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HIGH POST PILLAR RECOVERY IN PERMAFROST CONDITIONS: Survey and Discussion of Existing Information

M.C. Bétournay

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HIGH POST PILLAR RECOVERY IN PERMAFROST CONDITIONS:

Survey and Discussion of Existing Information

M.C. Bétourney*

ABSTRACT

This report provides background information and outlines the results of a literature survey aimed at providing technical knowledge for the planning and recovery of high post pillars under frozen rock conditions.

The report contains background information on the Nanisivik mine, an enumeration of sources of information used in the literature survey, a discussion of pertinent published information and a discussion of general considerations for this project.

An extensive bibliography of publications applicable to the project, directly or indirectly, is included.

KEYWORDS: permafrost, post pillars, mining method, pillar extraction, ground control.

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RÉCUPÉRATION DE GRANDS STOTS EN CONDITIONS DE PERGÉLISOL:

Sondage et Discussion de l'Information Existante

M.C. Bétournay*

RÉSUMÉ

Ce rapport contient de l'information de base et présente les résultats d'une campagne de recherche bibliographique dans le but de fournir des connaissances techniques à la conception et récupération de grands stots en milieu de roc gelé.

Le rapport contient de l'information de base sur la mine Nanisivik, une énumération de sources d'informations utilisées pour la recherche bibliographique, une discussion de l'information pertinente publiée et une discussion de considérations générales pour ce projet.

Une bibliographie considérable de publications applicable au projet, directement ou indirectement, est inclue.

MOTS CLÉS: pergélisol, stots, méthode minière, récupération de piliers, contrôle des terrains.

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CONTENTS

Page
ABSTRACT i
RÉSUMÉ ii
INTRODUCTION 1
DESCRIPTION OF SITE CONDITIONS 1
    Background 1
    Mining Method 1
    Ground Control 2
ENUMERATION OF INFORMATION SOURCES 3
    Bibliography Content 3
    Subjects 3
    Databases 3
    Review of Foreign Technical Journals 4
    Contacts 4
DISCUSSION OF SURVEY INFORMATION 4
    Pillar Recovery Plan 4
    Permafrost Conditions 5
    Maintaining Heat Balance 5
    Effects of Pillar Recovery 6
    Methods of Pillar Recovery 6
    Monitoring 9
    Other Subjects 9
OTHER CONSIDERATIONS 9
REFERENCES 12
BIBLIOGRAPHY 15

FIGURES

No. Page
1. a) Plan view Nanisivik mine, west and central portions 21
1. b) Plan view Nanisivik mine, east portion 22
2. Mining method (blasthole for higher stopes), Polaris mine using foot wall haulage drift 23
3. Summary of strength data for frozen granular fill, Polaris mine 24
4. Unconfined compression strength versus curing and testing temperature, Polaris mine fill 25

INTRODUCTION

The objective of this technical review is to identify relevant information for the economic and safe recovery of post pillars in permafrost terrain, more specifically the Nanisivik mine, North West Territories.

By referring to data bases, reviewing articles, and consulting national and international experts on underground excavations in permafrost a wide range of data was obtained. This was used to determine the experience of other operations in pillar recovery, and related technical issues, in permafrost terrain similar to Nanisivik.

DESCRIPTION OF SITE CONDITIONS

Background (1)

The Nanisivik Mine, located at latitude 73° north, went into production in 1976. The orebody is mined for zinc, lead and silver and is entirely in permafrost. The depth of the frozen ground extends to 600 m and envelops the mining area which is 100 m down from surface, Figure 1.

The orebody is approximately 3 km long, 100 m wide and up to 20 m thick (usually 5-10 m thick). It is flat and hosted by dolomite. Mineralization consists primarily of sulphides, 90% massive pyrite, with the remainder made up by sphalerite with some galena and silver.

Mining Method

A room and pillar mining method is used. The pillars are 7 m X 7 m in plan, spaced 25 m center to center. When oregrades are low, rib pillars are formed. The excavations remain open.

Drilling at Nanisivik is fully mechanized and drill jumbos are used. Dry drilling is used because water would deteriorate the permafrost environment. Solutions of calcium chloride, normally used for drilling in such terrain, would corrode the equipment. The drilling pattern for drift rounds is 1 m by 1 m; 48 holes are drilled per round. For slashing and benching a pattern between 1 and 1.2 m is used. Drill steels, 4 m long with 4.4 cm button bits, are used. Bit and steel life average 150 and 170 m respectively. Benching is performed, up to 5 m per lift, from the hanging wall, until the foot wall is reached.

Blasting is carried out with ANFO (6% fuel oil mixture). Detonators are set off with detonating cord and all blasting performed from surface with a central electrical blasting system.

Muck is hauled from the west zone by 5 cubic yard scooptrams to an orepass in the western portion of the mine. All other ore is moved by trucks loaded by front end loaders. There is an excavated area used for stockpiling.

A jaw crusher is located underground to take the ore from a feeder located at the bottom of the 12 m long orepass. A secondary cone crusher processes the ore before it is sent to the mill via two 350 m conveyor belts. A crushed ore bin, located along the conveyor line, is used as storage to maintain constant mill feed.

Ground Control (1)(2)

Three types of roof conditions exist. A dolomite back forms very competent ground. Sulphide areas are variable and are accompanied by calcite; the back fragments easily and is usually scaled to competent dolomite. In areas where shale is exposed, the backs, and sometimes the walls, are screened; this ground is the least competent in the mine.

The hanging wall is regular, and unsupported spans of 30 m in good ground are stable. The roof is only bolted when more than 5 m of ore is taken out, 1.8 m split set bolts have been used regularly on a 1.2 m^2 pattern but bolts up to 2.4 m have been used for special purposes.

Sublimation of ice with time reduces rock cohesion with the consequence that large unexpected falls of ground occur. The backs are then scaled down for safety.

ENUMERATION OF INFORMATION SOURCES

Bibliography Content

The 60 sources of information listed in the bibliography represent relevant available information on permafrost. The subjects treated in these are very variable but are related generally to aspects of excavation in frozen soil or frozen rock. The literature survey was kept broad in the belief that some information could be found relevant to the Nanisivik project. A-priori, little experience, or information for that matter, was thought to exist pertaining to the project.

Subjects

The discussion that follows will bear out that very little information exists on mining practices in frozen rock and hardly any deals with methods of pillar recovery under such circumstances.

The main source of information pertains to the Polaris and Black Angel mines of the Arctic and research carried out by the U.S. Army's Cold Regions Research and Engineering Laboratory (CRREL). Russian-based references provided limited verbal descriptives of experiences and tended to carry on from a very theoretical basis; also, most of their experience was related to rudimentary equipment working in frozen soil. One other case was reported, on a coal mine excavated by longwall techniques.

Databases

The MINTEC database, because of its dedication to mining, formed the foundation for this literature review by providing a large number of the references cited in the bibliography. Four other databases were consulted: the Engineering Index database, Georef database, NTIS database and Soviet Science and Technology database. In all cases, all relevant mining, exploration, drilling and other permafrost references were gathered.

Review of Foreign Technical Journals

Recognizing that other countries have faced permafrost mining situations a thorough search of foreign technical journals was undertaken. A search of technical journals from the Scandinavian countries, the U.S.S.R. and the U.S.A. were undertaken at McGill University and at the CANMET library. As well, all CRREL publications were reviewed.

Contacts

National and international expertise as well as particular references were obtained via the assistance of Mr. T.W.H. Baker of the National Research Council. Dr. Mellor of CRREL was contacted but a site visit could not be arranged.

DISCUSSION OF SURVEY INFORMATION

Pillar Recovery Plan (1)(3)

Primary post pillars (numbering approx. 350) are in place at Nanisivik to maintain a stable back. The mine is now considering recovering all, or most, of the pillars to extend mine life.

The mine is confident that the underground openings can stand free with no support from pillars. The existing pillars show no sign of stress. The mine hopes that 40% of the pillars can be recovered (giving an overall extraction of 93%) without the use of more stabilizing means. Removal of the remaining 60% of the pillars might require special stabilizing means (after ground conditions are assessed during the mining of the first pillars) based on this survey of literature.

The recovery method is planned by conventional drill and blast and mucking from the excavation or from sublevels using ore chutes.

Permafrost Conditions (2)

The permanently frozen ground, reaching a depth well below mine workings, imposes a number of conditions to the rock mass. Permafrost conditions are continuous in the mine workings. The rock temperature remains close to -12°C. The host rock has pores, vugs (extensive and found in many places) and joints often filled with ice. The rock mass temperature causes moisture from ventilation and underground mining activity to frost rock surfaces.

Maintaining Heat Balance

In all cases where permanently frozen rock has been encountered, it has been imperative to maintain rock temperature (surface at least) well below freezing point (2)(4)(5)(6). This is to maintain a solid rock mass while excavating the great spans required of an economic operation and to maintain a poor quality rock in place, without serious degradation.

It is a common trait that the Polaris, Black Angel and Nanisivik mines, all excavations in permafrost, share in the condition of their ground. At Polaris, the host rock is bedded, brecciated and faulted; the ore granular and porous. Weak carbonates in most cases heal the rock but the openings desintegrate rapidly when permitted to thaw. At Nanisivik, although the dolomite host rock is essentially unjointed and massive, the roofs can be difficult to control because weak material can be found there. At Black Angel the rock crumbles with thawing.

Ice content of the rock must thus be known if warming effects are to be evaluated. It takes very little latent heat to thaw the Nanisivik rock with 3% (7) (by weight) pore ice. As well, the nature of the infilling (vugs, joints, etc.) will determine the ground problems associated with warming effects. Jointing is not common at Nanisivik.

Heat balance studies such as the one performed at Polaris (8), which take into consideration ice content, indicate to what extent new sources of heat (e.g. from rockfill or backfill for pillar recovery) can be detrimental to pillar and roof stability.

Effects of Pillar Recovery

The literature surveyed is void of pillar recovery effects on roof control, or for that matter void of cases where very wide room spans have been encountered.

The only instance of mining with planned extraction of residual pillars is at the Polaris Mine. Although the process of installing frozen rockfill for support is well described (4)(9), the experience of removing pillars from that point has yet to be assessed.

Methods of Pillar Recovery

The only referenced mining method to safely and efficiently achieve maximum post pillar recovery in frozen rock is related to the Polaris mine case. The Black Angel has only begun to consider pillar removal and installing frozen rockfill.

Pillar recovery methods there are expected to be similar to the primary stoping methods used, subject to modification depending on the stability of the backfill used(4). The orebody is 10 to 30 cm high in the upper levels to about 110 m at the lower level. Stoping panels are separated by rib pillars 10 to 15 m in width.

Drilling is conventional, done by two double-boom electric-hydraulic drill jumbos and one single boom jumbo. Drilling is dry, with dust collectors, cuttings flushed with compressed air. Blasting is done with ANFO.

Drilling patterns and blast sequencing are not reported.

Development and production mucking is handled by a fleet of four eight-yd^3 scooptrams from drawpoints in a haulage drift driven at the footwall of the stope in the adjoining pillar, Figure 2.

After crushing (with 42 x 48 inch double toggle jaw crusher with vibratory feeder) ore is carried to surface processing facilities on 0.9 m wide conveyors suspended from the back of the decline.

A general support, split set bolting, is used; this is only applied to the roof. The only supplementary support used for pillar removal is frozen rockfill. Hydraulic fill was not used because it would introduce an amount of heat that would significantly alter thermal equilibrium.

Tests in a cold temperature lab showed that shale fragments (obtained from surface outcrops) frozen with snow/ice/water would provide the free-standing structural characteristics for about 1 year (4). Moisture ranged from 10 to 12% by weight. Critical free standing height, it was found, is heavily dependent on temperature (8). From a temperature of -10°C, where 60 m of height can be achieved (< 250 days), to 40 m at -2°C (< 120 days) to no possible height at 0°C.

This type of fill has been placed (as soon as each stope is finished) using six foot diameter raise- bored holes extending from surface to the stopes. Fill, once delivered underground is distributed within the stope by a small bulldozer and the top 1 m flung into place leaving only a few centimeters of space. No scientific observation on fill stability was made as of 1986, but after preliminary pillar extraction the backfill has remained visually competent (9).

In addition to thermal and free standing requirements, long term load bearing capability must be assessed in the context of time for pillar removal.

All fills with frozen water content will creep over time; general laboratory observations for the Polaris rockfill were registered (8):

- The cohesion, from ice bonding, governs frictional and creep response.
- Cohesion is directly related to density, Figure 3.
- Unconfined compressive strength increases with decreasing sub-zero curing temperatures, Figure 4.
- Strength and deformation characteristics depend on: density, ice content, fill temperature, stress level, time and rate of loading.
- The strength formula is:

  $$\tau = c\ (\theta, t) + \sigma_n \tan \emptyset.$$

- The deformation formula is

  $$\dot{\varepsilon} = \dot{\varepsilon}_c\ (\sigma/\sigma_c)^n - f\ (\sigma_3,\ \theta)$$

where c = cohesion
t = time
θ = temperature
$\emptyset$ = angle of internal friction
$\dot{\varepsilon}$ = rate of strain
$\dot{\varepsilon}_c$ = reference rate of strain
n = creep coefficient
σ_3 = confining pressure
σ_n = normal stress
τ = shear stress

Although no other ground support systems emplaced for pillar removal are described technically in the literature, mention has been made of using ice as means of wall support (10)(11).

Sequencing and speed of pillar recovery has not been reported in the Polaris or other cases.

Monitoring

The instrumentation mentioned in the publications are temperature sensors, thermistors/thermocouples, used in frozen soils (12)(13) or frozen rock (4).

In a practical sense (12)(14), techniques of installation, long term monitoring programs and examples are given.

Other Subjects

A variety of other subjects, of potential interest to the objectives of the Nanisivik pillar recovery project are absent from published information. These are listed as follows:

- drilling patterns
- application of explosive technology
- mucking procedures.
- mining equipment alternatives
- rock mass characterization
- numerical modelling
- pillar sequencing
- geomechanical monitoring instrumentation

For the purpose of report completeness, a general discussion of aspects pertaining to design for high post pillar recovery in frozen rock conditions is presented next.

OTHER CONSIDERATIONS

Underground operations in permafrost are generally more effective for the same environment than operations without permafrost. The rock mass is more competent and ground control problems are lessened. Pillars and stope backs will remain sound beyond limit conditions for the same unfrozen rock.

But rock breaking involves higher explosive consumption and muck handling is difficult in sub-freezing temperatures. Cratering studies (15)(16) identify augmented energy level, loading rate and travel velocities necessary to overcome the plastic behaviour of frozen ore to reach shock type (rather than the shear type adding plastic deformations) failures and satisfactory fragmentation.

Using controlled blasting practices is important at any stage, especially the pillar recovery stage to reduce roof damage and mobilize full roof strength within the required sequencing plan. Application of numerical modelling results is representative when conditions are controllable. Summary perimeter blasting recommendations for frozen rocks are presented in Mellor (17).

There have been laboratory studies (18)(19) on frozen tailings for use as permafrost mine support backfill, but no in-situ study component. The studies concluded that frozen slurried tailings has high instantaneous uniaxial compressive strength (7.8 MPa at a water content of 15-20%); long term deformation and strength is highly dependent on strain rate.

In pillar recovery programs with very wide openings, roof rock mass quality and pillar strength are very important. Few studies have been carried out on rock strength under frozen conditions. The Mellor (20) study showed that short term strength increases with decreasing subzero temperature, deformability decreases. The strength increase becomes more important with pore water content. Freezing has the effect of plugging cracks and pore with ice, so that the controlling defect size of the rock tends to decrease with decreasing temperature. The general shape of the compressive stress/strain curve for saturated porous rocks is altered by freezing pore water. The typical initial positive curvature disappears as pore water freezes and initial tangent modulus increases sharply as temperature decreases reaching values very much higher than those for the unfrozen state.

Rock mass characterization, from core and/or in-situ future observations such as borehole cameras provide badly needed factual information on potential unseen problems in the backs of wide openings, as well as any spacial variations in ice content.

Added to rock material behaviour is the effect of ice which depends on time and on temperature. It is thus necessary to have rock temperature readings (if not also air temperature readings) coupled with rock strain, opening closure measurements and indication of ice content variations.

Geomechanical instrumentation would then address roof rock temperature at various depths, direct pillar roof strain monitoring (for monitoring stress changes), roof to floor opening convergence.

Beyond the behaviour of frozen rock with mine air, heat is released and dissipated due to long term mass straining originating from workings with pillar recovery; very large volumes of frozen rock and substantial mass forces participate in the deformation process.

The laws of thermodynamics can be used to establish the link between deformation and temperature. Mechanically, non-linear behaviour models could be more representative of rock deformation compared to linear elasticity.

Numerical modelling, adopting a representative behavioural model and sufficient in-situ data, presents a solution to predicting opening stand-up time and controllable opening spans. In this fashion sequencing and extraction ratios can be calculated for safe, efficient recovery of high post pillars in frozen rock conditions. The amount of support required and location can be indicated with the help of modelling. The nature of ground support (rockfill, cable bolting, etc.) can then be decided on.

REFERENCES

1. de Ruyter, H. "Nanisivik Mine, Canada's first mine north of the acrtic circle"; Erzmetall; 36 #9; pp. 419-427; 1983.

2. Fish, R. "Nanisivik Mines in Canada's high arctic"; Can. Min. J.; pp. 34-48; September, 1979.

3. Bailey, F., Personal Communication, January 1989.

4. Drake, J.S. and Keohane, P.G. "The Polaris Mine"; CIM Bulletin; 78 #880; pp. 49-53; 1985.

5. Fish, R. "Mining in Arctic lands, the Black Angel experience"; Canadian Mining Journal; pp. 24-36; August, 1974.

6. Brugmans, P.J. "Spitsbergen - mining coal within the arctic circle"; Mining Magazine; 156 #6; pp. 479-486; 1987.

7. Clow, G., Personal Communication, January 1989.

8. Eigenbrod, K.D. and Roggensack, W.D. "Thermal considerations for mine development and backfill design, Polaris Mine"; Proceedings 36th Canadian Geotechnical Conference; 1983.

9. Hopkins, J.L. "Beyond resolute"; Canadian Mining Journal; 107 #8, pp. 12-15; 1986.

10. North, Oliver, S. "Today's patents"; Engineering and Mining Journal; April 1974.

11. Fangel, H. "Use of ice fill is being developed as an important new mining technique; Northern Miner; June 19, 1975.

REFERENCES (Cont'd)

12. Ladanyi, B. and Johnston, G.H. "Field investigations in frozen ground"; in "Geotechnical Engineering for Cold Regions"; O.A. Andersland and D.M. Anderson editors; McGraw-Hill; pp. 216-275; 1978.

13. Huang, S.L., Anghenbaugh, N.B. and Wu, M.C. "Stability study of CRREL permafrost tunnel"; American Society of Civil Engineers Journal; 112 #8; pp. 777-791; 1986.

14. Klein, C.A., Wilson, C.R., Benson, B.D. and Carpenter, G.W. "Installations of thermistor strings in test borings"; Proceedings 4th Conference of Cold Regions Engineering, ASCE; pp. 200-206; 1983.

15. Bauer, A., Harris, G.R., Lang, L. Preziosi, P. and Selleck, D.J. "Review of Iron Ore's Company's high-explosives cratering research program"; Proceedings Rock Mechanics Symposium; University of Toronto; Mines Branch, Energy, Mines and Resources Canada; pp. 107-119; 1965.

16. Lang, L.C. "New permafrost blasting method developed at Asbestos Hill"; Canadian Mining Journal; pp. 48-53; March 1977.

17. Mellor, M. "Controlled perimeter blasting in cold regions"; Proceedings Second Conference on Explosives and Blasting Techniques"; pp. 279-300; 1976.

18. Nantar Engineering Limited "The behaviour of frozen backfill in underground mines"; Final Contract Report; CANMET Contract; Energy, Mines and Resources; 1983.

19. Nantar Engineering Limited "Time dependent behaviour of frozen pelletized tailings in underground mines"; Final Contract Report; CANMET Contract 26SQ.234440-4-9129; Energy, Mines and Resources, Canada; 1985.

REFERENCES (Cont'd)

20. Mellor, M. "Strength and deformability of rocks at low temperatures"; U.S. Army Cold Regions Research and Engineering Laboratory; Research Report 294; 1971.

BIBLIOGRAPHY

(Anonymous) "The Black Angel, Canadian mining experience in the High Arctic"; Western Miner; pp. 21, 22, 24; October 1976.

Babe, G., Bondarev, E.A., Kanibolotskii, M.A., Skula, V.N. and Avksentiev, I.V. "Approximate method of calculation for thermal insulation of mine workings in permafrost"; Soviet Mining Science; 10 # 2; pp. 127-131; 1974.

Bauer, A., Harris, G.R., Lang, L. Preziosi, P. and Selleck, D.J. "Review of Iron Ore's Company's high-explosives cratering research program"; Proceedings Rock Mechanics Symposium; University of Toronto; Mines Branch, Energy, Mines and Resources Canada; pp. 107-119; 1965.

Bauer, A. "Trends in drilling and blasting"; CIM Bulletin; 71 #797; pp. 81-90; 1978.

Bertson, V.G., Davydov, S.A. and Korenistov, A.V. "Blastability of rocks under permafrost conditions"; Hydrotechnical Construction; #3; pp. 252-255; March 1986.

Brown, R.J.E. "Permafrost in Canada: Its influence on northern development"; University of Toronto Press; 234 p.; 1970.

Brugmans, P.J. "Spitsbergen - mining coal within the arctic circle"; Mining Magazine; 156 #6; pp. 479-486; 1987.

Cox, G.F.N. and Johnson, J.B. "Stress measurement in ice"; U.S. Army Cold Regions Research and Engineering Laboratory; Report 83-23; 1983.

de Ruiter, H. "Nanisivik Mine, Canada's first mine north of the Arctic circle"; Erzmetall; 36 #9; pp. 419-427; 1983.

Dorman, K. and Gooch, A.E. "Spray-applied polyurethane foam to insulate heated rooms excavated in permafrost"; U.S.B.M. Report of Investigations #7392; 1970.

BIBLIOGRAPHY (Cont'd)

Drake, J.S. and Keohane, P.G. "The Polaris Mine"; CIM Bulletin; 78 #880; pp. 49-53; 1985.

Dubnie, A. "Northern mining problems with particular reference to unit operations in permafrost"; Mines Branch Report TB 148; Energy, Mines and Resources, Canada; 1972.

Dubnie, A. "Notes on a field trip to Asbestos Hill and Labrador"; Mines Branch Technical Report 73-121(INT); Energy, Mines and Resources, Canada; 1973.

Duval, D. "Innovations in permafrost drilling at Nanisivik"; Northern Miner; p. 12; May 31, 1979.

Eigenbrod, K.D. and Roggensack, W.D. "Thermal considerations for mine development and backfill design, Polaris Mine"; Proceedings 36th Canadian Geotechnical Conference; 1983.

Elchanninow, E.A., Shor, A.I. and Rozenbaum, M.A. "The stability of underground workings in permafrost"; Proc. Third International Conference on Permafrost; Vol. 1; pp. 922-927; 1978.

Espley, G.H. "Experience with permafrost in gold mining"; Procedings Third Canadian Conference on Permafrost; pp. 59-64; 1969.

Fish, R. "Mining in Arctic lands, the Black Angel experience"; Canadian Mining Journal; pp. 24-36; August, 1974.

Foster-Miller Associates Inc. "A description of programs and background in mining, tunnelling and excavation technology";

Giegrich, H.M. "Arctic mining in permafrost"; Proceedings Fifth International Permafrost Conference; pp. 1382-1387; 1988.

BIBLIOGRAPHY (Cont'd)

Goodman, M.A. "Arctic drilling operations present unique problems"; World Oil; pp. 95-110; November 1977.

Goodman, M.A. "How permafrost thaw/freeze creates well bore loading"; World Oil; pp. 107-112; October 1977.

Goodman, M.A. "Logging, coring and testing for permafrost evaluation"; World Oil; pp. 93-99; January 1978.

Hopkins, J.L. "Beyond resolute"; Canadian Mining Journal; 107 #8; pp. 12-15; 1986.

Huang, S.L., Anghenbaugh, N.B. and Wu, M.C. "Stability study of CRREL permafrost tunnel"; American Society of Civil Engineers Journal; 112 #8; pp. 777-791; 1986.

Izakson, V.Y. and Petrov, E.V. "Engineering method for predicting and controlling the size of thaw aureoles around mine workings in a permafrost region"; translated from Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh; #5; pp. 33-38; 1985.

Johansen, N.I., Huang, S.L. and Aughenbough, N.B. "Alaska's CRREL permafrost tunnel"; Tunnelling and Underground Space Technology; 3 #1; pp. 19-24; 1988.

Journal of Cold Regions Engineering; American Society of Civil Engineering; 1987-1988.

Journal of Cold Regions Science and Technology; Elsivier; 1979-1989.

Journal of Soviet Mining Science; 1965-1989.

Kilgour, R.J. "Mining experience with permafrost"; Proceedings Third Canadian Conference on Permafrost; pp. 65-70; 1969.

BIBLIOGRAPHY (Cont'd)

Ladanyi, B. and Johnston, G.H. "Field investigations of frozen ground"; in "Geotechnical engineering in cold regions"; Andersland, O.B. and Anderson, D.M. editors; McGraw-Hill.

Lang, L.C. "New permafrost blasting method developed at Asbestos Hill"; Canadian Mining Journal; pp. 48-53; March 1977.

McCusker "The use of tunnelling to develop arctic oil and gas reserves"; CIM Bulletin; 69 # 775; pp. 111-112; 1976.

Mellor, M. "Controlled perimeter blasting in cold regions"; Proceedings Second Conference on Explosives and Blasting Techniques"; pp. 279-300; 1976.

Mellor, M. "Phase composition of pore water in cold rocks"; U.S. Army Cold Regions Research and Engineering Laboratory; Research Report #292; 1970.

Mellor, M. "Strength and deformability of rocks at low temperatures"; U.S. Army Cold Regions Research and Engineering Laboratory; Research Report 294; 1971.

Mellor, M. and Sellmann, P.V. "General considerations for drill system design"; U.S. Army Cold Regions Research and Engineering Laboratory; Technical Report #264; 1975.

Nantar Engineering Limited "The behaviour of frozen backfill in underground mines"; Final Contract Report; CANMET Contract; Energy, Mines and Resources; 1983.

Nantar Engineering Limited "Time dependent behaviour of frozen pelletized tailings in underground mines"; Final Contract Report; CANMET Contract 26SQ.234440-4-9129; Energy, Mines and Resources, Canada; 1985.

BIBLIOGRAPHY (Cont'd)

Norwegian Geotechnical Institute; Technical Reports; 1956-1989.

"Permafrost; Engineering Design and Construction"; Edited by G.H. Johnston; Wiley & Sons, 540 p.; 1981.

Potapenko, V.V. "Development of underground mining of permanently frozen placers"; Problems of the North; #9; pp. 138-146; 1965.

Proceedings Conference of Applied Techniques for Cold Environments; American Society of Civil Engineering; 1167 p.; 1978.

Proceedings Fifth International Conference on Permafrost, Trondheim, Norway, 1988.

Proceedings of Fourth Conference of Cold Regions Engineering; American Society of Civil Engineering; W.A. Ryan editor; 788 p.; 1983.

Slusarchuk, W.A. and Foulger, P.H. "Development and calibration of a thermal conductivity probe apparatus for use in the field and laboratory"; National Research Council, Technical Paper 388, Science and Technology, Canada; 1973.

SME Mining Engineering Handbook; Volume 1, 2; Cummins, A.B. and Given, I.A., Editors; 1754 p.; 1982.

SME Underground Mining Methods Handbook, Hustrulid, W.A., Editor, 1982.

Széchy, K. "The art of tunnelling"; Hungarian Academy of Science; 1097 p.; 1973.

Taylor, A. and Judge, A. "Mining companies assist in studies of permafrost in northern Quebec"; Northern Miner; p. 15; November 1978.

BIBLIOGRAPHY (Cont'd)

Tseutral'nyi Nauchno-Issledovatel'skii I Proektno-Eksperimental'nyi Institut Organizatsii Mekhananizatsii I Tekhnicheskoi Pomoshehi Stroitel'stvii, Gosstroi SSR "Guide for the application of drilling and blasting method of loosening frozen and perennially frozen ground and moraines" (translated from Russian); Izdatel'stvo Literatury Po Stroitel'stvu, Moscva; 1972 (Translation 225, NRC, Building Research, 1976).

Tsytovich, N.A. "The mechanics of frozen ground"; McGraw-Hill; 426 p.; 1975.

U.S. Army Cold Regions Research and Engineering Laboratory; Technical Reports/Research Reports/Monographs/Translations; 1953-1989.

Van der Walt, J. "Cooling the world's coldest mine"; J. Mine Vent. Soc. S. Afr.; 37 #12; pp. 138-142; 1984.

Walsh, A.R. "Mine development in the high arctic"; CIM Bulletin; 68 #761; pp. 91-96; 1975.

Weidmark, P.E. "Tenth supplement to bibliography of Canadian contributions in the field of rock mechanics"; CIM Bulletin; 73 #826; pp. 124-126; 1980.

Weidmark, P.E. "Sixteenth supplement to bibliography of Canadian contributions in the field of rock mechanics"; CIM Bulletin; 67 #754; pp. 98-126; 1974.

Weidmark, P.E. "Seventeenth supplement to bibliography of Canadian contributions in the field of rock mechanics"; CIM Bulletin; 74 #839; pp. 100-103; 1981.

Weidmark, P.E. "Eighteenth supplement to bibliography of Canadian contributions in the field of rock mechanics"; Divisional Report TID 82-2(J); CANMET, Energy, Mines and Resources, Canada; 1982.

Figure 1 (a). Plan view Nanisivik mine, west and central portions.

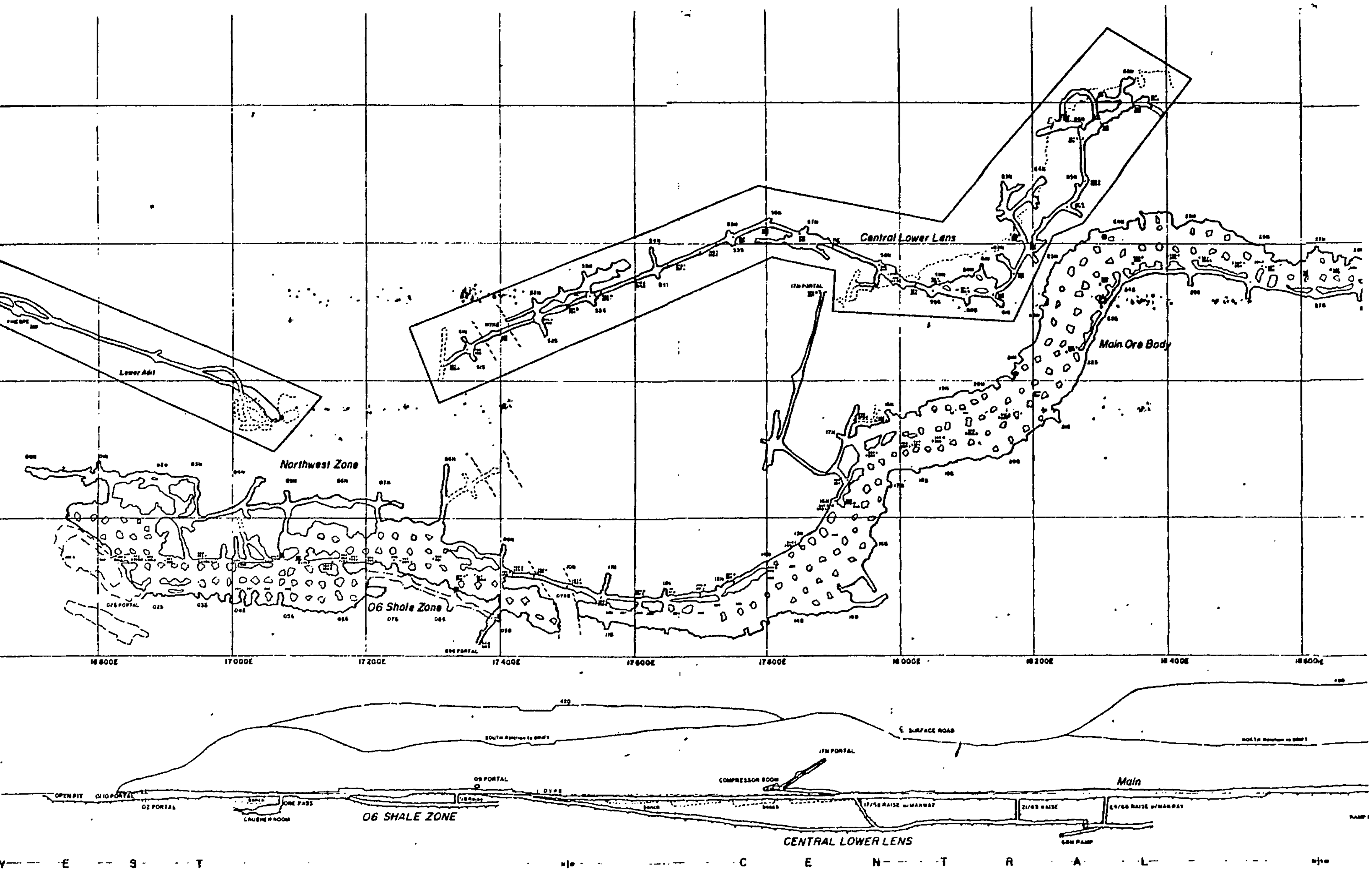
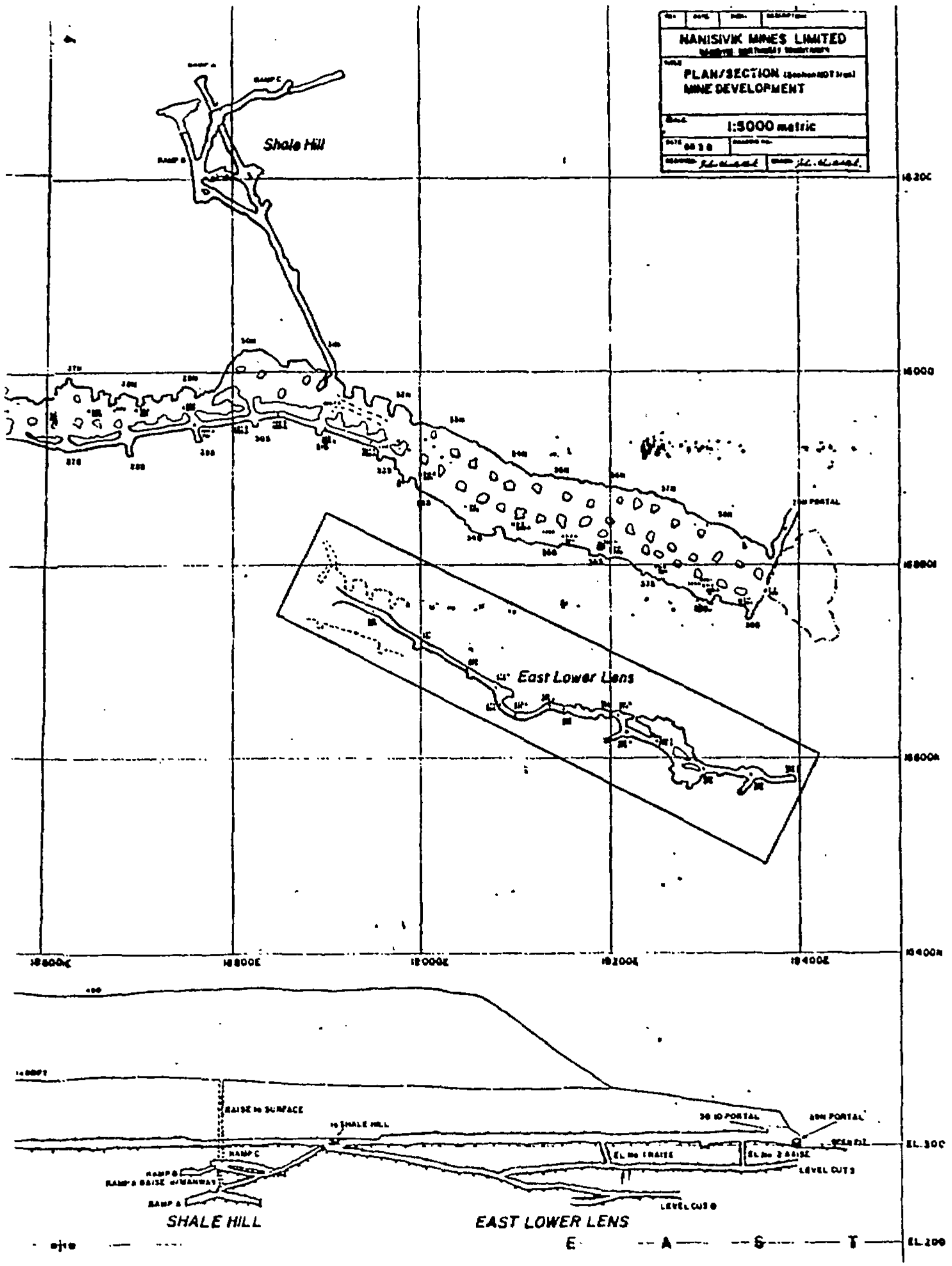
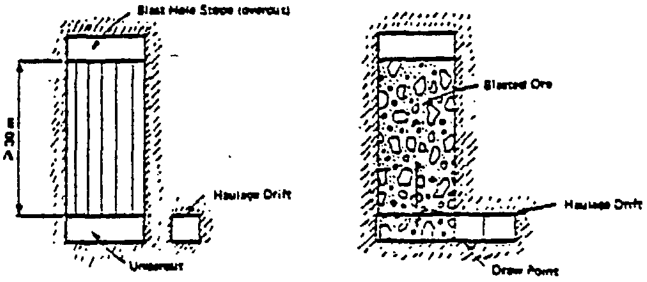


Figure 1 (b). Plan view Nanisivik mine, east portion.





PHASE 1: BLAST HOLE DRILLING

PHASE 2: STOPE EXTRACTION

SCHEME OF ORE EXTRACTION BY BLAST HOLE TECHNIQUE

Figure 2 - Mining method (blasthole for higher stopes), Polaris mine using foot wall haulage drift (8).

CURVE NO.	MATERIAL TYPE	STRAIN RATE 1/s	φ	c (MPa)
1	LOOSE ROCK FILL (-10°C)	4×10^{-6}, 4×10^{-6}	32°	0.3
2		8×10^{-5}	35°	0.5
3	DENSE ROCK FILL (-10°C)	8×10^{-5}	35°	0.75
4		6×10^{-7}	39°	0.6
5	FROZEN OTTAWA SAND t = 3.91°C (SAYLES, 1973)	5×10^{-4}	32°	2.4

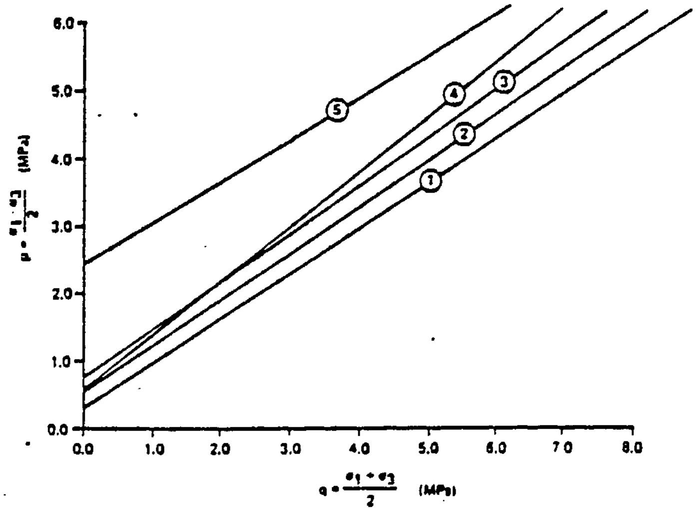


Figure 3 - Summary of strength data for frozen granular fill, Polaris mine (8).

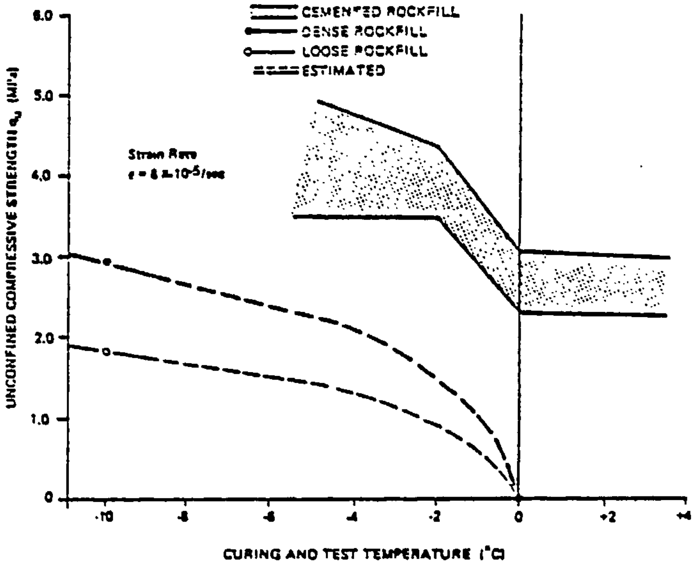


Figure 4 - Unconfined compression strength versus curing and testing temperature, Polaris mine fill (8).