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# Hydrothermally altered Silurian bedrock in Melbourne's North-East Link Tunnel

H. Hughes-Adams, D. Tepavac, B. Carnes
*Delve Underground Ltd, Melbourne, Australia*

C. Hunt
*Delve Underground Ltd, Vancouver, Canada*

J. Martin
*Spark Consortium, North East Link, Melbourne, Australia*

ABSTRACT: The North East Link Project is a 26-kilometre tolled motorway scheme in Melbourne, Australia, which includes a 6.5 km tunnel that was constructed using both sequential excavation methods (SEM) and a tunnel boring machine (TBM). The 450 m section of SEM tunnel encountered hydrothermally altered rock in the excavation of the top heading. The altered rock derivate presented as a "soil like" material formed from the Silurian sedimentary parent rock. The hydrothermally altered siltstone is nearly indiscernible from the fresh and unaltered Silurian siltstone by visual inspection, yet it may bear vastly different geotechnical and geomechanical properties, as well as tunnelling conditions. In the presence of minor water inflow, the altered siltstone slakes, disintegrates and may create a "running ground" condition, a significant potential risk to the safety of the works. This paper focuses on Silurian-age siltstone and sandstones and how the unique characteristics of the hydrothermally altered derivates present unique risks to tunnel excavation and support implementation. The paper also explores the experiences of encountering hydrothermally altered siltstone on the North East Link tunnels and sets out a series of design and construction risk mitigation measures adopted on the project. These measures are not unique to the North East Link project but form the basis of a proposed set of good practices with respect to underground excavation in hydrothermally altered rock.

## 1 INTRODUCTION

This paper aims to present the experiences of the design and construction of SEM tunnelling in rock mass conditions that contain hydrothermally altered rock within Silurian siltstone and sandstone. The paper presents the geological background and mechanism of hydrothermal alteration. Additionally, recovered samples were tested and reviewed in order to determine engineering design parameters and comparison with pre-construction parameters was made. The knowledge gained from the experience is summarized herewith; the risks of tunnelling in these conditions are presented with the ultimate solutions and outcomes highlighted.

## 2 GEOLOGICAL BACKGROUND OF PROJECT

The North East Link (NEL) project area is founded on the Anderson Creek and Melbourne formation. Both formations are sufficiently similar that throughout the project they have been referred to as the "Silurian formation". This bedded sedimentary formation, consisting of mostly siltstone with some sandstone, was deposited in a deep marine environment during the Silurian era, approximately 420 to 440 million years ago (mya). In the middle Devonian (approximately 380 mya), this formation underwent an orogenic deformation event, which resulted in folding and faulting of the bedrock into a series of synclines and anticlines trending NE to SW. In the late Devonian, this bedrock was intruded by a series of plutonic rocks in the granite family. These intrusions have weathered into soft white clay inferred to consist largely of kaolinite. The bedrock was subsequently incised by the Yarra River and its tributaries, and then later infilled with Quaternary sediments.

During the tectonic movement of the Devonian period, the Silurian bedrock underwent another period of deformation, which included hydrothermal alteration. This hydrothermal alteration occurred in discontinuous and seemingly random locations and is therefore difficult to predict in the project area. The mineralogy of the altered formation indicated the presence of chlorite and sericite (Golder, 2023a), giving the altered rock a slight greenish hue, though this largely remained similar to fresh rock. The strength of the hydrothermally altered siltstone was inferred to vary based on intensity of alteration and ranges between a clay-like consistency and rock with low hardness (Golder, 2023a).

The four primary units within the Silurian bedrock have been classified based on strength and weathering grade, and have been numbered S1, S2, S3 and S4, with increased numbers corresponding to higher weathering grade and decreased strength. S1 is classified as fresh bedrock.

## 3 HYDROTHERMAL ALTERATION

Hydrothermal alteration can be defined as a very complex process involving mineralogical, chemical and textural changes resulting from the interaction of hot aqueous fluids with the rocks through which they pass, under evolving physicochemical conditions (Pirajno, 1992). It is considered that as part of Devonian tectonic deformation and metamorphism, hot aqueous fluids circulated through the defections and pores in rocks, dissolving and depositing minerals, leading to changes in the rock's composition and structure. The altered areas often surround intrusions or fault zones, indicating the source and path of the hydrothermal fluids.

One critical observation regarding the on-site assessment of hydrothermal alteration was that there is often no obvious visual difference between rock inferred to have been hydrothermally altered and the surrounding unaltered rock mass. However, the behaviour of the ground as a result of excavation and potential for groundwater-induced erosion upon excavation (running ground conditions) were vastly different, as is discussed further below.

## 4 DESIGN STAGE RISK MINIMIZATION MEASURES

Fundamentally, one of the greatest sources of risk with tunnelling projects in rock mass conditions containing hydrothermally altered rock is twofold. First, identifying the altered siltstone material in advance of the tunnel heading based on visual inspection or interpretation of the preconstruction site investigation is extremely difficult. Second, the altered siltstone is highly variable in terms of strength and stiffness, as well as in size and extent.

During the preconstruction stage, one intention of the geotechnical interpretation was to highlight the risk of the material but was unable to quantify its extent and location given the practical limitation of using boreholes. Where the altered siltstone was inferred to be encountered during geotechnical drilling (see Figure 1) it was visually very similar to the surrounding fresh rock, as discussed above.

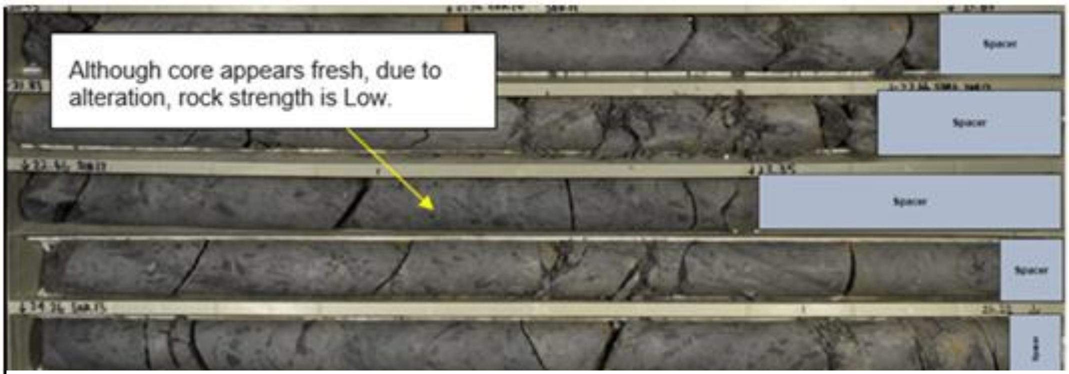


Figure 1 Borehole results indicating hydrothermally altered rock within surrounding fresh rock.

Nevertheless, the geotechnical interpretation was able to provide estimated rock mass characteristics and expected behaviour and parameters of the hydrothermally altered siltstone, which enabled the designers to develop support and sequence in anticipation of encountering the conditions. The design support concept focused on managing expected ground behaviour by providing pre-support elements like spiles, face support bolts, and thicker heading crown shotcrete with optional mesh reinforcement and a tighter bolt pattern.

Addressing the next challenge of identifying the material ahead of the tunnel face was attempted to be mitigated via systematic forward probing. The foundational risk mitigation measure developed at the detailed design phase was forward probing for geotechnical features such as altered siltstone and groundwater inflow. The intention for the requirements for probe cuttings to be inspected, monitoring of penetration rates, groundwater inflow rates and endoscopic inspection during design was to identify hydrothermally altered ground.

## 5 ENCOUNTERING HYDROTHERMAL ALTERATION

Hydrothermal alteration was first inferred to have been encountered on the project during excavation of the cut-and-cover box adjacent to the mainline portal at the Trinity site (Bulleen End) and throughout the excavation of the top heading.

During excavation in the lower levels of the Trinity cut-and-cover box adjacent to the northbound mainline drive, a section of medium-strength clay was encountered by the geotechnical team at a similar elevation to the tunnel crown. This clay was greenish in hue and surrounded by S4 rock, as predicted by the geotechnical interpretation (Golder, 2023a). Due to the greenish coloration of the clay, it was inferred to be hydrothermally altered S4 rock. Due to entry and space restrictions, this material was not sampled. An image of the inferred hydrothermally altered siltstone is shown below in Figure 2.

Figure 2. Inferred hydrothermally altered rock with clay-like strength in the northbound portal excavation (left). Inferred hydrothermally altered rock with decreased strength from surrounding rock in heading excavation denoted by red circles (right).

Delve Underground's Construction Phase Service (CPS) team also inferred the presence of hydrothermally altered S1 siltstone in several tunnel heading advances. In the mainline excavation, hydrothermal alteration typically appeared in discrete zones within the headings and was typically presented in relatively localized areas, 2 to 5 metres in width and length, and adjacent or in proximity to faulting and inclusions. Some areas presented as a greenish-grey colouring, appearing slightly weathered to fresh rock, but would "delaminate" and peel away from surrounding rock in the form of thin wedges, or larger wedges where the outer bounds of the altered siltstone interacted with steeply dipping bedding partings. The failure surfaces that remained irregular and had no clear joint orientations or discernible bedding fabric. In some instances, the altered siltstone appeared as dark grey and similar to that of fresh rock. However, the bedding fabric would be difficult to discern, and the affected rock would typically slake when washed with water, disintegrating into a soil-like material.

In all cases, the stand-up time of the material was the biggest risk with respect to profile control and face stability. As the colour of the rock was not a reliable indicator of the presence of alteration, the behaviour and lack of bedding of the altered siltstone was largely used to discern where the rock was likely to be hydrothermally altered. Most of the hydrothermally altered rock encountered on the project was identified in the tunnel face, and less commonly identified in the sidewalls and crown. In some cases, however, where the hydrothermally altered siltstone was found in the crown or sidewalls, overbreak was common. Large areas of increased intensity could potentially have more serious impacts on tunnel stability and stand-up time of the excavated faces.

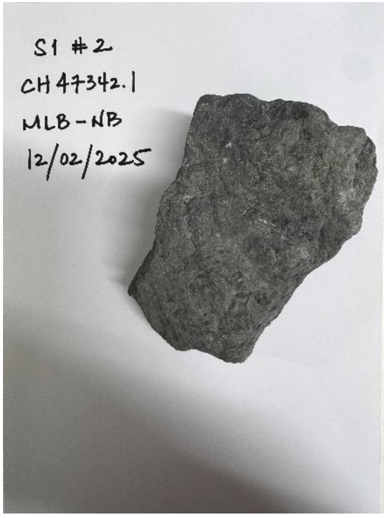
Groundwater inflows in the tunnel were generally minimal, with minor seepage commonly observed in the lower half the top heading excavation. High groundwater inflows should be considered a high risk in tunnel projects where hydrothermal alteration is present based on the observations of this material to slake and swell when in contact with water.

## 6 LAB TESTING

The geotechnical interpretation (Golder, 2023a) used on the project provided anticipated geomechanical properties for the hydrothermally altered siltstone; however, these values were derived largely from regional experience and engineering estimates. As part of this publication and post-construction, Delve Underground, with support by the Project, commissioned laboratory testing on the hydrothermally altered siltstone that was recovered in the mainline of the SEM tunnel to review and analyze the design parameters of the encountered material. It should be noted the recovered material was not representative of the inferred hydrothermally altered clay-like material that was observed and mapped at the tunnel portal.

## 6.1 *Sampling methodology*

Hand samples of hydrothermally altered siltstone were extracted after completion of an excavation with hydrothermally altered siltstone present. In preparation for laboratory testing, all samples were field strength tested and visually inspected in order to confirm them as typical S1 or hydrothermally altered rock before being air dried, photographed and sent to the lab for testing, as demonstrated in Figure 3.



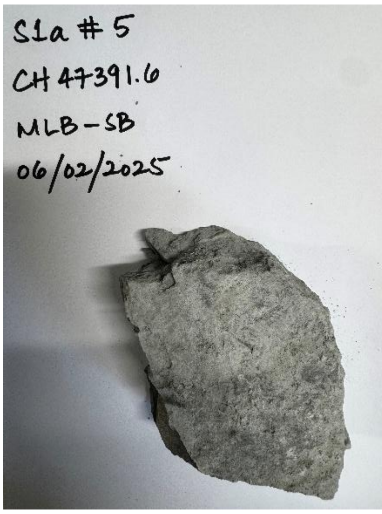




Figure 3. Fresh unaltered Silurian rock s1 sample (left). Inferred hydrothermally altered sample (right).

## 6.2 *Lab testing*

The intent of the lab testing regime was to better understand the geomechanical properties of the hydrothermally altered siltstone, including uniaxial compressive strength (UCS), cohesion and friction angle. Three unaltered samples and three hydrothermally altered samples underwent point load tests (PLTs) to characterize the changes in strength due to alteration. The hydrothermally altered siltstone was collected from S1 rock mass for comparison.

Additionally, two hydrothermally altered samples were saturated in water for 24 hours and then point load tested to investigate the effect of moisture content on the strength of the rock. A three-stage triaxial test was completed on the largest sample of altered siltstone, which was saturated prior to testing in order to yield conservative results. Due to the irregular shape and limited size of the samples, however, most of the testing completed was irregular lump point load testing.

## 6.3 *Lab results*

The PLT results returned indicated a clear difference in point load strength index ($I_{s(50)}$) between the air-dried hydrothermal samples and the air-dried unaltered samples. Please see Table 1 below, which compares unaltered sample strength to altered samples. The arithmetic mean unaltered sample $I_{s(50)}$ strength was 2.43 MPa, compared to the arithmetic mean hydrothermally altered siltstone strength of 0.34 MPa.

Table 1. Air-dried point load testing results

| Sample # | Point Load Strength Index ($I_{s(50)}$) MPa |
|---|---|
| Sample 1 (unaltered) | 1.40 |
| Sample 2 (unaltered) | 1.70 |
| Sample 3 (unaltered) | 4.20 |
| Sample 4 (hydrothermally altered) | 0.77 |
| Sample 5 (hydrothermally altered) | 0.08 |
| Sample 7 (hydrothermally altered) | 0.16 |

Table 2 below, shows the point load testing results from the two saturated samples. The results appeared consistent with other hydrothermally altered samples but did not indicate that strength results were discernibly lower than air-dried samples. During excavation, the hydrothermally altered siltstone in the tunnel excavation would typically disintegrate, slake and create shallow raveling failure upon contact with water. However, the point load testing results of saturated hydrothermally altered samples did not present a discernible decrease in strength compared to the air-dried samples. The arithmetic mean strength of the saturated samples was 0.33 MPa.

Table 2. Saturated point load testing results for hydrothermally altered samples

| Sample # | Point Load Strength Index ($I_{s(50)}$) MPa |
|---|---|
| Sample 2 (hydrothermally altered) | 0.22 |
| Sample 3 (hydrothermally altered) | 0.45 |

All PLT samples failed as a fracture through the rock substance and did not appear to be influenced by weak planes such as bedding partings. The largest hydrothermally altered sample was cored to a length of 115.8 mm and a diameter of 48.5 mm, then saturated in water for 24 hours. A three-stage triaxial test was completed, yielding the results shown in Table 3 and Figure 4, below. The deduced uniaxial strength was achieved by using a Mohr-Coulomb failure linear approximation on the test results presented in Figure 4. Minor vs major principal stress from triaxial testing.

Table 3. Results from three-stage triaxial test.

| Property | Result | Unit |
|---|---|---|
| Rock density | 2531 | kg/m$^3$ |
| Peak confining pressure | 6.00 | MPa |
| Peak failure stress | 27.8 | MPa |
| Failure load | 48.5 | ken |
| Deduced cohesion | 1.60 | MPa |
| Peak angle of shearing resistance, $\varphi_p$ | 32.6 | MPa |
| Residual angle of shearing resistance, φr | 31.6 | MPa |
| Deduced UCS (peak) | 5.70 | MPa |
| Residual UCS (residual) | 4.80 | MPa |
| $m_i$ | 3.34 | - |

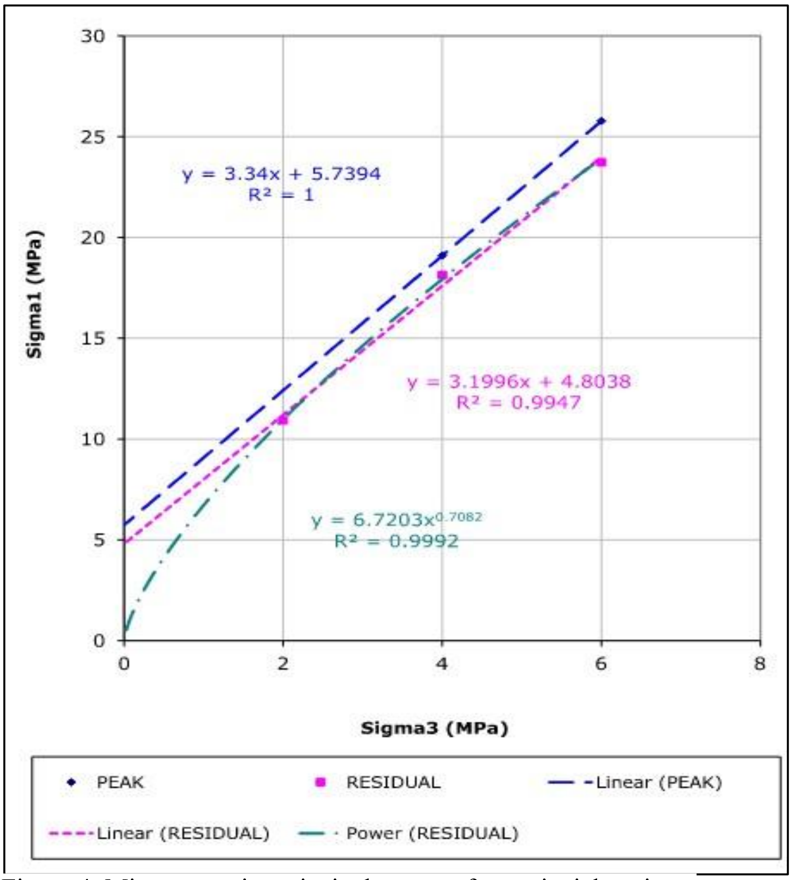


Figure 4. Minor vs major principal stresses from triaxial testing.

### 6.4 *Results analysis*

While there are many empirical methods that exist to correlate PLT to UCS strength based on rock type, there are few methods that may account for hydrothermal alteration. Complications further arise when considering the strength of the altered rock can vary greatly depending on the intensity of the alteration and therefore multiple correlations would be required depending on inferred alteration intensity.

The 2002 Hoek-Brown failure criterion was used to relate the results to the inferred Geological Strength Index (GSI) observed on site. Following the original guidance by Hoek (1994), Delve Underground CPS staff estimated the GSI through qualitative field assessments of the rock structure and discontinuity conditions within the zone of hydrothermally altered siltstone. Noting the limitations of GSI and based on geological judgment, the GSI adopted for this method was 30 and a disturbance factor D of 0, given the survey-guidance controlled excavation with the roadheader (Hoek, 2002).

The corrected value for "tunnel scale" cohesion becomes $c' = 0.31\ MPa$; and the corrected friction angle becomes $\varphi' = 9.7°$. Compared to the preconstruction geotechnical interpretation, the calculated results differ from the strength parameters suggested during the design phase, which were $c' = 0.13\ MPa$ and $\varphi' = 45°$; however, due to inherent limitations and uncertainties of lab testing, more data is needed to verify these results.

## 7 FIELD SOLUTIONS AND CONSIDERATIONS

As discussed in Section 4, the preconstruction geotechnical interpretation was unable to provide a design case for hydrothermally altered siltstone, nor was it able to predict any expected locations within the tunnelling works. Due to the random and localized nature of the altered rock mass, it was difficult to intersect during forward probing investigations. Should it have been encountered during probing, the apparent lack of weathering as described above made it difficult to differentiate from fresh rock, and the localized nature of the softer material was unlikely to have a noticeable impact on the overall drill rate of the 30 to 40 m long probe holes. Hence, hydrothermally altered rock was difficult to predict and was primarily identified during geotechnical mapping works. When encountered, the CPS team raised a construction request for information to the designer for the Design team to confirm support and sequencing requirements for the observed conditions. The outcomes of that design guidance is provided below.

### 7.1 *Spile bars and GRP CT bolts*

Where the local stability and/or integrity of the tunnel profile was a concern, localized spiling, in the form of GRP (glass-reinforced polymer) CT bolts was the solution implemented to support and confine the hydrothermally altered rock mass and allow the surrounding ground to redistribute stresses around the affected localized zone of altered siltstone. This was inferred to significantly reduce the overbreak in the tunnel profile. GRP CT rock bolts allowed for remote installation and grouting, which ensured that personnel were not entering unsupported ground These GRP CT bolts were installed at a low angle within the tunnel face as close as practical to the tunnel excavation profile. GRP bolts were also cuttable and hence removed the need for a "saw-tooth" support profile. This allowed for the maintenance of tunnel profile control during the subsequent excavations, as excavation times could span multiple hours.

Face support was also a critical consideration when tunnelling in hydrothermally altered siltstone. Where required, pattern or spot GRP CT rock bolts with a minimum 2.0 m overlap were deployed when the altered siltstone was identified. Face support pattern geometry extents and timing relative to advance were all determined by the Delve Underground CPS team and supported by design guidance.

### 7.2 *Support installation sequencing*

Typically, the tunnel support installation construction cycle during the SEM mainline excavation was to first excavate, then install tunnel crown and sidewall rock bolts, then install the fibre-reinforced shotcrete. In some instances, the presence of altered siltstone in the tunnel face and in the crown presented a stability risk during excavation. In these cases, a geotechnical inspection was requested by the operator mid-excavation. The CPS team and the tunnel designers occasionally opted to alter the sequencing.

Occasionally, reducing the tunnel/heading advance length to a "half cut" was specified to reduce the tunnel support cycle time and therefore mitigate the stand-up time limitations of the material. In another case, direction was made to temporarily pause excavation and install localized support in the affected rock mass area (see Figure 5). The excavation cycle was then resumed per normal operation. Finally, in one instance, the direction was given to install the initial layer of shotcrete before beginning the bolting cycle. As previously mentioned in this paper, the material occasionally presented as local raveling ground when the face was washed with water. When this behaviour was encountered within the tunnel profile during geotechnical mapping, rock bolting was not deemed a viable solution for temporary support in order to mitigate the stand-up time limits. Therefore, the initial layer of shotcrete was installed to immediately provide confinement and reduce atmospheric exposure of the hydrothermally altered siltstone.

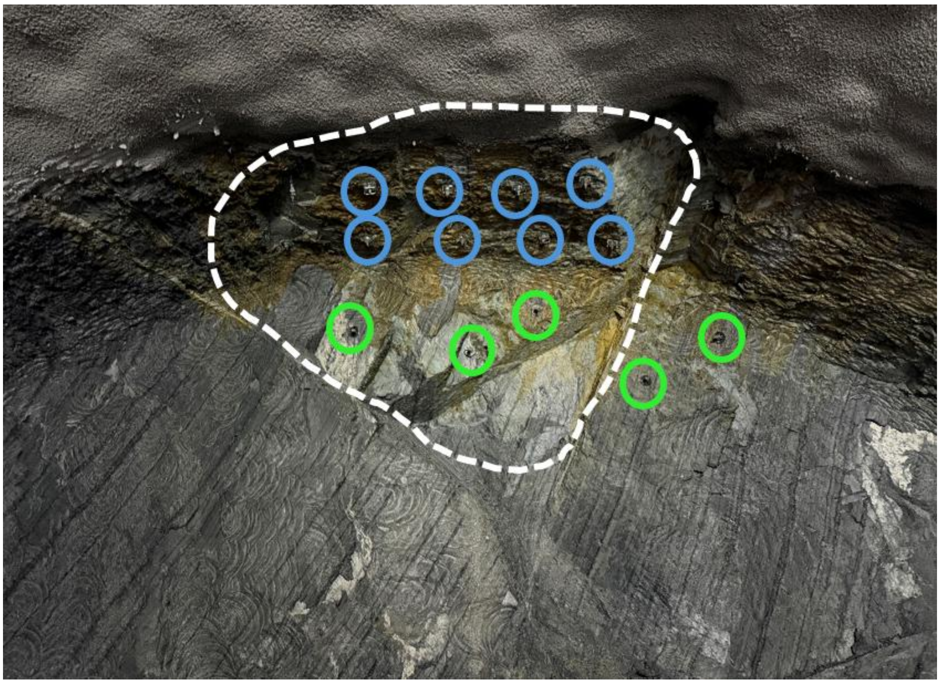


Figure 5. Pattern CT rock bolts (blue) and GRP face dowels (green) installed mid-excavation with inferred altered rock denoted (white).

### 7.3 *Mechanical and hydro scaling*

The altered siltstone typically presented in localized areas in the tunnel face at minimal depth, often less than one tunnel advance (1.25 to 3.0 m) length. In these cases, the primary risk was tunnel localized face stability and the loosening of rock sliding off the face and rolling beyond the excavation exclusion zone. In these instances, and after a thorough risk assessment, tThe CPS team would request that the loose rock be mechanically scaled off the face using the excavator bucket during the "muck out" of the excavated spoil. If an excavator was not available at the time of inspection, the bolting arm of the Robodrill was also used to scale off the weaker material.

Finally, the remaining loose material would be scaled using the high-pressure hydroscaler on the shotcrete rig prior to shotcrete application. Given the volatility of the altered rock when interacting with water, this would only be carried out following an assessment of the overall stability of the tunnel excavation and extent of the altered siltstone.

All three methods of scaling were performed remotely by operators within cabins and/or under supported ground at a safe distance away from the exclusion zone to avoid interaction with loosened material.

## 8 CONCLUSION AND RECOMMENDATIONS

The experience of completing the construction of the SEM mainline tunnels and having successfully managed the risks of hydrothermally altered rock in Silurian siltstone and sandstone have resulted in several recommendations for future design and construction in similar conditions. These include the following:

- Hydrothermally altered material can have highly variable strength and is likely spatially unpredictable. The intensity of alteration and its extent in conjunction with groundwater presence can influence the stand-up time and stability of an underground excavation, and in some cases may even require a passive support solution.
- On projects where hydrothermally altered material may be present, risk minimization measures to be developed during the design phase. If a design case cannot be accurately established, risk controls should be developed based on the difficulties of identifying the material strength and extent in advance of tunnel excavation. The primary risk control method

based on the NEL experience is to develop a toolbox of support items, which include face support and pre-support, such as utilizing cuttable dowels, reduced heading/tunnel advance and increased shotcrete thickness. The toolbox selection criteria should be prescriptive and well-defined.

- During the site investigation stage, hydrothermally altered material should be tested and characterized if encountered. Attempts to establish a design case including location and extent should be pursued as far as reasonably practical.
- Forward probing for geotechnical features such as hydrothermally altered material is a reasonable base case design mitigation measure; however, guidance should be provided that it is not an all-encompassing measure, and probing may miss the zone of hydrothermally altered material or prove to be ineffective for identification. The probing regime should be carefully considered for each case.
- Hydrothermally altered material has highly variable strength. The extent and location, although loosely associated with faulting, is also variable. While sampling and testing of altered material encountered behind the tunnel portal was not recovered, qualitative observations identified that the material was very low strength and behaved as clay, which likely contained significant deviation in strength from the surrounding rocks. Had the highly altered clay-like material been encountered during mainline excavation, a fully passive support solution would likely have been required.
- Further research should be completed to understand the effect of hydrothermal alteration on underground projects.

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