewness) of the underlying Is50 Weibull distribution
- Heavily defected rock
  - Is50 shape factors typically lower, ~0.5-2.0
  - Results in spalling factors of ~0.2-0.33*UCS
  - Consistent with veined rock factors proposed by Bewick (2021)
- Undefected rock
  - Is50 shape factors typically higher, ~5-10
  - Results in higher spalling factor of ~0.4*UCS
  - Consistent with "typical" range from spalling theory
- Used to generate rock mass UCS block model from Is50 model….



Rock Mass UCS Block Model (Upper Bound)

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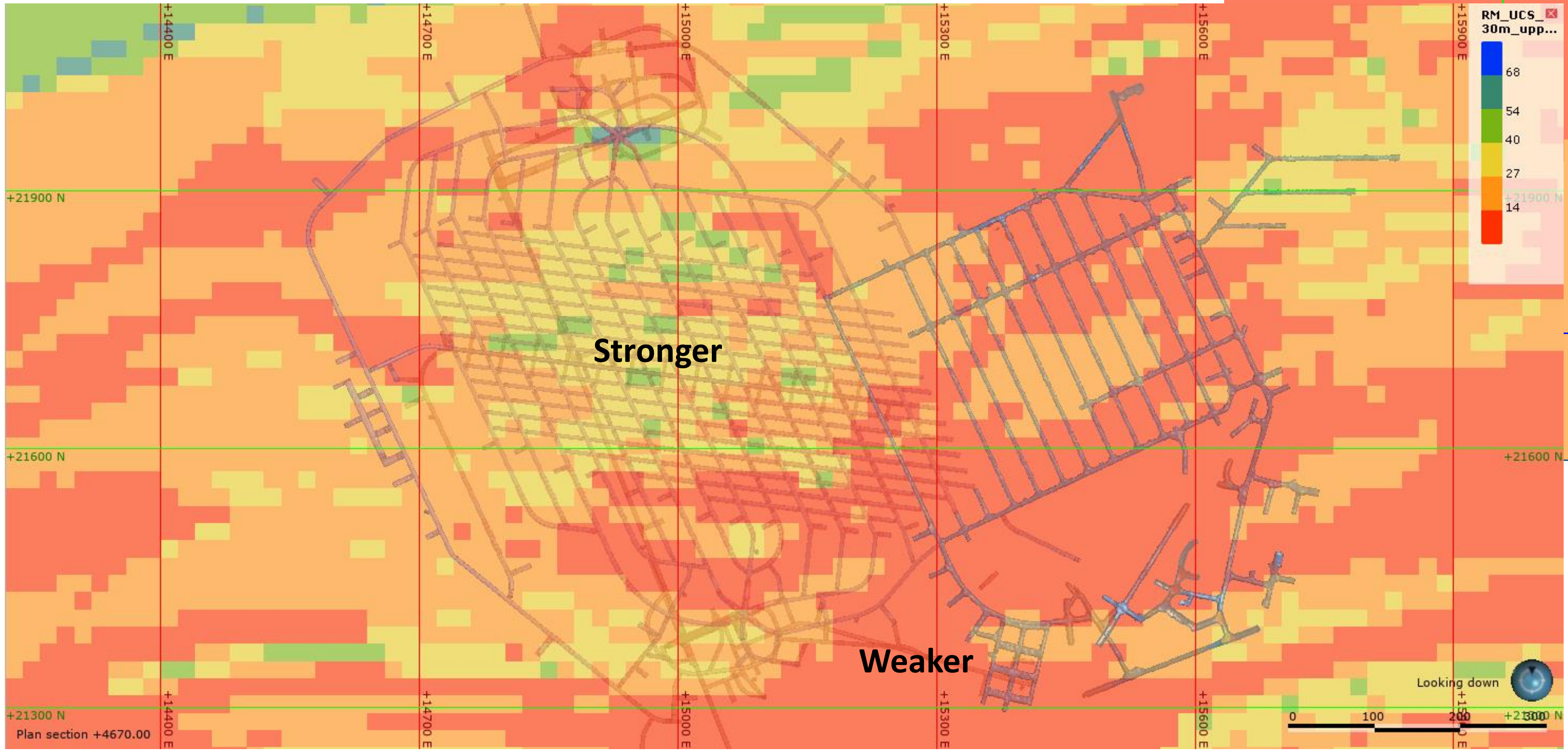

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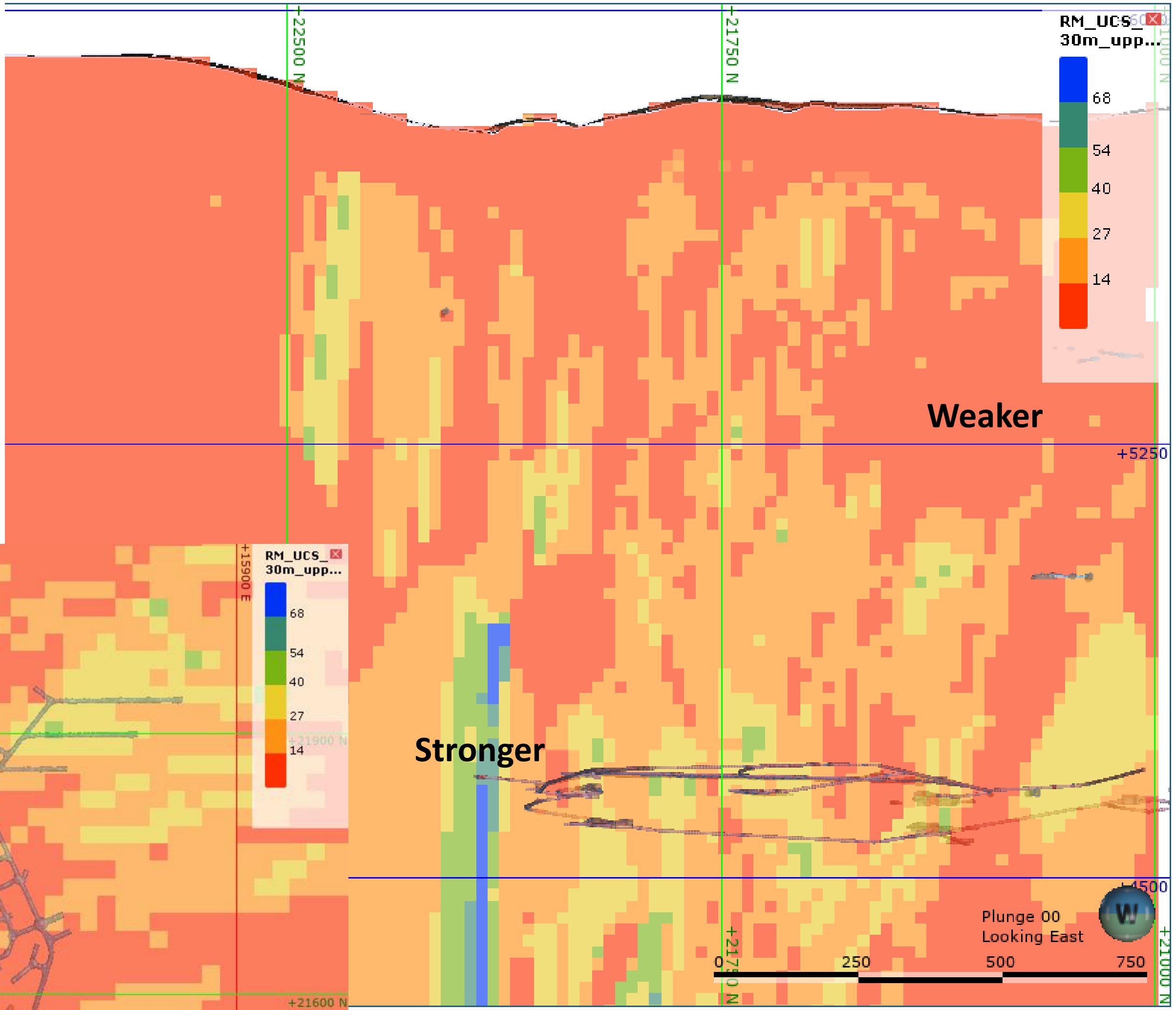

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Future Work

- Incorporate testing of reference materials to aid in quantification of point load test precision and accuracy
- Explore opportunities for more continuous testing of rock core, such as the Minpraxis tester (http://www.minpraxis.com/minpraxis-tester-2/; Nadolski et al, 2023)
- Incorporate additional data into training of machine learning models for Is50 (e.g. borehole imaging, hyperspectral scanning)
- Refine procedures for identifying drilling/handling-induced core breaks and estimating Is50 for incorporation into strength distribution
- Expand use of Is50 and rock mass strength block models within cave mine and mill performance forecasting workflows

Appendix: Systematic PLT Guidelines

Systematic Point Load Testing Guidelines

- Systematic point load testing should be carried out in accordance with ISRM standards (ISRM, 1989), with the exception that tests are conducted at a regular fixed spacing rather than clustered around UCS tests for the purposes of correlation.
- In addition, all valid tests should be retained (high and low values are not discarded).
- Careful consideration must be given to maintenance of testing points, as worn points resulted in a larger proportion of invalid tests.
- Testing locations are marked on the core at strict, regular intervals, using a sleeve to mark the circumference of the core.
- A single diametral test should be conducted at each test location, with axial tests conducted periodically to check for anisotropy.
- The spacing between point load tests is commonly 1m in initial holes, with spacings adjusted appropriately once an understanding of strength variability is developed.

Systematic Point Load Testing Guidelines

- The following data is collected at each test location:
  - Test location (distance along core)
  - Core condition
    - Intact: Non-defected intact rock
    - Structure: Closed veins, foliation, bedding, microdefects
    - Disturbed: This designates that it was not possible to obtain a sample containing the test location mark that is of valid dimension and character. The cause should be noted:
      - Lost core
      - Soft core
      - Broken core. It should be noted whether this is due to:
        - Natural open breaks (Is50=0). Note failure type (see below).
        - Unintentional drilling/handling-induced breaks (indicator of low Is50). Note failure type (see below).
        - Purposefully induced breaks (e.g., at the end of a core run or to fit the core into the box). These latter are normally marked a such on the core by the drillers and/or loggers as “mechanical” and are disregarded.
  - Sample dimensions: Diameter and length

Systematic Point Load Testing Guidelines

- Test type
  - Diametral: If a structure is present for a diametral test, it should be aligned parallel to the testing direction so that the points lay on the structure itself. This enables the strength of the structure to be measured. If there is no structure present, the testing direction during a diametral test is not relevant.
  - Axial
  - None: Test not possible due to induced or disturbed core condition.
- Test result
  - Peak hydraulic pressure
  - Test validity (see ISRM, 1989)
- Failure type
  - Intact: Single fracture through intact rock only
  - Multiple: Multiple fractures through intact rock
  - Structure: Single fracture through structure only. The structure type (vein, foliation, bedding, microdefect) and thickness as well as the alpha angle, roughness, and mineralogy of the break surface should be noted.
  - Combined: Single fracture through combination of structure and intact rock

References

References

Altmann, A., Toloşi, L., Sander, O., and Lengauer, T. (2010). Permutation Importance: A Corrected Feature Importance Measure, Bioinformatics 26(10), 1340–1347. Bewick, R. P. 2021, 'The Strength of Massive to Moderately Jointed Rock and its Application to Cave Mining'. Rock Mechanics and Rock Engineering, 1-33.

Bouzeran, L., Pierce, M., Andrieux, P., & Williams, E. (2019). The role of rock mass heterogeneity and buckling mechanisms in excavation performance in foliated ground at Westwood Mine, Quebec. Journal of the Southern African Institute of Mining and Metallurgy, 120(1), 41-48.

Bridgwater, J., R. Utsumi, Z. Zhang, and T. Tuladhar. "Particle attrition due to shearing—the effects of stress, strain and particle shape." Chemical Engineering Science 58, no. 20 (2003): 4649-4665.

Douglas & Sharrock (2008). Personal communication.

Flores-Gonzalez, G 2019, 'Major hazards associated with cave mining: are they manageable?', in J Wesseloo (ed.), MGR 2019: Proceedings of the First International Conference on Mining Geomechanical Risk, Australian Centre for Geomechanics, Perth, pp. 31-46, https://doi.org/10.36487/ACG_rep/1905_0.3_Flores-Gonzalez

Garza-Cruz, T., & Pierce, M. (2014). A 3DEC model for heavily veined massive rock masses. In 48th US Rock Mechanics/Geomechanics Symposium. American Rock Mechanics Association.

Garza-Cruz, T. and Pierce, M. (2016). Impact of rock mass strength variability on caving. In Proceedings of MassMin 2016.

ISRM (1989). Suggested method for determining point load strength, RTH 325-9.

Lett, J, Castro, R, Pereira, M, Osorio, A & Alvarez, P 2022, 'BCRisk applications for rill swell hazard analysis in PC1: case study at Cadia East Operations', in Y Potvin (ed.), Caving 2022: Fifth International Conference on Block and Sublevel Caving, Australian Centre for Geomechanics, Perth, pp. 561-572, https://doi.org/10.36487/ACG_repo/2205_38

References

Lohr, S. L. (2019). Sampling: design and analysis. Chapman and Hall/CRC.

Nadolski S, G. Pizarro, M. Hesse, E. Diaz, D. Henriquez, & B. Klein (2023) Improving orebody knowledge with high-resolution rock strength characterization using the Minpraxis Tester. SAG 2023 Conference, Vancouver, September.

Pierce, ME (2010). A model for gravity flow of fragmented rock in block caving mines. PhD Thesis. Brisbane, Australia: University of Queensland.

Pierce, M. (2014) Geomechanical Feasibility Analyses of Caving at Niobec Mine. ICG report 13–2768–62 to Iamgold, February.

Pierce, ME, Llewelyn, K, Campbell, R, Taylor, K, Fuenzalida, MA & Diering, M 2022, 'Development, reconciliation and visualisation of hang-up frequency and fines entry forecasts at PT Freeport Indonesia', in Y Potvin (ed.), Caving 2022: Fifth International Conference on Block and Sublevel Caving, Australian Centre for Geomechanics, Perth, pp. 531-544, https://doi.org/10.36487/ACG_repo/2205_36

Pierce, ME, Stonestreet, P, Orrego, C, Tennant, D, Garza-Cruz, TV, Furtney, J & Thielsen, C (2022). 'Development of rock mass strength block models at Cadia East mine', in Y Potvin (ed.), Caving 2022: Fifth International Conference on Block and Sublevel Caving, Australian Centre for Geomechanics, Perth, pp. 1033-1046, https://doi.org/10.36487/ACG_repo/2205_71

Renani, H. R., Martin, C. D., Varona, P., & Lorig, L. (2019). Stability analysis of slopes with spatially variable strength properties. Rock Mechanics and Rock Engineering, 52(10), 3791-3808.

Thielsen, C., Furtney, J., Valencia, M.E., Pierce, M., Orrego, C., Stonestreet, P. and Tennant, D. 2022, ‘Application of Machine Learning to the Estimation of Intact Rock Strength from Core Logging Data: A Case Study at the Newcrest Cadia East Mine’. Proceedings of 56th US Rock Mechanics/Geomechanics Symposium, Santa Fe, New Mexico, USA, June.

Wyering, L.D., Villeneuve, M.C., Wallis, I.C., Siratovich, P.A., Kennedy, B.M., and Gravley, D.M. (2015). The development and application of the alteration strength index equation, Engineering Geology, 199, 48-61, ISSN 0013-7952, https://doi.org/10.1016/j.enggeo.2015.10.003.