Technical Review — Crown Pillar Subsidence and Hydrologic Stability Assessment for the Proposed Eagle Mine

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May 2006

Ref: ICG06-2376-23

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Executive Summary

There is concern that mining-induced subsidence will adversely affect the hydrologic environment surrounding the proposed Kennecott Eagle Mine in the Upper Peninsula of Michigan. The objective of this review is to determine whether the conclusions made within the Eagle Project Mining Permit Application regarding crown pillar subsidence and hydrologic stability are defensible.

Due to the difficulties associated with determining the mechanical properties of a particular rock mass, mining rock mechanics can be a subjective science. However, many best-practice data collection and analysis techniques have been established to eliminate many of the uncertainties associated with prediction of the response of a rock mass to mining.

The analysis techniques used to assess the Eagle crown pillar stability do not reflect industry best-practice. In addition, the hydrologic stability of the crown pillar has not been considered. Therefore, the conclusions made within the Eagle Project Mining Permit Application regarding crown pillar subsidence are not considered to be defensible.

The Scaled Span analysis conducted clearly indicates that stability of the proposed Eagle crown pillar should be a concern, although this concern has not been raised within the conclusions of the Eagle Project Geotechnical Study. Considering the sensitive nature of the hydrological environment surrounding the Eagle project, further detailed analysis should be conducted to fully understand the expected short- and long-term crown pillar subsidence and hydrologic stability.

Specific issues that impact the conclusions made regarding the crown pillar stability are detailed below.

- The ASTM Standard Test Method D 5731-95 (ASTM, 1995) states that point load test results alone should not be used for design or analytical purposes.

- The procedure used to determine the equivalent UCS is based upon procedure no longer current within the mining industry. This method used is inconsistent with the current standard test methods for determining the point load strength index of rock. The point load testing approach that was adopted causes significant uncertainty in the intact rock strength that was determined for each lithological unit.

- The horizontal stresses assumed throughout the stability and subsidence analyses have been underestimated. Based upon the excessive horizontal stresses observed at the White Pine Copper Mine in the Michigan Upper Peninsula (Parker, 1966), a sensitivity study should be conducted to determine crown pillar behavior under a variety of possible horizontal stress conditions.

- A discrete sub-vertical fault plane that intersects the Eagle deposit has not been considered in any of the stability or subsidence analyses.

- Considering the very low factor of safety achieved with the Scaled Span analysis, and Carter's suggestion that a factor of safety of 1.2 represents a very short-term serviceable life, the possibility of crown pillar failure should be a serious concern.

- Considering the uncertainties with the modeling input parameters and the significant limitations of the elastic analysis, a very low level of confidence should be applied to the predicted subsidence levels of the Eagle crown pillar.

- Crown pillar hydrologic stability was not considered in the crown pillar subsidence analysis or the bedrock hydrogeological investigation.

- The long-term, time-dependant behavior of the Eagle crown pillar was not considered as part of the analyses. Carter (2000), Carter and Miller (1996) and Hutchinson (2000) indicate that the time-dependant degradation of surface crown pillars is a serious concern.

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1.0 INTRODUCTION

Surface subsidence, to a greater or lesser degree, is an inevitable consequence of almost all types of underground mining (Brady and Brown, 1994). There is concern that mining-induced subsidence will adversely affect the hydrologic environment surrounding the proposed Kennecott Eagle Mine in the Upper Peninsula of Michigan.

Itasca Consulting Group, Inc. (Itasca) has been retained to conduct a technical review of the Eagle Mine crown pillar stability analysis that has been conducted by Golder Associates Ltd. (Golder, 2005; Golder 2006a; Golder 2006b) and submitted to the Michigan Department of Environmental Quality (MDEQ) by Kennecott Eagle Minerals Company as part of a mining permit application.

The specific documents, contained in the Eagle Project Mining Permit Application, that have been reviewed are:

- ***Eagle Project Geotechnical Study***, Appendix C-2, Golder Associates Ltd., Report to Kennecott Exploration Company, 04-1193-020, 2005;
- ***Eagle Project Additional Geotechnical Scope***, Appendix C-3. Golder Associates Ltd., Report to Kennecott Minerals Company, 05-1193-011, 2006;
- ***Bedrock Hydrogeological Modeling to Assess Inflow to Proposed Eagle Project***, Appendix B-4, Golder Associates Ltd., Report to Kennecott Eagle Minerals Company, 05-3236-2c, 2006b;

Clarification of certain technical issues have been addressed in the following technical memorandums:

- ***Clarification on RMR Classification Systems***, Golder Associates Ltd., Technical Memorandum, 05-1193-011, 2006c;
- ***Eagle Crown Pillar Discussion***, Golder Associates Ltd., Technical Memorandum, 05-1193-011, 2006d.

The objective of this review is to determine whether the conclusions made within the Eagle Project Mining Permit Application regarding crown pillar subsidence and hydrologic stability are defensible.

2.0 BACKGROUND

The Kennecott Eagle Mine is located in Marquette County, in the Upper Peninsula of Michigan. The dominant host rock mass is the intrusive igneous rock, Yellow Dog Peridotite. The intrusive body is hosted by sedimentary units (siltstone and sandstone). Drilling in the wetland area directly above the peridotite indicates an overburden consisting of 10-12 m of glacial till.

The Eagle Project Mining Permit Application (Kennecott, 2006) describes the proposed mining plan as a transverse longhole method. Mining of the open stopes will use primary and secondary mining sequences with delayed placement of backfill. Mining will progress from mine level 143 m (~ 295 m below ground surface) upward to mine level 353 m (~ 85 m below ground surface). Mine level 383 m (~ 55 m below ground surface) will be mined selectively based upon future geotechnical analysis. The contact between the peridotite and the overlying glacial till is located at the 415 m level and results in a peridotite crown pillar thickness of either 57.5 m or 27.5 m, depending whether the 383 m level is extracted. Figure 1 illustrates a schematic of the proposed Eagle Mine stoping geometry.

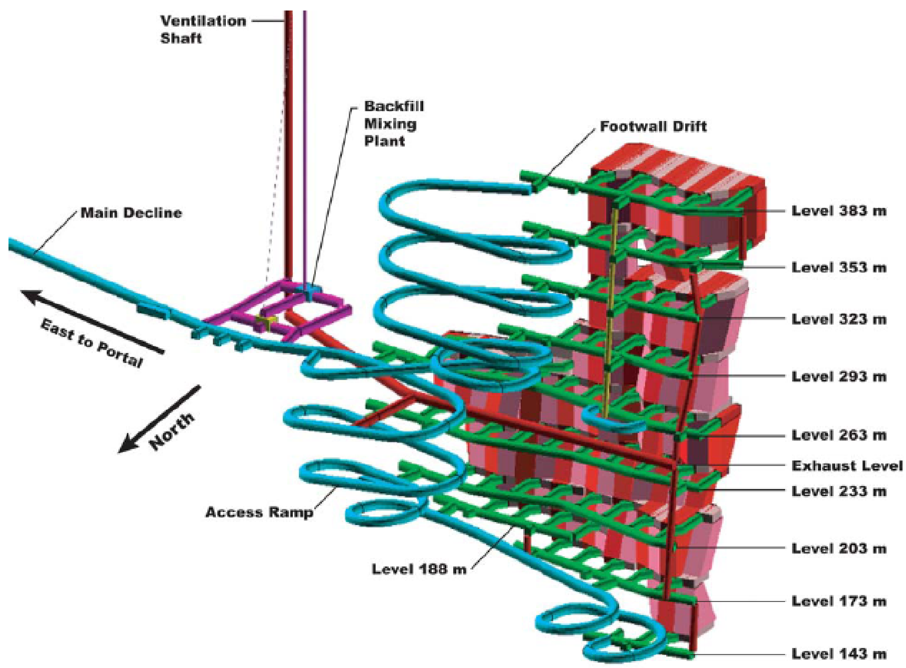

Figure 1 Schematic of proposed Eagle Mine stoping geometry (Kennecott, 2006)

The Salmon Trout River flows above the orebody, and the area is surrounded by wetlands, as illustrated in Figure 2a and Figure 2b.

The Eagle Project Mining Permit Application (Kennecott, 2006) concludes that vertical subsidence at the bedrock/alluvium contact will be no greater than 2 cm. The predicted crown pillar subsidence has not been coupled with the groundwater flow analysis to estimate the impact of increased rock mass permeability, caused by mining induced rock mass deformation, and how the Salmon Trout River may be affected.

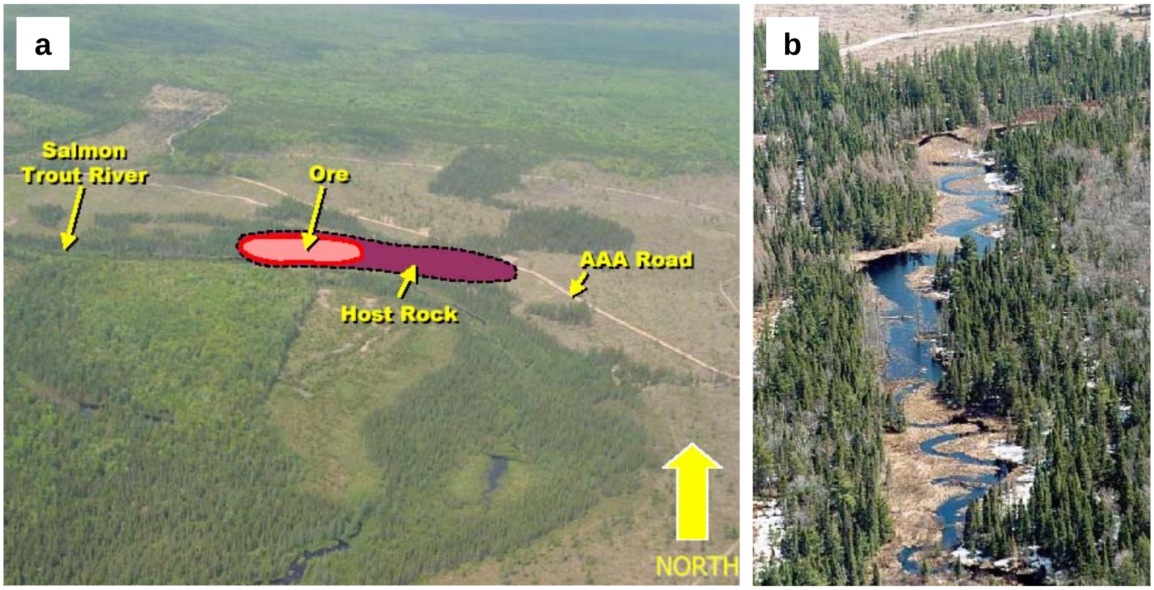

Figure 2 a) Aerial view of the proposed underground mine; b) Salmon Trout River above orebody

3.0 DETERMINATION OF INTACT ROCK STRENGTH

The intact rock strength has a direct effect on rock mass classification rating and the derivation of rock mass strength and deformation properties.

The uniaxial compression test is used to determine uniaxial compressive strength (UCS) of rock specimens. When extensive testing is required for preliminary and reconnaissance information, alternative tests, such as the point load test, can be used in the field to reduce the time and cost associated with uniaxial compressive strength tests.

The point load strength test is used as an index test for strength classification of rock materials; it is useful when interpolating the UCS of rock specimens between actual UCS test results. In order to provide confidence in the estimated UCS, based on point load tests, a correlation factor should be calibrated to actual UCS results obtained from the same drill core (ASTM, 1995).

Unconfined compressive strength tests were not used to calibrate the point load test results within the Eagle Project Geotechnical Study (Golder, 2005). The ASTM Standard Test Method D 5731 95 (ASTM, 1995) states that point load test results alone should not be used for design or analytical purposes.

The procedure used to determine the point load index and equivalent UCS within the Eagle Project Geotechnical Study (Golder, 2005) is based on an outdated method originally proposed by Bieniawski (1975) and later reported by Hoek and Brown (1980). The method used in the study is no longer considered industry standard, and is not consistent with the current International Society of Rock Mechanics (ISRM) suggested method for determining point load strength (ISRM, 1985) or the ASTM standard test method for determining the point load strength index of rock (ASTM, 1995). The current standard methods apply a size correction factor and a UCS correlation factor to the uncorrected point load strength index. Figure 3 illustrates the significant difference that can be obtained when using the current standard point load determination method with the default conversion factor (24), compared to the outdated methods.

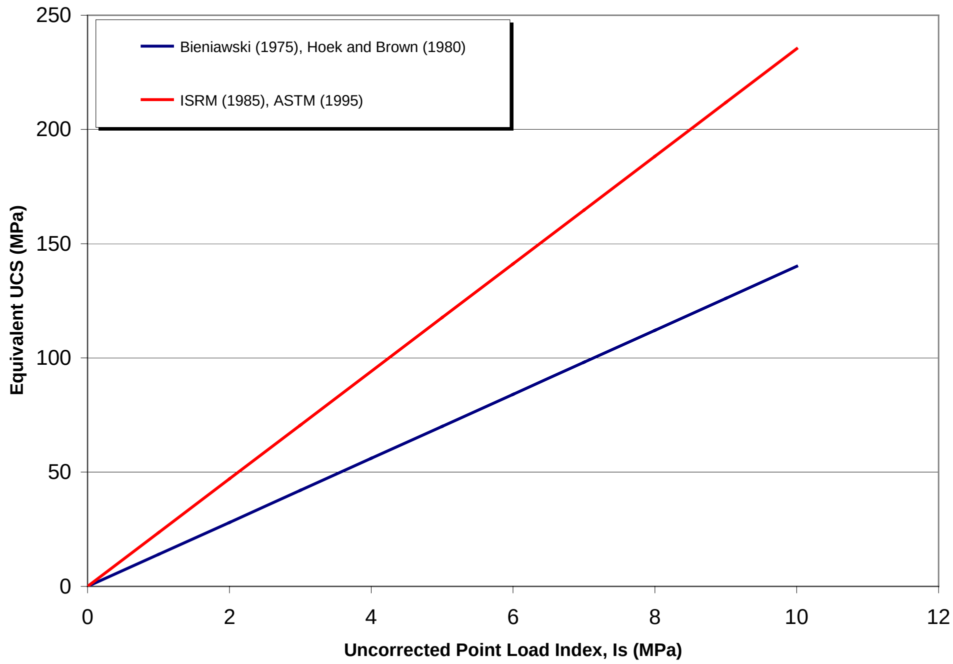

Figure 3 Comparison between equivalent UCS obtained using the Bieniawski (1975) method and the current ISRM and ASTM methods assuming the default conversion factor of 24

The point load testing approach that was adopted for the Eagle Project Geotechnical Study (Golder, 2005) causes significant uncertainty in the intact rock strength that was determined for each lithological unit. The approach is not consistent with industry best-practice and causes significant uncertainty with the rock mass classification rating applied to each unit. This, in turn, has an effect upon all subsequent design calculations that rely upon the rock mass rating, as well as the determination of rock mass mechanical properties for numerical modeling.

4.0 ROCK MASS CLASSIFICATION

Rock mass classification schemes have been developed for over 100 years as a means to categorize the character and behavior of a particular rock mass. In mining rock mechanics, several rock mass classification schemes are commonly used. These include RMR_{76} (Bieniawski, 1976), RMR_{89} (Bieniawski, 1989), Q (Barton et al., 1974), MRMR (Laubscher and Jakubec, 2001) and GSI (Hoek et al., 1995). Rock mass classification schemes are used in the empirical assessment of ground support design and excavation stability, along with the derivation of equivalent rock mass strength and deformation properties.

The actual version of RMR scheme used throughout the Eagle Project Geotechnical Study (Golder, 2005) has not been referenced, and the description of the scheme used within the text of the report is not consistent with either the RMR_{76} or RMR_{89} scheme. Clarification by Golder (2006c) indicates that the actual RMR scheme used was RMR_{76}, although a typographical error was made within the text in which the maximum rating for ground water condition (A5) was reported as 15 rather than 10.

A groundwater condition rating of 10 assumes completely dry conditions. This is a non-conservative assumption, and it is not consistent with the bedrock hydrogeological investigation (Golder, 2006b) or the limit-equilibrium crown pillar analysis, in which completely saturated conditions were assumed. The typical RMR_{76} value assigned to the peridotite crown pillar originally was calculated to be 75 (Golder, 2005). This was later reduced to a value of 70 (Golder, 2006a).

Although the derivation of a particular rock mass rating can be subjective, it is important to note that the relation between rock mass rating and rock mass strength is an exponential function, as illustrated in Figure 4. At high RMR_{76} values, a minor variation in rating results in a significant variation in the equivalent rock mass strength.

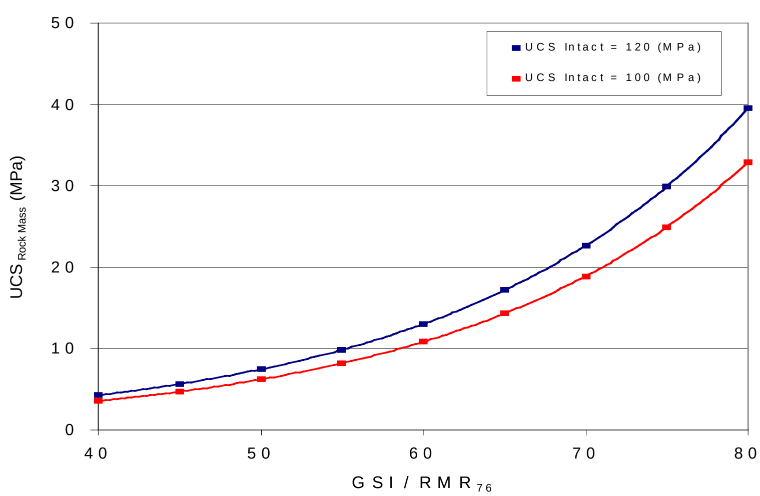

Figure 4 Increase in $UCS_{rock\ mass}$ with increasing GSI or RMR_{76}

5.0 PRE-MINING *IN SITU* STRESS

The pre-mining *in situ* stress regime has a significant effect on the behavior of underground excavations. Thus, an accurate estimate of the *in situ* stresses is just as important as rock mass strength. The vertical component of pre-mining *in situ* stress is a function of gravitational loading of the overburden material, while the horizontal component of stress is a function of tectonic forces, especially in near-surface conditions.

The ratio of the average horizontal stress to the vertical stress is denoted by the letter *k*. At low horizontal stress (*k* ratios), the crown pillar behavior is likely to be governed by gravity-induced tensile failure. At high horizontal stresses, the crown pillar behavior is likely to be governed by shear failure.

Measurements of horizontal stresses at civil and mining sites around the world show that the ratio *k* tends to be high at shallow depth and decreases with depth (Hoek et al., 1995). Iannacchione et al. (1998) report that *k* ratios of 10.0 have been measured in shallow mines throughout the Midwest region of the U.S, while Parker (1966) found that excessive horizontal stresses, several times the magnitude of the vertical stress, at the White Pine Copper Mine in the Upper Peninsula of Michigan were the cause of stability problems in the underground room-and-pillar operation.

The *k* ratio assumed throughout the Eagle Mine Geotechnical Study (Golder, 2005 and 2006) was 2.0. This is based on an equation proposed by Herget (1988) to predict horizontal stresses for underground excavations in the Canadian Shield rock units:

$$k = \frac{251.68}{z} + 1.14$$

where z = depth below surface (m).

A depth of 300 m was used to determine the *k* ratio of 2.0. However, near the surface in the area of the crown pillar, Herget's equation predicts significantly higher *k* ratios, as illustrated in Figure 5. Assuming a depth of 50 m that better approximates the elevation range expected for the upper stopes for the proposed mine, the predicted *k* ratio is 6.2.

Without further analysis, it is not clear how the increased *k* ratio would affect the behavior of the proposed crown pillar. Based upon the excessive horizontal stresses observed at the White Pine Copper Mine, a sensitivity study is recommended to properly determine the crown pillar behavior under a variety of possible horizontal stress conditions.

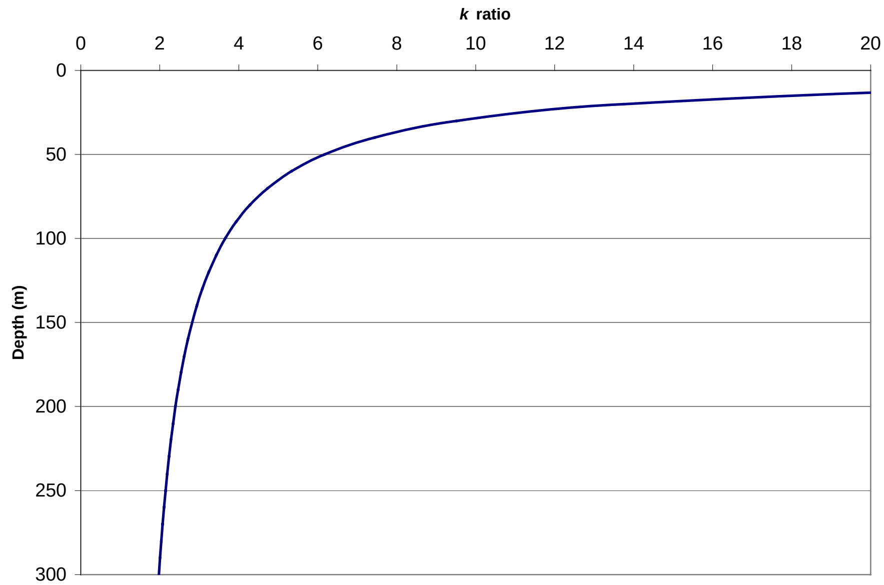

Figure 5 Variation of k ratio with depth based upon Herget's (1988) equation

6.0 CROWN PILLAR STABILITY ANALYSIS

Crown pillar stability was investigated using both empirical (Scaled Span) and limit-equilibrium (CPillar) analysis methods. Analyses were conducted for crown pillar thicknesses of 27.5 m and 57.5 m. The analysis results discussed herein refer to a crown pillar thickness of 57.5 m.

Extreme caution should be exercised when delineating the actual crown pillar geometry and the topography of the bedrock/alluvium contact. Weathering within the upper parts of the bedrock should also be considered when establishing the crown pillar thickness. It is not clear within the Eagle Geotechnical Study (Golder, 2005) what methods were used to accurately define the nature and character of the crown pillar. Most crown pillar failures occur when the stability analysis conducted is not representative of the actual geological condition.

6.1 Scaled Span

The Scaled Span concept was developed by Carter (1992) as a procedure for empirically dimensioning the geometry of crown pillars over near-surface mined openings, based on precedent and experience.

Based upon a crown pillar thickness of 57.5 m, which assumes that the 383 m Level is not extracted, and considering a typical RMR_{76} value of 70, the crown pillar is predicted to have a factor of safety of 1.2 (Golder, 2006a). Carter (2000) suggests that a Scaled Span factor of safety of 1.2 has a very short-term serviceable life (2-5 years) and has an undesirable risk of failure for temporary civil works. He states that such crown pillars have a high level of concern with regard to a regulatory position on closure.

Golder (2006a) states that the Eagle crown pillar is potentially unstable when considering an expected minimum RMR_{76} value of 60, which results in a factor of safety of 0.73. However, Carter (2000) suggests that a Scaled Span factor of safety of less than 1.0 has no effective serviceable life and is totally unacceptable with regard to a regulatory position on closure.

Considering the very low factor of safety achieved with the Scaled Span analysis, and Carter's suggestion that even a factor of safety of 1.2 represents a very short-term serviceable life, the possibility of complete crown pillar failure should be a serious concern. If tight backfilling can be achieved to prevent complete collapse of the crown pillar, yielding caused by stress induced shear failure can still severely impact the hydrologic stability of the crown pillar.

6.2 CPillar

The CPillar program (Hoek, 1989; RocScience, 2005a) can be used to assess the probability of crown pillar "plug" failure using limit equilibrium analysis. Failure of a plug of rock into the excavation below could occur by shear failure through intact massive rock or by sliding along discontinuities. A parametric analysis using the CPillar program led Hoek (1989) to conclude that the analysis results are particularly sensitive to changes in the quality of the rock mass and the *in situ* stress ratio (*k*).

Based upon a crown pillar thickness of 57.5 m, Golder (2006a) reports that the CPillar analysis indicates that the factor of safety for the crown pillar with RMR_{76} values of 60 and 70 are 3.65 and 6.40, respectively.

When designing the crown pillar at INCO's South Mine in Sudbury, Ontario, Canada, which occurs in a similar geotechnical setting to the Eagle project, McKinnon et al. (2002) concluded that a CPillar analysis represented the simplest design approach and resulted in a high factor of safety. However, despite the large implied safety margin, the approach was not considered to be a realistic mode of failure. Rigorous three-dimensional numerical modeling with the distinct element method resulted in a significantly lower factor of safety than predicted by the CPillar analysis. In addition, based upon the database used to develop the Scaled Span analysis, Carter (2000) suggests that failure in pure shear is rare.

Based on the investigation conducted at INCO's South Mine, the high factor of safety resulting from the CPillar analysis for the Eagle Project should not be considered to be representative of the stability of the Eagle crown pillar.

7.0 MODELING OF SUBSIDENCE

Numerical modeling was conducted with the three-dimensional modeling code MAP3D (Mine Modeling Pty Ltd, 2005) and the two-dimensional modeling code Phase^2 (RocScience, 2005b). The modeling assumed that the crown pillar behaved as a linear elastic material. Therefore, no shear or tensile failure of the rock mass was considered.

7.1 Material Properties

The deformation modulus of a rock mass is an important input parameter in any analysis of rock mass behavior that includes deformations, and is one of the primary input parameters of an elastic analysis. Consequently, several authors have proposed empirical relations for estimating the value of an isotropic rock mass deformation modulus on the basis of classification schemes such as the Rock Mass Rating RMR_{76} (Bieniawski, 1976), the Tunnelling Quality Index Q (Barton et al., 1974) and the Geological Strength Index GSI (Hoek et al., 1995).

The rock mass deformation modulus (referred to as the Young's modulus within Eagle Geotechnical Study) used to simulate the elastic response of the Eagle crown pillar was 56.6 GPa. The method used to determine the deformation modulus has not been referenced, but the same value has been used to simulate the deformation modulus of a rock mass with an RMR_{76} of 75 (Golder, 2005) and a value of 70 (Golder, 2006a).

Table 1 presents the deformation modulus predicted using the most commonly used empirical relations for an RMR_{76} of 70. The value used throughout the modeling exercise is significantly higher than what is predicted using the most common empirical relations used to determine the rock mass deformation modulus.

Table 1 Rock mass deformation modulus predicted by the most commonly used empirical relations

	RMR_{76}	UCS (MPa)	E_{rm} (GPa)
Bieniawski (1978)	70	120	40.0
Serafim and Pereira (1983)	70	120	31.6
Hoek and Brown (1997)	70	120	37.9
Hoek, Corkum and Carranza Torres (2002)	70	120	31.6
Hoek and Diederichs (2005) - Simplified Equation	70	120	38.8
Golder (2005, 2006a, 2006d)	**70**	**120**	**56.6**

Derivation of the high deformation modulus used throughout the modeling analyses has not been substantiated and is not consistent with the most commonly used empirical relations. Use of the high deformation modulus will result in lower predicted subsidence displacements, and cause significant uncertainty with the predicted behavior of the Eagle crown pillar.

7.2 Modeling Methodology

The Eagle Project Mining Permit Application states that both plastic and elastic deformations of the crown pillar rock mass were evaluated. In fact, no analyses were conducted using plasticity theory to predict shear and tensile failure of the rock mass.

A simplified analysis was conducted to estimate whether unraveling of the crown pillar could propagate to the surface, although this does not represent an analysis of plastic deformation. A bulking factor of 30% was assumed to determine the height of caved rock within the crown pillar. The bulking factor represents the increase in volume as a rock mass disintegrates from an *in situ* state to a crushed state. This transition takes place over a significant amount of strain. Although the crown pillar may not have bulked fully all the way to the surface, only a relatively small amount of strain (and, therefore, bulking) is required for a rock mass to experience an increase in permeability. Abel and Lee (1980) state that subsurface aquifer disruption may occur due to yielding within rocks above the mined-out region, without any manifestation of subsidence on the ground surface.

Golder (2006d) states that linear-elastic analyses were appropriate for the analysis because the major principal stress within the crown pillar region was predicted to be low within the Phase^2 model results. However, the elastic modeling results indicate that tensile failure of the crown pillar is the dominant failure mechanism of the Eagle crown pillar. Hutchinson et al. (2002) state that elastic analysis is of equal importance to the delineation of locations of high stress as for indicating areas of confinement reduction or relaxation when investigating crown pillar stability. Hutchinson (2000) suggests that non-linear (as opposed to linear elastic) or distinct element modeling codes are required for rigorous analysis of crown pillar stability.

The long-term, time-dependant behavior of the Eagle crown pillar was not considered in any of the analyses. Carter (2000), Carter and Miller (1996) and Hutchinson (2000) all highlight the fact that the time-dependant degradation of surface crown pillars is a serious concern.

7.3 Model Results

7.3.1 Phase^2 Model Results

Figure 6 illustrates the two-dimensional model geometry used to investigate crown pillar subsidence with the Phase^2 code. The two-dimensional, plane-strain analysis assumes that the crown pillar span is 68 m and infinitely long. The actual span is approximately 50 m, and its length is approximately 68 m.

The model is not considered to be realistic, as the finite element mesh used to discretize the crown pillar is extremely coarse and severely limits the accuracy of the modeling results. Only one or two three-noded triangle elements have been specified across the thickness of the crown pillar. The default value suggested within the Phase^2 program to ensure accurate modeling results is 10 elements (RocScience, 2005a).

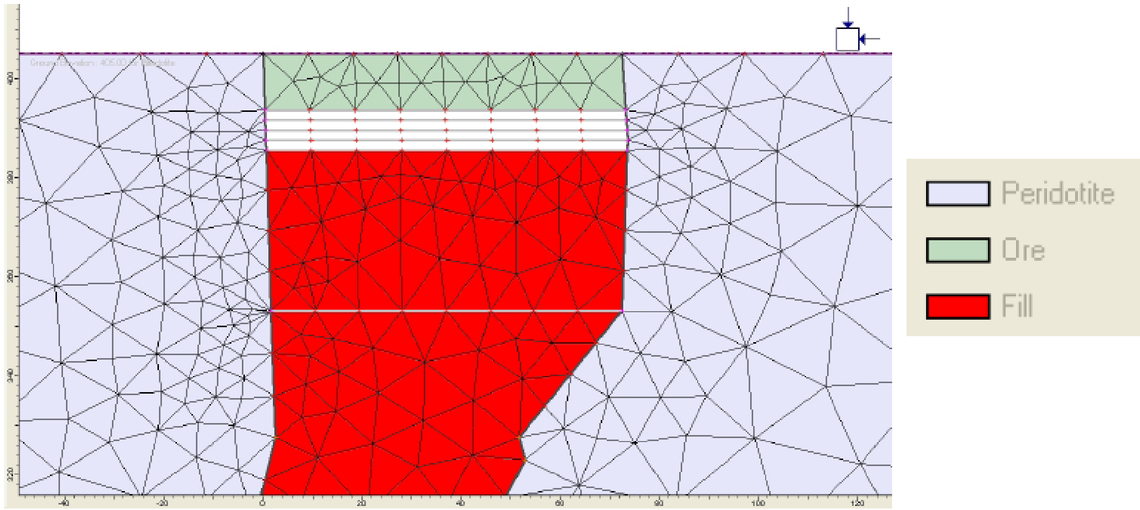

Figure 6 Phase^2 model geometry and finite element mesh (Golder, 2006c)

7.3.2 MAP3D Model Results

A three-dimensional numerical linear-elastic model was constructed with the MAP3D code in order to investigate the stability and expected subsidence of the Eagle crown pillar.

Based upon the MAP3D analyses conduced by Golder (2005, 2006a, 2006c), the Eagle Project Mining Permit Application (Kennecott, 2006) concludes that plastic deformation of the crown pillar will be limited to no more than 2 cm at the bedrock/alluvium contact.

Considering the uncertainties with the modeling input parameters and the significant limitations of the elastic analysis, a very low level of confidence should be applied to the predicted subsidence levels of the Eagle crown pillar. Rigorous non-linear analysis is required to understand the potential for tensile and shear failure of the crown pillar, while a sensitivity analysis should be conducted to understand the range of expected behavior under all possible geotechnical conditions.

8.0 EFFECT OF A DISCRETE SUB-VERTICAL FAULT

A discrete sub-vertical fault plane has been identified that intersects the Eagle deposit (Golder, 2005). The effect of this fault has not been considered in any of the stability or subsidence analyses.

Discrete sub-vertical faults have been identified as the cause of significant subsidence that was observed at the Athens Mine, in the Michigan Upper Peninsula, which is approximately 20 miles from the Kennecott Eagle project (Boyum, 1961). Vertical propagation of rock mass failure was controlled by sub-vertical fault planes, as illustrated in Figure 7.

The presence of a nearby fault was identified as a potential cause of instability and subsidence when designing the crown pillar at INCO's South Mine (McKinnon et al., 2002). A three-dimensional distinct-element numerical model was used to conduct a rigorous investigation of the influence of the fault on crown pillar stability. The analysis demonstrated that slip along the fault was likely to occur; however, as the fault is located an adequate distance from the crown pillar, it would not affect stability.

The potential for shear failure along the sub-vertical fault should be investigated to determine the effect of the fault upon crown pillar stability.

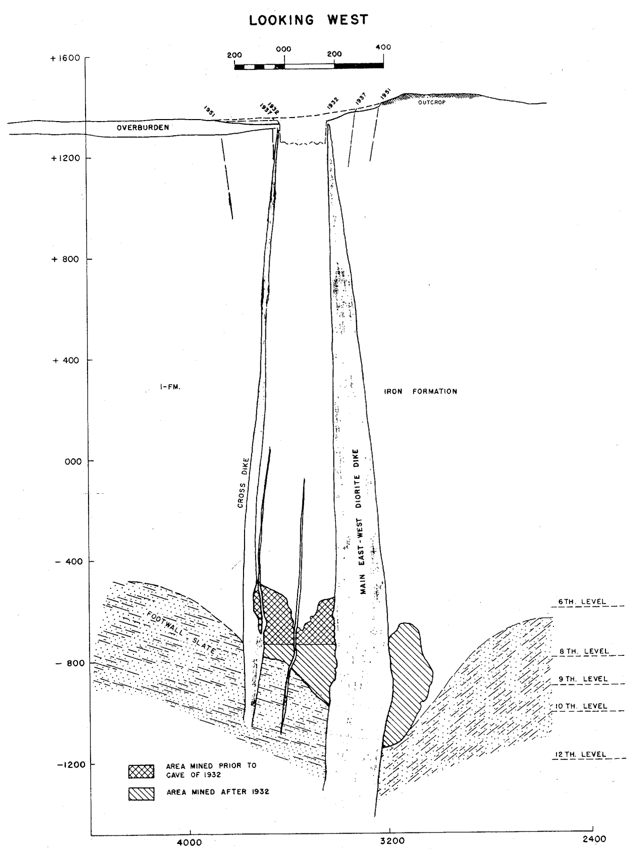

Figure 7 Schematic of surface subsidence observed at the Athens Mine (Boyum, 1961)

9.0 CROWN PILLAR HYDROLOGIC STABILITY

Crown pillar hydrologic stability refers to the integrity of the crown pillar with regard to increases in hydraulic conductivity caused by stress-induced deformation of the crown pillar rock mass. Crown pillar hydrologic stability was not considered in the crown pillar subsidence analysis or the bedrock hydrogeological investigation.

Mining extraction will produce increasing stress and deformation in the crown pillar as mining progresses upward, reducing the thickness of the crown pillar. As a rock mass deforms, pre-existing joints shear and dilate, while failure of the intact rock blocks form new open fractures. This process causes a significant increase in permeability of the rock mass.

Min (2004) reports that the change in permeability of a fractured rock mass caused by a change in stress can be several orders of magnitude.

Many rock mechanics practitioners have investigated the effects of mining-induced subsidence on aquifers, aquitards and surface bodies of water (Wohlrab, 1969; Nishida and Goto, 1969; Babcock and Hooker, 1977; Singh and Kendorski, 1981). The Society of Mining Engineers (Singh, 2003) suggests that induced horizontal strain should be less than 0.005 for there to be no significant impacts to surface bodies of water from mining.

Hardy et al. (1999) adopted this approach for assessment of the proposed Crandon deposit in Wisconsin, which is located below environmentally sensitive wetlands. Mining induced strain surrounding the proposed crown pillar was analyzed using a non-linear modeling code to determine areas that exceed the suggested strain limit. Figure 8 illustrates the area within the proposed Crandon crown pillar that exceeded a strain limit of -0.005 (-5.00e-03).

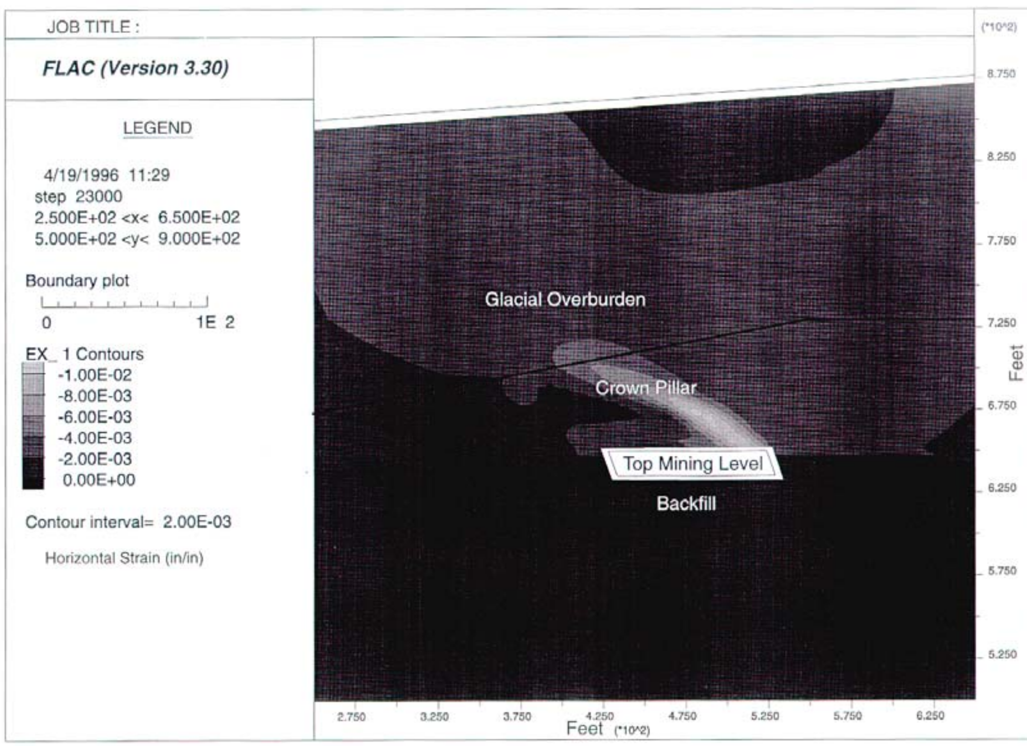

Figure 8 Location of excessive rock mass strain within Crandon crown pillar (Hardy et al., 1999)

Further analyses were conducted to determine specific areas where shear dilation along the predominant joint sets would occur, as illustrated in Figure 9. Detailed distinct element models then were analyzed to relate the changes in joint aperture to a change in hydraulic conductivity. This level of analysis was considered industry-best practice for evaluation of crown pillar subsidence and hydrologic stability in 1999.

Golder (2006b) reports that the hydraulic conductivity of the bedrock units were increased by a factor of three within 15 m of the underground excavations to simulate the damage caused by blasting and relaxation of the rock mass. As observed in Figure 9, shear dilation along the predominant joint sets at the Crandon deposit was predicted a distance of 400 ft (121 m) from the mining excavations. In addition, the increase in hydraulic conductivity caused by blast and rock mass yielding is generally several orders of magnitude, significantly greater than a factor of three, as described in Table 2.

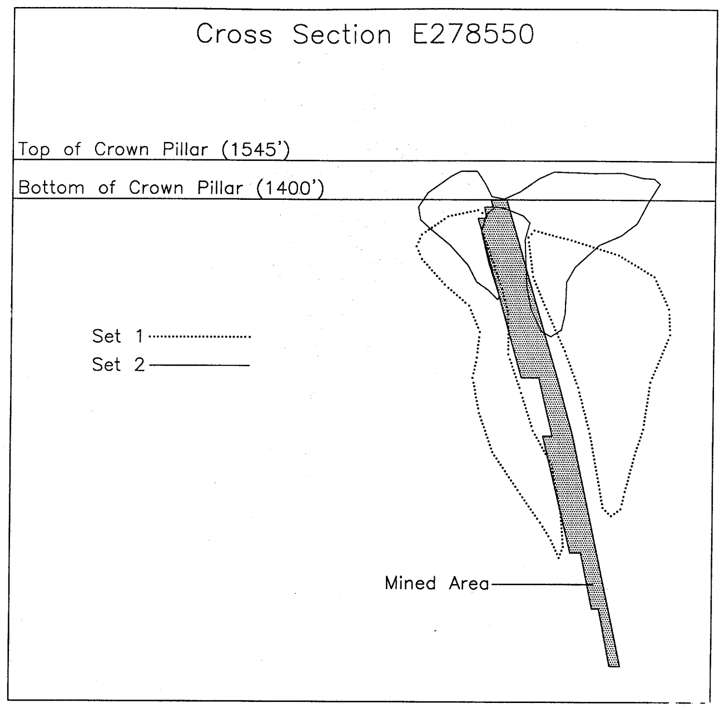

Figure 9 Contours of factor of safety = 1 for predominant joint sets (width of orebody = 100 ft) (Hardy et al., 1999)

Table 2 Table of saturated hydraulic conductivity (k) values (Bear, 1972)

***k* (cm/s)**	100	10	1	0.1	0.01	0.001	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}
Rock Type	Highly Fractured Rocks				Oil Reservoir Rocks			Fresh Sandstone		Fresh Limestone		Fresh Granite	

Gurrieri and Furniss (2004) suggest that hydrologic disruptions to lakes and streams by underground mining is not common, although it has happened in the U.S. with regular frequency. Of particular interest is the damage to springs and streams above the Stillwater Mine in Montana (Blodgett and Kuipers, 2002). A small watershed containing several springs and a perennial stream remain dry after the development of an adit located a vertical distance of 830 ft (253 m) below the surface.

Considering the environmentally sensitive nature of the proposed Eagle project, detailed investigation of crown pillar hydrologic stability to the same level as that conducted for the nearby Crandon deposit is warranted. The cause of hydrologic disruptions at other mining operations should be investigated with respect to the geological conditions expected at the Eagle project.

10.0 DISCUSSION AND CONCLUSIONS

Due to the difficulties associated with determining the mechanical properties of a particular rock mass, mining rock mechanics can be a subjective science. However, many best-practice data collection and analysis techniques have been established to eliminate many of the uncertainties associated with prediction of the response of a rock mass to mining.

The analysis techniques used to assess the Eagle crown pillar stability do not reflect industry-best practice. In addition, the hydrologic stability of the crown pillar has not been considered. Therefore, the conclusions made within the Eagle Project Mining Permit Application regarding crown pillar subsidence are not considered to be defensible.

The Scaled Span analysis conducted clearly indicates that stability of the proposed Eagle crown pillar should be a concern, although this concern has not been raised within the conclusions of the Eagle Project Geotechnical Study. Considering the sensitive nature of the hydrological environment surrounding the Eagle project, further detailed analysis should be conducted to fully understand the expected short- and long-term crown pillar subsidence and hydrologic stability.

Specific issues that impact the conclusions made regarding the crown pillar stability are detailed below.

- The ASTM Standard Test Method D 5731-95 (ASTM, 1995) states that point load test results alone should not be used for design or analytical purposes.

- The procedure used to determine the equivalent UCS is based on a procedure no longer current within the mining industry. This method used is inconsistent with the current standard test methods for determining the point load strength index of rock. The point load testing approach that was adopted causes significant uncertainty in the intact rock strength that was determined for each lithological unit.

- The horizontal stresses assumed throughout the stability and subsidence analyses have been underestimated. Based upon the excessive horizontal stresses observed at the White Pine Copper Mine in the Michigan Upper Peninsula (Parker, 1966), a sensitivity study should be conducted to determine crown pillar behavior under a variety of possible horizontal stress conditions.

- A discrete sub-vertical fault plane that intersects the Eagle deposit has not been considered in any of the stability or subsidence analyses.

- Considering the very low factor of safety achieved with the Scaled Span analysis, and Carter's suggestion that a factor of safety of 1.2 represents a very short-term serviceable life, the possibility of crown pillar failure should be a serious concern.

- Considering the uncertainties with the modeling input parameters and the significant limitations of the elastic analysis, a very low level of confidence should be applied to the predicted subsidence levels of the Eagle crown pillar.

- Crown pillar hydrologic stability was not considered in the crown pillar subsidence analysis or the bedrock hydrogeological investigation.

- The long-term, time-dependant behavior of the Eagle crown pillar was not considered as part of the analyses. Carter (2000), Carter and Miller (1996) and Hutchinson (2000) indicate that the time-dependant degradation of surface crown pillars is a serious concern.

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