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Technical challenges of ground support in a northern permafrost environment: 30 years of operational experience at Raglan mine

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Abstract

Operating underground mines in permafrost conditions presents unique challenges to ground support design, installation, and long-term performance. This paper draws on 30 years of operational experience at Raglan mine, a high-grade nickel-copper operation in northern Quebec, to document the key technical challenges encountered across all 3 tiers of ground support – primary, secondary, and surface – and the practical solutions developed in response.

For primary ground support, inflatable Swellex bolts suffered progressive, corrosion-induced, capacity loss driven by brine water exposure and sulphides, culminating in isolated fall-of-ground events. The solution was a full transition to grouted resin rebar. Cold permafrost temperatures introduced new challenges for resin activation, addressed through heated cartridge storage and in situ thermal monitoring. A monthly QAQC protocol was developed to safely extend resin cartridge service life under arctic storage conditions.

For secondary ground support, the introduction of the Cabletec drilling and cementation rig required a new grout formulation. General use Portland Cement combined with SikaSet RHE accelerant was identified as the solution, with performance validated through pull-out and end-beam testing across a wide range of mix proportions and ambient temperatures, and from the in situ performance of stopes.

For surface support, locally sourced shotcrete aggregate proved unsuitable due to gradation variability. The mix currently in use – MS-D3 Raglan – was developed specifically for site conditions using brine as the mix water and maintains consistent performance across the full operational range of brine concentrations.

Together, these case studies provide practical insights into adapting ground support systems for permafrost environments, with relevance to the growing number of mining operations in arctic and subarctic regions.

Keywords: *permafrost, ground support, inflatable bolts, resin rebar, cable bolting, shotcrete, corrosion, arctic mining*

1 Introduction

The history of mining in Canada's north predates the modern era of mechanised extraction by centuries. Dimmell (2022) reports that mining activity began with the First Nations people upon their arrival on the North American continent some 13,000 to 15,000 years ago, with a quartzite quarry documented more than 10,000 years before present. European prospectors began working their way into the subarctic interior following the gold discoveries of the 1850s and 1860s in British Columbia. The pivotal moment came with the Klondike gold rush of 1896 (Berton 2001), which demonstrated that large-scale resource extraction in northern conditions was both technically feasible and economically transformative, drawing thousands of prospectors into the Yukon Territory and establishing the logistical and cultural frameworks that would underpin all subsequent arctic mining development (Udd & Bétournay 1999).

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Throughout the twentieth century, the geographic reach of Canadian mining progressively extended northward. Operations at Polaris on Little Cornwallis Island, Nanisivik on Baffin Island, and the Lupin gold mine on the shore of Echo Bay in the Northwest Territories demonstrated that continuous permafrost conditions, with ground frozen to depths of several hundred metres, did not preclude viable production. These operations collectively established the foundational understanding of the geomechanical challenges unique to permafrost mining – most notably that the stability of openings in frozen ground is critically dependent on maintaining sub-zero temperatures, and that any thawing of the surrounding rock mass results in rapid and often irreversible loss of strength.

1.1 Geological setting of the Raglan mine

The Raglan Ni-Cu-Co-PGE deposits are situated within the early Paleoproterozoic Cape Smith Belt of Nunavik, Quebec. Mineralisation occurs along the 'Raglan Horizon', the contact between footwall gabbro and metasediments below and ultramafic (komatiitic) volcanic rocks above (Bleeker & Kamo 2020). As shown in Figure 1, the ore lenses are concentrated in pockets along this footwall contact.

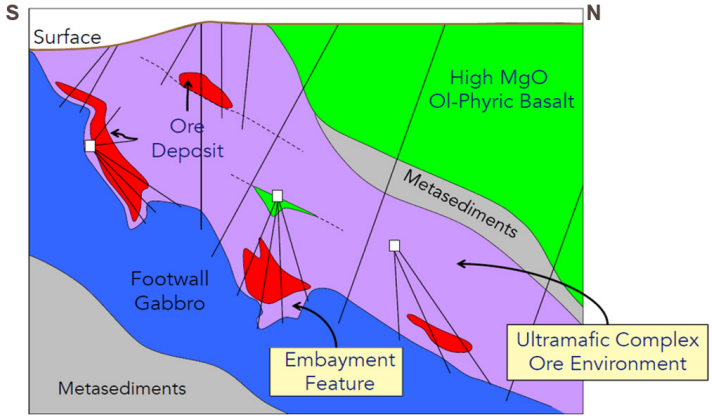


Figure 1 Mineralisation setting on the gabbro footwall at Raglan mine

As illustrated in Figure 2, mineralisation extends along approximately 70 km of strike as a series of over 110 discrete high-grade sulphide lenses spread among 10 deposit clusters. These lenses dip at a mean of 30–40° toward the north-northwest and vary in size from approximately 40,000 to several million tonnes, collectively representing 35 million tonnes of measured, indicated, and inferred resources averaging 3.17% Ni.

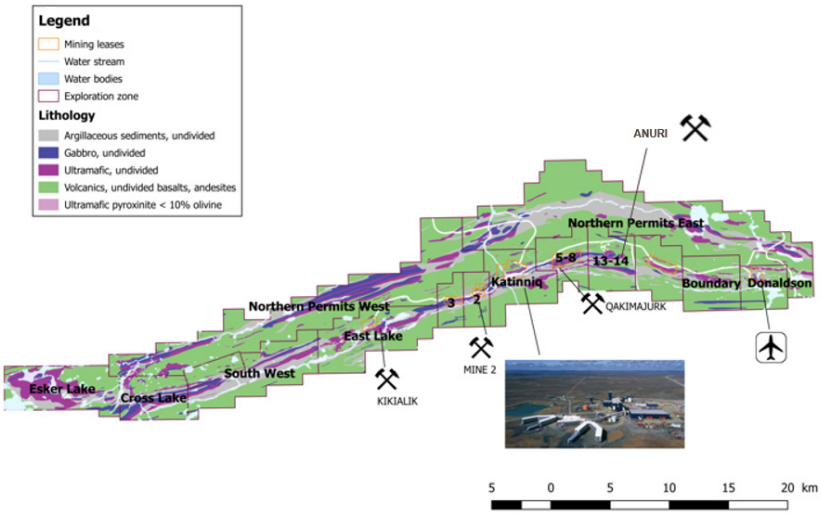


Figure 2 Top view of the Raglan ore deposit along the Raglan Horizon

2 Mining operations at Raglan mine

2.1 Overview and production history

From the start of commercial production in 1998 until approximately 2003, Raglan mine operated using a combination of open pit and underground mining. The open pit operations targeted shallow ore zones accessible near surface, while underground development progressively expanded to access the deeper, higher-grade portions of the deposit. Two more open pits were mined sporadically until 2014. After 2014, all production transitioned to fully underground operations, reflecting both the depletion of near-surface resources and the continued development of deeper ore zones across the property. The shallow open pit operations enabled the development of underground mine portals in competent rock as illustrated in Figure 3, below the zone of surface damage caused by periglacial action and meteorological weathering associated with freeze-thaw cycles in the active layer of the permafrost (Chen et al. 2021; Lei et al. 2022).



Figure 3 Kikialik mine: open pit to underground transition

2.2 Mining methods

The selection of an appropriate mining method and backfill strategy at Raglan was the subject of extensive evaluation prior to and during the early years of production, as documented by Pronovost (1999). The ore lens geometry – wide, steeply dipping, and distributed across multiple sub-levels – precluded extraction in a single open stope without backfill support. Cemented rockfill, the conventional solution for such geometries, was rejected early in the evaluation process due to the prohibitive cost and logistical difficulty of supplying cement to a remote arctic site accessible only by seasonal sealift. An alternative was investigated that sought to exploit the ambient cold conditions: using frozen water as a binding agent by allowing blasthole stopes filled with waste rock and water to freeze progressively under a continuous flow of cold fresh air. However, thermomechanical modelling demonstrated that only approximately 1.5 m of frozen backfill could be expected to develop around the perimeter of a stope after 2 years – far insufficient to provide structural support for adjacent mining. The option of installing freeze pipes within the filled stopes to accelerate freezing was considered but again rejected on cost grounds. The solution ultimately adopted was a combination method for early mining, balancing ore recovery against backfill requirements. The ‘combination’ in the name refers to the fact that this method combines elements of both cut and fill (sequential panel extraction with immediate backfill) and blasthole stoping (the panels themselves are blasted rather than mechanically cut), in a hybrid approach tailored specifically to the geometry and backfill constraints of the Raglan deposits. Shotcrete pillars were used sporadically to supplement ore pillar and improve recovery as illustrated in Figure 4.



Figure 4 Shotcrete pillars used as an ore pillar recovery tool during cut-and-fill mining, Raglan mine (2006)

Two primary underground mining methods are currently employed at Raglan, selected based on geometry, width, and rock mass conditions of the orebody. The dominant method is longhole open stoping, applied to wider, more competent ore zones. Stopes are extracted using a primary-secondary sequence with voids backfilled using either cemented rockfill or uncemented rockfill depending on the structural role of the stope. Rib and sill pillars are left where required to maintain regional stability.

The current mining method is controlled by the orebody width as presented in Figure 5. Since most of the lenses dip between 30 and 40°, when width is insufficient for open stoping, the operation shifts to mechanised cut and fill mining, typically in panels up to 10 m wide developed by crosscut access. In this method, each cut is mined sequentially and backfilled before mining resumes in the cut directly above, progressing upward through the ore column. Square ore pillars are left between panels as part of the extraction sequence.

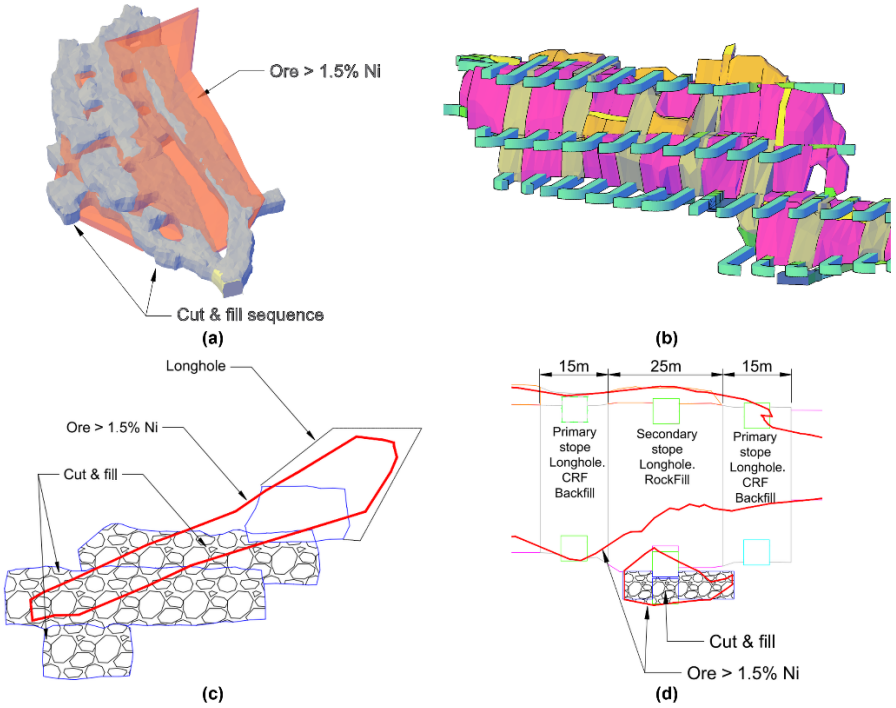


Figure 5 Current underground mining method selection at Raglan mine: application of cut-and-fill and longhole stoping in response to ore lens geometry, size and a regional dip of 30–40°. (a) Whole view of a small lens (orange, ~40 kt); (b) partial view of a larger lens (~2 Mt) with multiple longhole levels; (c) section view of a typical cut-and-fill operation with 4 lifts, the last lift mined with uphole; (d) typical section view of a longhole operation with a cut-and-fill bench, primary stopes backfilled with cemented rockfill

3 Permafrost and its influence on ground conditions

Raglan mine lies within the zone of continuous permafrost of the Cape Smith Belt as showed in Figure 6. Underground rock temperatures measure approximately −7°C near surface, increasing by approximately 1.5°C per 100 vertical metres to a depth of ~550 m. The pervasive presence of frozen ground fundamentally defines the geomechanical environment in which ground support must perform.

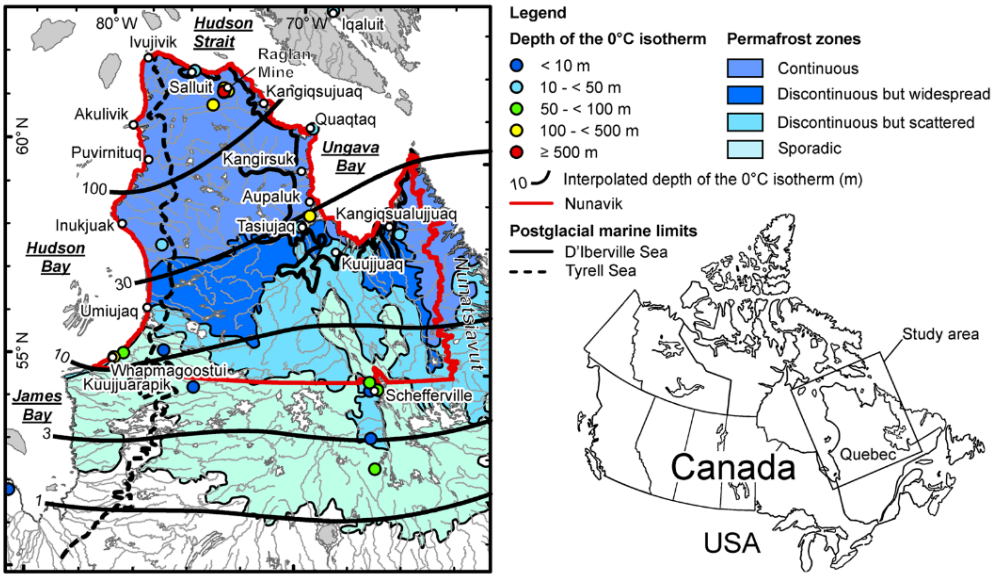


Figure 6 Permafrost presence in northern Quebec (Lemieux et al. 2016)

In permafrost conditions, porewater within the rock mass is frozen, which significantly enhances the in situ cohesion of the rock mass (Krautblatter et al. 2013). Ice acts as a cementing agent within fractures and discontinuities, effectively improving the apparent rock mass quality relative to what would be observed in unfrozen ground. This benefit manifests as greater stand-up time in unsupported excavations and reduced immediate fall-out, particularly in fractured rock types such as argillite. Therefore, during the early years of operation, relatively light ground support schemes were deemed sufficient for most development headings as described in Section 4.

4 Evolution of primary ground support: 4 operational eras

The evolution of primary ground support at Raglan mine reflects 3 decades of operational learning in a uniquely challenging environment. The approach has evolved through 4 distinct eras, each defined by significant shifts in support philosophy, materials selection, and quality control practices.

4.1 Era 1 (1997–2000): establishment of underground operations under intact permafrost conditions

During the initial years of underground development at Raglan, drift geometry was largely dictated by the equipment fleet in use at the time. The primary haulage unit was the Minetruck MT436B, a smaller-format truck whose dimensions resulted in excavation spans that were inherently more self-supporting than those developed in later years with larger equipment. Development proceeded through 3 principal rock types – gabbro, peridotite, and argillite – each of which presented distinct ground behaviour. The gabbro, which hosts no mineralisation but forms the majority of the development corridor, produced large, well-defined blocks with good stand-up time, requiring no systematic surface support. Metallic straps connecting mechanical rockbolts were applied selectively to discrete, specific ground issues, rather than as a pattern support applied across broader zones. The peridotite, which hosts the mineralisation, and the argillite required more systematic support, including mesh where ground conditions warranted.

The intact permafrost conditions provided a significant ground stability advantage throughout this era. The frozen rock mass exhibited markedly improved cohesion relative to unfrozen equivalents, reducing the frequency and severity of fall-out events. Primary ground support consisted of mechanical rockbolts in the backs, with 2.4 m resin-grouted rebar added at intersections and in poorer ground. These rebars were installed using oil-based resin cartridges, selected for their superior performance at low temperatures relative to water-based formulations. During summer and autumn, installation proceeded without special precautions; during winter months, cartridges were transported directly from heated storage to the face to ensure adequate activation temperatures. The management of resin installation in cold conditions, combined with the objective of improving mining cycle times, given that most of the ore production derived from cut and fill panels as described in Section 2, created operational pressure to identify a simpler primary support solution.

The transition to Swellex inflatable friction bolts was driven by precisely these considerations. The Swellex system offered immediate, installation-ready support without the thermal management requirements of resin chemistry, directly improving cycle times in the active cut and fill panels. Given that the projected mine life of Katinniq at that time was approximately 10 years and given the evidence from early pull-out testing that corrosion rates were low in the cold, dry underground environment, the long-term durability of inflatable bolts was not considered a primary concern.

In areas intersecting fault zones or structurally complex ground, shotcrete was applied as a supplementary measure. Recognising both the logistical challenges of arctic supply and the potential cost savings of local production, the mine investigated the feasibility of producing shotcrete using aggregate sourced from a local esker, a glacial deposit of naturally sorted sand and gravel. However, direct shear testing of wall samples (Figure 7) revealed that the particle size distribution of the locally available sand – and critically, its moisture content – was too variable to permit the production of a consistent, reliable shotcrete mix. The onsite aggregate initiative was consequently discontinued.

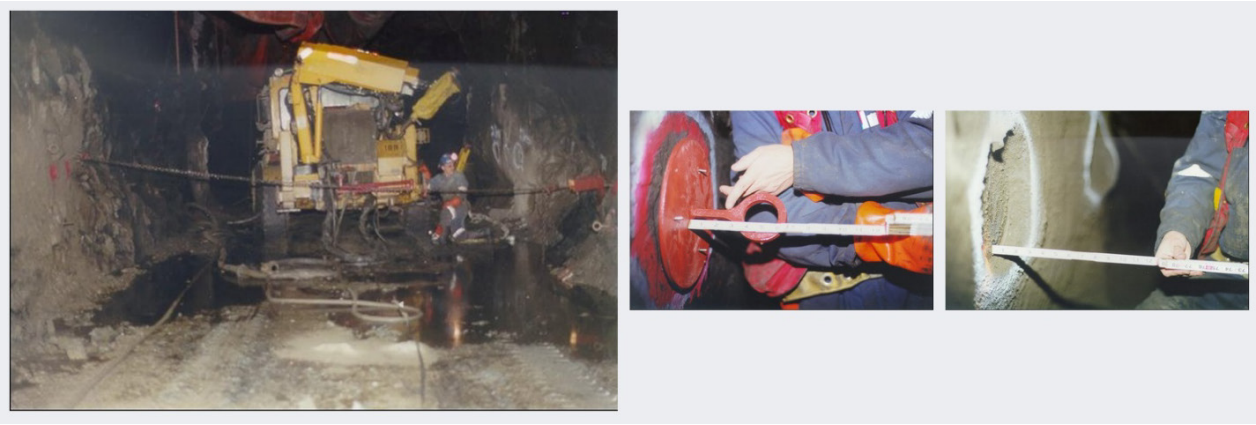


Figure 7 Onsite shotcrete trial using locally sourced esker aggregate, Raglan mine – application and wall thickness measurements

4.2 Era 2 (2000–2008): large-scale use of inflatable bolts

Throughout this period, a recurring pattern of structurally controlled ground instabilities emerged in the longhole stoping operations. In October 2006, an estimated 1,880 m³ of hanging wall material failed in the TE-1280(1300) stope at Katinniq, detaching along subparallel geological structures in the hanging wall following a series of production blasts. The following month, the north wall of cut S-1380 failed, releasing approximately 550 tonnes of highly fractured, serpentinite-filled peridotite – a rock mass with a rock quality designation (RQD) value between 20 and 40 and structural surfaces that offered little frictional resistance. Neither event resulted in injuries, as no personnel were present, but both underscored the sensitivity of wide-span excavations to structurally controlled failure in the presence of weak, serpentinite-infilled discontinuities. Internal analysis highlighted that the standard Swellex-and-mesh support scheme, while adequate for routine development headings, was insufficient to stabilise hanging walls of this scale once key structural blocks were destabilised.

A significant event of the era occurred on 22 August 2008, when approximately 12,500 tonnes of ore caved catastrophically in Stope 3F-1310 at Mine 3, approximately one hour after a development blast on the level above. An independent technical review concluded that the failure was gravity-driven and structurally controlled by local joint sets and a weak, flat-dipping hanging wall fault. The investigation identified several compounding factors: the large open back span created by the extraction sequence, with no remaining post pillars; the proximity of active development blasting above the open stope; and the possibility that warm summer ambient temperatures had thawed the near-surface rock mass to depths of up to 5.5 m, reducing cohesion in a permafrost environment that otherwise provided a natural stability benefit.

The Swellex bolts and cable bolts in place were unable to arrest the failure once momentum had been gained – a mechanism analogous to the TE-1280(1300) stope failure of October 2006. The Itasca review identified the absence of consolidated backfill as the common root cause across these large-scale failures, arguing that without the ability to fill primary stopes before opening adjacent secondary stopes, the extraction sequence inevitably created back spans too large to be supported by surface reinforcement alone.

By the end of Era 2, the evidence from structural failures, pull-out testing, corrosion investigations, and independent technical reviews had established a clear diagnosis: the Swellex system was incompatible with the long-term demands of an expanding mine in a brine-saturated permafrost environment, and the extraction sequences in use for wide-ore longhole stopes required fundamental reconsideration. These conclusions shaped the framework for the 2 subsequent operational phases, marked by the introduction of a primary-secondary mining sequence using cemented rockfill.

4.3 Era 3 (2008–2019): expansion, deeper mining, and the emergence of corrosion

The third operational era was marked by significant expansion of the underground footprint at Raglan, with the development and extension of new mines: Kikialik, Qakimajurq, Mine 3, and Mine 2. As mining progressed to greater depths and into areas that had been in service for longer periods, the limitations of the Swellex inflatable bolt system in the Raglan environment became increasingly apparent.

The primary ground support philosophy remained unchanged from Era 2, with Swellex bolts and mesh forming the basis of the support system across all active workings.

Isolated falls of ground in previously developed headings, historically advanced at rates of up to 12 km per year, were primarily driven by gravitational wedge failure and sliding along major fault zones. The investigation of these events revealed a critical loss of strength in retrieved bolts, with detailed examination identifying the root cause as aggressive corrosion of the bolt shell resulting from multiple interacting corrosive mechanisms. The most obvious source was direct exposure to brine water within the rock mass – both naturally occurring saline groundwater and the calcium chloride solutions used for drilling operations – which created a highly corrosive electrochemical environment that the bare steel of the Swellex bolt was unable to withstand over multi-year service lives, as shown in Figure 8.



(a) (b)

Figure 8 Corrosion-induced damage in underground conditions: (a) corrosion plume developing along an in situ geological discontinuity; (b) corrosion-driven delamination of a Swellex bolt surface at collar, leading to steel loss and reduced mechanical capacity

However, direct water flow was not the only driver of corrosion. At Mine 2, a fall-of-ground occurred in Ramp 1320 at a location with no active water inflow but high ambient humidity during summer months. Moisture-laden air penetrated fractures in the rock mass, condensing on bolt surfaces and within structural wedges, and was sufficient to initiate corrosion of the Swellex shells – a process likely accelerated by stress corrosion cracking at points of mechanical loading. This event demonstrated that even in the absence of flowing brine, atmospheric moisture alone could produce conditions aggressive enough to compromise bolt integrity over time.

A further contributing factor was identified in areas such as the 8H zone, where the host rock mineralogy itself intensified the corrosive environment. Petrographic examination of wall rock samples identified disseminated pyrrhotite; sulphide minerals of this type are well known to generate acidic oxidation products on contact with moisture. This mechanism is currently under investigation, with long-term corrosion coupons installed to quantify its effect in accordance with the protocol described by Dorion et al. (2009).

Corrosion was particularly severe at 2 critical locations: the collar zone, where bolts were most exposed to atmospheric moisture and brine ingress; and at points of contact with brine-saturated or mineralogically reactive fractures, where material loss was most pronounced. Figure 9 presents over 20 years of pull-out test results on inflatable bolts, with surface characterisation of corrosion levels C1 to C6 as defined by (Dorion 2019). Only destructive tests – those resulting in bolt failure – are represented, as a significantly larger number of tests were conducted without reaching failure. As the overlapping of corrosion levels illustrates, collar corrosion is not a reliable indicator of residual load-bearing capacity, a conclusion further supported by the post-failure analysis of rock mass caving events. Pitting corrosion, occurring at discrete locations along rock joints that act as conduits for humidity or water ingress, is frequently observed in situ and can drive bolt failure independently of the condition visible at the collar. Based on this body of evidence, the general assessment at Raglan is that standard inflatable bolts have an effective service life of approximately 6 years before rehabilitation is required.

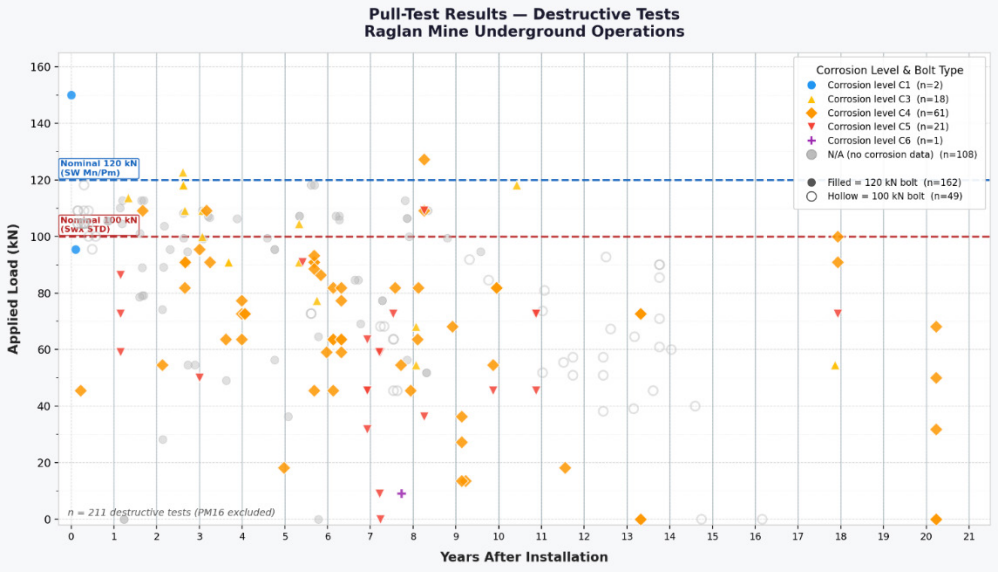


Figure 9 Destructive tests for 20 years of usage of inflatable bolts

As part of this investigation, a sustained effort was made over several years – initially in collaboration with Atlas Copco – to develop a plasticoated variant of the Swellex bolt that could provide a physical barrier between the steel shell and the corrosive environment. The plasticoating process had originally been developed for automotive components with relatively simple geometries. Adapting it to the complex profile of an inflatable bolt proved far more difficult. The irregular shape of the Swellex – particularly the flared inflation head and the U-shaped cross-section of the bolt profile – prevented the coating process from achieving a uniform thickness across all surfaces. The concave geometry of the inflation head was especially problematic: it retained water at precisely the location where the bolt head bears against the face plate and

mesh, concentrating corrosive attack at one of the most structurally critical points. The external surface of the inflation head, where the inflation mandrel engages the bolt, also proved difficult to coat reliably.

Efforts were made to improve coating adhesion by cleaning and preparing the steel surface prior to application, but a more fundamental problem emerged with time. The plastic material used in these early generations was sensitive to prolonged ultraviolet exposure during surface storage. After extended periods in sunlight, the coating became brittle and dry, losing its adhesion to the steel substrate. In the field, this manifested as delamination: miners reported that during insertion, contact between the bolt and the irregular walls of the drillhole caused the degraded coating to peel back from the collar, exposing the underlying steel at precisely the location most vulnerable to brine ingress. The peeling was particularly pronounced in fractured ground and was exacerbated where the bolt passed through face plates with sharp-edged holes that acted as cutting surfaces against the weakened coating.

It should be noted that the plasticoating process has since undergone substantial development. The original coating material and application process have been abandoned entirely, and current generation plasticoated bolts are of markedly improved quality, offering effective and durable protection during insertion.

However, an important limitation remains unresolved regardless of coating quality. Once an inflatable bolt is expanded in place and the inflation water drains from the bolt interior, the inflation hole remains open to the underground atmosphere. This opening allows contaminants – blast gases, diesel exhaust fumes, and ambient moisture – to migrate into the hollow interior of the bolt over time. Corrosion therefore proceeds from the inside outward as observed in Figure 10, a mechanism against which even a flawless external coating offers no protection. This internal corrosion pathway was ultimately one of the factors that reinforced the decision to transition away from inflatable bolts entirely, as described in the following section.

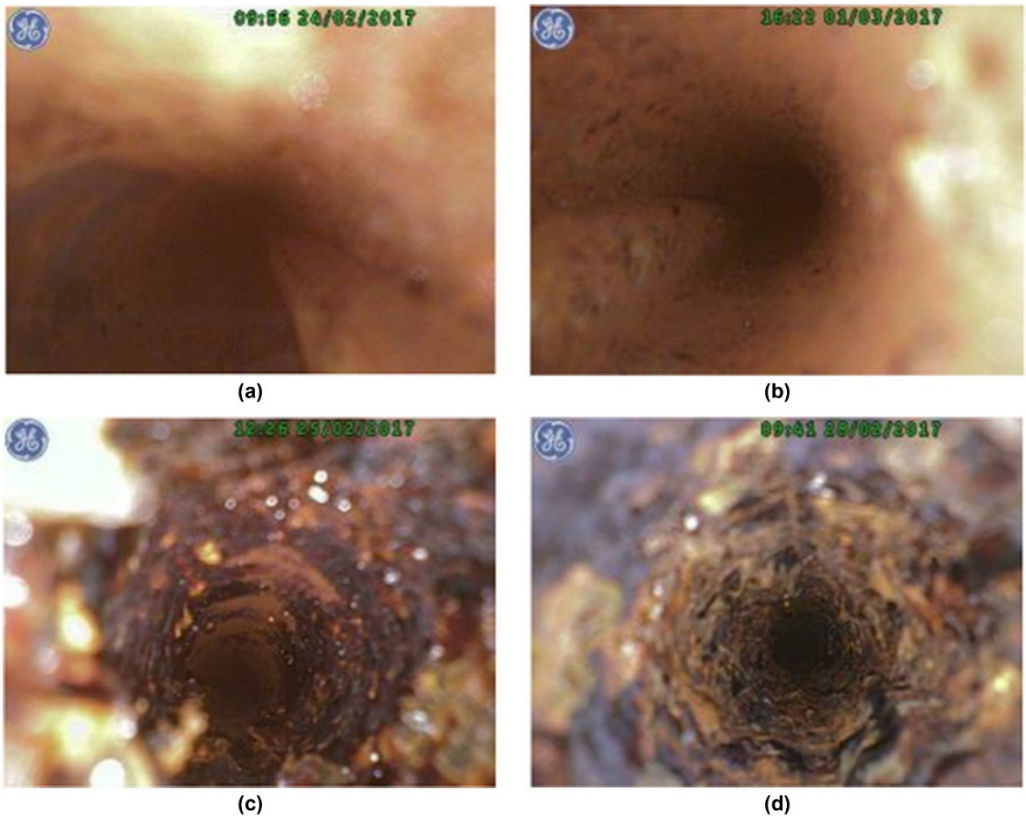


Figure 10 In situ corrosion classification of Swellex bolt interiors at Raglan mine: (a) surface corrosion, C3, corrosion affects more than 75% of the surface; (b) advanced corrosion, C4, the interior of the bolt is covered by a layer of corrosion; (c) very advanced corrosion, C5, a rust layer begins to form intermittently around the interior, with a thickness of at least 1 mm; (d) extreme corrosion, C5+, the interior of the bolt is severely affected, a significant rust layer has formed and the inner diameter is visibly reduced

4.4 Era 4 (2019–Present): transition to resin rebar, galvanised friction bolts and spin cables among new challenges

The accumulation of evidence from pull-out testing, corrosion investigations, and critically, isolated fall-of-ground events attributable to bolt capacity loss, drove a fundamental reassessment of the primary ground support strategy at Raglan. The decision was made to transition from inflatable friction bolts to grouted, resin-based 22 mm rebar as the standard primary roof support element across all mine areas, with a transition to 20 mm rebar due to installation difficulties encountered with the MacLean bolter. Galvanised split-set bolts were selected as the standard support for wall applications. This transition was accompanied by an extensive rehabilitation program covering approximately 12.5 km of existing development drift, in which degraded Swellex bolts were supplemented or replaced with resin rebar installations. Since the completion of this rehabilitation program no fall-of-ground events attributable to ground support corrosion have been recorded.

While the corrosion resistance of resin-anchored rebar represented a significant improvement over inflatable bolts in the Raglan environment, the transition introduced an entirely new set of technical challenges associated with resin performance in cold permafrost conditions. These challenges were further compounded by the need to successfully integrate 5 m-long spin cable bolts to replace 3.6 m SuperSwellex for intersection support, with the objective of avoiding cement-grouted cables that negatively impact mine development cycle times.

4.4.1 Resin performance in cold environments

Polyester resin curing is thermally driven, and at Raglan, underground rock temperatures consistently below 0°C severely retard or prevent catalysis if cartridges are not actively managed. An in situ temperature measurement program confirmed that unmanaged cartridges at the face fell below the manufacturer's minimum activation threshold. The solution was heated storage boxes on bolters, combined with procedural controls to minimise heat loss during transfer. Pull-out testing validated adequate bond development when cartridge temperatures at insertion were maintained above 10°C.

Viscosity increases at low temperatures also raised insertion forces and mixing torque for spin cable installations. For the longer cycle times involved in the installation of spin cables, 15 to 20 minutes, residual cartridge heat was insufficient to prevent premature stiffening, causing shear pin failures before the full cable length had been inserted. The cable length was reduced from 6 to 5 m to mitigate this, and thermal protocols were adjusted accordingly.

4.4.2 Resin shelf life and supply chain management

Raglan's remote location limits sea access to roughly June–March, requiring large onsite inventories of consumables. Standard resin cartridges carry a 12-month shelf life, but sub-zero temperature onsite storage conditions significantly retard chemical degradation beyond this nominal limit. Rather than discarding expired batches, a costly and operationally disruptive option, the mine implemented a QAQC protocol combining installation testing and pull-out testing to verify that expired cartridges meet performance criteria before continued use. The protocol applies to any resin more than 3 months past its nominal expiry date, regardless of resin type. Five rebars are installed using a single resin cartridge at the bottom of the hole, respecting the resin's set time, and are then subjected to a pull-out test to a maximum of 13.6 tonnes, along with a torque check confirming that the shear pin can be broken and the nut threaded after set. The first test series is performed once the resin reaches 4 months past expiry, and testing is repeated every 3 months thereafter for as long as the batch remains in use. If all 5 installations and pull-out tests meet the acceptance criteria, no action is required and the resin remains in service. If even one sample fails to meet the criteria, the entire batch is considered non-conforming and is withdrawn from installation, with operations notified to discontinue its use.

5 Secondary ground support: cable bolting in permafrost

Cable bolting has been used at Raglan mine as secondary ground support in areas requiring reinforcement beyond the capacity of the primary bolt pattern, including the backs of wide stopes, major fault intersections, and areas of elevated stress.

Historically, cable bolts were grouted using MSGROUT (Sika), a pre-packaged cementitious product specifically formulated to achieve rapid strength gain – a critical requirement when grouting against a permafrost rock surface where heat loss to the substrate is immediate and the risk of grout freezing before adequate strength development is real.

The introduction of the Cabletec drilling and cementation rig (Epiroc) imposed new constraints on the grouting operation. The Cabletec system's installation cycle and equipment geometry required a grout formulation compatible with its pumping and injection parameters, and MSGROUT was no longer suitable. Following a systematic testing program, the solution identified was general use (GU) Portland cement combined with SikaSet RHE, a non-chloride accelerating admixture that provides both early strength gain and freeze protection at the concentrations required.

As presented in Figure 11, pull-out test results compiled across a wide range of water-to-cement ratios and SikaSet RHE concentrations demonstrate consistently satisfactory bond performance, confirming that the GU + SikaSet RHE formulation is robust across the range of mix proportions likely to be encountered in practice.

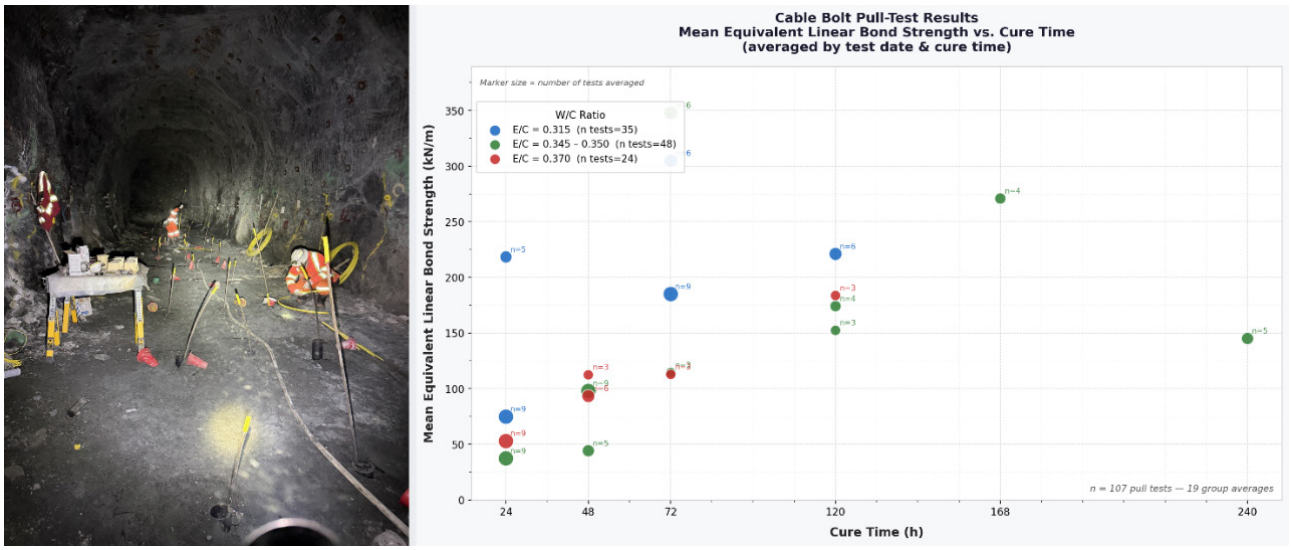


Figure 11 Pull-out test field array for SikaSet RHE concentration optimisation, Raglan mine

Figure 12 presents the results of end-beam tests (methodology from Bernard 2005) conducted in parallel with the pull-out program and as part of the QAQC routine carried out throughout the year across a wide range of ambient temperatures at cable bolting locations. These results confirm that grout systems maintain adequate performance under the variable thermal conditions encountered across the mine's operating areas.

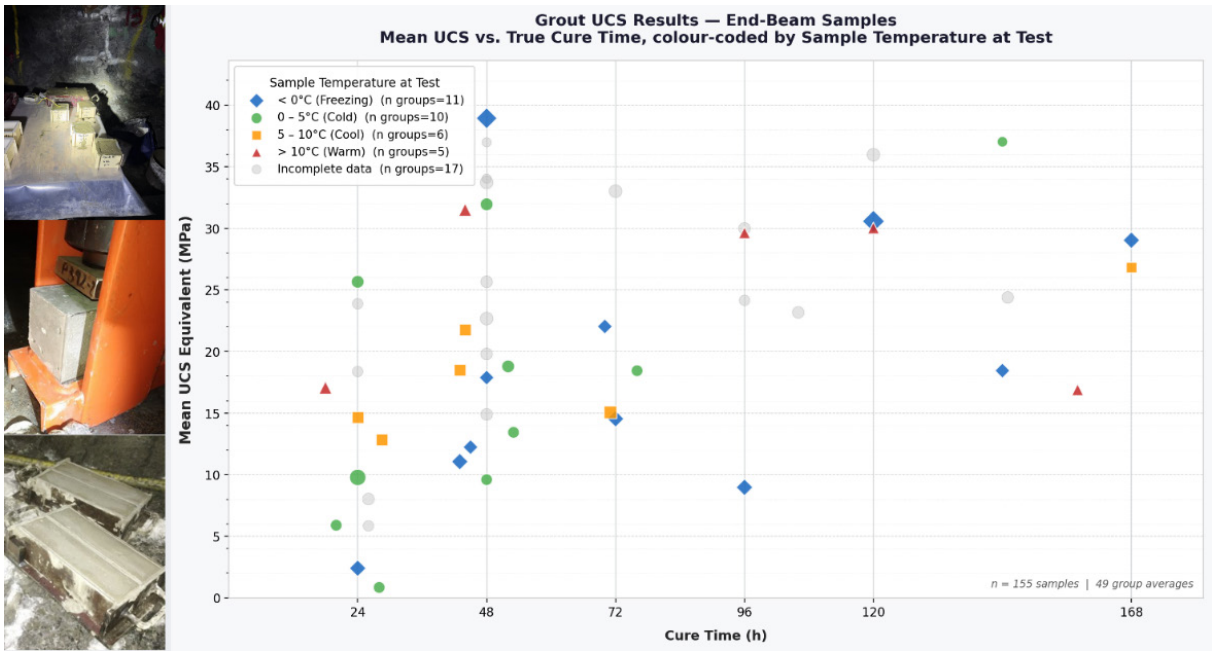


Figure 12 General use cement + SikaSet RHE accelerant uniaxial compressive strength (UCS) versus curing time, Raglan mine conditions

6 Surface support: shotcrete in a brine environment

Shotcrete (when necessary to supplement regular galvanised mesh) forms the third tier of the ground support system at Raglan mine, applied as surface support in areas requiring areal coverage and confinement in addition to point-anchored reinforcement.

The shotcrete mix currently used at Raglan – designated MS-D3 Raglan – was developed specifically for the site's thermal conditions in collaboration with King/Sika. A key design constraint is that freshwater cannot be used in the underground environment due to the risk of freezing in distribution lines and mixing equipment. Brine water – the calcium chloride solution used throughout underground operations – is therefore used as the mix water for shotcrete production. The MS-D3 Raglan formulation was optimised to perform across the range of brine concentrations encountered in practice, which vary seasonally depending on operational freeze protection requirements.

As presented in Figure 13, end-beam-derived UCS-equivalent results compiled across a range of brine concentrations confirm that the mix maintains adequate strength performance across the full operational range. These results form the basis of the ongoing QAQC program for shotcrete at Raglan, providing confidence that mix performance remains within design limits despite the variability inherent in brine concentration across the mine's operating conditions.

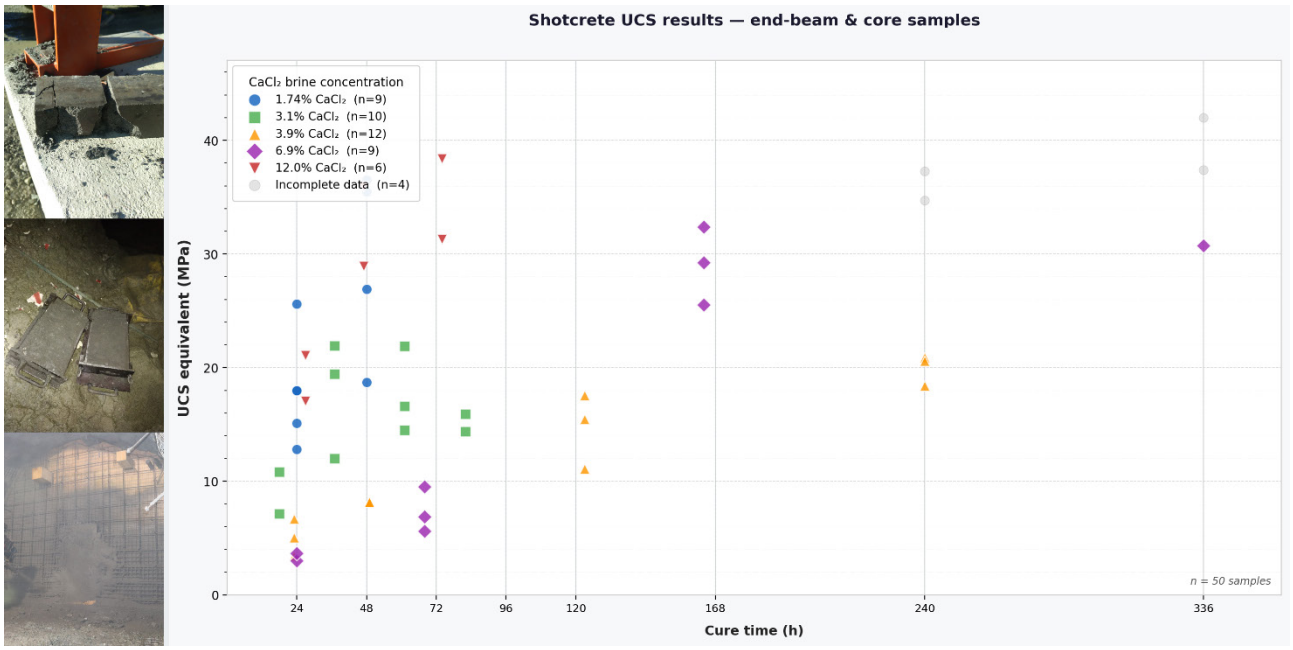


Figure 13 End-beam test setup and results: uniaxial compressive strength (UCS) equivalent versus curing time, across varying calcium chloride ($CaCl_2$) brine concentrations

7 Conclusion

The 30-year operational experience at Raglan mine provides a comprehensive case study of the iterative challenges and practical solutions associated with ground support in a permafrost environment. Several themes emerge consistently across the 3 tiers of support examined in this paper.

- The permafrost environment confers genuine geomechanical benefits in the form of improved rock mass cohesion, but these benefits are contingent on maintaining frozen conditions and cannot be relied upon indefinitely as excavations age and the disturbed zone around openings undergo thermal and mechanical change. The corrosion-induced capacity loss experienced with Swellex bolts illustrates that even where the rock mass remains stable, support elements are subject to environmental degradation mechanisms that are uniquely severe in brine-saturated permafrost ground.
- The transition from inflatable Swellex bolts to grouted resin rebar in combination with spin cables for intersections as the primary support element was necessitated by this corrosion-induced capacity loss and has proven effective: no fall-of-ground events attributable to ground support corrosion have occurred since the completion of the rehabilitation program.
- Essentially every standard ground support material and procedure requires meaningful adaptation for the arctic environment. Resin cartridges, cement grouts, and shotcrete mixes all perform differently at sub-zero temperatures and in the presence of calcium chloride, and the degree of adaptation required is non-trivial. Resin bolt installation requires active thermal management of cartridges to ensure adequate activation, and a site-specific QAQC protocol for cartridges beyond their nominal shelf life provides a practical solution to the supply chain constraints of arctic logistics.
- Cable bolt grouting requires careful selection of grout formulation: the combination of GU Portland Cement with SikaSet RHE admixture provides the necessary balance of workability and early strength gain for Cabletec installation at Raglan.
- Shotcrete performance is directly influenced by the calcium chloride concentration of the brine mix water, and the MS-D3 Raglan formulation, developed specifically for site conditions, maintains adequate strength across the full operational range of brine concentrations.

- Finally, the logistical constraints imposed by the remote arctic location amplify the consequences of every ground support decision. Materials that would be trivially replaced in a more accessible operation may be months away from re-supply, making robust testing and quality assurance protocols essential not only for safety but for operational continuity. The collective experience documented here is intended to serve as a practical reference for practitioners at other arctic and subarctic mining operations facing similar challenges, a category that is growing as mineral exploration and development extends further into northern permafrost environments.

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Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used Opus 4.8 and 5.0 (Anthropic) to assist with editing manuscript text for clarity and concision, formatting in-text citations and the reference list in accordance with ACG style guidelines, and preparing composite multi-panel figures. The authors have reviewed the content and edited it where required and take full responsibility for said content.

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