Long-Term Stability Considerations and Engineering Applications for a Decommissioning Mine in Permafrost

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Abstract

Shallow stopes of inactive metal mines have been regularly subject to failures. Over time, site information is lost. Until recently, no closure plans have been routinely formulated. A national manual, issued by CANMET MMSL has been used here to support the decommissioning of the Nanisivik Mine shallow stopes. It serves as a guide to apply the relevant and complete range of philosophy, experience, as well as the engineering step-by-step procedures to apply long-term analytical, numerical and empirical stability evaluation means for a mine in permafrost, derive related risk analysis and recommend long-term stabilization, monitoring and land use aspects for the site. Remediation and physical site closure aspects will also be covered from an environmental and human use perspective, key to assuring a safe site.

1 Introduction

Over the last several years, mine decommissioning has required a-priori planning to evaluate and mitigate long-term rock mass degradation, permafrost thawing and potential for rock mass movements affecting surface integrity.

The mine decommissioning standard written to meet the needs of the mining operations, engineers of record and government review agencies [Bétournay, 2001][Bétournay and Udd, 2001] is applied to support the mine decommissioning plans of the Nanisivik Mine.

The primary emphasis of this article will be given to the engineering stability, engineering solutions and site management aspects of mine decommissioning (Figure 1). This will include rock mass instability-based hazard and acid mine drainage considerations.

2 Mining Context

The Nanisivik Mine is located on Northern Baffin Island, at latitude 73E North in the Canadian Arctic. It is 4 km from the southern shore of Strathcona Sound, a deep-water fjord. The mean annual temperature is -14EC, with an average temperature of +6EC in the warmest period. Low annual precipitation ranks the area as semi-desert environment. Permafrost is encountered throughout the whole area, and drilling has indicated that it extends down to some 600 m. Despite this, groundwater drops had found their way through the permafrost and formed stalagmites and ice cascades on walls in the mine [Fish, 1979]. The underground rock temperature is constant at -12EC.

The mine's production ended in 2002, with over 16 million tonnes of zinc-lead ore having been extracted at the rate of about 2,200 to 2,500 t/day. The mineralized deposits are hosted by dolomites within a sedimentary sequence that have been block-faulted in an east-west trend (Figure 2). Mineralization in the area consists essentially of sulphides, which are almost always massive. About 90% is pyrite, the remainder being mainly sphalerite and some galena and silver. The mineralization was formed by the replacement of the host rock. The moisture content of the ore is between 1.5 and 2% by weight in the form of ice, 9% by volume of the rock. Ice-filled vugs occur frequently in the mineralized zone with a volume of up to several cubic metres.

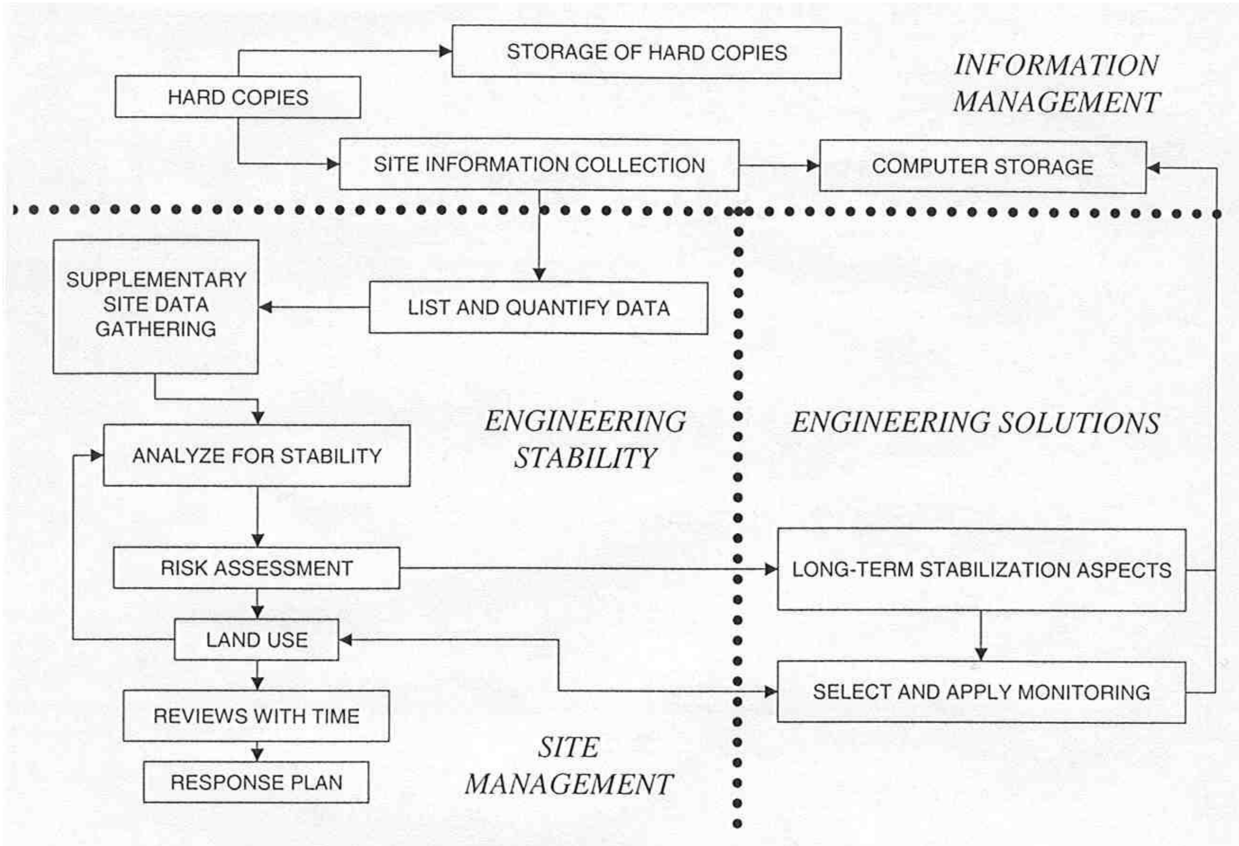

Figure 1: Shallow stope decommissioning flow chart [Bétournay, 2001].

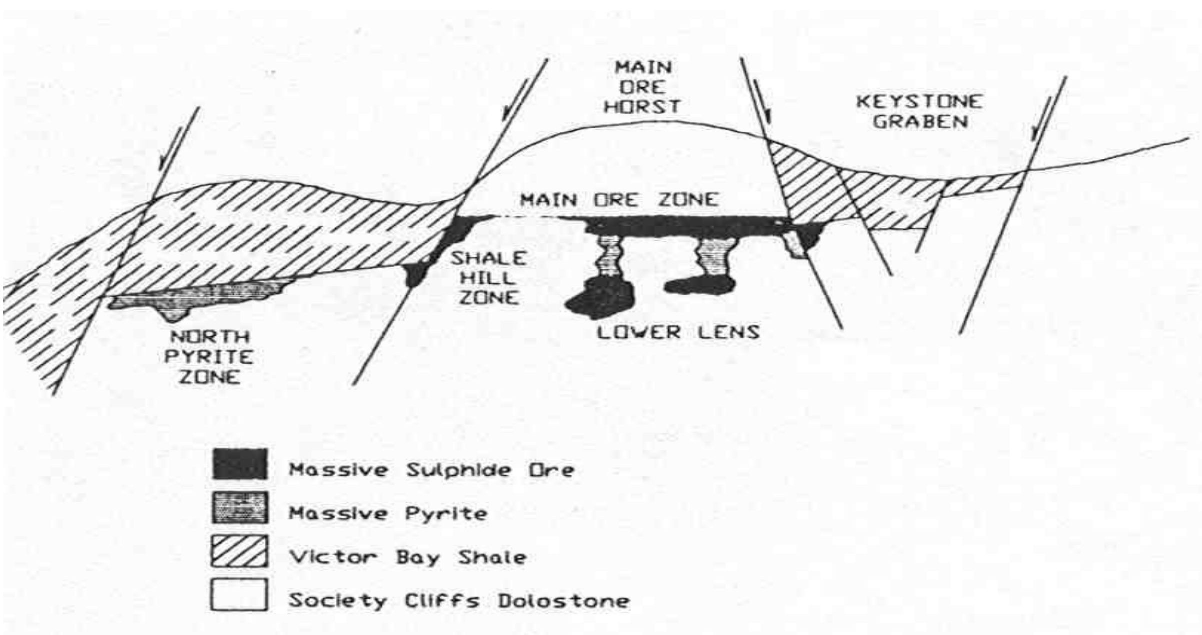

Figure 2: Schematic Nanisivik Mine geology, looking east [Lecuyer, 2001].

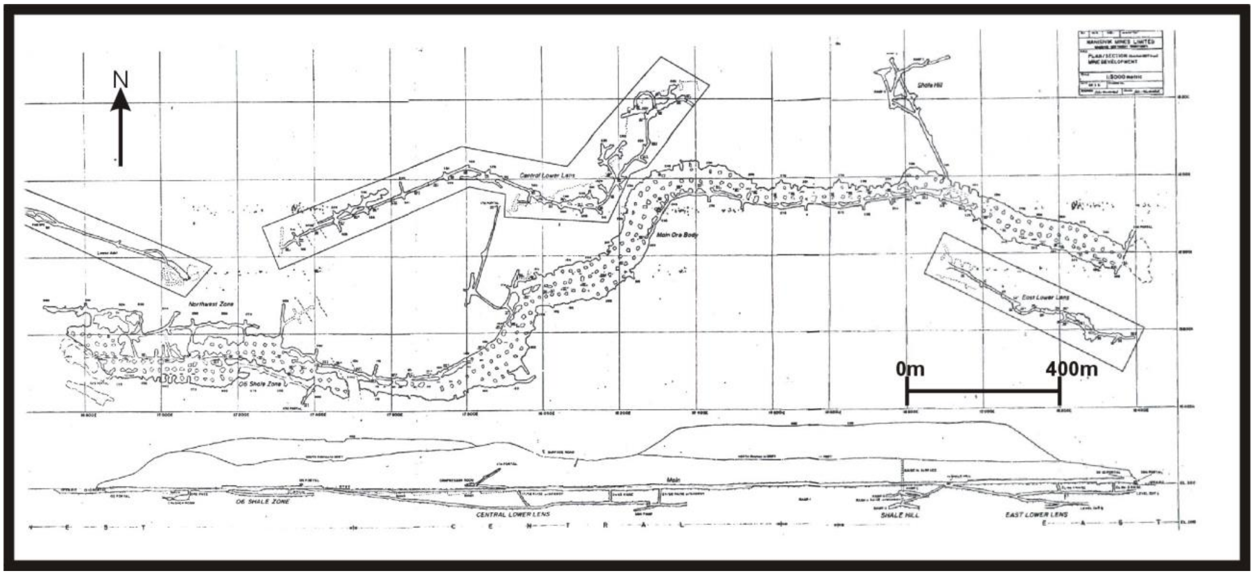

Figure 3: Plan and section view of the Nanisivik Mine, upper and lower levels, at the end of primary extraction.

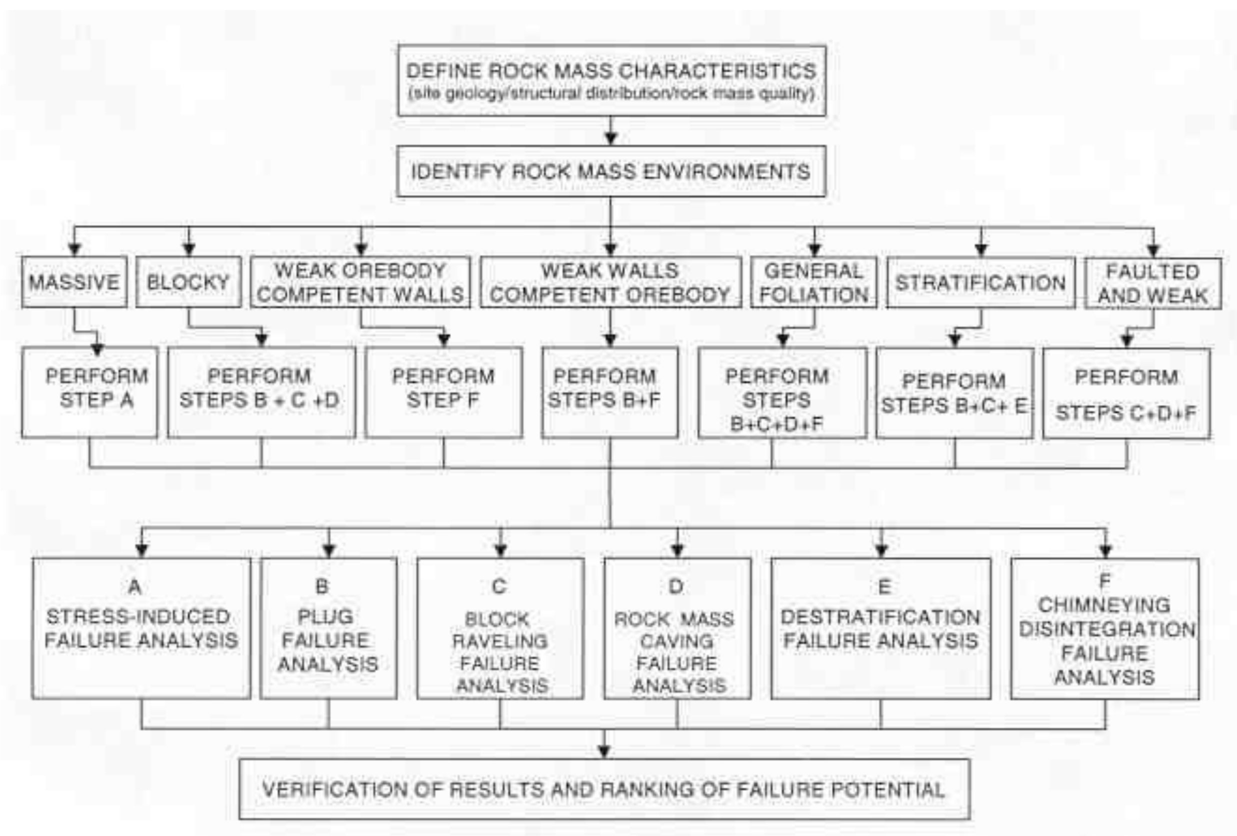

Figure 4: Shallow stope stability evaluation flow chart [Bétournay, 2001].

The sulphides, mineralized or not, occur as horizontal lenses, rarely above the main ore zone, but a second lens of mineralization occurs 30-40 m below the main lens (Figure 3). The orebody was flat, S-shaped, and divided into three zones: West, Central and East. The grade and tonnage decreased from West to East. The orebody was approximately 3 km long, 100 m wide, and 5-10 m thick, but up to 20 m in certain areas. The room and pillar mining method took advantage of the flatness of the orebody and its regular hangingwall. The base pattern was to use square pillars (5 m x 5 m to 7 m x 7 m) at a distance of 22 m to 25 m from centre to centre. Where high/low grade zoning appeared (mainly in the East Zone), rib pillars were left in the lower grade material. The maximum unsupported span was 30 m. Limited open pit mining was also carried out, amounting to about 5% of the total mineable reserves.

3 Ground Control

The roof of the excavation is predominantly composed of the dolomite host rock. This offered very good ground conditions and was only bolted when a height of more than 5 m of ore was taken out, usually with 1.8 m long Scott friction type split set bolts. In some areas where shale is exposed, ground conditions were weaker and the backs, and sometimes the walls, were screened. In some parts of the mine, a layer of 2 to 3 m of low-grade sulphides was left in the back. These backs were not reliable because of the interstitial ice and white calcite layers found in the porous sulphides. The ice sublimated with time and no cohesion was left in the rock, which caused large falls of ground. However, the problem was resolved by taking down the back before further production could take place.

After primary extraction had taken place, 25% of the ore remained within 350 pillars left behind. Consideration was given to recovering all of the pillars given the predominantly good quality of the dolomite roof. CANMET carried out several ground control studies to evaluate the stability of the mine back without pillar support. These were defined within an integrated approach considering the permafrost aspects of the rock mass conditions. Laboratory strength tests, field definition of rock mass deformation modulus, in-situ ground stress value determination, and numerical modeling of the rock mass response leading to monitoring of the ground response during pillar removal were carried out [Arjang and Herget, 1989][Arjang et al., 1991][Herget and Arjang, 1989][Judge, 1998][Vongpaisal et al., 1990][Vongpaisal et al., 1991a][Vongpaisal et al., 1991b]. The modeling results indicated that all of the pillars could be removed with little ground control effect, giving an overall extraction of 100%. Monitoring of the ground response with pillar removal has indicated minor roof displacements except in areas where ground falls occurred due to rock block wedge or the presence of shallow angle slips [Lecuyer, 2001].

4 Nanisivik Mine Decommissioning Aspects

Engineering Stability

The design and ground support for shallow mine workings in permafrost terrains carried out during the life of the mine should be independent of the provision of long-term stability and prevention of surface disruption. This becomes a critical issue when rock mass environments can be inherently difficult to stabilize if the benefits of ice filling may disappear in the long-term with thawing. Despite the advancements in the field of rock mechanics, shallow rock masses remain complex environments for which to design in. But common failure types exist. These may be precluded from occurring if the presence of ice in the rock mass is effective in mitigating discontinuity and rock mass disintegrating effects.

At the site, long-term failures must be evaluated, owing to the fact that the Nanisivik underground openings will remain open (unfilled) in perpetuity. The approach used here is to adopt a worst-case situation with respect to the presence of stabilizing ice and artificial ground support, i.e. surface frost from ventilated air and vugular ice have sublimated (a process observed to date) and oxidation of the bolts and screens has occurred over a lengthy period. In this case, the impact would be certain in localized weak areas of sulphide and of shale in the back. In sulphides, limited ground falls would occur owing to their limited extent. The presence of shale and boundary faults could create the potential for significant ground falls and failure heights. This will be discussed in more detail later in this section.

Given the rock mass characteristics at the site, Table 1, the application of the stability evaluation flow chart (Figure 4) indicates that strata failures and caving failures are possibilities. The lack of pervasive jointing, wide steep-dipping discontinuities, or very low cohesion rock precludes raveling, plug or chimneying disintegration failures.

TABLE 1: Nanisivik rock and rock mass values.

	Rock Properties				**Field properties**		
	Young's Modulus GPa *	Poisson's Ratio *	($_r$ kN/m^3-T/m^3	Unconfined Compressive Strength MPa	RMR *	Hoek and Brown (1988) Parameters ⊥	
						m_{field}	s_{field}
Dolomite	26.0	0.24	28.0	110	80	4.2	0.10
Massive sulphide	14.0	0.30	42.0	45	60	1.3	0.008
Gabbro dyke	32.0	0.20	28.0	180	90	8.0	0.16

* Arjang and Herget, 1989. ⊥ Evaluated from RMR value and with reference table.

Three complementary stability evaluation approaches are used here to identify the long-term stability of the site: analytical, empirical and numerical.

Analytical equations developed for the calculations of heights associated with strata failures [Bétournay, 1994] indicate that the associated cavity created will only reach a height of about 70% of the shortest opening span. In this case, should a failure completely span the extraction area 100 m wide, the maximum failure height anticipated would be 70 m. A rock mass thickness of 70 m is available over most of the mine except at the portal areas.

Caving of the overlying rock mass requires that the bulking of the broken material be insufficient to choke the failure before it reaches surface. In this case, a very large cavity is available for caving of the shale unit. Equating the volume of failed material with the space available provides the maximum height of caving anticipated, in the case of a circular caving cross-section:

$$(1)\ V_{caved} = kz\pi r^2$$

$$(2)\ V_{space} = (z\pi r^2) + [\frac{\pi h}{3}((r + h\cot\phi)^2 + (r + h\cot\phi)(r) + r^2)]$$

where, k= bulking factor (~1.15 for weak shale [Bétournay, 2001])
z= height of the collapse chimney
r= radius of collapse chimney
h= height of the underground opening
N= angle of repose of caved rock (~20E-25E for shale material)

As an extreme example, a truncated cone of caved material with N=20E, forming within an opening height of 10 m from a 20 m wide caving span will permit a caving height of 26 m above the opening, assuming all in shale. Since the occurrence of the shale unit is of limited lateral extent, caving to surface within this rock mass will probably not be an issue.

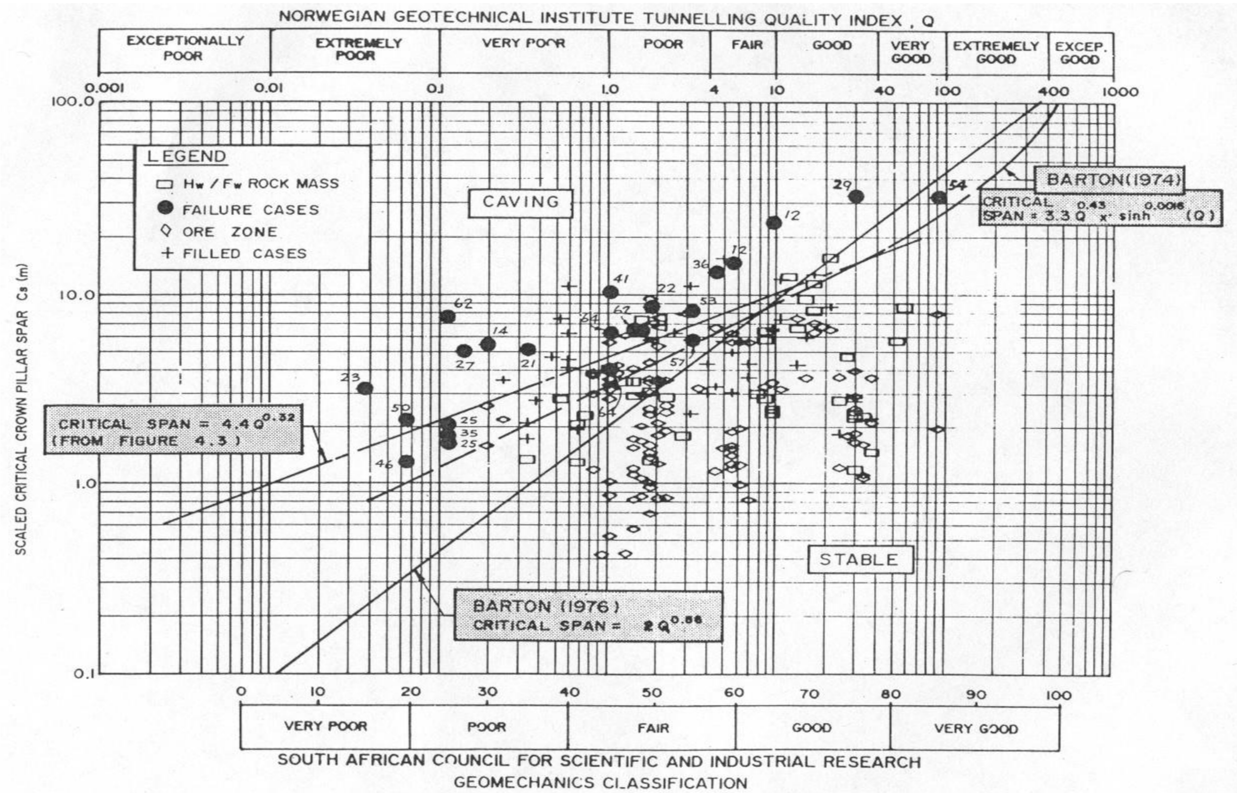

Figure 5: Critical empirical span for shallow stope surface crown pillars [CANMET Contract, 1990].

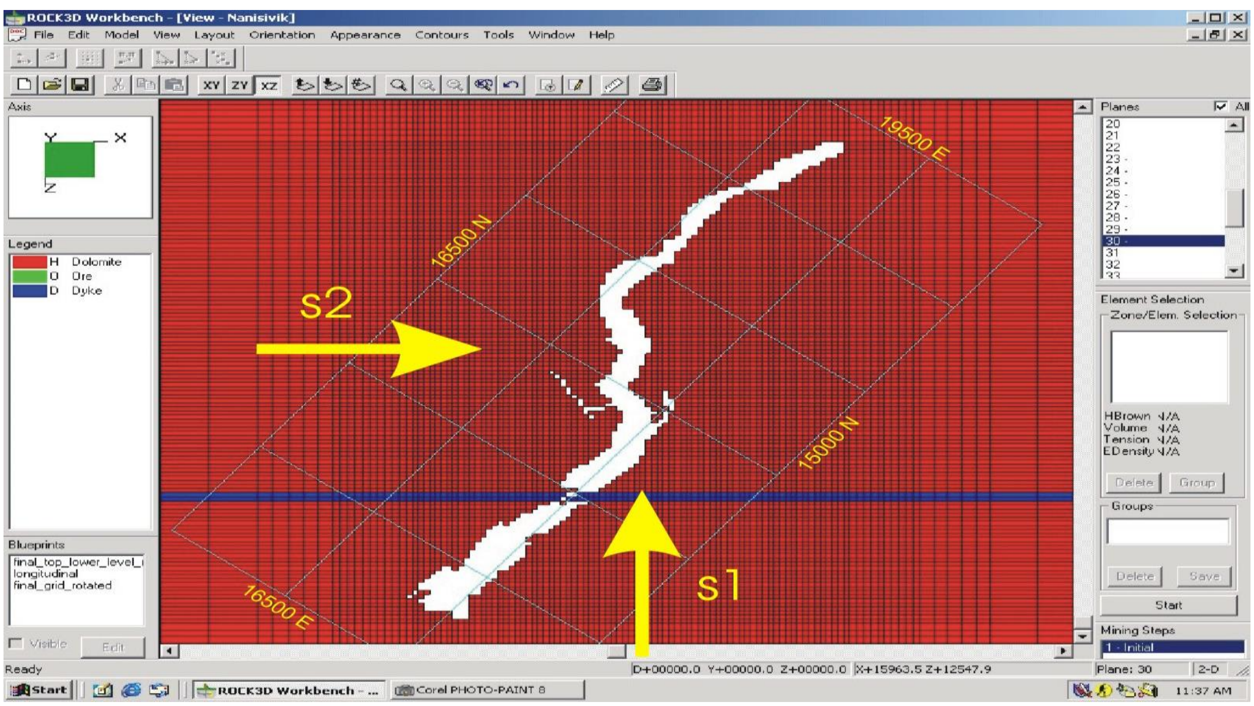

Figure 6: Nanisivik Mine geology and in-situ stress orientation, main mine level.

One dedicated empirical evaluation method has been established to evaluate the relative stability of specific cases while considering the wide body of shallow stope experiences [CANMET Contract, 1990]. It is based on over 230 shallow stope case studies (no frozen rock mass cases were included), including 32 failures and delineates a qualitative "stable" or "unstable" situation based on the value of the rock mass rating and the critical span value (Figure 5):

$$(3)\ Cs = L\left[\frac{\gamma r}{t(1+L/S)(1-0.4\cos\psi)}\right]^{0.5}$$

where L= stope span (m)
S= stope strike length (m)
t= surface crown pillar thickness (m)
P=major discontinuity dip (degrees)
($_r$=rock unit weight (tons/m^3)

As a worse case, using a stope span of 100 m, strike length of 3,000 m, discontinuity dip of 10E, unit weight of 2.5 T/m^3, an overhead rock mass thickness of 70 m, and no stability contribution from the presence of ice, the dolomite with an RMR of 80 plots in the area of the Fs=1critical span line.

A global mine stability approach was used with the 3D numerical modeling approach, i.e. the entire mine was modeled, compared to the previous 2D approach applied over several cross sections. For simplification, the Nanisivik model considered only the dolomite unit as roof and floor material, the ice-filled massive sulfide (orebody horizon) and the gabbro dyke crossing the Western ore zone. (Figure 6).

The Nanisivik model was developed using CANMET MMSL's linear elastic finite element ROCK3D software. In this case, the model consisted of 842,886 elements (974,984 nodes). The geometry of the orebody was simplified. The ore zone was assumed to be 20 m thick and horizontal. The floor of the main level was 173 m below surface, and the surface was assumed to be flat (no variation in elevation). The floor of the lower level was 39 m below the floor of the main level. The lower level was assumed 10 m thick and horizontal. For simplicity, the infrastructure (drifts, raises, etc.) was not included in the model. The geomechanical properties used are found in Table 1.

The in situ stress assumed, measured in previous geotechnical site investigations (Arjang and Herget, 1989) were: Φ_1/Φ_2=3.2, Φ_1/Φ_v=3.15, Φ_2/Φ_v=0.95. Φ_v had a value equal to the weight of rock times depth; Φ_v was vertical, Φ_1 was horizontal, oriented 50E from north, and Φ_2 was horizontal, 320E from north.

The results showed that the excavations are fundamentally subjected to compressive stresses, with low or zero confining stress levels appearing in portions of the Western and Eastern main ore zones (Figures 7 to 10). While failure from tensile stress imposition would probably not occur, initiation of ground falls from weak rock, strata failures and block caving would remain a possibility, especially between the lower and upper ore zones.

Site Management

Better site management for inactive mines requires well-defined long-term risk assessment and mitigation. Owing to the unpredictable distribution of rock mass elements (especially ice), their variability (and that it is difficult to completely quantify) engineering shallow stope rock masses is inherently difficult especially considering the open-ended time frame anticipated for their existence. Normally, a quantitative analysis of risk will be required at the time of decommissioning when site remediation and management decisions must be made. This involves the combination of the quantified probability of occurrence of a hazard and the quantified occurrence impact.

Normally, the quantification of hazard assessment would require the calculation of a probabilistic factor of safety for each failure mechanism. The measurement of impact consequence must be based on an exhaustive range of affected elements, such as the example developed by Bétournay (2001), which includes proportionality elements in the Public, Economic and Environmental categories. In the case of the Nanisivk Mine the possibility of occurrence of failure to surface is very low. Furthermore, because of the remoteness of the mine location, only the safety (hunters), and environmental categories are related to a failure consequence. In the case of the former, loss of life could occur, in the case of latter minor species disruption could occur with minor habitat effects. Given the occasional nature of the presence of humans and animal species and the low probability of failure, the risk related to a mine instability is probably very low.

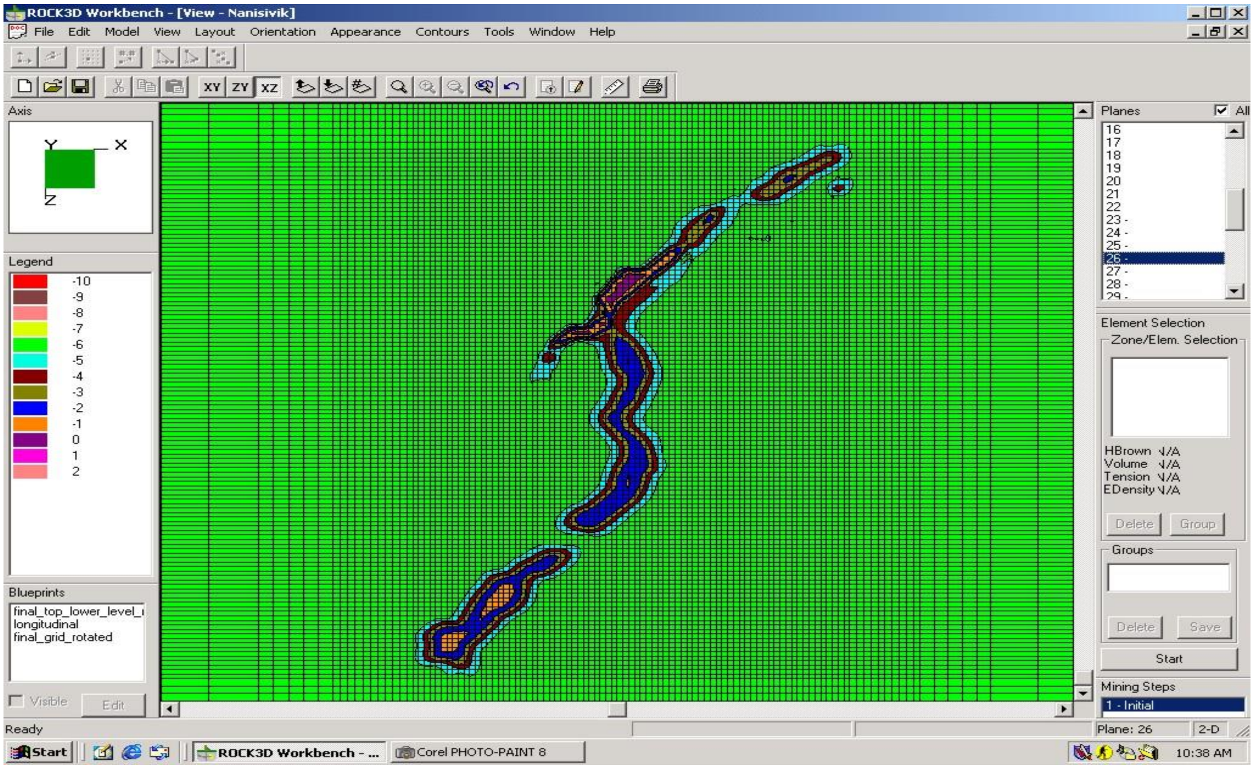

Figure 7: ROCK3D minor principal stress distribution on a horizontal section above the lower ore zone.

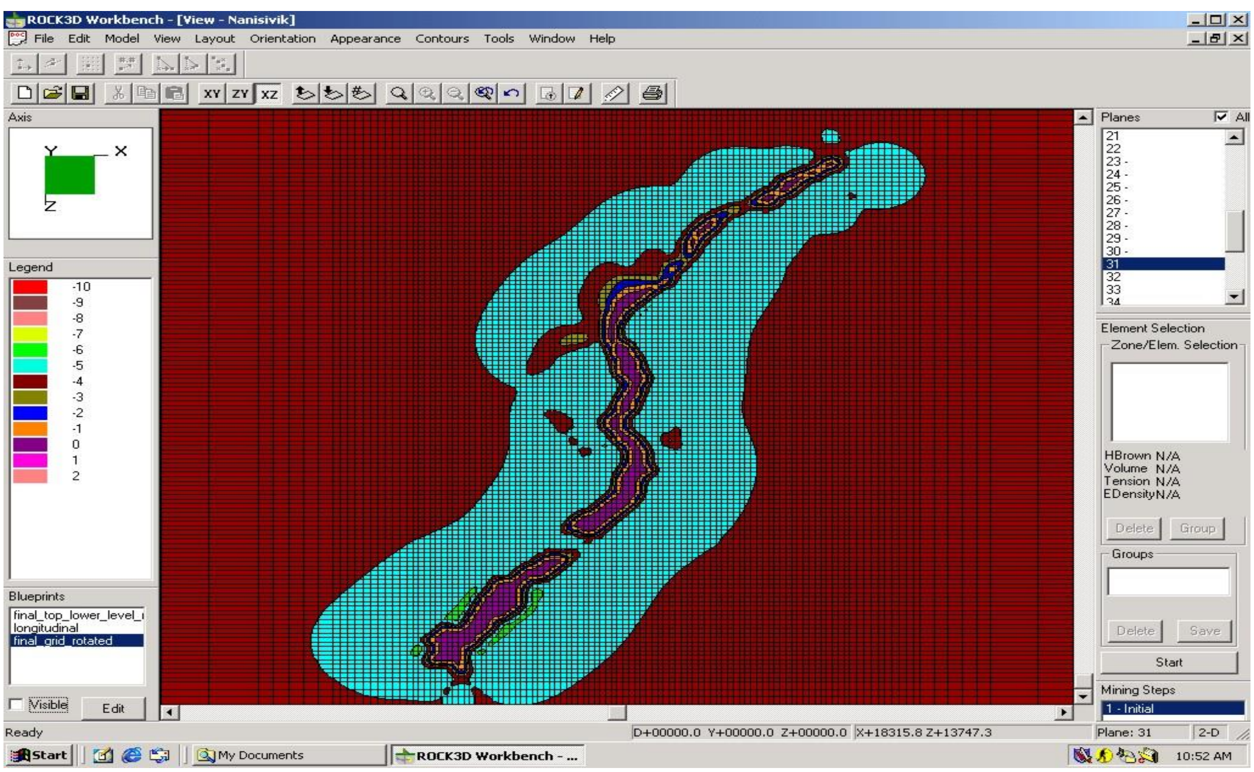

Figure 8: ROCK3D minor principal stress distribution on a horizontal section above the main ore zone.

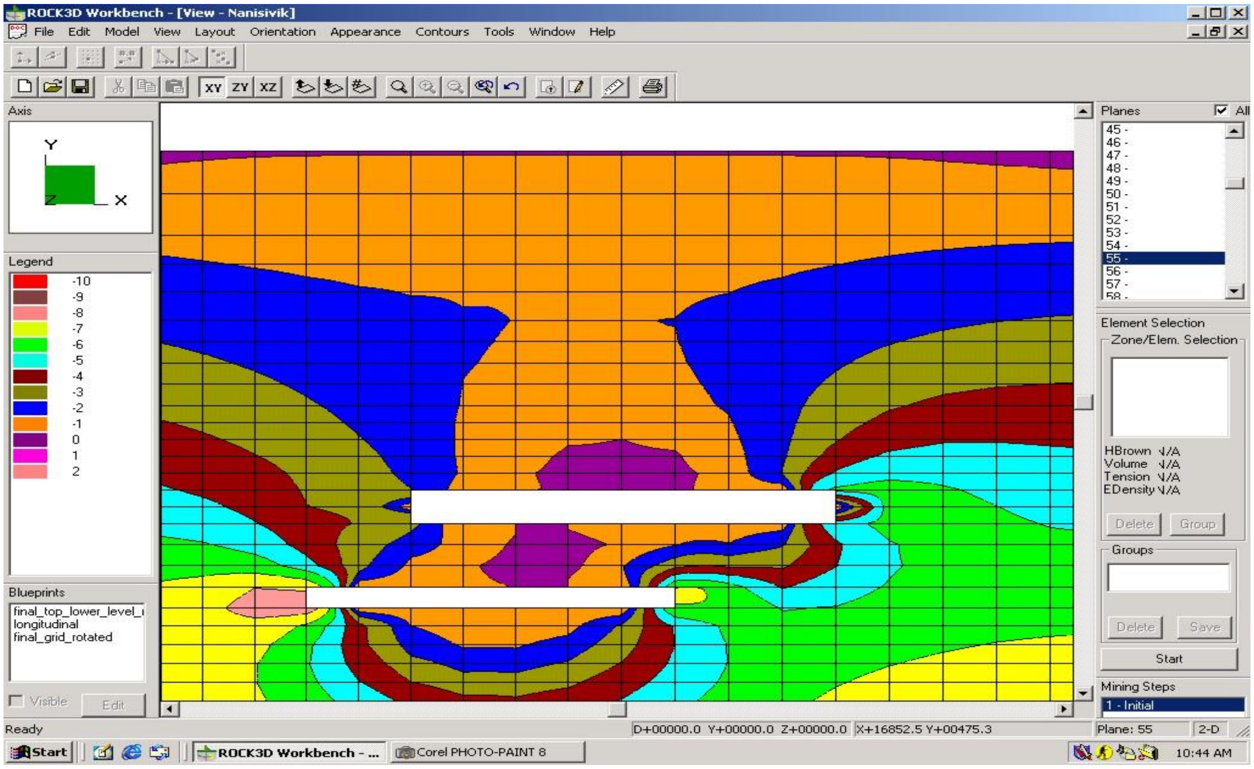

Figure 9: ROCK3D minor principal stress distribution at cross-section 55, looking east.

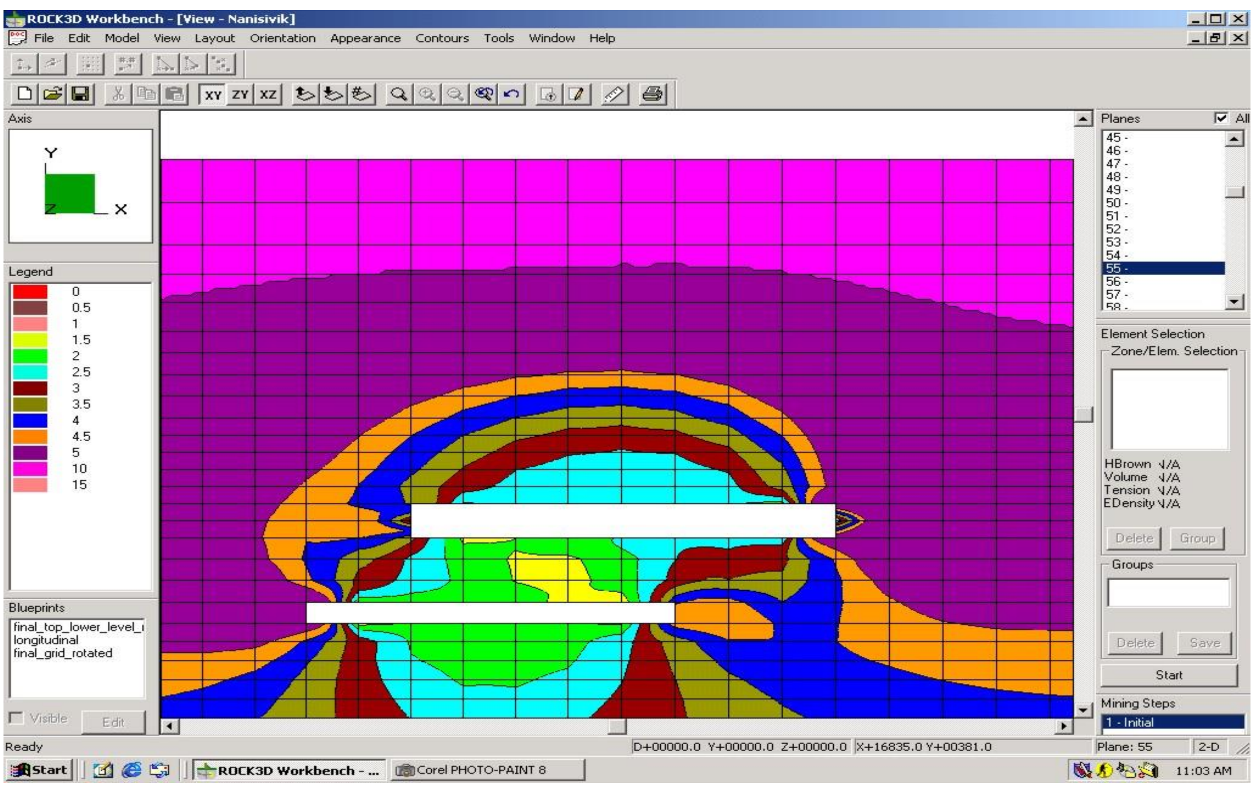

Figure 10: ROCK3D modeling results, Hoek and Brown failure criterion safety factors, section 55 looking east.

In order to mitigate any risk, several remediation options are available [Bétournay, 2001]: signs/monuments, fencing, concrete caps, backfilling, blast removal of unstable rock masses. In this case limiting or preventing site access is probably not required, but warning and alerting those present on the site would be advisable. This would therefore require that signs and monuments be installed at proper site locations on surface, such as above the mine and at mine portals. These signs have a limited effective life. They should be inspected in the context of a regular site visual monitoring campaign (rock mass instrumentation would not be warranted until failure indications occur). More site remediation will be required if ground movements occur.

Other aspects to monitor over the long-term is that of acid mine drainage. The presence of a mine portal existing at the base of a topographic high and on-level with a pyrite rich orebody requires that an analysis be made of the penetration of groundwater through the rock mass with exits at the mine horizon. This was highlighted in the consideration of a similar mine setting in the U.S. Rocky Mountains [Bétournay et al., 2003]. While the Nanisivik site receives very little precipitation, and only a few drops of water enter the mining cavity, the chemistry of the mine effluent water should also be monitored.

5 Summary

In this article, the Nanisivik mine and site properties have been reviewed in order to provide long-term stability considerations for decommissioning. Ground control issues of note include the instabilities, which are anticipated from the sublimation of the ice occurring in the weak sulphide and shale units. The resulting problems should be limited to localized ground falls. The shale unit can cave, but given its limited periphery exposure, such a failure cavity would not reach surface. No other failure type is expected to reach surface even if it begins over the full width of the main ore zone.

Given this low physical hazard possibility, and the limited consequences that a failure to surface would generate, the long-term physical instability risks are very low. However, warning signs should be posted strategically on the Nanisivik site to warn native hunters and other site visitors. Regular visual monitoring of the site stability should be performed. If related site degradation occurs, other remediation and monitoring means should be applied to mitigate developing hazards. Careful attention to the chemistry of any effluent water and visual assessment of acid mine drainage should also be practiced given the possibility of groundwater contamination from the pyrite rich rock horizons even if very limited quantities of water actually make it through the permafrost rock mass and into the underground opening at this minesite.

6 Biographies

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John Udd received his Bachelors, Masters, and Doctorate degrees, in Mining Engineering, from McGill University, in Montreal. After teaching at McGill for several years, and progressing to Director of the Mining Program, he joined Falconbridge, in Sudbury, as Senior Ground Control Engineer. Appointed the Director of the Mining Research Laboratories of the Government of Canada, in 1984, he presently occupies the position of Principal Scientist. Dr. Udd has written extensively on various topics in rock mechanics, mining education, and mining history. He is a Fellow of both the Canadian Academy of Engineering and the Canadian Institute of Mining, Metallurgy and Petroleum.

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Marc C. Bétournay received his Bachelors, Masters, and Doctorate degrees, in Civil Engineering, Engineering Geology and Mining Engineering, from McGill University, in Montreal. He joined CANMET in 1982 as a geomechanics project leader. Progressing to Manager of the Mining Laboratories and later Senior Scientist, Dr.

Bétournay has been a technical and project development leader internationally, working with a broad range of industry, research, and government organizations.

He has developed considerable expertise on various geomechanics aspects, including mine-wide stability, stability of abandoned mines for which he has written the Canadian Standard, and co-implemented the international initiative to apply fuel cell to mine vehicles, including the world's first industrial fuel cell vehicle. He is a Fellow of the Canadian Institute of Mining, Metallurgy and Petroleum.

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Russell Boyle received his Bachelor in Geology from the University of Ottawa. In 1977 he joined CANMET's Ore Reserve Assessment Group as a computer programmer. In the late 1980's he joined the Numerical Modeling Group of the same organization. He is presently a project leader in numerical modeling of the Mining and Mineral Sciences Laboratories; part of his time is also spent working in seismic monitoring for the oil industry. He is a member of the Canadian Institute of Mining, Metallurgy and Petroleum.

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