# ***Assessment of Potential for Caving-Induced Fault Slip Seismicity at Resolution Copper Mine***

ITASCA
Consulting Group, Inc.

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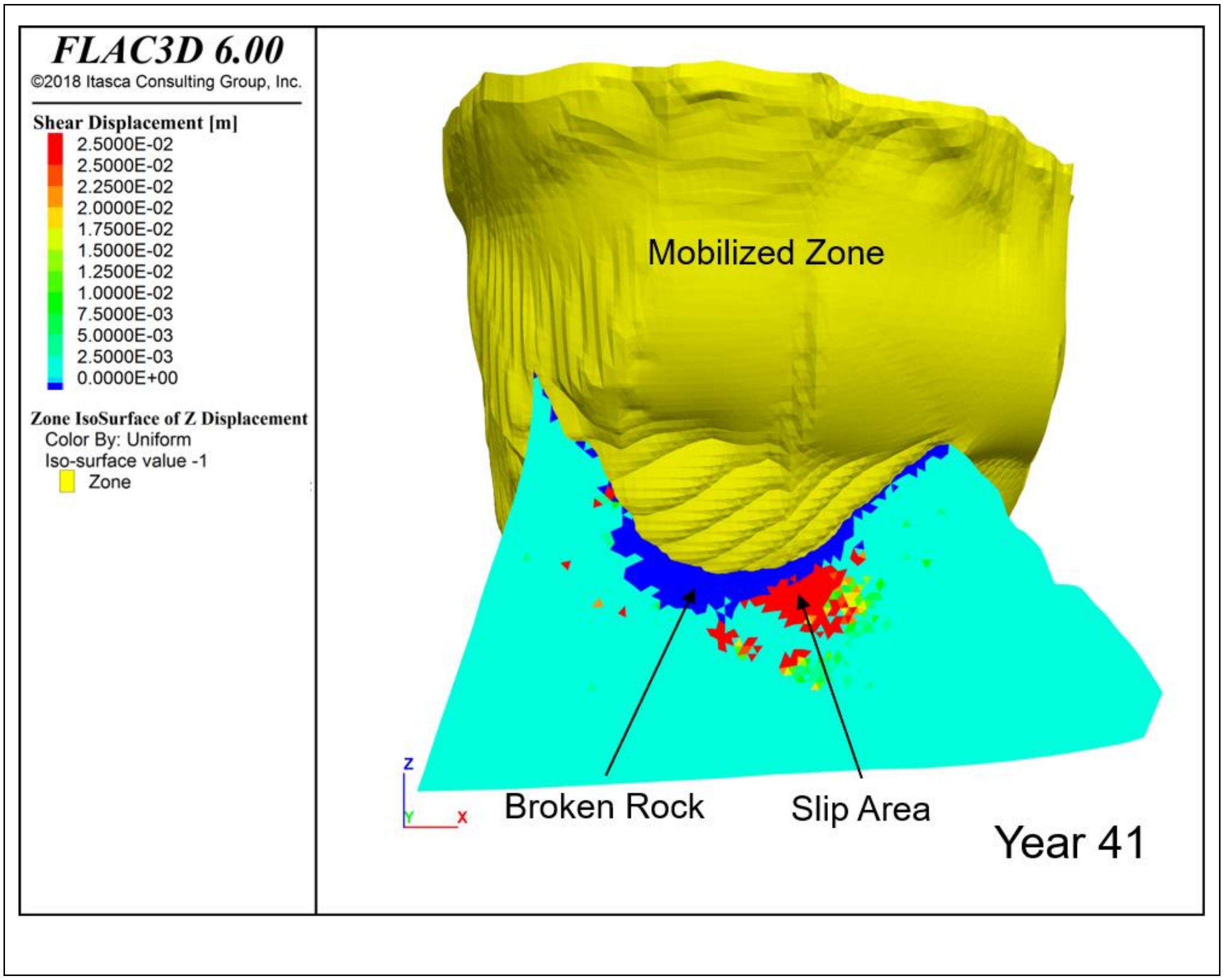


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## ***Executive Summary***

This report summarizes the results of an assessment of the potential for mining-induced fault slip seismicity performed by Itasca Consulting Group, Inc. (Itasca) for Resolution Copper Mining, LLC (Resolution Copper). This work utilizes the previous numerical model of caving developed by Itasca (Garza-Cruz & Pierce, 2017).

The methodology used to estimate seismicity follows the guidelines given by Aki and Richards (1980) to predict the seismic moment due to fault-slip. Using the seismic moment, it is possible to calculate the moment magnitude to characterize a seismic event.

This study considers a conservative condition to estimate the shear displacement occurring in the faults. First, the local shear displacements in the faults must be calculated considering the principal strain values relative to the local fault orientation due to the fact that the faults were modeled as a band of weaker zones rather than a discrete surface. Second, the methodology to calculate the seismic moment presumes that all the energy is released at once in a single, large event. The energy could be released gradually due to multiple slip events, which would lead to a larger number of smaller events (low magnitude).

The results of the *FLAC3D* model predict that 19 faults will have seismic activity during the life of mine (of the total of 31 modeled). The maximum moment magnitude estimated for fault-slip seismic events is lower than 3.0. Eleven faults could have a seismic event with a magnitude greater than 2.5. A concentration of seismic activity is predicted to occur between years 5 and 10 due the cave-back reaching different faults. It is important to note that the reported moment magnitude presumes that all the energy is released in one large event instead of several minor events.

The seismic hazard assessment performed here, though rough, gives a good first estimate of potential seismic events due fault-slip at Resolution Mine.

## *Table of Contents*

## 1.0 INTRODUCTION

Long-term assessment of seismic hazard is perhaps of greatest potential value from the perspectives of safety and economics, because the objective is to minimize the occurrence of rockbursts through optimization of mine planning.

Rockbursts have been a problem in deep mines for several decades. There appears to be general agreement that the mechanism of rockbursting falls into at least two classes, one associated with the crushing of highly stressed volumes of rock, and one associated with unstable slip or rupture along weakness planes in the rock mass. Hedley (1992) has termed these “strain” (or “volume”) and “fault-slip” modes of rockbursting, respectively.

A significant body of published data identifies a primary shear failure mechanism for mine seismicity as failure associated with pre-existing planes of geologic structure (Board, 1994). Numerical models are often employed to estimate the hazard or potential for seismicity.

This report summarizes the results of a caving-induced fault-slip seismicity assessment at Resolution using the *FLAC3D* caving model developed by Itasca to assess the surface subsidence associated with caving (Garza-Cruz & Pierce, 2017). This study aims to answer the following questions assuming fault-slip as the primary mechanism of seismicity.

- What geologic structures will be primary contributors to large-scale seismicity?
- What is the range of possible event magnitudes that may occur?
- How many large events may be expected? Will large events be highly infrequent, or can they be expected regularly as excavation continues?

The above questions are not geared towards defining exact times and locations of events. Rather, the information used in design is of a general nature, employing best estimates of the seismic potential from which the risk of damage can be assessed.

## 2.0 NUMERICAL MODELING

The *FLAC3D* model used in this study is described in detail by Garza-Cruz and Pierce (2017). This section will describe the faults included in the *FLAC3D* model, their characterization, and the methodology used to estimate the caving-induced seismicity due to fault-slip.

### 2.1 Faults in the *FLAC3D* Model

The structural geology was provided by Resolution personnel in the form of 3D triangulated surfaces along with their associated descriptions. The faults were implicitly incorporated into the model as regions of weaker and softer material. Figure 1 shows the spatial location of the faults with respect to the projection of the footprint from the mine plan of operation. The faults were qualitatively ranked as strong, medium, or weak based on their character. In general, faults described as either slickensided shears, heavily damaged, brecciated and/or with gouge were classified as weak. Faults described as either mixed open and/or annealed shears, with local gouge and/or with local intense damage were classified as medium. Those described as strongly annealed were classified as strong. Table 1 lists the qualitative ranking of the faults. The spatial distribution of lithology units, along with modeled faults intersected by an east-west and north-south cross-section, are shown in Figure 2 and Figure 3, respectively.

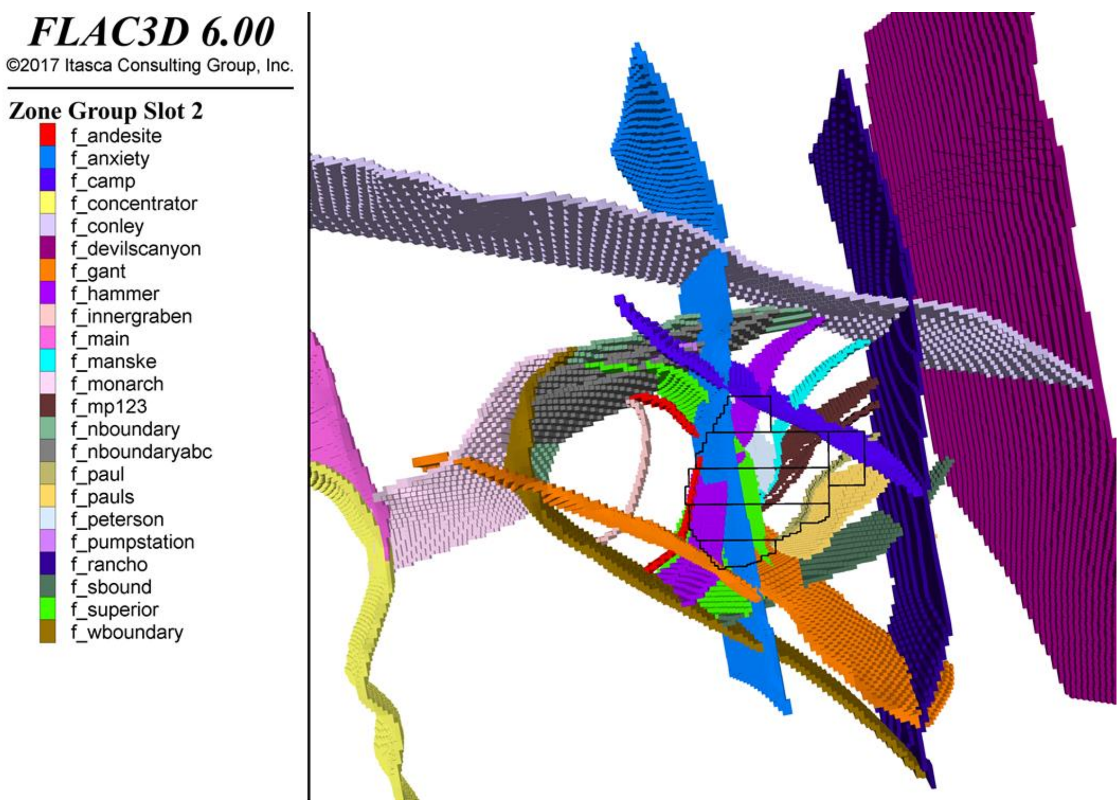


***Figure 1 FLAC3D implicit representation of the faults at Resolution. The projection of the Permitting footprint is shown in black.***

***Table 1 Qualitative ranking of the faults used in the FLAC3D model.***

| Strong (75% $\sigma_{cm}$) | Medium (50% $\sigma_{cm}$) | Weak (residual prop) |
|---|---|---|
| Manske | Andesite | 326 Pump Station |
| Monarch | Camp | Anxiety |
| MP-1 | Hammer N | Concentrator |
| MP-2 | Hammer S | Conley Spring |
| MP-3 | Hammer SW | Devils Canyon |
| South Boundary | Intergraben | Gant E |
| | North Boundary A | Gant W |
| | North Boundary B | Main |
| | North Boundary C | North Boundary |
| | Paul | Rancho Rio |
| | Paul S | West Boundary |
| | Peterson | |
| | Superior | |
| | Superior A | |

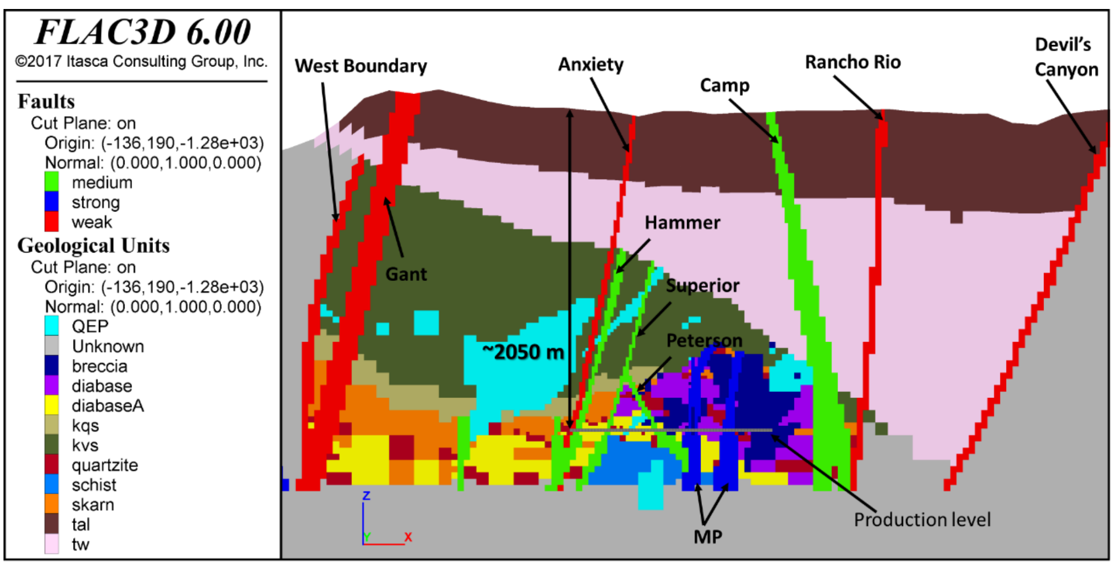


***Figure 2 Spatial distribution of lithology on an East-West cross-section looking North. The intersected faults are colored based on their qualitative ranking (medium, strong and weak).***

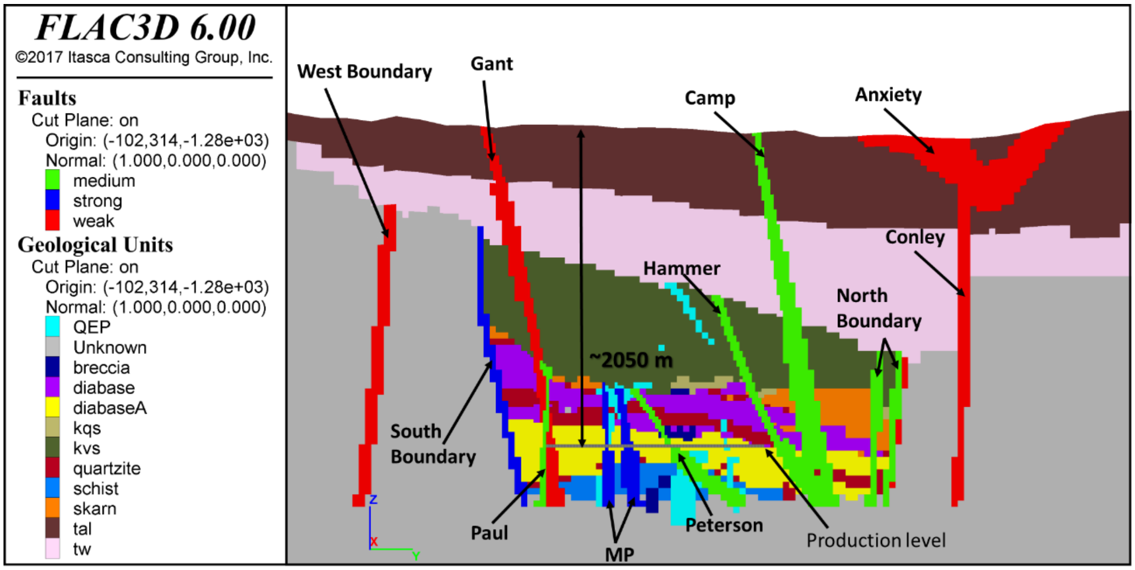


***Figure 3 Spatial distribution of lithology on North-South cross-section looking West. The intersected faults are colored based on their qualitative ranking (medium, strong and weak).***

As a base case, the strong and medium faults were assigned 75% and 50% of the local rock mass global strength ($\sigma_{cm}$), respectively. The weak faults were assumed to have zero cohesion, zero tensile strength, and 35° friction angle. $\sigma_{cm}$ is the unconfined compressive strength defined by a Mohr-Coulomb fit to the Hoek-Brown curve over a range of confinement from 0 to 25% of the laboratory intact UCS. To simplify assigning the desired percentage of the local rock-mass global-strength (a function of both GSI and UCS), a relationship was generated between variances in both the GSI and the UCS and the resulting global strength, as shown in Figure 5. The qualitative ranking and strength characterization were discussed and approved by Resolution personnel (personal communication, Jacques Tshisens). The relative classification of faults persistent to ground surface is shown in Figure 4.

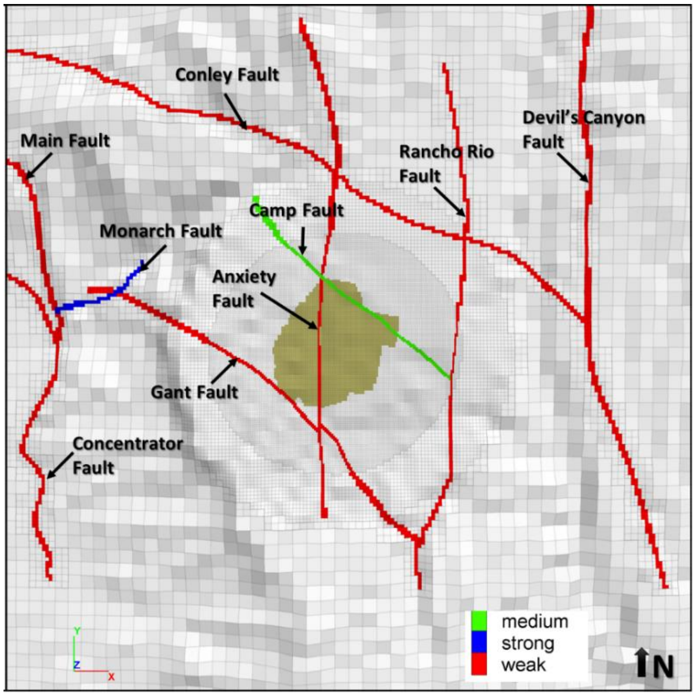


***Figure 4 Faults assumed to be persistent to surface and their relative classification.***

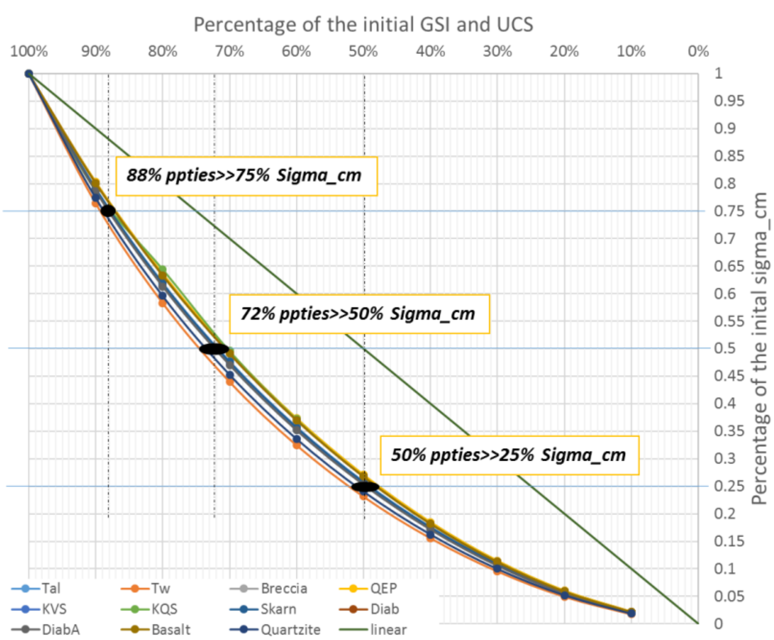


***Figure 5 Relationship between initial GSI and UCS and resulting global strength ($\sigma_{cm}$)***

## 2.2 Methodology to Estimate Seismicity Using Numerical Modeling

The most convenient and generally understood way of describing the strength of a seismic event is to use the term "magnitude." The magnitude is a measure of the size of an event based on the amplitude of a specific seismic wave measured at a particular frequency, suitably scaled for distance from the focus of the source and the sensitivity settings of the seismograph. There are many magnitude scales that have been developed for different geographic regions; thus, some confusion arises in discussion of event size. To eliminate this confusion, a physically meaningful measure of event size is the seismic moment. Seismic moment is a simple and robust measure of the magnitude of a fault-slip event in that it is determined directly, without use of a simplifying model. The moment is the shear magnitude of a double-couple source and is given by Aki and Richards (1980):

$$M_{oij} = G * \left(u_{avei} n_j + u_{avej} n_i\right) * A \qquad \text{Equation 1}$$

Where $M_{oij}$ = seismic moment tensor,

G = shear modulus of the rock mass,

$u_{avei}$ = mean ride or slip vector averaged over the fault surface in direction i,

A = area of the slipping fault surface, and

$n_i$ = unit normal vector of the fault surface.

$M_{oij}$ is a second-rank tensor which has units of MN-m and a scalar magnitude (termed the "seismic moment") of:

$$M_o = G * u_{ave} * A \qquad \text{Equation 2}$$

As described in section 2.1, the representation of the faults within the *FLAC3D* model was achieved by including weaker bands of zones around the geometries of the faults. Due to this, the following procedure was used to estimate the average slip magnitude ($u_{ave}$), area of the slipping fault surface (A), and shear modulus (G) to finally calculate the seismic moment given by Equation 2.

Using the fault geometry (3D triangulated-mesh), a search sphere was defined for each polygon (centroid) defining the geometry. All the zones representing the fault inside that sphere were used to calculate the following:

1. Weighted Average Plastic Shear Strain ($\varepsilon_s^p$)
2. Diameter of the search sphere ($D_s$), defined as follows:

$$D_s = \sqrt[3]{n\ zones\ inside\ the\ sphere} * average\ zone\ size$$ Equation 3

Then the shear displacement for each polygon is calculated as follows:

$$u_{poly} = \varepsilon_s^p * D_s$$ Equation 4

Figure 6 shows an example of the resulting shear displacement for each polygon in Anxiety fault during the 7th year of operation (following the available draw schedule). It can be noted that there are shear displacements near the ground surface, which correlates better to an opening of the fault (extension) than to a shear failure mode due to the cave reaching the ground surface (polygons in blue). This elucidated the need to distinguish between seismic and aseismic shear displacements.

Considering the onset of fracture studied by Martin (1993) and described by Equation 5, it is expected that the seismic activity occurs in an environment with a deviatoric stress greater than 40% of UCS of the surrounding rock mass. This concept is also used to define the seismogenic zone, a region around an underground excavation or cave where the microseismic activity is concentrated (after Diederichs, 1999).

$$\frac{\sigma_1 - \sigma_3}{UCS} = 0.4\ \pm 0.1$$ Equation 5

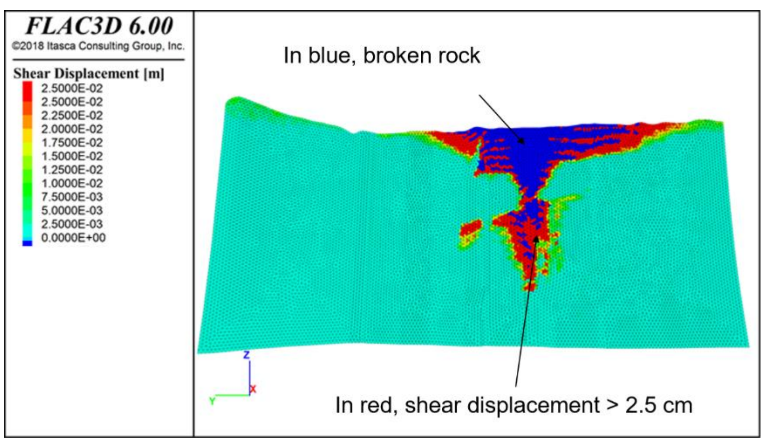


***Figure 6 Shear displacement in Anxiety Fault during year 7 of operation.***

Using Equation 5, an attempt was made to distinguish between seismic and aseismic shear displacements given a stress state and calculating the shear displacement for the fault only when the deviatoric stress ($\sigma_1 - \sigma_3$) is greater than 40% of the UCS. Figure 7 shows the results for shear displacement related to potential seismicity in Anxiety Fault during the 7th year of operation. It can be noted that a shear displacement that meets the deviatoric stress criterion near the surface is absent and the potentially seismic shear displacement only occurs at greater depth.

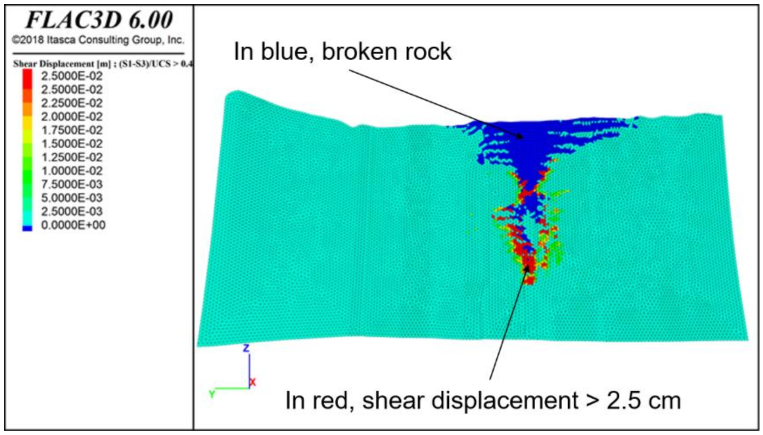


***Figure 7 Shear displacement related to seismicity in Anxiety Fault during year 7 of operation.***

The maximum Seismic Moment is calculated from the average cumulative shear displacement of all the polygons in the fault that have experienced plasticity (it means, inside the slip area) and the slip area. Note that this assumes a condition where all the seismic activity happens in one large event, which is conservative. In reality, this seismic energy can also be released in a series of smaller slip events. The shear modulus is calculated as an average of the shear modulus of the surrounding rock mass, where the highest shear displacement in the fault is regarded as the hypocenter of the seismic event. Finally, the seismic moment is calculated from Equation 2.

The moment magnitude (M) of a seismic event, in terms of seismic moment, is given by Kanamori and Anderson (1975) as:

$$M = \frac{2}{3}(\log_{10} M_o - 9.1) \qquad \text{Equation 6}$$

Where the seismic moment, $M_o$, is in Nm.

## 3.0 RESULTS

The results of maximum seismicity due to fault-slip at Resolution are summarized in Table 2.

***Table 2 Caving-induced Seismicity Due to Fault-slip at Resolution Mine.***

| Fault | Initial Period | Final Period | Maximum Moment Magnitude | Depth [m] |
|---|---|---|---|---|
| MP 3 | YR 1 | YR 3 | 2.1 | 1950 |
| MP 1 | YR 2 | YR 40 | 2.6 | 1900 |
| MP 2 | YR 2 | YR 2 | 1.9 | 1900 |
| Manske | YR 3 | YR 3 | 2.6 | 1900 |
| Paul | YR 3 | YR 15 | 2.6 | 1900 |
| Camp | YR 4 | YR 4 | 2.6 | 1300 |
| Peterson | YR 4 | YR 5 | 2.1 | 1800 |
| Superior | YR 5 | YR 6 | 2.6 | 1600 |
| Hammer N | YR 6 | YR 6 | 2.4 | 1750 |
| Hammer S | YR 7 | YR 23 | 2.8 | 1600 |
| Anxiety | YR 7 | YR 7 | 2.9 | 1500 |
| Andesite | YR 8 | YR 15 | 2.1 | 1950 |
| Gant E | YR 8 | YR 10 | 2.9 | 1550 |
| Paul S | YR 8 | YR 10 | 2.8 | 1680 |
| Hammer SW | YR 15 | YR 18 | 2.4 | 1850 |
| Gant W | YR 21 | YR 26 | 2.6 | 1400 |
| S Boundary | YR 22 | YR 41 | 2.9 | 1700 |
| W Boundary | YR 28 | YR 41 | 1.5 | 1100 |
| Rancho Rio | YR 33 | YR 41 | 1.9 | 1450 |

The faults listed in Table 1 that are not listed in Table 2 correspond to those with no or very low seismic hazard because they are distant from the site of active mining. This means that only 19 faults—of the total of 31 modeled—are predicted to have seismic activity due to mining at Resolution.

It is important to understand that the moment magnitudes listed in Table 2 correspond to the maximum possible seismic event if all the energy is released at once. For example, MP 3 slip can result in a seismic event between years 1 and 3, with a maximum moment magnitude of 2.1, if all the energy is released at once. It is possible that minor seismic events (lower magnitude) can occur, releasing the energy gradually. The period of seismic hazard is limited to year 3 for MP 3 because after this period, the cave-back reaches the fault, and the energy is dissipated.

Figure 8 summarizes the results in Table 2 for the faults with potential seismicity during the caving mine life. The lines represent the time period of a potential seismic event for a single fault (one color per fault) at a specific depth, with a maximum moment magnitude indicated by the number above the line. For example, Figure 8 shows that there is a potential seismic hazard with a maximum moment magnitude of 2.5 between years 28 and 41 related to the fault W Boundary. This can be a single magnitude 2.5 event, or several minor seismic events (of magnitude lower than 2.5) where the energy is released gradually. Illustrative figures for the faults with the biggest moment magnitude (2.9) can be found in Appendix I.

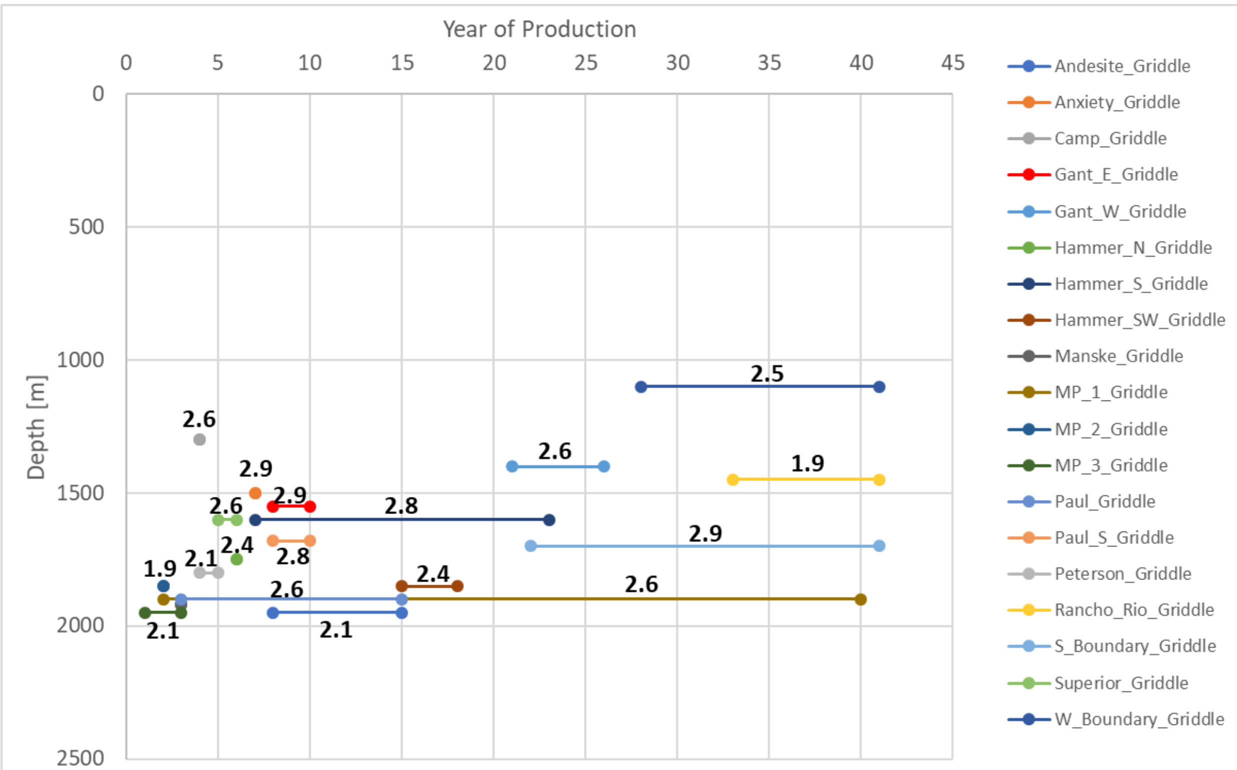


***Figure 8*** ***Maximum caving-induced seismicity (Moment Magnitude) due to fault-slip at Resolution.***

## 4.0 CONCLUSIONS

A seismic hazard assessment has been performed using the numerical model from a caving study for Resolution performed by Garza-Cruz and Pierce (2017). The methodology used to estimate seismicity follows the guidelines given by Aki and Richards (1980) to predict the maximum seismic moment due to fault-slip. Using the seismic moment, it was possible to calculate the moment magnitude to characterize the seismic event.

This study considers a conservative condition to estimate the shear displacement occurring in the faults. First, the plastic shear strain used to calculate the shear displacement in the faults is calculated considering the principal strain magnitudes without resolving them to a preferential direction of anisotropy (the faults were modeled as a band of weaker zones, with no strength anisotropy). Second, the methodology to calculate the seismic moment presumes that all the energy is released at once in a single, large event. The energy could be released gradually due to several minor events (low magnitude).

The results of the *FLAC3D* model predict that 19 faults will potentially have seismic activity during the life of mine (of the total of 31 modeled). The maximum moment magnitude estimated for fault-slip seismic events is lower than 3.0. Eleven faults could have a seismic event with a magnitude greater than 2.5. A concentration of seismic activity is predicted to occur between years 5 and 10 due the cave-back reaching different faults. It is important to note that the reported moment magnitude presumes that all the energy is released in one large event instead of several minor events.

The seismic hazard assessment performed here, though approximate, gives a good first estimate of potential seismic events due to fault-slip at Resolution Mine.

## 5.0 REFERENCES

Aki, K. and P. G. Richards. (1980) ***Quantitative Seismology, Theory and Methods***. San Francisco: Freeman.

Garza-Cruz T. & M. Pierce (2017) "Assessment of Surface Subsidence Associated with Caving Resolution Copper Mine Plan of Operations", Itasca Consulting Group, Inc., Technical Report to Resolution Copper Company.

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Hedley D.G.F. (1992) "Rockburst Handbook for Ontario Hardrock Mines". CANMET, Special Report SP 92-1E.

Kanamori H. and D. L. Anderson. (1975) "Theoretical basis of some empirical relations in seismology". *Bulletin of the Seismological Society of America*, ***65*** (5): 1073-1095.

Martin C. D. (1993) "The Strength of Massive Lac du Bonnet Granite Around Underground Openings". PhD Thesis. University of Manitoba, Canada.

# 6.0 APPENDIX I

This section contains figures of the three faults (S Boundary, Anxiety and Gant E) with the highest maximum moment magnitude (2.9) during the life of mine at Resolution.

## 6.1 S Boundary Fault

S Boundary Fault, shown in Figure 9, could present caving-induced seismicity between years 22 and 41 (end of life of mine), with a maximum possible seismic event of magnitude 2.9.

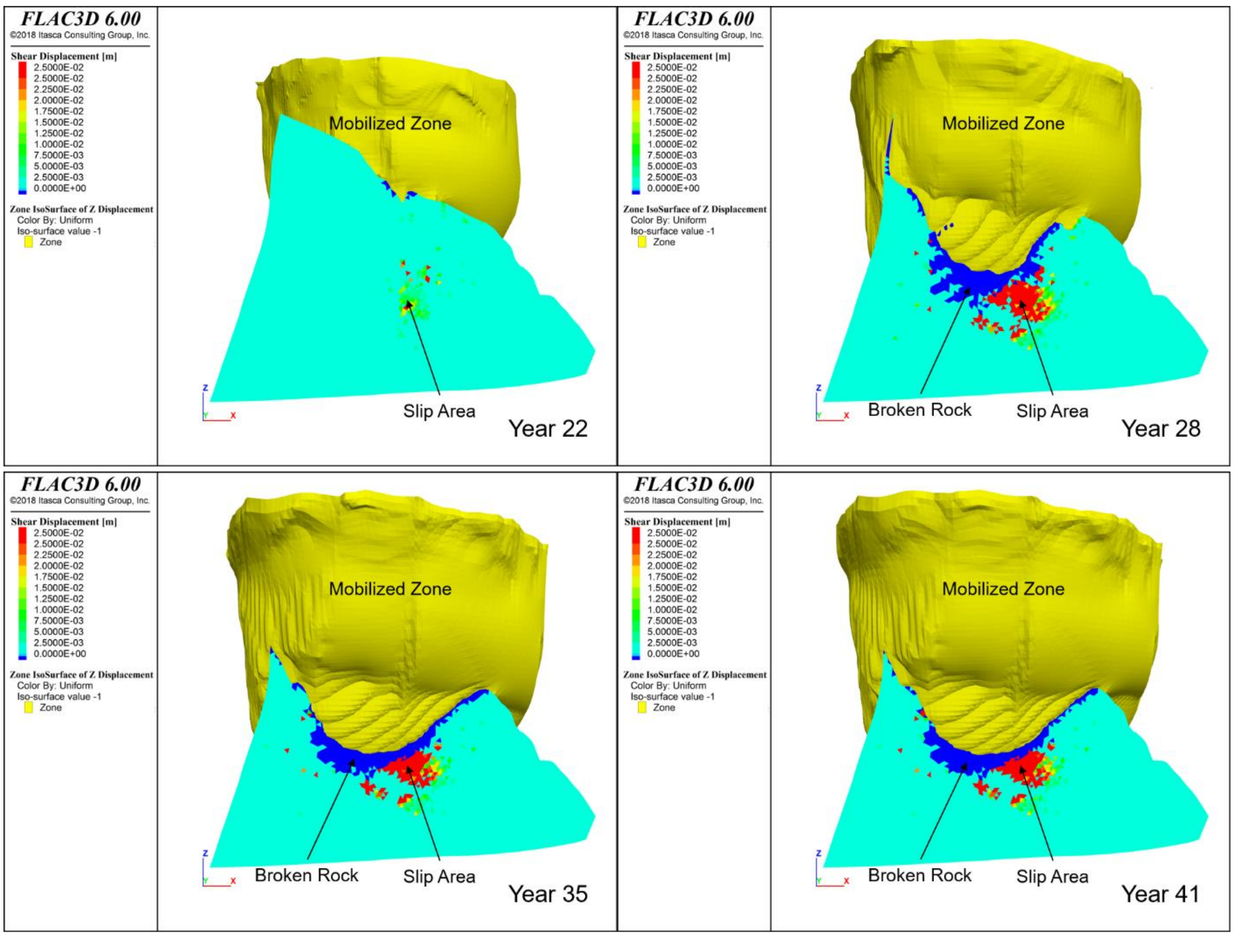


***Figure 9 Caving-induced seismicity due S Boundary fault-slip at Resolution.***

## 6.2 Anxiety Fault

Anxiety Fault, shown in Figure 10, could present caving-induced seismicity during the 7$^{th}$ year of operation, with a maximum possible seismic event of magnitude 2.9.

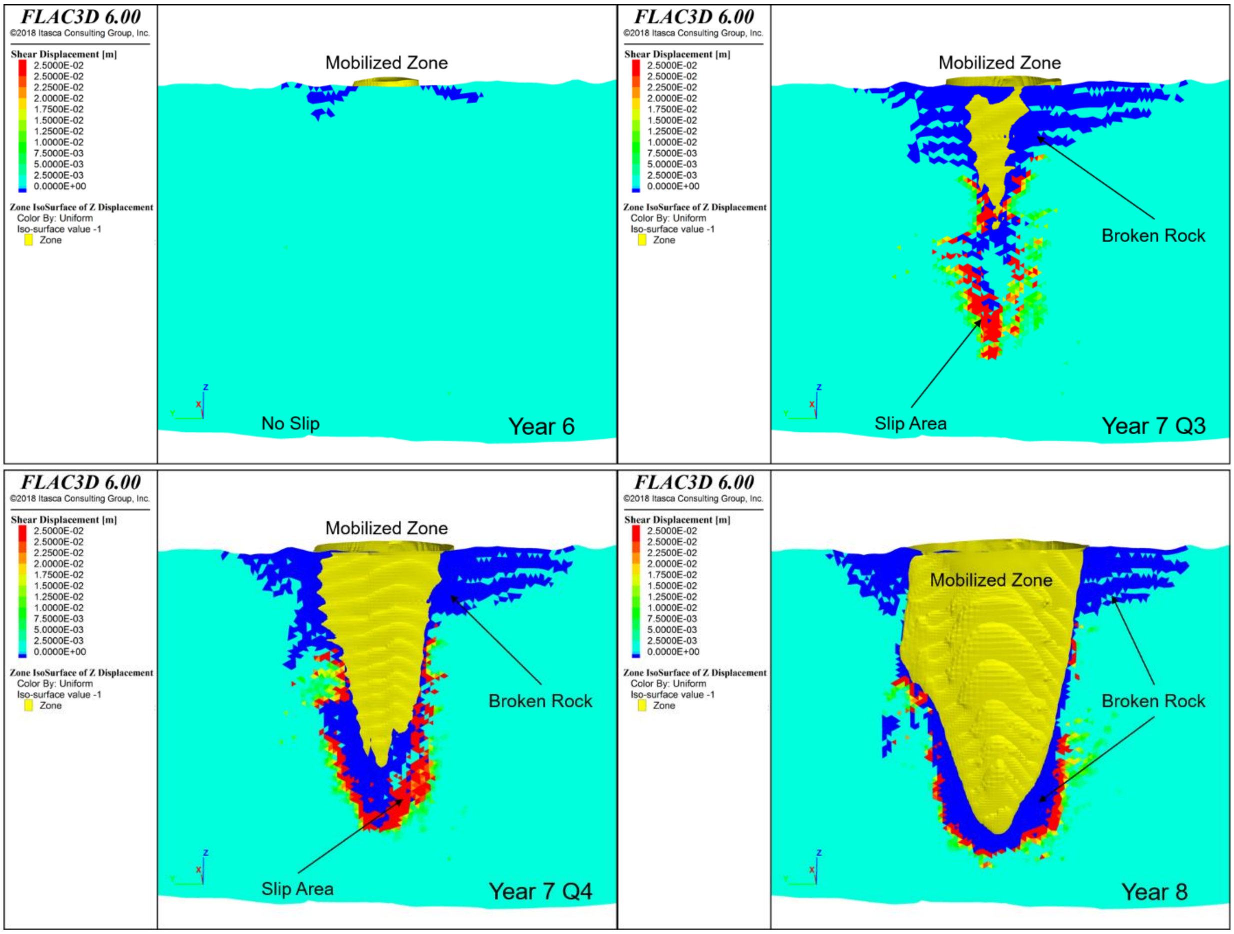


***Figure 10 Caving-induced seismicity due Anxiety fault-slip at Resolution.***

## 6.3 Gant E Fault

Gant E Fault, shown in Figure 11, could present caving-induced seismicity between years 8 and 10, with a maximum possible seismic event of magnitude 2.9.

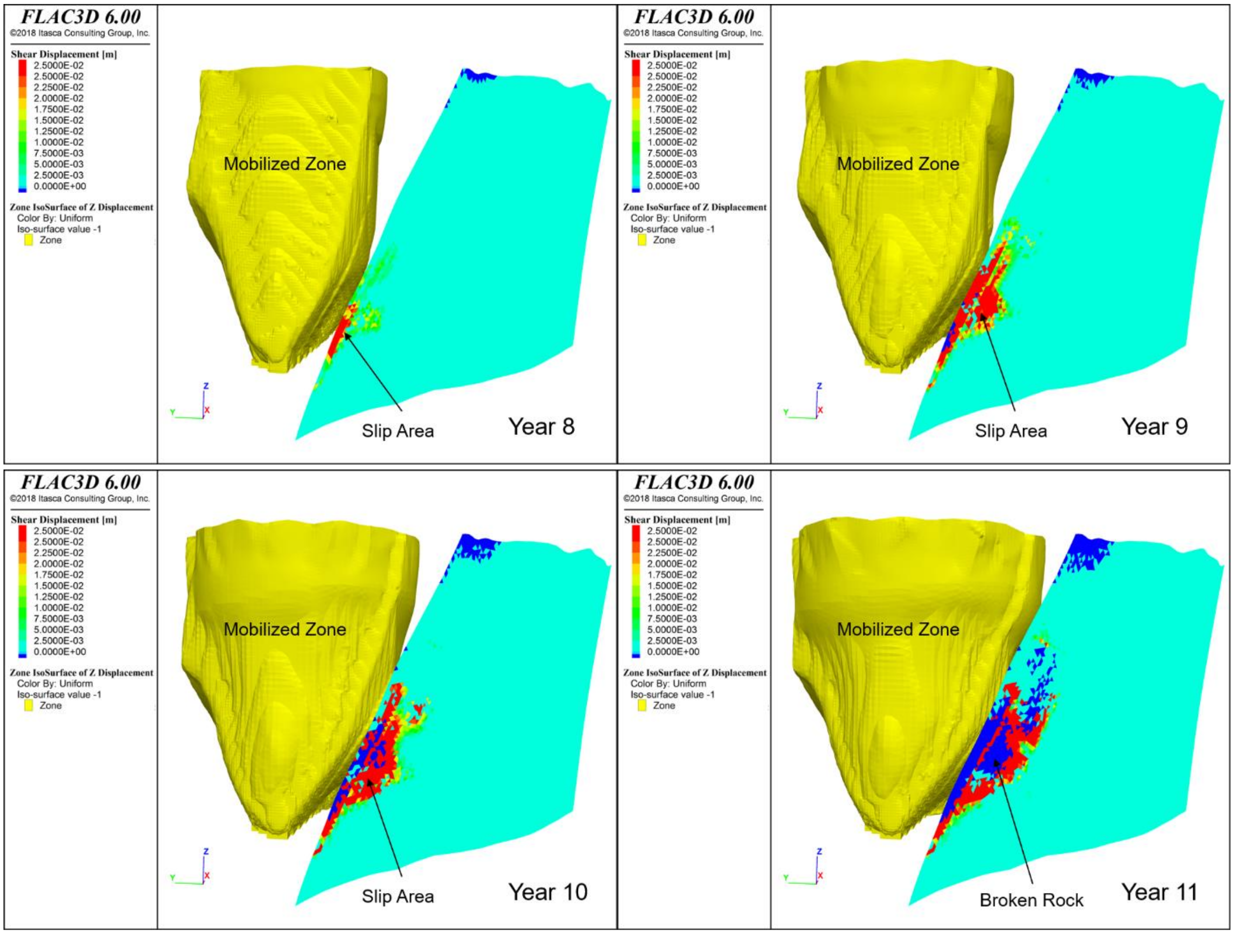


***Figure 11 Caving-induced seismicity due Gant E fault-slip at Resolution.***

RESOLUTION
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14 April 2020

Via email to: mary.rasmussen@usda.gov

Mary Rasmussen
US Forest Service
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2324E McDowell Road
Phoenix, AZ 85006-2496

**Subject: Resolution Copper Mining, LLC – Mine Plan of Operations and Land Exchange – Response to Action Item GS-16 (Geology, Subsidence, Seismicity) and Follow-up Action from the Failure Modes and Effects Analysis (FMEA) Workshop**

Dear Ms. Rasmussen,

Enclosed for your review and consideration and in response to Geo-Subsidence/Seismicity Action Item # GS-16 and a follow up question from the FMEA Workshop (February 5-6, 2020) please see the information below:

1. Response to Action Item GS-16: *Provide additional information that may be available on induced seismicity or land instability related to the block cave operations, potentially including: site-specific analysis of induced fault motion; propagation of these effects; pertinent experiences when constructing Shaft 10; and any analysis of noise and vibration, if that analysis exists. These effects should be focused on the movement of the block cave itself*.
    a. Attachment 1: Technical memorandum by Itasca (2020) titled "*Assessment of Potential for Caving-Induced Fault Slip Seismicity at Resolution Copper Mine*."
    b. Attachment 2: Technical memorandum by Lettis Consultants International, Inc. (2020) titled "*Response to Action Item GS-16 and Follow-up from FMEA Workshop: Induced Earthquakes at the Resolution Copper Mine and TSF* assessing the level of ground shaking that could be produced by caving-induced fault-slip events (earthquakes) at the proposed Resolution Copper Mine as described in Itasca (2019).
    c. There have been no instances of induced seismicity related to the construction Shaft 10.

2. A follow up action item from the Failure Modes and Effects Workshop (February 5-6, 2020).
    a. Technical memorandum by Lettis Consultants International, Inc. (2020) titled "*Response to Action Item GS-16 and Follow-up from FMEA Workshop: Induced Earthquakes at the Resolution Copper Mine and TSF*" assessing the potential for induced seismicity as observed in water impoundment dams, due to the development of the proposed TSF.

Should you have any questions or require further information please do not hesitate to contact me.

Sincerely,

Vicky Peacey
Senior Manager, Permitting and Approvals; Resolution Copper Company, as Manager of Resolution Copper Mining LLC

Attachments:

Attachment 1 – Itasca (2020), Assessment of Potential for Caving-Induced Fault Slip Seismicity at Resolution Copper Mine

Attachment 2 - Lettis Consultants International, Inc. (2020), Response to Action Item GS-16 and Follow-up from FMEA Workshop: Induced Earthquakes at the Resolution Copper Mine and TSF