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Adapting to rapid change in demand for ground support systems at Jokisivu mine

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Abstract

This paper presents an assessment of adapting ground control practices for deeper stope mining at the Jokisivu narrow-vein longitudinal benching gold mine in Finland. Existing ground support systems in oredrives – primarily 2.4 m hydroformed expansion friction rockbolts and plain shotcrete – performed well for the majority of the mine's 8-year operational life. However, this system proved unsuitable for responding to the rapid onset of stress-induced damage at depths greater than 300 m. Structured observational and analytical investigations were conducted to understand failure modes and their timing. Observed damage ranged from intact rock failure forming a fractured excavation surface leading to spalling, through to occasional larger falls of ground, likely associated with seismic shakedown. Unreinforced shotcrete applied after expansion friction rockbolts debonded and failed together with spalled slabs, while rockbolt and plate performance remained adequate. Damage was dominated by brittle, stress-induced spalling of intact rock in drive backs and shoulders, driven by high horizontal stresses induced during panel retreat toward a central access and upward toward sill pillars. Spalling depths ranged from 0.5 to 1 m in both stiff massive diorite and slightly weaker veined diorite and pegmatite.

Available mine equipment and ground support products were reconfigured to implement immediate changes to ground control systems, improving both ground support reliability and personnel safety. The initial modification – installing weld mesh over existing plain shotcrete, with three-square mesh overlaps secured using the original 2.4 m expansion friction rockbolts – demonstrated significantly improved risk mitigation. For new development, ground support standards were modified to include either fibre-reinforced shotcrete or weld mesh reinforced plain shotcrete secured with the same hydroformed expansion rockbolts. Controlled installation practices for development advance were implemented, oredrive development timing was adjusted, sill pillar sizing and stope extraction sequencing were optimised. The lowest extracted stoping panel, at depths of 585–645 m, was successfully completed in 2024 to planned extraction tonnage and rates. Despite increased rock noise events, no significant falls of ground were recorded.

Keywords: *ground support, demand change, ground conditions, spalling damage, rehabilitation, development timing*

1 Introduction

Jokisivu mine, operated by Dragon Mining, is a narrow-vein stoping gold operation in south-western Finland. Stope extraction is carried out longitudinally using benching with unconsolidated rockfill mainly and sill pillars are retained between successive panels retreated to a central access. This paper presents a case study assessment of ground control practices adapted for deeper stope mining at Jokisivu, based on underground observation, laboratory rock strength testing, and technical assessment carried out by SRK Consulting and Dragon Mining between late 2022 and late 2023.

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For the majority of the mine's 8-year operational life, the existing ground support system in oredrives – primarily 2.4 m expansion friction rockbolts and plain shotcrete – performed well. However, this system proved unsuitable for responding to the relatively rapid and unexpected onset of stress-induced damage that developed as mining progressed in levels below approximately 350 m below surface.

This paper has 4 objectives:

1. To describe and characterise the change in demand placed on ground support systems as mining progressed in deeper panels
2. To diagnose the observed failure modes and their timing
3. To describe and assess the ground support and operational practices adapted in response
4. To comment on the performance of the adapted system in the lowest extracted stoping panel, 585–645 m, completed in 2024.

2 Jokisivu mine and original ground support context

2.1 Mine geology, layout and mining method

The Jokisivu narrow-vein gold orebody is hosted within quartz diorite and mica gneiss, cut by pegmatite intrusions and fold parallel quartz-veined ground. Folding events have created the Kujankallio and Arpola limbs and hinge zones, hosting ore veins of typically 1–2 m wide with 0.2 to 10 m range. The complicated geometry of ore zones for selective narrow-vein mining in the plunging fold also includes parallel mineralised lenses from <3 m to 10 m separation. Variable dip angles, from as low as 40° in the main zone areas and steeper 80–90° dip in the hinge zone areas, created localised access and stoping challenges. Mining panels are approximately 75 m in vertical height, extracted in 15 m sublevel vertical spacing with 4.5 m minimum width. Sill pillars separating the panels initially ranged from 5 to 7 m vertical height in upper areas, depending on the ore dip and position in the fold. Figure 1 is an oblique view of the Kujankallio and Arpola deposit areas displaying stopes extracted until early 2023. At the time of the investigation, the 340–265 m panel was fully mined out, the 420–350 m and 495–435 m panels retained several remnant stopes, the 570–510 m panel was the main production panel. The 645–585 m panel was under development with oredrive advance on the 615 level and stoping scheduled to commence in October 2023.

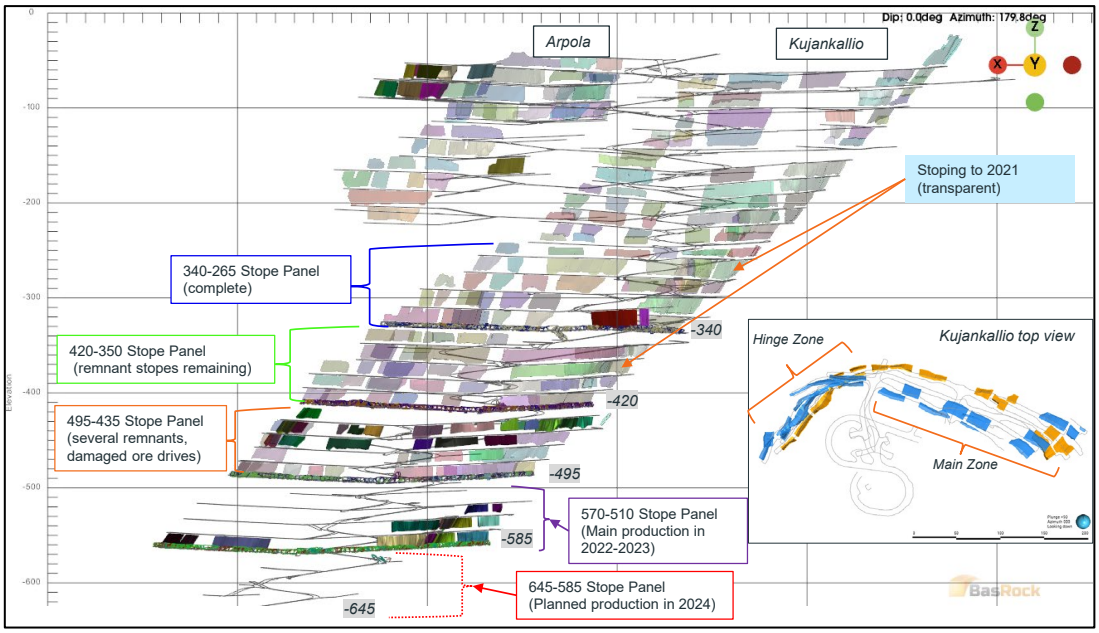


Figure 1 Jokisivu mine overall layout looking southeast, showing 75 m high stoping panels, sill pillars and panel retreat sequence. The inset is a top view of the 405, 420 and 430 levels (SRK Consulting 2023)

2.2 Rock mass conditions and stress environment

Massive quartz diorite, hosting the ore lenses, generally performed well in initial development and stope mining but was increasingly susceptible to intact rock failure by brittle spalling under increasing induced stress. Pegmatite and quartz-rich zones both crosscut and are parallel to ore and these showed more severe local stress damage, including drillhole squeezing and strainbursting in some areas.

To understand the stress to strength relationship, initial rock mass characterisation was carried out. Rock quality estimates were made from underground observations, core inspections as well as material strength tests from a mixture of core and lump samples. Laboratory tests were carried out on diorite, mica gneiss and pegmatite that were tested at Stress Measurement Company Oy in Finland. Tests included uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), triaxial compressive strength, and point load testing. Quartz vein material was not sampled, though field observations indicate it behaves as a weaker, more brittle rock type than diorite. Rock mass properties are summarised in Table 1 by ranges in material parameters and Geological Strength Index (GSI) estimates.

No site specific stress measurements were available for Jokisivu at the time of the investigation, so the stress regime was benchmarked against other Finnish mines, including Kittilä and Pyhäsalmi (Bergström et al. 2014). A horizontal-to-vertical stress ratio (k) of approximately 2:1 was assumed, to be consistent with the common regime observed elsewhere in Finland and attributable to the similar pattern of damage observed underground. Maximum principal stress is likely sub-horizontal and normally oriented perpendicular to the deposit strike; however, the tight folding and plunging geometry, along with structural complexity in the Jokisivu orebody, has likely concentrated and potentially reoriented stress along the fold limbs, particularly near fold hinge zones, where stress may also be locally 'locked in'.

Table 1 Indicative rock strength properties and Geological Strength Index (GSI) estimate by rock type

Rock type	Uniaxial compressive strength (MPa)	Brazilian tensile strength (MPa)	GSI	Jointing	Quality
Diorite (massive)	140–180	9–12	65–75	Sparsely jointed	Very Good
Diorite (veined)	90–120	6–9	50–60	Sparsely jointed	Very Good
Pegmatite	100–140	6–10	55–65	Jointed	Good–Very Good
Mica gneiss	110–150	7–11	55–65	Jointed	Good–Very Good
Quartz vein	–	–	–	Jointed	Good–Very Good

2.3 Summary of damage and increase in demand on ground support systems

The majority of ground control issues at Jokisivu were found to be developing below the 350 m level, generally restricted to minor but continuous damage in oredrive backs and shoulders, related to stope panel retreat toward sill pillars and toward diminishing pillars at level access points. In contrast, no significant issues were identified in the footwall declines, level accesses or other footwall infrastructure. Support demand shifted from managing occasional damage to containing systematic, stress-induced spalling together with an increased incidence of microseismic activity as identified by rock noise report records.

The baseline ground support system comprised 2.4 m hydroformed expansion friction rockbolts – typically Jennmar ERB120+ or Sandvik Omega expansion bolts – as the primary reinforcement with nominal supplier listed technical properties of 120 kN breaking load and minimum 20% elongation (www.jennmar.com). These are referred to as 'expansion friction rockbolts' further in the paper. Mechanical bolter installation is utilised with 150 mm square plates, and then plain shotcrete was applied after bolting in the oredrives. This system performed satisfactorily for most of the upper oredrive development and stoping, with only minor and infrequent stress-related damage recorded above approximately 350 m depth. The mine operated safely

with an observational approach to identify ground support issues, mainly the areas to mechanically scale and replace shotcrete where the original layer had fallen or was removed by scaling. As mining progressed below 350 m, the rate and severity of stress-induced damage increased rapidly and unexpectedly, resulting in the original support system no longer able to reliably contain the damaged rock mass.

The entire Kujankallio decline or level access drives (in the footwall) were not showing evidence of stress-induced damage, even at 645 m depth. This is attributed to the use of fibre-reinforced shotcrete in the original ground support standards for these areas.

3 Investigation methods: observational and analytical

The response to the changing ground conditions was informed by a combined program of structured underground observation and targeted analytical work. A structured observation program was carried out across the levels most affected by the onset of stress damage. This included inspection of the 320 to 435 levels that were accessed for remnant stope mining. The 450 to 495 levels were inspected as these were approaching final stope extraction in that panel. At that time, the level from 510 to 570 were the main stope production panel, and oredrive development had advanced with issues also developing away from stoping. The 600 and 615 levels were in new development with stress-related issues evident in development advance.

With specific attention paid to oredrives and drive/stope intersections, the inspection process comprised aspects relating to ground control and excavation performance issues that included:

- the damage mechanism apparent and changes over time, including local rock type differences
- the extent and timing of shotcrete cracking and debonding
- depth of failure and location of spalling in the excavation perimeter
- type and condition of the ground support and how many passes of installation in each area
- extent of floor cracking and heave including its proximity to stoping and extent of panel extraction when first observed.

Additionally, the reports of rock noise and evidence of minor strainburst events were determined by conversations with mining personnel.

3.1 Interpretations of damage and original ground support performance

The dominant damage evident was brittle, stress-induced spalling of intact rock in oredrive backs and shoulders, driven by high horizontal stresses generated as panels retreated toward the central access and upward toward sill pillars. Rock spalling and profile loss became continuous in the lower levels, occurring even during early stope panel extraction and in isolated development such as on the 615 level.

Observed damage ranged from intact rock spalling to occasional larger falls of ground, the latter likely associated with seismic shakedown. Depth of intact rock fracturing was generally less than 0.5 m but locally reached up to 1 m and produced larger fall-out in weaker ore and pegmatite veins of 1 to 2 m wide (see Figure 2a, 2b and 2e). Typical deterioration of ground support was unreinforced plain shotcrete, generally less than 50 mm thick, debonding and failing together with spalled rock as well as shotcrete panels falling away between bolts (Figure 2a and d). The low toughness of plain shotcrete meant it provided little post-crack load capacity once cracking initiated. In contrast, the 2.4 m friction bolts generally remained intact, with no widespread bolt failure reported, and plates showed only limited deformation, indicating that the primary rock reinforcement remained functional and adequate for the observed spalling depths.

Stope production drillhole squeezing was also observed in the ore zone rock mass (diorite and pegmatite). Floor cracking was recorded beneath sill pillars, for example at the 435 level (Figure 2b), and production drillholes at the 510 level showed ellipsoidal ‘dog-earing’ deformation indicative of stress concentration. Strainbursting occurred in development such as the 600 level hinge zone area (Figure 2f), although full failure and large-scale rockbursting were not expected on the evidence available.



Figure 2 Damage observations in oredrives on (a) 320 level remnant stope area; (b) 435 level oredrive shotcrete cracking and floor heave; (c) 450 level shoulder spalling and damage; (d) 555 level above extracted stopes; (e) 510 level deep failure in back; and (f) 600 level strainburst

The net effect at Jokisivu was that the primary reinforcement remained functional, while the unreinforced shotcrete, after cracking, could not retain fractured, subsequently bulked, and spalled rock between bolts. The mine had already identified this as the main rockfall risk requiring immediate mitigation by mechanical scaling and mesh installation in oredrive backs and shoulders. In summary, the generalised model for stress-induced damage progression from initial intact rock spalling, to deeper depth of failure, and the ground control risk from gravity or seismic shakedown is visually articulated in Figure 3.



Figure 3 Generalised model of failure progression of massive diorite due to increased stress and then seismic shakedown

4 Adaptation approach to ground control

The ground support system was adapted to deal with the prevailing ground conditions using the existing shotcreting and bolting equipment. This allowed for immediate implementation of changes which were compatible with the existing contractor practices. It was not deemed necessary or practical to introduce new bolt types in the short-term, so the operation needed to continue with the existing 2.4 m friction bolts, available mesh sheet size options, and shotcrete supply. The design philosophy adopted focused on improving the 'retain' component of the system by continuing to rely on the friction bolts and plates as the primary reinforcement but introducing installation sequence changes and quality improvements.

A summary of the resulting workflow approach is displayed in Figure 4, listing the different implementation stages used to alleviate key risk areas and establish changes that could be implemented using existing contractor practice. The authors note the rehabilitation activities were implemented concurrently with change in ground support approach in new development using the same equipment fleet and crew, maintaining stope production, which proved to be a scheduling challenge. Layout design and oredrive development timing were also adopted prior to the reaction to ground condition changes, and sill pillar sizing was increased from 5 to 8 m. Each stage is explained in more detail in later sections.

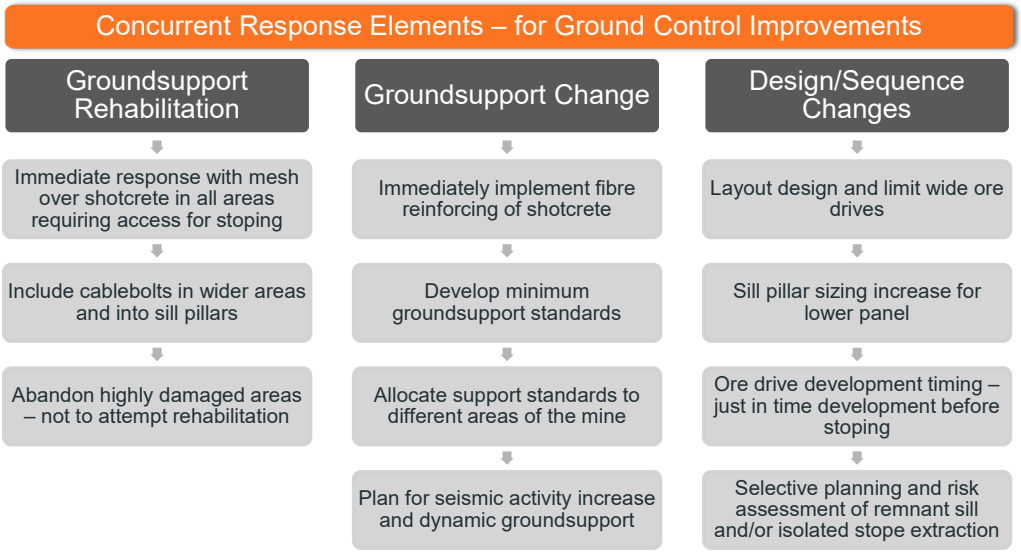


Figure 4 Overall process adopted for ground control improvement

4.1 Immediate rehabilitation

As an initial modification, welded mesh was installed over existing plain shotcrete in damaged and critical oredrives. Mesh sheets with dimensions of 2.5 × 2.9 m, manufactured using 5.5 mm diameter wire welded into 100 mm squares, were installed with the long-side across the drive back and shoulders extending to approximately 3 to 4 m above the floor. A minimum 3 square overlap (approximately 300 mm) was specified between sheets, and mesh was secured using the existing 2.4 m friction bolts and 150 mm domed plates, with bolt spacing adapted to ensure full mesh coverage.

This demonstrated a significant improvement in the retention of spalled rock. Examples are displayed in Figure 5. At 555 KLP11, scaling exposed spalled rock in the roof that was subsequently well contained by mesh. At 450 KLP11, mesh and bolts installation complied well with the design, but the absence of a proper mesh sheet overlap allowed some block movement in one area, where the mesh itself did not fail, highlighting the importance of the specified 3 square overlap.



(a) (b)

Figure 5 Examples of rehabilitation and ground support installation improvements. (a) 555 level oredrive rehabilitation and contained spalling; (b) 450 level mesh and bolts over plain shotcrete after scaling

4.2 Ground support options

For new oredrive development, ground support standards were modified to include either weld mesh over or under plain shotcrete or fibre-reinforced shotcrete (FRS) , with the same 2.4 m expansion friction rockbolts installed. Options identified were:

1. Initial welded mesh secured with rockbolts to 3.5 m from the floor, followed by plain shotcrete applied over the mesh down to 2.5 m from the floor.
2. FRS incorporating 30 kg/m³ steel fibre or 6 kg/m³ synthetic fibre (Concrete Institute of Australia, 2010), specified to a minimum thickness of 50 mm, sprayed to approximately 3.5 m from the floor and to the face, with shotcrete sprayed before bolting and a minimum curing time observed prior to bolt installation.
3. For high-deformation or seismically active ground expected for the deeper unmined panels, a higher dosage of 30 to 40 kg/m³ steel or 8 to 10 kg/m³ synthetic fibre was recommended, with increased bolting density. This additional bolting function was to also be the securing of mesh installed over the FRS, as part of the updated ground support standard. No new development had applied this at the time of writing.

4.3 Ground support standards and installation practice changes

Access to headings supported only by bolts, or only by plain shotcrete, was no longer permitted, since failure of rock and shotcrete between bolts was identified as the main rockfall risk. Three standardised support profiles were issued (Table 2):

1. Profile A1, for rehabilitation of any damaged areas, comprising mesh installed shoulder to shoulder to a maximum of 4.0 m from the floor, secured with 2.4 m ERB120+ or Omega bolts at a maximum spacing of 1.2 m within a ring and 1.3 m between rings, and a minimum three-square (300 mm) mesh overlap
2. Profile B1, for oredrive development, using the same mesh and bolt specification with plain shotcrete (no fibres, minimum 50 mm) sprayed over the mesh to 2.5 m from the floor
3. Profile C1 was provided as an option to only use FRS as surface support accompanied by bolts in the Kujankallio and Arpola decline and level access areas respectively (without dynamic demand). A staggered bolt pattern (Ring A: 5 bolts; Ring B: 4 bolts, at 1.6 m spacing) was prescribed. Shotcrete was sprayed before bolting, with a minimum 2 hour cure time prior to bolt installation.

Quality control requirements included minimum 3 square mesh overlap, plate contact with mesh or cured shotcrete, a maximum bolt spacing of 1.2 to 1.3 m between rings, and a maximum distance of 3.5 to 4.0 m from the floor to the lowest bolt in the walls.

Table 2 Summary of ground support standards and specifications

Profile	Application	Reinforcement pattern	Surface support
A1	Rehabilitation of damaged areas (always preceded by mechanical scaling)	2.4 m ERB120+/Omega bolts. 1.2 × 1.3 m spacing	Welded mesh shoulder–shoulder: 2.5 × 2.9 m sheets to 4.0 m from floor
B1	New oredrive development	2.4 m ERB120/Omega bolts. 1.2 × 1.3 m spacing	2.5 × 2.9 m sheets to 3.0 m from floor, Shotcrete, min. 50 mm, over mesh to 2.5 m from floor
C1	Fibre-reinforced shotcrete (FRS) only option for decline and level access development	2.4 m ERB120/Omega staggered 5/4 bolts in ring. 1.6 × 1.6 m spacing	FRS (steel 30 kg/m³ or synthetic 6 kg/m³ fibres), min. 50 mm, to 3.5 m from floor and to face

4.4 Development timing and re-entry

Controlled installation practices for advance were implemented. Oredrive development timing was already in place as a ‘just-in-time’ approach (since 2019). This was developed shortly ahead of stoping to limit the time available for stress damage to accumulate, and stope extraction sequencing was emphasised as a key ground control measure. Stope sequencing was optimised to limit oredrive exposure time to damaging induced stress conditions. Post-blast re-entry practice, allowing rock noise and stress-induced damage to stabilise before re-entry, was an already established practice and was retained. Wide oredrives (due to close ore lenses) were avoided where possible and where unavoidable, a separate ground support assessment was required, which included cable bolting for deep reinforcement already in place at the mine.

5 Performance in the deepest stoping panel (585–645 m)

The lowest extracted stoping panel at Kujankallio from 585–645 levels was developed and extracted, safely achieving the production plan. The ground response and operational performance observed during extraction of this panel was a case study of the adapted ground support system under the most demanding

conditions encountered at Jokisivu. Rock noise reports were more frequent and stress-induced spalling continued to occur but was contained within the designed ground support scheme for the applied profiles. No significant falls of ground were recorded during extraction of the panel, and no major support failures or uncontrolled collapses occurred.

Another design adjustment was the top oredrive in the panel development (immediately below the sill pillar) was stopped at less than half of the planned strike length. The sublevel below this was graded upwards to achieve stope drilling height reach with uphole method for stope blasting to complete the panel. This was implemented to remove the upper stope drive completely (normally required for downhole production drilling). Additionally, sill pillar thickness was increased, as the former sill pillar started to show signs of cracking or failing between the 570–585 levels.

The panel was completed in 2024 to the planned extraction tonnage and rate, with minimal production delay attributable to the operation's attention to revised layout design and good ground control practices.

6 Discussion

The adapted system markedly improved the containment of spalled rock which reduced gravity fall and shakedown risks in oredrives. The 2.4 m expansion friction bolts continued to provide adequate primary reinforcement once complemented by mesh or FRS and functioned effectively as the primary reinforcement element. The main initial improvement was the consistent and structured use of mesh with plain shotcrete, or shotcrete with fibre reinforcement – no plain, fibre-free shotcrete is used without mesh.

Some limitations and residual risks remain. There may be a need for more yielding or dynamic-capable rockbolts at greater depth at Kujankallio or under higher seismic demand than has been experienced to date. This residual risk still remains around the sill pillars and highly stressed hinge zones. Mines facing comparable conditions elsewhere have adopted rockbolts with greater yield capacity such as debonded sleeve rebar, dynamic split sets, hybrid bolts such as Kinloc, MDX, or X22, etc. Resin anchored bolting with increased capacity and additional cable bolting are recommended for further investigation in the lower levels, including for upper-panel finalisation, sill pillar support and final stopes retreated to near the level accesses. Mesh installation over FRS is common industry practice to accommodate shakedown and dynamic failure related to seismicity, as the seismic hazard potential is likely to increase in deeper mining.

Stope panel extraction deeper than 350 m indicated increased stress on sill pillars versus upper sill performance. The previous 5 m sill pillar design showed damage through its entire thickness, while the 7 m design already demonstrated a reasonable improvement that will require continued monitoring through final panel retreat. A minimum sill pillar height of 10 m in near vertical areas is recommended as separation between panels below approximately 500 m depth, due to the limited true thickness. Additionally, avoiding early extraction of the oredrive beneath a sill pillar was a key sequencing step so that it can remain intact for the life of the panel.

The Jokisivu experience illustrates the value of observational diagnosis ahead of major design changes, and of adapting support practice rapidly but in a controlled manner using existing equipment and products rather than waiting for comprehensive changes. Standardised ground support profiles and simple 'no access' rules proved effective in translating the revised ground control approach.

This experience is likely to be relevant to other narrow-vein mines facing a similar transition in depth and associated stress regime, and reinforces the value of integrating technical assessment, structured observation, and support design so that further changes in demand can be anticipated rather than only reacted to. Pro-actively meshing over FRS is seen as industry best practice to limit the rehabilitation efforts required in a seismically active mine with shakedown potential.

The current approach of close, responsive collaboration between the contractor and Dragon Mining personnel, combined with long-term site knowledge, has been an effective basis for ground control decision-making. Going forward, the operation would benefit from a structured damage recording database,

considering a seismic monitoring system to provide a three-dimensional understanding of microseismic response, and targeted displacement monitoring.

7 Conclusion

Existing ground support at Jokisivu mine, primarily 2.4 m expansion friction rockbolts and plain shotcrete, performed well for most of the mine's 8-year operational life, but proved unsuitable for the rapid onset of stress-induced damage that developed below approximately 350 m depth. Structured observational and analytical investigation identified brittle, stress-induced spalling of intact rock in oredrive backs and shoulders as the dominant damage mechanism, with rockbolts continuing to perform adequately while unreinforced shotcrete debonded and failed together with spalled slabs.

Available mine equipment and ground support products were reconfigured to implement immediate changes to ground control, improving both safety and longevity. Installing weld mesh over existing plain shotcrete, secured with the original 2.4 m expansion friction rockbolts, produced a significant and immediate improvement in performance, and new development followed new ground support standards using either mesh-reinforced plain shotcrete or FRS. Together with revised development timing and stope sequencing, these changes allowed the lowest extracted stoping panel, at 585–645 m depth, to be completed in 2024 to planned extraction tonnage and rates, with no significant falls of ground recorded despite increased rock noise.

Deeper mining at Kujankallio requires detailed planning and geotechnical assessment to provide engineering guidance for mine design and sequencing; as well as assessing the requirement for higher capacity ground control systems suited to stress damage and dynamic demand. Seismic monitoring systems are viewed as a requirement in similar seismically active mines across the industry and Jokisivu is encouraged to prioritise the design and installation of equipment for deeper stope extraction.

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