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WHAT DO WE REALLY KNOW ABOUT SURFACE CROWN PILLARS?

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WHAT DO WE REALLY KNOW ABOUT SURFACE CROWN PILLARS?

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ABSTRACT

Surface crown pillars are complex mining structures important for safe and economic extraction activity near surface. The existing body of information reveals that since 1984 case studies rather than advance in knowledge have occurred with the intensification of activity on the subject. Few exhaustive and detailed references exist on surface crown pillars; none exist for abandoned mines. Failure mechanisms, stress conditions, in situ surveys, consideration of 3-D rock volumes involved in the stability of the pillars, and numerical modelling are recognized as major components of pillar design. Improvements in design could be possible by obtaining exact 3-D conditions and applying failure specific modelling (as opposed to generic, generalized modelling) for the large cross section of rock mass conditions found in surface crown pillars. Factor of safety use versus a probabilistic approach is discussed as is the interrelationship between design and response.

Key words: Surface crown pillars, case studies, failure mechanism, in situ investigation, rock mass characterization, design, pillar recovery, in situ stress, factor of safety, probability of failure,

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QUE SAVONS NOUS DES PILIERS DE SURFACE?

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RÉSUMÉ

Les piliers de surface sont des structures minières complexes, importantes à l'activité souterraine sécuritaire et économique se déroulant près de la surface. L'ensemble des connaissances démontre que depuis 1984 ce sont des études de cas plutôt que des avancements dans le sujet qui prédominent suite à l'intensification d'activité dans ce domaine. Peu de références exhaustives et détaillées sont disponibles; aucunes n'existent pour les mines abandonnées. Les mécanismes de rupture, les pressions de terrains, les sondages en place, la considération en 3-D des volumes de roc incorporés dans la stabilité de piliers et la modélisation numérique sont reconnus comme les éléments majeurs de la conception de piliers. Des améliorations dans nos conceptions sont possibles en obtenant des conditions exactes en 3-D et en appliquant une modélisation reliée à la rupture particulière (contrairement à la modélisation générique et généralisée) pour les nombreux types de conditions de massifs rocheux reliés aux piliers de surface. L'utilisation du facteur de sécurité versus l'approche probabiliste est discuté de même que la relation entre la conception et le comportement.

<u>Mots clés</u>: Piliers de surface, études de cas, mécanismes de rupture, investigation en place, caractérisation de massifs rocheux, conception, récupération de pilier, contrainte naturelle, facteur de sécurité, probabilité de rupture

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INTRODUCTION

Since 1984, there has been an intensification of activity in the field of surface crown pillars. It has become evident that this is a complex subject which requires a broad knowledge of all geotechnical disciplines (structural geology, rock mechanics, soil mechanics, hydrology). These mining structures, situated above near-surface underground excavations figure 1, can range in material quality: from massive and competent for some to altered and weak for others.

Geotechnical and mining factors vary from minesite to minesite so that each pillar needs to be treated as a unique case. The challenge is to continuously evaluate their stability while optimizing their dimensions to maximize safety and extraction. In some cases, operators leave final dimensions for the life of the mine, in others the pillars are under continuing extraction; some pillars are recovered outright.

New design guidelines and dedicated applications of generic design methods are now in use for these structures.

This presentation, although it introduces the sum of knowledge from known sources of information, also examines more fundamental questions in relation to important stability elements and the interrelationship between design and material response. Some consideration is given to gaps in information and whether we can significantly improve our knowledge of complex situations and our ability to better our designs.

"SURFACE CROWN PILLAR": A ROCKMASS OF VARIABLE GEOMETRY, MINERALIZED OR NOT, SITUATED ABOVE AN UPPERMOST STOPE OF THE MINE, WHICH SERVES TO PERMANENTLY OR TEMPORARILY ENSURE THE STABILITY OF SURFACE ELEMENTS.

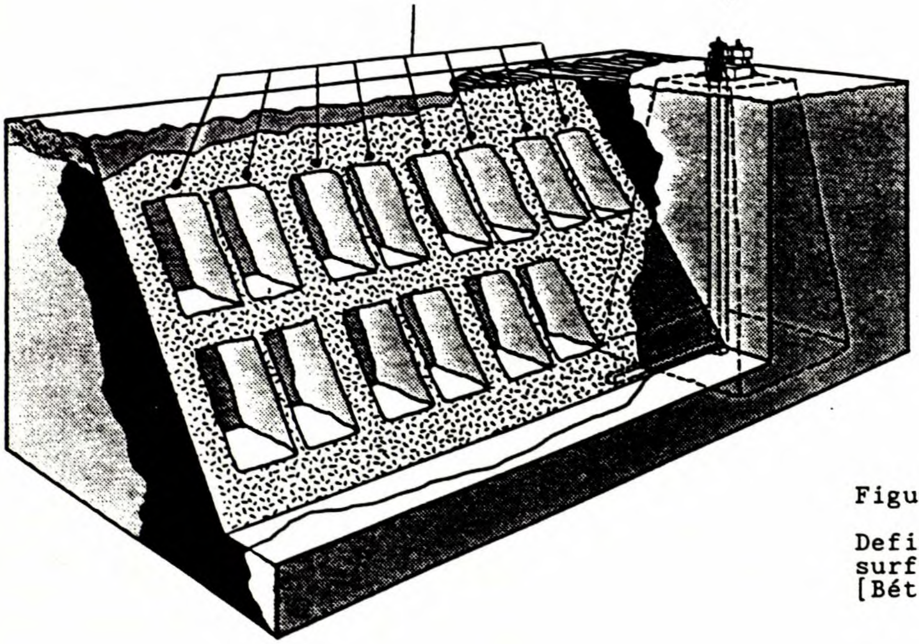


Figure 1.

Definition of a surface crown pillar [Bétournay 1986a]

REVIEW OF PUBLISHED INFORMATION

Table 1 presents a breakdown in the content of surface crown pillar publications published since 1984.

Prior to 1984, no specific process, tried method, case study, terminology or other helpful information related to these structures was published for hard rock settings. In effect, the thrust of early efforts [CANMET Contract 1984; CANMET Contract 1985; Bétournay 1986a] was to gather all relevant information. These works served as foundation upon which future research and advancement of knowledge about the nature of these structures could be based.

The case studies examined indicated a wide range of rock mass competence and geological assemblage. However, there was no tendency to increase pillar thickness when going from competent to poorly competent ground [Bétournay et al 1988], the thickness to width ratio usually taking on a value less than 5.

The first, and so far the only exhaustive discussion of surface crown pillars, was formulated in 1986 [Bétournay 1986a]. Its objective was to amalgamate applicable information from all geotechnical fields into a body of scientific information capable of supplying the reader with the "big picture" as well as the reference for design including advantages/disadvantages and limitations of formulas, methods and mining strategies for the benefit of attaining the goal of stable pillars. A design process was established, figure 2, to enumerate and place in perspective the progression of design. An updated and enlarged version is planned as a handbook to serve as a reference to mine operators and mine regulators. An equivalent guidebook for the problems associated with abandoned mines does not exist.

The exercise was repeated subsequently [Centre de Recherche Minérale 1986] with a narrower descriptive scope.

Major Components of Pillar Design

The idea of failure mechanisms as the focal point for the application of design and ground support methods was used sparsely at first [Steffen Robertson and Kirsten 1984; Bétournay 1986a; CANMET Contract 1986b; Biron and Labrie 1986] but has since been routinely taken into consideration. The failure mechanism concept is important. It places the onus on the field investigation, to be as complete and wide ranging as possible. It also challenges the designer to apply methods of dimensionning that can account for the failure mechanism(s). The proper application of one or several support types as well as a dedicated monitoring program could be achieved.

One study in particular is currently examining the failures of surface crown pillars of both active and abandoned mines [CANMET Contract 1988d]. Recognizing that the approach taken by most mines until recently relied heavily on "experience" and "rules of thumb" [Bétournay et al 1988] this study has undertaken to examine the factors that have controlled previous failures and those contributing to the stability of existing pillars. Basic geotechnical and mining data on a great number of minesites is

Table 1. Contents of surface crown pillar publications since 1984.

Reference	Exhaustive Listing of Information	Exhaustive Discussion of Information	Design Guidelines	Other Basic Information	Case Studies (#)	In Situ Investigations	Material Testing	Failure Mechanism	Application of Design/Stability Methods	Mining Methods	Ground Support	New Investigation Methods	New Design/ Stability Methods	New Mining Method	Pillar Recovery	Economic Analysis
CANMET Contract 1984	x				6											
Stefan Robertson, Kirsten 1984					18											
CANMET Contract 1985					1	x	x	x	x	x	x				x	
Bétournay 1986a	x	x	x					x								
Kelly et al. 1986					1					x				x	x	
CANMET Contract 1986a					1	x	x		x		x	x				
Udd and Bétournay 1986				x												
Biron and Labrie 1986					1	x	x									
Closset 1986					1	x			x	x						
Bétournay and Thivierge 1986					1		x	x	x							
Bourbonnais, 1986						x										
Lessard et Bienvenu, 1986																x
Bétournay 1986b			x													
Fortin and Gill													x			
Centre de Recherche Minérale 1986			x													
CANMET Contract 1986b					1											
Bétournay 1987					5	x		x	x						x	
CANMET Contract 1987a					1		x		x	x					x	
Bétournay et al 1987					1			x	x		x					
CANMET Contract 1987b					2	x						x				
CANMET Contract 1988a					1							x				
Bétournay et Labrie 1988					1	x	x	x	x	x	x					
CANMET Contract 1988b					1			x	x		x		x	x	x	
Bétournay 1988a		x	x					x								
Bétournay 1988b					1	x		x	x		x					
Bétournay et al 1988		x			24											
Yu et al 1988					1	x		x	x		x					
Bétournay 1988c					1			x	x		x					
CANMET Contract 1988c					4	x	x	x	x							
CANMET Contract 1988d					46	x	x	x	x							
Bétournay 1988d					6	x		x				x				
Closset 1988									x							
Bétournay 1988e				x												

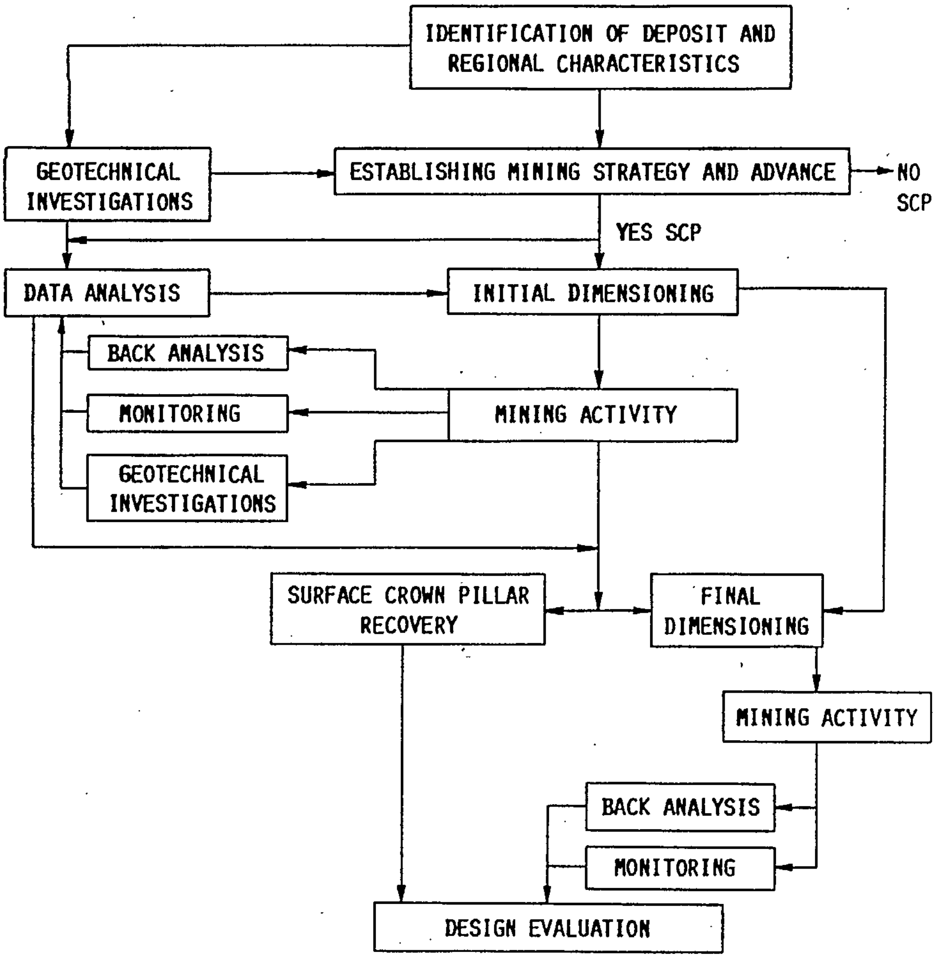


Figure 2. Surface crown pillar design process [Bétournay 1986a].

pieced together for individual mine situations. Back-analysis using a variety of methods, analytic solutions and numerical approaches will look at failure mechanisms, the effects of parameter variation, and level of stability/instability. The effectiveness of the approach for solving particular conditions is also outlined.

There has been to date no clear examination of in situ stress conditions near surface. Published results of stress measurements in Canada [Herget 1984] relate to depths of > 80 m. It is important to know what part stress effects play in helping surface crown pillar stability in order to carry out efficient designs and validate many of the postulated failure mechanisms. Speculation is that stresses near surface (0-20m) could vary greatly from established directional trends, figure 3. An extensive campaign [Bétournay 1988d] is presently underway to collect stress data near surface in undisturbed bedrock of various Canadian mining camps.

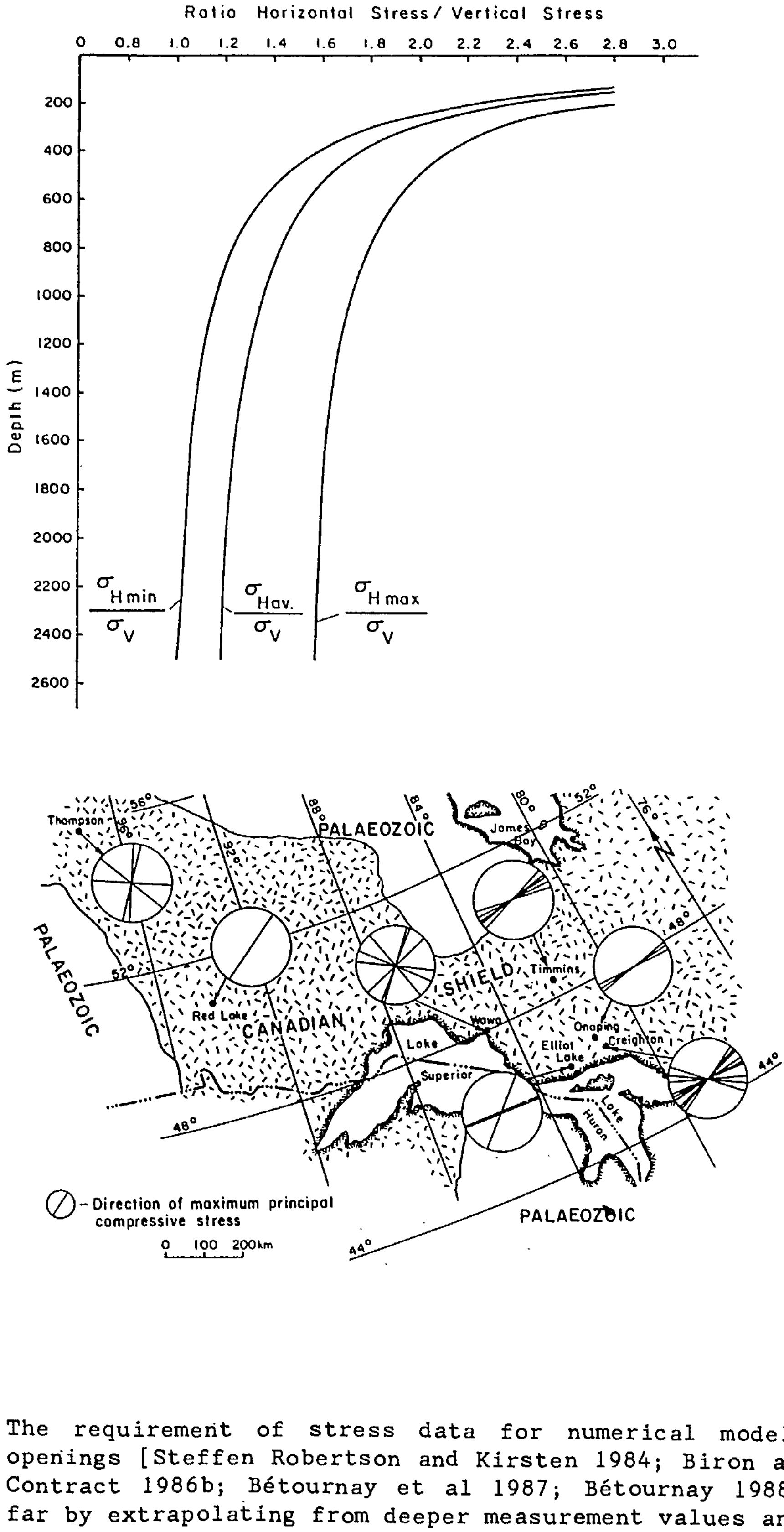


Figure 3.

Established levels and directional trends for ground stresses in the Canadian Shield [Herget 1984].

The requirement of stress data for numerical modelling of near surface openings [Steffen Robertson and Kirsten 1984; Biron and Labrie 1986; CANMET Contract 1986b; Bétournay et al 1987; Bétournay 1988c] has been filled so far by extrapolating from deeper measurement values and assuming zero stress at surface.

Other actual rock mass site investigations have by and large been limited to quality assessments and rock mass classifications [Steffen Robertson and Kirsten 1984; CANMET Contract 1986a; Bétournay et al 1987; Bétournay et Labrie 1988]. Classifications can only supply general outlines of site conditions and as such must not be used alone but in conjunction with other methods to formulate an overall design rationale. Thorough analysis of joint orientation, intersections, density and potential effects on stability is not practiced.

The dilatometer has become important in the estimate of general and localized brokenness of the rock mass. The data is used to specify the extent of rock mass competence indicated by the RQD of the drill core. For example, the upper bedrock of the Canadian Shield in contact with overburden has been proven to be a regolith of little competence [CANMET Contract 1988c; Monterval 1988]. Consideration of RQD data alone could not have confirmed this. Dilatometer tests can also be used to supply representative values of rock mass modulus of elasticity for numerical modelling.

Other in situ rock surveys such as hydraulic conductivity tests are not available. They could also indicate the extent of the rock mass integrity and qualify water effects on the stability of near surface openings.

Less is known about soil conditions. Although thicknesses and classification are commonly sought, actual field values for mechanical parameters remain unknown for the most part. Surveys of minesites now include in situ tests to measure density and shear strength of soils; samples are examined for water content and liquifaction potential.

So far available analytical formulas (elastic members, voussoir solutions, arch theory, etc.) and conventional numeric models (Finite Elements, Boundary Elements, etc.) [Bétournay 1986a] have been applied [Bétournay et al 1987; Bétournay 1988c; Bétournay et Labrie 1988; CANMET Contract 1987b; CANMET Contract 1988c; Steffen Robertson and Kirsten 1984; Yu et al 1988].

Numerical modelling has been recognized as the most powerful tool to solve the complex stability problems of these pillars, but it has been difficult adapting current models to field behaviour. Pillar behaviour rarely fits generic modelling assumptions: generalized failure, stress induced failure, homogeneous material types, etc. Localized, tensile/shear,non-linear and gravitational failures predominate. The closest fit has been in the application of block or distinct element codes for fissured but sound rock material. Dedicated models for surface crown pillars are beginning to be formulated [CANMET Contract 1986b; Fortin et Gill 1986].

Research

By far, the bulk of the information pertains to single case studies rather than research in aspects related to surface crown pillars (Table 1). In most of these cases limited field work, analysis, and design was performed. It would appear also that some mines limit themselves to laboratory strength tests. In the case of surface crown pillars there is no substitute for testing in situ strength and behaviour testing for rock and soil. It represents the best hope for achieving representative stability assessments.

The few innovations that have taken place have been wide ranging: new investigation techniques to situate rock mass features in 3-D [CANMET Contract 1987a], new design methods to calculate pillar stability [Fortin et Gill 1986; CANMET Contract 1986b] and to recover pillars without removal of overburden [CANMET Contract 1988b], new approaches to recovery pillars after overburden removal [Steffen Robertson and Kirsten 1984; Kelly et al. 1986; CANMET Contract 1987b], economic considerations [Lessard et Bienvenue 1986].

There have been few innovations in ground support and monitoring instruments dedicated to surface crown pillar problems: single anchor extensometers for altered rock [CANMET Contract 1988b] and movement of weak hangingwall rocks using multiple inflatable anchor extensometers [Bétournay 1988d].

CRITICAL ELEMENTS

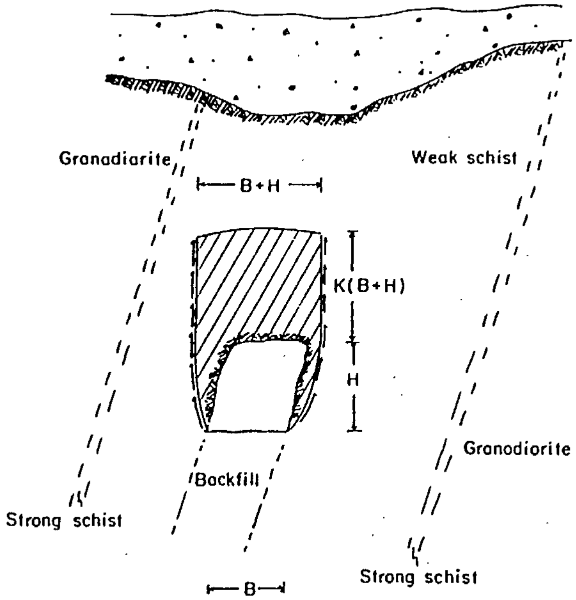
From the number of elements that can affect the stability of surface crown pillars the designer must identify which are the most critical, and how they combine to affect the integrity of the pillar. A short discussion of general and particular elements follows.

It is necessary to describe with confidence the existing water, soil and rock properties surrounding planned/existing openings. This is important in identifying stable and unstable situations. New conditions exist every time an opening is created/expanded. Specific examination is thus warranted before excavation is begun. The usual question "How much of a pillar do we leave behind?" should be rephrased "What is the rock volume that is mobilized by the effects of the opening?". A narrow view of the situation would be to consider only the thickness of rock between the soil and top of the opening: The rock mass which can influence pillar stability stretches laterally beyond the crown of the opening and even into the abutments of the openings, figure 4. The regolith in contact with the soil must be discounted from contributing resistance to failure. Furthermore, if failure occurs, will the new opening become self supporting? Can the soil remain stable above rock failure and not enter the opening? Water saturated soils have been known to flow [Gouvernement du Québec 1981]; dense till-like soils have been known not to [CANMET Contract 1988d; Bétournay 1989].

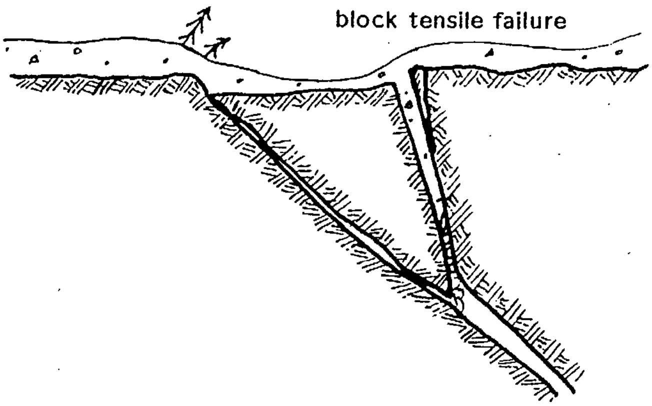
The importance of understanding and cataloguing failure mechanisms was underlined earlier. In itself it is one of the most important critical elements that must not be overlooked in design. Yet, within this consideration there reside several other caveats.

The broad range of rock mass settings shows us that there are different failure modes and ranks of failure possibilities, figure 4, while stress may or may not help stabilize. In massive rock [Bétournay et al 1987] localised degradation and readjustment to tensile stresses are expected. In sound rock environments, the location and connectivity of discontinuities is the most critical element. If the rock mass is not effectively fissured it can be several times more resistant than a rock mass where blocks are commonplace. Research now underway [CANMET Contract 1987a] will provide the means to map major discontinuities (>1m) and anomalous zones in 3-D. This important leap forward in rock mechanics is aimed at eliminating guess work about conditions around openings, greatly helping in understanding possible

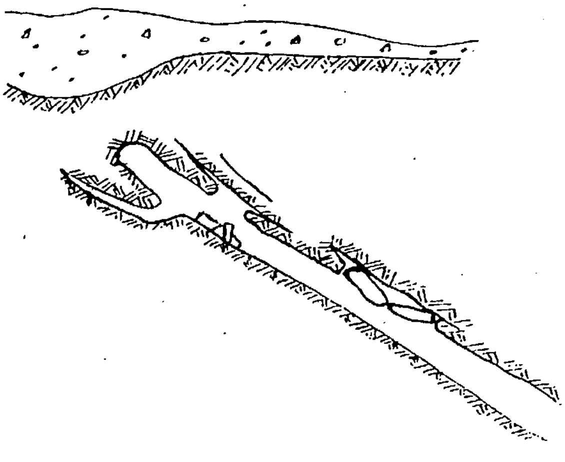
FAILURE ARCHING IN COHESIVE MATERIAL



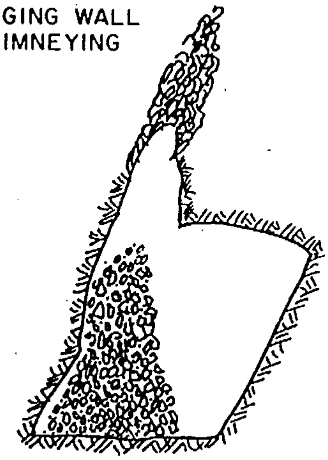
block tensile failure



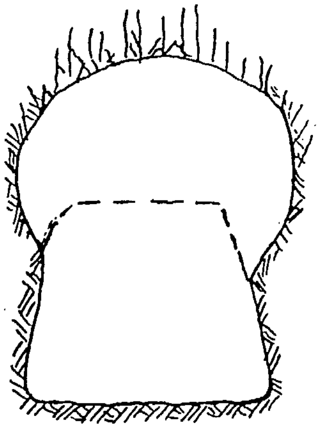
hangingwall slabbing and voussoir action



HANGING WALL CHIMNEYING



crown degradation in weak rock



PLUG-LIKE CROWN FAILURE

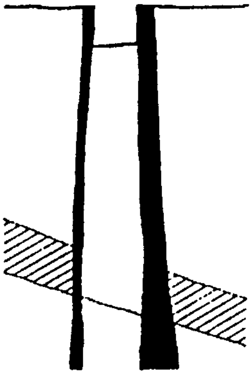


Figure 4 Examples of surface crown pillar failures and mobilized rock mass.

behaviours and making numerical models arrive at much more representative results. In altered rock, localised shear and tensile failures whether as chimneying, crown degradation or large scale movements are expected.

In all cases it is critical to know what values of stress exist and if the distribution around particular openings are sufficient to restrain gravity type failures, from sliding blocks to material degradation. Excellent indications of stress levels at failures have been obtained by back-analysis, [CANMET Contract 1988d] and confirmation of local Canadian shallow stresses [Bétournay 1988c] will provide working numbers. Further observations from back analysis studies confirm the expectations that the generic design methods widely thought to provide satisfactory estimates of stability, have narrow scopes of applicability and broad range of precision.

Proper care in sampling all materials, even altered rock, and in describing mechanical behaviour of all material types [CANMET Contract 1986a] is part of the overall goal of obtaining all the data and placing it in perspective with respect to openings, figure 5, to evaluate surrounding conditions. By using 2-D and 3-D projections, all of the geomechanical information can serve to separate the rock mass in zones of varying behaviour, figure 6.

IMPROVING OUR DESIGNS

The current process by which we arrive at our estimation of stability is one which has gaps in information, uses generic analysis methods and usually measures results by a very narrow indicator: The single factor of safety.

Given such circumstances, how much closer to failure than anticipated is the material response? Historically, few failures have occurred while an active mine was creating surface crown pillars. One even discovers that past mining practices that have come perilously close to overburden contact have left openings which remain stable for long periods of time.

Can we then infer that we are currently erring on the conservative side and that the margin of allowable error is large? If this is true, designs incorporating exhaustive consideration of information and application of enlightened design methods should substantially reduce the risk of possible problems and perhaps permit higher extraction at satisfactory levels of safety.

Placing in perspective our grasp of these structures and our use of design methods, it is apparent that we are currently working with 3 generations of information, figure 7.

The first, the rudimentary experience, is limited to personal experience with little scientific information involved; limited effectiveness is achievable. The second consists of applying conventional tools (finite element modelling, general analytical methods, etc) which use detailed scientific information obtained on a bulk or generalised basis. Improved effectiveness is achievable and the use of several methods provides a range of possibilities. The third generation consists of using design methods dedicated to recognized conditions, obtained from sound knowledge of the location of elements surrounding the opening. An example of this is the

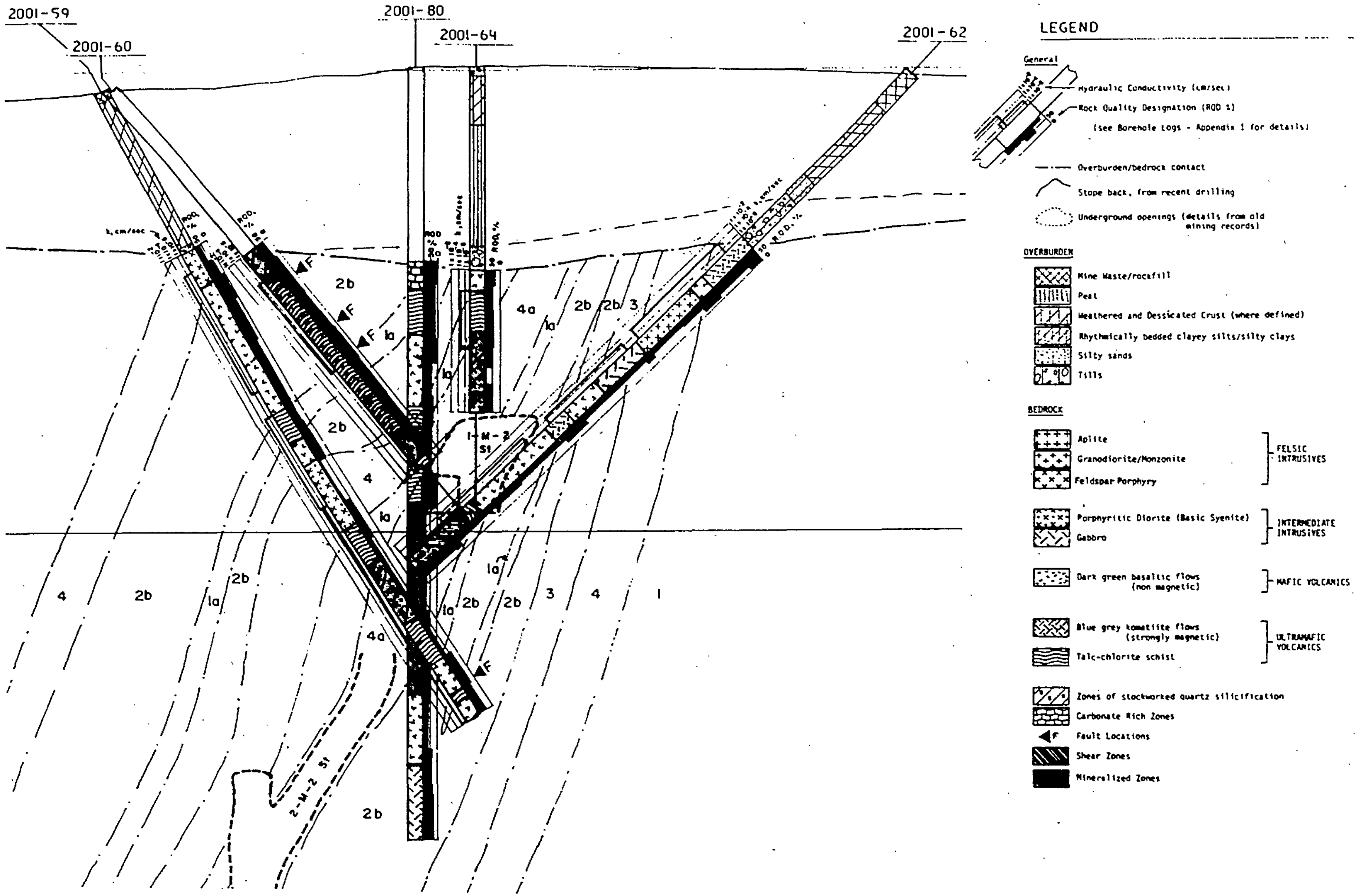
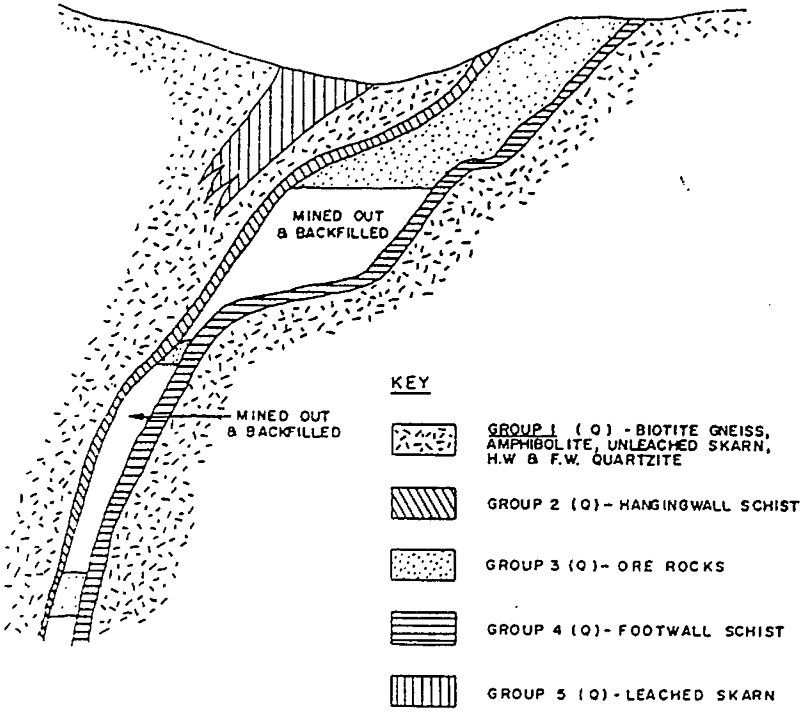


Figure 5. Borehole data placed in perspective to stopes (transverse section) [CANMET Contract 1988d]



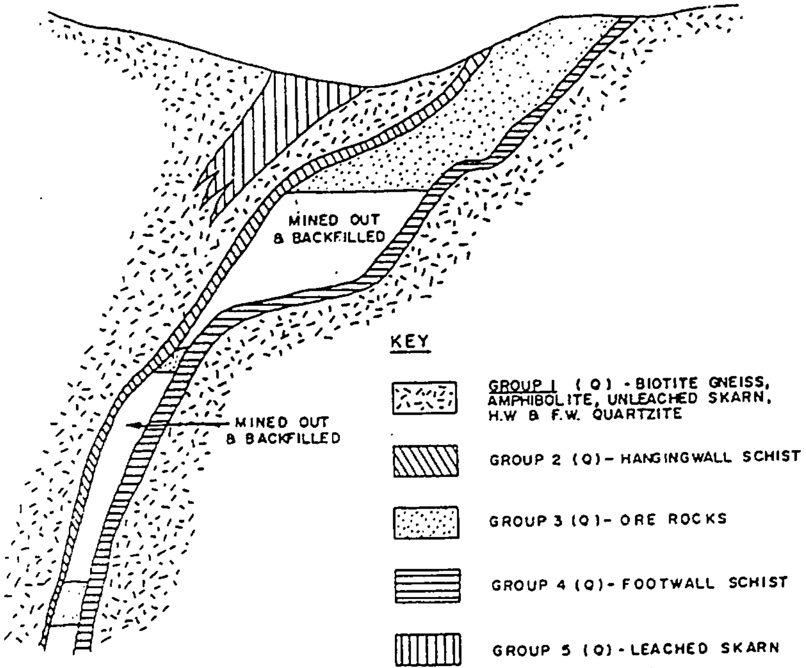
Class I (6 < Q < 11) - biotite gneiss, amphibolite, skarn (unleached, hangingwall quartzite and footwall quartzite).

Class II (3 < Q < 6) - Hangingwall schist (anisotropic properties).

Class III (3 < Q < 6) - Ore Rocks.

Class IV (Q = 1) - Footwall schist (anisotropic properties) Range Q = 0.1 to 3.

Class V (Q = 0.03) - Skarn (leached) Range Q = 0.001 to 0.1.



Group 1 - Biotite Gneiss, Amphibolite, Unleached Skarn, Hangingwall Quartzite and Footwall Quartzite with mean rock mass uniaxial compressive strength of 10 MPa (1450 psi); and deformation modulus of 25 GPa (3.6 x 10E6 psi).

Group 2 - Hangingwall Schist with mean rock mass uniaxial compressive strength of 3.5 MPa (500 psi) and deformation modulus of 20 GPA (2.9 x 10E6 psi).

Group 3 - Ore Rocks with mean rock mass uniaxial compressive strength of 3 MPa (435 psi) and deformation modulus of 10 GPa (1.4 x 10E6 psi).

Group 4 - Footwall Schists with mean rock mass uniaxial compressive strength of 1.5 MPa (220 psi) and deformation modulus of 5 GPa (0.7 x 10E6 psi).

Group 5 - Leached Skarn with mean rock mass uniaxial compressive strength of 0.5 MPa (72 psi) and deformation modulus of 1 GPa (0.15 x 10E6 psi).

Figure 6 Separation of a near-surface rock mass into zones of varying behaviour [Steffen Robertson and Kirsten 1984]

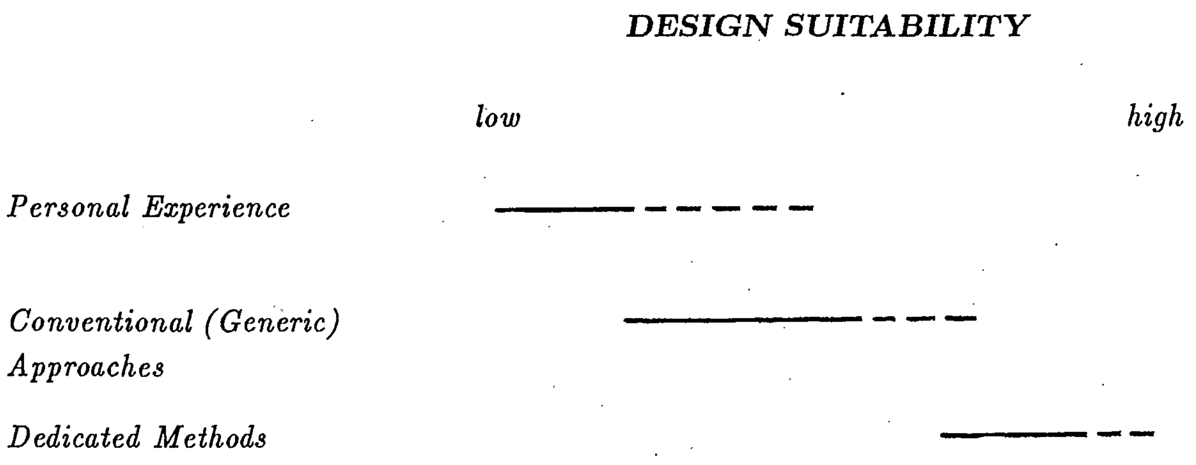


Figure 7. Three generations of surface crown pillar design methods and their range of suitability.

application of block codes to sound fissured rock. But for the most part such methods are absent, which therefore leaves us without ideal design tools for most of the existing types of pillar conditions.

One must keep in mind however that personal experience, when well founded, can contribute to the effectiveness of the second or third generation methods.

The effectiveness of the design is also affected by our basis for judging stability. Given the complexity of the problem, a factor of safety tends to simplify the situation. Even by using advanced tools such as modelling, the results are based on one failure criterion. The true nature of the rock volume involved in the stability/instabilities and progression of behaviour is not seen. One exception to this would be distinct modelling for blocky conditions. Furthermore, a factor of safety is based on well known conditions with predictable material behaviour. There is no limit to the "safe" value it can take on, i.e. >1.0. A factor of safety does not afford security in proportion to its value. There is always the possibility of failure or other problems, regardless of the value of the factor.

The probabilistic approach is better defined: a range of 0 to 1 is used, but it also requires all the necessary geomechanical information as input. However, it is the possibility to qualify each input (variability and certainty) and the combination of information to a qualified level of stability that makes this approach superior.

It goes without saying that in arriving at stability assessments several design methods should be used in the context of the existing problem.

By and large, the design of surface crown pillars has so far been done for short term stability (<20 years). Changing rock mass conditions can occur over time and are more obvious for weak rock material or rock masses tending to deform on structural features. Failures reaching the overburden in altered rock masses or in weak hanging-walls occur in days. In cases of thin pillars composed of sound rock, the opening can remain stable for decades even under adverse water conditions and imposed surface loads.

To be able to quantify the behaviour of underground openings with time would be of immense benefit not only to mine operators but also for regulatory agencies with respect to land use purposes.

Whereas conventional rib and post pillars have been designed on a yielding basis under a short term high extraction basis, similar approaches for surface crown pillars would present a very difficult challenge. For one, instantaneous failures rather than progressive failures could take place.

For another, the large number of elements controlling pillar behaviour may be too much for such a low factor of safety design. It is perhaps wiser to recover all of the pillar with bulk mining methods rather than risk worker safety and mine viability.

On the aspects of long term stand up time of surface crown pillars, it would be interesting to incorporate time steps in each of the advanced design methods for each type of ground condition. In this case, as in other cases where integrity of the underground operation is primordial, dedicated instrumentation have to be put in long term service.

CONCLUSIONS

Surface crown pillars remain a complex subject. To arrive at knowledgeable stability assessments few dedicated tools or methods are available. Comparatively little research has been performed to provide these.

No design of surface crown pillars should be performed without a high degree of confidence and completeness about existing conditions being available.

Obtaining critical parameters in the three dimensions of the rock volume above and surrounding the upper portion of the underground opening is crucial to grasp the situation.

The adequacy of current rock mass classification schemes must be measured. The formulation of a scheme dedicated to near surface environments might be worth considering.

Consequences of failure have to be fully understood in regards to soil inflow. In weak or uncertain conditions recovery of pillars should then be made wherever possible with methods not involving upward underground progression. Backfilling and extraction from surface, whether with filled stopes or blasting rock down in the opening, are safer alternatives.

More dedicated, less generic design methods are needed to address possible failure mechanisms. Specialized numerical modelling methods must be developed to study shallow opening behaviour in weak, lowly stressed rock conditions, e.g. viable design methods for failures such as chimneying and plug types do not exist. Since back-analysis of failures shows stresses to be low in the surface crown pillars, modelling methods must use a workable failure criterion at such levels. Modelling must also consider all of the rock mass involved in the stability of the pillar.

As is the case for other rock mechanics/geotechnical problems, even with advanced approaches the subject of surface crown pillar is not expected to become an exact science.

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