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Combined geophysical techniques to predict and map rock mechanics parameters

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Abstract

At the former Brukunga pyrite-sulphur mine site (in South Australia) we investigate the possibility of using cross-borehole seismic travel time tomography with enhanced analysis of borehole wireline data to predict fracture intensity (such as RQD) and rock strength (UCS) as a case history test whether we can predict rock mechanical information and extrapolate to a rock volume. Our proposed methodology provides quantitative and repeatable measurements suitable for physical modelling and offers the opportunity to populate rock block models with engineering data in engineering units.

Engineering of rock mass properties are often interpolated from relatively sparse data spanning tens to hundreds of metres away from diamond-core drilling or interpolated by hand logging and interpretation of rock-core. Geophysical methods should be the natural supporting data for inferring and interpolating information around and between boreholes. Fundamental shared relationships between geophysics measurements and mechanical properties of rock have been noted, tested and studied. However, a well-structured, statistically testable, and economically viable approach of melding geophysical measurement and rock engineering properties does not seem to be regular practice in mining, or in many civil engineering projects. Many issues were rediscovered in our tests and these provide some insights into the practicality of implementing the concept.

Combining borehole and diamond core analysis with imaging with seismic wave propagation produced valuable insights into the structural, mechanical, and dynamic behaviour of rock masse at Brukunga. We were able to use geophysical logging data to find different domains of rock strength, plus characterise the nature of fractures from logging. These developments combined with maps of P- and S-wave velocity in a block model offers vast potential in decision making by allowing informed plans with better safety instead of reactive measures or allowing dilution or waste in mining.

Keywords

UCS, RQD, Geophysics, Petrophysics, Tomography.

1 Introduction

The main issue we try address is that engineers do not have enough volumetric data (Barton, 2006; van As, 2025). Rock classification systems (ASTM STP 984, Kirkaldie, 1988) use various measures, weighting and derating factors and provide guidelines for sampling and measurement. Standards measure such the ASTM standard for Unconfined Rock Strength (UCS; ASTM, 2010) tend to assume representivity and focus upon accuracy and consistency. If the rock mass is very uniform, then a small number of samples and measurements will characterise the rock mass well. In many mining scenarios it is not the case (Jackson, 2019; van As, 2025) as the ore deposit is often associated with complex alterations to pre-existing rocks. Barton (2006) suggests that we should be able to link petrophysics-geophysics and engineering data into rock classification systems, a concept we explore at a test site in Australia.

2 Data and analysis

2.1 Brukunga test area

The Brukunga mine site is 46km east of the city of Adelaide, South Australia and was established in 1950s and closed in 1972 (Skinner, 1958). The Brukunga area is composed of dark pyrite rich siltstones with sandstones and minor calc-silicate interbeds and a massive sandstone unit at its base. The geology is typical of many mineral resource environments in Australia: Cambrian age or olderwith significant metamorphisms, deformation, and intrusions.

The aim was to usea combination of (density, mag-susc, nat gamma, sonic, electrical) petrophysical logging and cross-borehole seismic tomography, with laboratory and core measurements to interpolate important rock mass variables. HQ diameter boreholes, each approximately 300 m deep, and two just 5 m apart (V and G)to verify predictability, were drilled vertically through the same geological units. Samples for rock mechanical testing were taken from different geological units, including adjacent intervals. Core logging and scanning was also involved with calculation of RQD measurements and routine reports. Wireline logging of petrophysics with imaging was also performed. In total, 93 UCS specimens were tested from borehole V, and 60 UCS specimens from borehole G based on ASTM standards (ASTM, 2010).

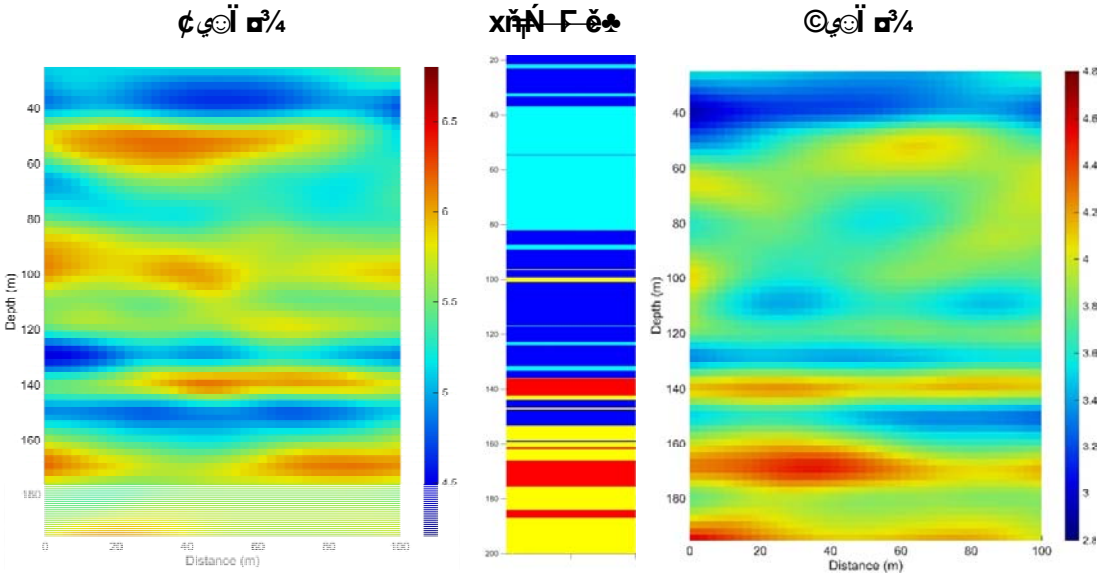


Fig. 1 P- and S-wave velocity tomograms integrated with petrophysically defined lithology for the former Brukunga pyrite mine, near Adelaide, South Australia. The 35–85 m depth interval is characterized by high sulphide mineral content, predominantly pyrite. Thick massive pyrite-rich bands typically correspond to low-velocity zones in both P- and S-wave tomograms, whereas narrow high-velocity zones are interpreted as dolerite sills (shown in red in the clustered lithology). Tomographic inversion was performed using a 2.5 m cell size, yielding an effective vertical resolution of approximately 5 m for resolved layers. (Modified from Kepic et al., 2024).

2.2 Tomography

Seismic while drilling with diamond drill rigs in conjunction with grouted geophone sensor arrays proved feasible in producing tomograms that reflect known geological structures despite relatively low seismic energy (fig 1). The sensor installation and subsequent data acquisition was performed by the drilling crew and supervised by geophysicists from afar. This was done to make tomography more accessible and cost-effective by being compatible with normal geological-engineering assessment processes in hard-crystalline rock. Both P-wave and S-wave tomograms were produced with very high resolution (Kepic, 2024), achieving 5m resolving power, down to at least 150 m depth. S-waves appear to provide slightly higher spatial resolution in the tomograms. The lithology log was produced from Fuzzy Cluster analysis (Bezdek, 1984) from petrophysical logging. These clusters, which match known rock units, were also used in future domaining of the log data to characterise the engineering parameters of various rock units so we could later extrapolate these parameters to the volume with tomography.

2.3 Fractures and Rock Quality Designation

Straightforward use of a previously successful Rock Quality Designation (RQD, Deere and Deere, 1988) prediction methodology (Kieu, 2018) using Full-wave sonic (FWS) wireline logs and seismic data with data domaining was initially unsuccessful in matching the manual RQD logs in our Brukunga test. Initial investigations revealed that FWS tool operating parameters and standard analysis routines were a significant problem. Dedicated FWS analysis algorithms to extract intact rock velocities and separate out fractures by direct attributes produced considerably better results (Kieu, 2024, and fig2). The new FWS analyses methods reliably detected fractures and joints to a resolution of measurement spacing (12-25 cm during logging).

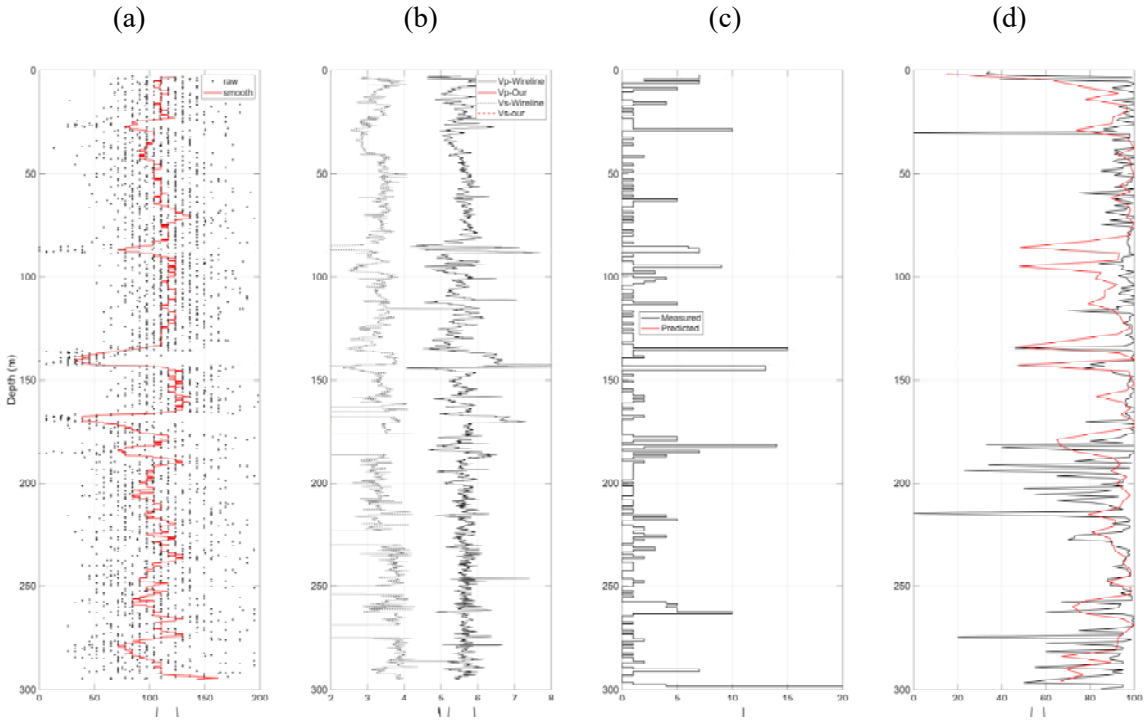


Fig. 2 Borehole data: Natural gamma logs (a); Comparison between P-wave and S-wave computed by WellCAD software and our algorithm from full waveform sonic (FWS) data (b), our results show significant improvement particularly in Vs data. The improvement of Vp and Vs data quality combination with other FWS attributes enabled the prediction of Fracture density (number of fractures per meter, left panel) (c) and RQD (d).

Various cross-comparisons of RQD and fracture measures of two 300m HQ holes only 5m apart with the manual versus FWS analyses demonstrated that RQD and fracture frequency prediction was similar with the various methods (fig 2). Differences in core handing and drilling technique are possible culprits for differences, or geology. Jackson and Sellers (2019) similarly experienced unexpectedly poor matching between adjacent holes at the Olympic Dam mine. FWS analysis and manual acoustic-televiewer (ATV) analysis produced similar results, with both in-situ techniques indicating less fractures that the traditional manual logging of core. A mismatch between the resolution of FWS logs and the minimum intact pieces of 10cm is a possible source of discrepancies.

The more heavily jointed-fractured zones appear to be related to certain cluster-domains, or at certain boundaries. Thus, we feel that the P and S-wave tomographs could be used to extrapolate these zones and provide some measure of volumetric rock mass fracture characteristics. We have not yet performed any significant seismic attribute analysis or anisotropy measures as proposed by Barton (2006), but anticipate these would improve robustness of predictions.

2.4 Unconfined Compressive Strength (UCS)

Various studies show that sonic velocities (Lui. 2022; Parsajoo, 2021) are strongly related to rock strength, with relatively high correlation of R^2=0.95 in the case Parsajoo (2021) by adding density as a factor. Barton also presents much data supporting the sonic-UCS link via elastic properties, but with far less correlation and more caveats. There are also works such as Jauch (2000) where there is much less predictability. Our initial efforts followed the approaches of others, such as Lui (2022) and Parsajoo (2021) where a combination of data domaining and machine-learning was used on a training borehole (V-hole) and then tested on G-hole. Scatter plots of various critical parameters (not shown), such as velocity and density versus UCS did not show clear predictive ability. Using an adaptive domaining-clustering approach with good in-situ measurements of sonic velocity and density to estimate elastic modulus inputs to our prediction ability (fig 3) appears to be quite usable and useful with tomography, but not particularly good.

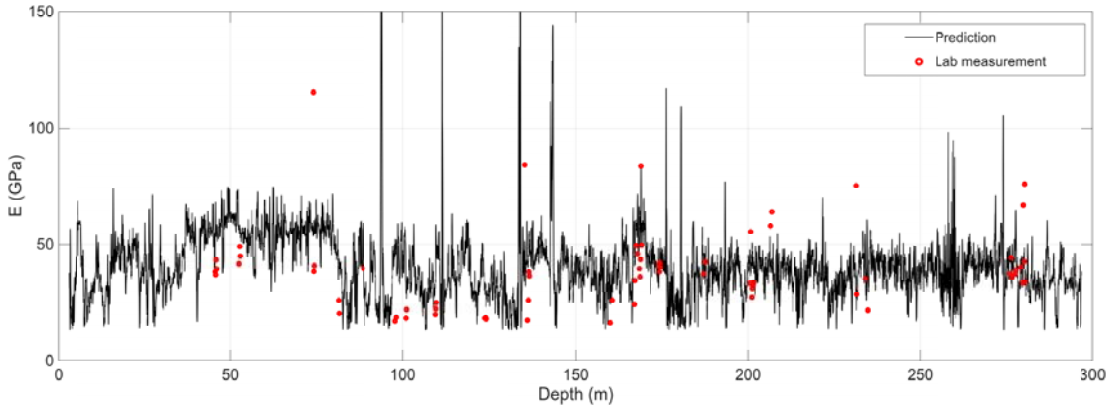


Fig. 3 The comparison between Machine-Learning predicted (black curve – from a nearby hole) of UCS from petrophysics with FCM and lab measurements (Red circles) of sampesfrom borehole G hole(as a blind test).

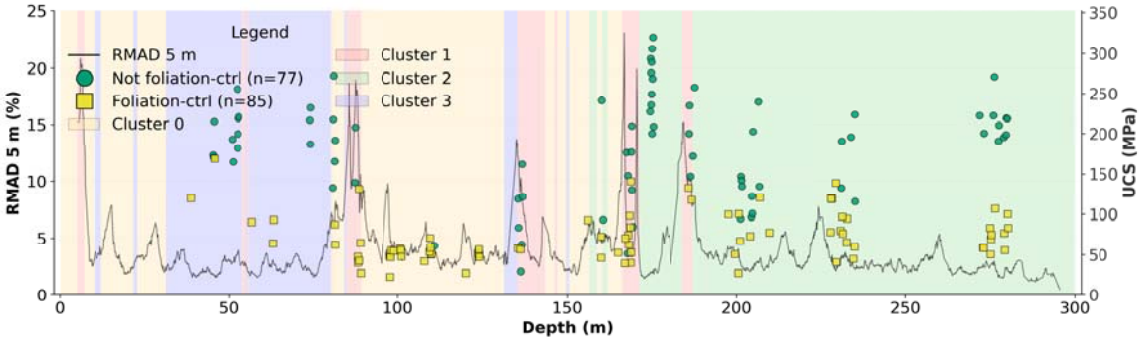


Fig. 4 A comparison between UCS data sorted as Foliated (hetrogeneous – yellow square), Non-Foliated (homogeneous – greed dots) versus a measure of FWS sonic derived elastic propert yvarability (RMAD) with background colour a cluster-domain of rocks with common characteristics (geochemical and pysical).

In gathering the samples for UCS testing it was noted that samples taken within centimetres of each other in similar rock could range between 70 and 250 MPa, rocks in the same cluster-domain. This posed many issues: what is a representative sample to compare to sonic velocities and how should we sample? This is not just a serious issue for our study but poses serious risks for implementing many rock mass rating systems in more complex geological settings.

A measure of sonic variability was introduced by Shakib (2024) (fig 4) to see if we could map these regions of UCS variability. This was partially successful in guiding further sampling but did not seem to detect areas of significant UCS variation. Further samples were collected for UCS testing for in follow up studies and these samples were also tested with ultrasonic pulse transmission between the

sample cylinder faces to measure velocity and other sonic attributes (fig 5).UCS measurements on the first batch of samples from V-hole indicated that at depths >160mhas a bi-modal distribution of values. Furthermore, during the ultrasonic measurements it was note that the received pulse changed shape substantially in some samples, and that these samples had visible heterogenous features. The samples were visually categorised into Foliated and Non-Foliated (fig 4) and similarly with ultrasonic measurements to heterogeneous and homogenous. The homogenous samples tend to be Non-Foliated and provide clean receive pulses. Whereas the Foliated samples had heterogeneous ultrasonic signals, with multi-path/scattering evident in the received signal. Fig 6 shows that the heterogeneous samples clearly are weaker (cluster 3 in Fig 6), and that sonic methods at the sample scale can detect heterogeneity that determines UCS strength.

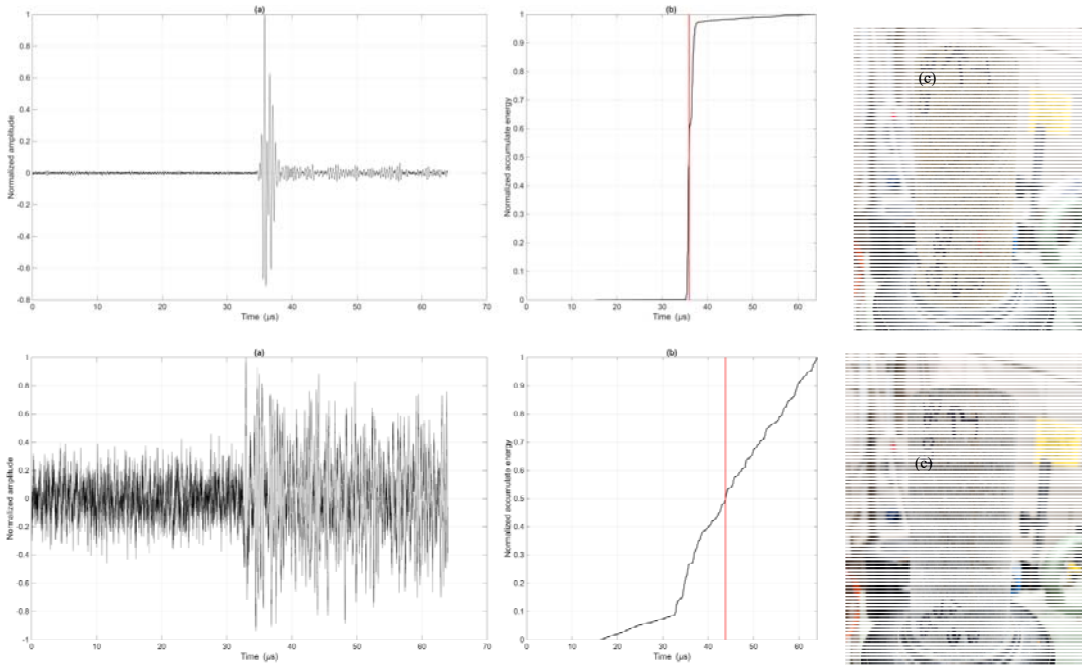


Fig. 5 Laboratory ultrasonic measurements include pulsewaveform (a), accumulated energy (b), and sample photo (c). The red line in Figure (b) indicates the time corresponding to 50% accumulated energy. The later arrival time for Sample 2 compared to Sample 1 suggests that Sample 2 is more heterogeneous. This observation is consistent with the waveform characteristics: Sample 1 exhibits a clear pulse waveform, whereas Sample 2 shows sever multi-path and scattering.

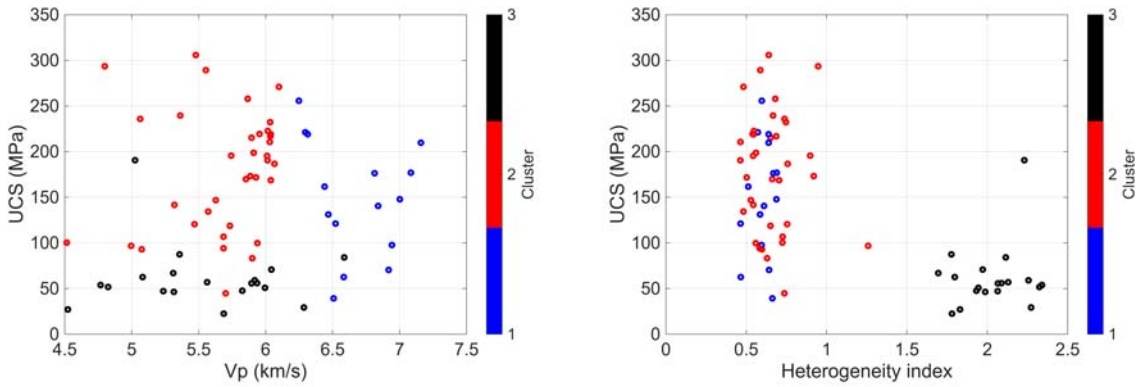


Fig. 6 Cross-plot of Vp and Heterogeneity Index versus UCS. The clusters are results of ultrasonic full-waveform sonic data. Cluster 3 corresponds to the samples exhibiting the highest degree of heterogeneity and lowest UCS.

Rock textures at various scales matter greatly when relating the petrophysical and geophysical domains with engineering parameter domains. The sample ultrasonic measurements demonstrate what could be achieved with sonic logging with higher resolution and precision. The physical variations and macro-textures in rocks influence greatly the rock mass appraisal.

3 Conclusions

Our tests at the Brukunga mine site demonstrated that petrophysical properties and key engineering rock parameters can be estimated as robustly as resampling with conventional methods. Thus, it is possible to extrapolate beyond the borehole with measured data from tomography. Sparse sampling is a barrier to understanding the rock mass properly. Wireline logging with high resolution, especially full-wave sonic, can translate to engineering properties at various scales with a physically plausible methodology. The significant problems of using geophysics for rock mechanical parameter estimation lies mostly with spatial aliasing of the geophysical data and the reference engineering data from samples. Higher resolution physical measurement creates a better understanding of parameter variations and is critical to finding a representative measure of rock parameters for better risk management and optimisation.

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References

ASTM, A. (2010). Standard test method for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures.

Barton, N. (2006) Rock quality, seismic velocity, attenuation and anisotropy. CRC press.

Bezdek, J. C., Ehrlich, R., and Full, W., (1984), FCM: The fuzzy c-means clustering algorithm: Computers & Geosciences, v. 10, no. 2-3, p. 191-203.

Deere, D. U. and Deere, D. W., (1988) The rock quality designation (RQD) index in practice. In Rock classification systems for engineering purposes. ASTM STP 984 American Society for Testing and Materials.

Jackson, J. & Sellers, E. (2019) Blasting related indices as the key to underground blasting improvements in a challenging rock mass. The 13th AusIMM underground operators' conference Gold Coast, QLD, Australia. The Australasian Institute of Mining and Metallurgy, AusIMM, 2017. 23-32.

Jauch, F.., (2000) Using borehole geophysics for geotechnical classifications of crystalline rock masses in tunnelling, PhD dissertation., ETH Zurich.

Kieu, D. T. and Kepic, A. (2018). Building 3D Model of Rock Quality Designation Assisted by Co-Operative Inversion of Seismic and Borehole Data. ASEG Extended Abstracts, 2018(1), 1–5.

Kirkaldie, L. (Ed.). (1988). Rock Classification Systems for Engineering Purposes, ASTM STP 984, American Society for Testing and Materials, Philadelphia

Kepic, A., Kieu, D., Crettenden, B. and Zawadzki, R., (2024) Seismic Tomography with Diamond Drilling and Permanent Arrays. In NSG 2024 5th Conference on Geophysics for Mineral Exploration and Mining (Vol. 2024, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.

Kieu, D., Parsajoo, M. and Kepic, A., (2024), September. Predicting rock quality designation with geophysical wireline data. In NSG 2024 5th Conference on Geophysics for Mineral Exploration and Mining (Vol. 2024, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.

Liu, P.H., Wu, J.H. and Lee, D.H., (2022). New rock strength-based UCS-Vp correlation equation for different rock types by statistical regression methods. Geomechanics for Energy and the Environment, 32, p.100403.

Parsajoo, M., Jahed Armaghani, D., Mohammed, A., Khari, M.,and Jahandari, S., S. (2021). Tensile strength prediction of rock material using non-destructive tests: A comparative intelligent study. Transportation Geotechnics. 31.

Shakib, A., Kepic, A., Kieu, D., Bunch, M. & Cook, N. (2025) Estimating the Confidence in UCS Measurements with Wireline Logging Data. NSG 2025: 6th Conference on Geophysics for Mineral Exploration and Mining, 2025. European Association of Geoscientists & Engineers, 1-5.

Skinner, B. J. (1958). The geology and metamorphism of the Nairne pyritic formation, a sedimentary sulfide deposit in South Australia. Economic Geology, 53, 546-562.Kieu (2018) Kevitsa study of RQD

van As, A. (2025). Geotechnical Engineering for Mass Mining. In: Wood Ao, D. & Hedenquist, J. (eds.) Geology and Mining: Evolution of Best Practice. Society of Economic Geologists