BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

RESOLUTION COPPER PROJECT & LAND EXCHANGE ENVIRONMENTAL IMPACT STATEMENT

GEOLOGIC DATA AND SUBSIDENCE MODELING EVALUATION REPORT

EIS TEAM – GEOLOGY AND SUBSIDENCE WORKGROUP

PROJECT NO.: 1704007-03 DATE: December 15, 2020

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LIMITATIONS

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1.0 SUMMARY OF DATA REVIEWED AND REVIEW PROCESS

A Geology and Subsidence Workgroup (Workgroup) was convened as part of the Resolution Copper Project Environmental Impact Statement (EIS) team. The purpose of the Workgroup was to review Resolution Copper Mining's (RCM) procedures, data, and geologic and geotechnical baseline documents to:

1. Determine whether the methods employed by RCM in collecting and documenting geologic data are appropriate, adequate, and according to industry standards.
2. Determine whether RCM's interpretations of geologic structures, faults, geotechnical data, rock properties, and assumptions are reasonable.
3. Identify any significant data gaps.
4. Identify uncertainty with the interpretations, with consideration of data gaps.
5. Determine if there are cases where RCM's interpretations are not considered reasonable and, if so, provide alternative interpretations and supporting rationale.

The names of members of the Workgroup, and their respective areas of expertise within the group, are summarized in Table 1-1 below. The credentials of the team members are summarized in Section 9.0.

Table 1-1. Geology/subsidence workgroup team members.

Team Member	Company	Expertise
Laurie Brandt, CPG	DOWL	General geology, faults, structures, geologic interpretations
Robert (Nick) Enos, CPG	BGC	General geology, faults, structures, geologic interpretations
Amir Karami, PhD, P.Eng.	BGC	Geotechnical data, rock mechanics, industry standards, geologic and subsidence modeling, panel caving methods
Diana Cook, PhD, PE	BGC	Geotechnical and seismic data, industry standards, rock properties, geologic and subsidence modeling
Michael Henderson, PE	BGC	Geotechnical data, industry standards, rock mechanics, geologic and subsidence modeling
Rex Bryan, PhD	Geostat Systems	Geostatistics, statistical adequacy and quality assurance/ quality control (QA/QC) of procedures and interpretations

1.1. Timeline and Summary of Data Collection Process

The EIS team was assembled and led by SWCA Environmental Consultants (SWCA) and the USDA Forest Service Tonto National Forest (TNF), starting in 2016. The General Plan of Operations (GPO) (RCM, 2016a) and other documents were provided to the EIS team by RCM and others at that time. An initial site visit by the EIS team on November 15 and 16, 2016 provided an opportunity for discussions with RCM staff and their consultants and to view the site geology, components of the existing RCM operation, and the proposed RCM sites as presented in the GPO. Field trips and presentations were given to the EIS team during the November 2016 meetings. Of the personnel listed in Table 1-1, A. Karami was not on the EIS team until January 2018, when he replaced a previous BGC geotechnical engineer and rock mechanics expert, Gastón Gonzales, who left the firm at that time. Of the Workgroup members listed in Table 1-1, L. Brandt, N. Enos, D. Cook, and M. Henderson were present for the initial November 2016 site visit, field trips and presentations.

Following the initial site visit, various baseline data requests were submitted for geologic and geotechnical information, as summarized in the Table A1 (Appendix A), which lists the key activities and data submittals relating to geological, geotechnical, and subsidence components of the proposed project. Details of the data requests, meetings and RCM responses are provided in Table A1 and are not repeated here.

A second site visit was conducted by L. Brandt, G. Gonzales, and R. Bryan on May 4-5, 2017, and hosted by RCM geologic, geotechnical, hydrologic, and metallurgic staff. The purpose of this site visit was to tour the East Plant Site (EPS), Oak Flats, the core storage and processing building, and other areas near Superior, AZ to view the geologic setting, faults, and current RCM operation. The process of in-house geological logging and testing of core, as well as the Quality Assurance /Quality Control (QA/QC) protocols, were further observed and discussed. Presentations and discussions of the Vulcan 3D geologic model (Maptek, 2020) and acQuire software (Pere et al., 2011) were also part of this site visit. A summary of this site visit is documented separately in Brandt et al. (July 7, 2017).

During the course of the baseline date review by the EIS team, several additional workgroups were organized by SWCA, covering review topics related to geochemistry, water quality, hydrology, reclamation, and seismic, among others. This report is limited to review by the Geology and Subsidence Workgroup only. The formal workshop meetings of the Geology and Subsidence Workgroup included:

<u>Pre-Draft Environmental Impact Statement (DEIS)</u>

September 13, 2017 - Meeting #1
November 29, 2017 - Meeting #2
January 26, 2018 - Meeting #3
March 16, 2018 - Meeting #4
May 16, 2018 - Meeting #5
June 12, 2018 - Meeting #6
August 8, 2018 - Meeting #7

<u>Post-DEIS</u>

January 21, 2020 - Meeting #8
February 11, 2020 - Meeting #9
March 24, 2020 - Meeting #10

Several TNF geologists and related specialists also participated in the Geology and Subsidence Workgroup meetings and contributed greatly to the discussion. These included J. Sampson, P. Werner, D. Tafoya, G. Olsen, J. Gurrieri, and T. Stroope.

As summarized in Table A1, there are meeting minutes available for each of these meetings. Generally, the purpose of these Wrokgroup meetings was to discuss RCM's responses to data requests, to get further explanations and presentations by RCM staff and their consultants, and to identify additional information needed by the Workgroup to perform their review.

1.2. Summary of Review Process

The Workgroup initially reviewed data supplied by RCM and their consultants in the GPO, and other available data submitted as part of the GPO application package. As formal baseline data requests were subsequently submitted to RCM, starting in March 2017, RCM typically responded with various reports, letters, graphics, and other related documents. This process is summarized in Table A1. Formal Workgroup meetings were initiated in September 2017, which included presentations and detailed discussions for the benefit of the Workgroup. These were effective forums to allow for in-depth discussions with RCM staff who performed much of the data collection, analysis, and geologic modeling, as well as RCM's consultants such as M. Pierce with Itasca Consulting Group Inc. (Itasca) and Pierce Engineering, who conducted the subsidence modeling for RCM. In total, nine baseline data requests were submitted by the Workgroup to RCM.

Following publication of the DEIS (TNF, Aug. 9, 2019) and the associated public review period, the Workgroup attended three meetings to review and address public comments related to geology and subsidence. Of note, Malach Consulting LLC (Malach) submitted public comments and questions related to RCM's data collection methodologies, processes and subsidence model results (Malach, March 17, 2019). The Workgroup completed a detailed review of Malach's comments and questions, and provided this documentation in a separate report (BGC, July 21, 2020).

The Workgroup meeting (#10) on March 24, 2020 was dedicated to review and discussion of RCM's proposed Subsidence Monitoring Plan (RCM, May 5, 2018). The Workgroup reviewed the Subsidence Monitoring Plan and provided additional comments and questions. Addressing the Workgroup's comments, RCM submitted a revised Subsidence Monitoring Plan (RCM, August 2020).

2.0 REFERENCE STANDARDS

This section summarizes the standards, methods, and best practices applicable to the geological and geotechnical programs associated with the Resolution Copper Project. However, it is not intended to include an exhaustive list of all standards for geological or geotechnical field programs, laboratory testing, data analysis, geological modeling, or subsidence modeling. In some cases, a formal standard may exist, such as American Standards for Testing and Materials (ASTM) standards or International Society for Rock Mechanics (ISRM) guidelines pertinent to laboratory testing procedures. However, in most cases methods and procedures rely on the "state-of-practice", or industry "best practices", or in peer-reviewed industry research and literature. Due to the variety of topography, geology, and site-specific issues often encountered at mining projects, there is a range of appropriate methods and procedures that may be adopted in the interpretation of geological and geotechnical data. This section therefore largely focuses on best practices as they specifically relate to the Project site, while also considering general best practices for mining and other large-scale civil projects. Finally, this section covers the general approach taken by the Workgroup in reviewing and validating the work performed by RCM and their consultants.

2.1. Industry Best Practices

Resolution Copper is a limited liability company with 55% ownership by Rio Tinto (the Operator) and 45% ownership by BHP-Billiton. Under ownership of Rio Tinto, which is a publicly traded company, RCM's exploration field program (i.e., drilling, sampling, logging, assay testing) is required to follow mineral resource and reserve reporting requirements for such programs set forth in the U.S. Security and Exchange Commission (SEC) Industry Guide 7 (SEC, 2018) and the Australasian Joint Ore Reserves Committee (JORC) code (JORC, 2012). The SEC and JORC, as well as industry best practices, require that disclosure of exploration results and mineral resources and reserves be based on, and accurately reflect, information and supporting documentation prepared by a mining expert, defined by the SEC as a "qualified person", or a "competent person" as defined in the JORC code. This is important because mineral resource and reserve estimates are based on interpretations of geologic information, and therefore rely on the competence and qualifications of those preparing or verifying that information. In the case of Resolution Copper, the geological Program Manager, who oversees the entire geologic field program, fills this role. In addition, the field program is reviewed periodically by qualified independent third parties who verify that the geologic and ore deposit models meet the standards set forth in the SEC and JORC codes. Besides the SEC and JORC requirements, there are other mineral resource reporting frameworks in use throughout the industry, and specific requirements vary by country. One common example is Canada's National Instrument 43-101 (NI 43-101), which includes *Standards of Disclosure for Mineral Projects* for mining projects within Canada. NI 43-101 is a codified set of rules and guidelines for reporting and displaying information related to mineral properties owned by, or explored by, companies which report these results on stock exchanges within Canada. While NI 43-101 is more prescriptive than JORC, it shares the same intent of involving qualified and competent expertise in the reporting of mineral resources. It is not the role of this Workgroup to comment on which reporting standards are applicable for the purposes of securities reporting. However, the Workgroup finds that RCM's geologic program, and its adherence to JORC and SEC standards, meets industry best practices.

This approach for publicly disclosing mineral resources for the Resolution Copper Project also incorporates or overlaps with industry standards for geological or geotechnical field programs in general, including the estimation of rock properties and input parameters for geological and engineering analyses (e.g., subsidence modeling). RCM's geotechnical information and geotechnical analyses are also reviewed periodically by an independent third-party Geotechnical Review Board (GRB) and by various reviewers who audit the process and review procedures and conclusions. The GRB and auditors are independent consultants and industry experts retained by RCM for internal quality management and due diligence. In order to protect the rigorous and frank openness of the due diligence process, reports from these internal reviews are generally not available to the public, or this Workgroup.

2.2. Applicable Industry Standards

The following general procedures were used by RCM (March 24, 2017), and meet or exceed industry standard methods, which are summarized in Table A2 (Appendix A). In some cases, there are multiple methods or alternative procedures that would be considered an "industry standard". The typical methods and industry standards used by RCM are discussed below:

2.2.1. Drilling

- Drilling of core oriented using Acoustic Borehole Imaging (ABI) geophysical surveys to provide data on rock mass condition and discontinuity orientation at depth. Approximately 70% of core drilled are oriented. Core orientation (ABI survey) was completed where rock conditions allow.
- Boreholes oriented in a variety of directions - in general, vertical boreholes show lithology, and angled boreholes are used to show structures and to better define the ore body.
- Pre-collar holes are drilled with rotary drilling or "PQ" diameter drill core (core with an outside diameter of 3.345 inches (85 mm) (Boart Longyear, 2018)) to depths of 2800 ft (853 m) to 5500 ft (1676 m), then cased and cemented in place. All "HQ" diameter holes (core with an outside diameter of 2.5 inches (63.5 mm) (Boart Longyear, 2018)) or smaller are completed as core tails from pre-collar holes, and are completed with total length of greater than 7500 ft (2286 m) from surface.
- Sub-foot accuracy of drill hole collar survey is established through repeat surveys by multiple Registered Land Surveyors. The coordinate system was standardized with the current realization of US Arizona State Plane of 1983 (NAD 83) Central Zone for horizontal and North American Vertical Datum of 1988 (NAVD 88). Down-hole surveys on directional holes are primarily north-seeking gyroscopic surveys.
- Quality control (QC) includes repeat surveys, and comparison to multiple magnetic survey techniques (Single Shot and ABI).

2.2.2. Sample Recovery and Logging

- An initial log of core is completed as core is received daily (i.e., core logging). Rock Quality Designation (RQD) measurements are taken using standard methods (e.g., Deere, 1989; Deere and Deere, 1988).
- Each core run is cleaned and photographed with special care to maintain its correct orientation, along with the retention of voids and broken rock. All core is photographed prior to any cutting and boxing.
- Care is taken to meet or exceed industry standards for core logging and interpretation. Regular oversight by the lead geologist, and collaboration amongst the logging staff of geologists, contributes to consistency and competency over time. The lead geologist uses a "story board" as a reference for the interpretation of segments of core.
- All recovered core is logged in detail, and each borehole is usually logged by at least three different geologists. The lead geologist spends time observing and advising the ongoing core logging.
- Core logging is checked randomly on a weekly basis, by the lead geologist.
- Core logging information includes lithology, mineralogy, alteration, anhydrites, fractures and faults (orientation and types), and geotechnical parameters as inputs for rock mass classification systems used by RCM.
- Core logging and borehole fractures are compared to on-screen ABI logs to verify orientation and other details. The lead logger (geotechnical QC) reviews a random (blind) domain once a week to check on the consistency of the logging amongst the geologists.
- Core recovery is observed to be relatively high at Resolution, with an average recovery of 98.2% across the deposit and 92% in fault zones. Fault zones account for less than 2% of core at Resolution. All recovered cores, a total of 430,312 ft (131,159 m), have been logged in detail (RCM, October 5, 2017).
- The lead geologist re-logs a core barrel segment every 300 feet (91.4 m) of core and signs off on each re-logged section while the staff observed to ensure competency and consistency with the logging procedures and with the lithologic and geotechnical domains (Brandt et al., July 7, 2017). The primary geotechnical characteristics recorded in the core are RQD, open joints, structures (> 0.8 in (2 cm) width), cemented joints/veins, and degree of alteration.
- Geologic and geotechnical logging are entered directly into a digital logging system using the "acQuire" Geoscientific Information Management (GIM) software package (http://www.acquire.com; Pere et al., 2011). The acQuire data model is described in the next section.

2.2.3. Data Management

- Resolution uses the quantitative digital logging system acQuire (Pere et al., 2011) to manage the borehole data. In addition to capturing detailed lithology, alteration and mineralization attributes, the system accommodates the capture of detailed geotechnical data, with all data gathered in a single pass by a geologist. It includes a formal training program, as well as quality control systems to ensure consistency and accuracy for both geologic and geotechnical logging in support of geologic and resource modeling, and mining and metallurgical studies.

- The database contains a total of 438 drill holes (Brandt et al., July 7, 2017) (including 130 boreholes drilled by RCM between 2001-2016, and 5 holes by Magma/BHP between 1995-1998 (RCM, March 24, 2018)) which include both geology and geotechnical features and properties, archived geologic data from the Magma Mine, and the newer RCM Shaft No. 10.
- Data have been verified through third-party review, as previously discussed.

2.2.4. Laboratory Testing

- Most of the laboratory testing was performed by independent laboratories and is understood to generally follow ASTM or ISRM guidelines.
- Testing included:
    - Unconfined Compressive Strength (UCS) testing
    - Point load tests (PLT) correlated with UCS testing (ASTM D5731-05)
    - Triaxial Compressive Strength (TCS) testing (at various confinement pressures)
    - Brazilian tensile strength testing (BT)
    - Sonic testing (also under confinement) to evaluate dynamic elastic moduli.

The following benefits accrue from following established ISRM guidelines or ASTM standard methods:

- Standard specimen size and shape due to scale effects and considering the natural variability in intact rock conditions
- Standard method for specimen preparation
- Standard testing method to obtain comparable results regardless of the laboratory facility used
- QA and QC on laboratory test results.

Malach (March 17, 2019) provided public comments that RCM's geotechnical data were poorly described or were not available for review. The Workgroup reviewed RCM's data collection procedures and QA/QC processes in detail. In some cases, the Workgroup requested additional information, including but not limited to the description of faults/fault zones, drill holes intersecting the faults, and a structural geology model of the major interpreted faults. The Workgroup found that RCM's data collection and QA/QC procedures and processes meet or exceed industry best practice.

Malach (March 17, 2019) further commented that geotechnical information to develop geotechnical properties for geotechnical domains were not available to evaluate. The Workgroup requested and reviewed RCM's latest rock mass characterization report (RCM, October 5, 2017) and requested additional information on site-wide point load test data, uncertainty in material properties of Tw and Tal rock domains, and the back analysis of Tw and Tal rock units based on experience obtained during sinking of Shaft No. 10. The Workgroup found that this information and methodology meet or exceed industry best practice. BGC conducted a detailed review of Malach's public comments and provided responses in BGC (July 21, 2020).

2.3. Data Analysis and Subsidence Modeling

This section provides a brief overview of the typical methods used in the assessment of rock mass properties and subsidence modeling, and the general application of these methods by RCM. The input parameters and subsidence modeling are covered in greater detail in Section 5.0 of this report.

2.3.1. Assessment of Input Parameters

RCM used several rock mass rating systems that are commonly used in mining and other applications that rely on rock mass characterization and behavior. These include the Rock Tunneling Quality Index system or Q system (Barton et al., 1974), the Rock Mass Rating, RMR (Bieniawski, 1989), the Geological Strength Index, GSI (Cai et al., 2004), and the Mining Rock Mass Rating, MRMR (Laubscher, 2000). In addition, the well-established Generalized Hoek-Brown constitutive model (Hoek et al., 2002) was used by RCM to derive rock mass strength for the geotechnical domains based on statistical distributions of the UCS, TCS, and GSI data within each domain. Rock mass strength distribution was assessed by Itasca (April 6, 2018) for sensitivity analyses using a Monte Carlo statistical analysis, which is a well-established technique that, in this case, involved randomly sampling the input parameters for the Hoek-Brown model parameters (e.g., Li et al., 2012; Sari et al., 2010). UCS values were scaled by a factor of 0.8 to account for the drop in intact strength expected when moving from laboratory-scale to cave-scale (Hoek and Brown, 1980). The 0.8 factor is considered reasonable because RCM reported that 75% of samples taken for intact rock strength testing failed along defects or along a combination of defects and intact rock segments. As such, the measured strength (referred to as the defective strength (RCM, October 5, 2017)) already takes into account impact of defects on intact rock strength. The 0.8 factor was applied to the defective strength value further downgrading the measured rock strength. As a check, by applying the Laubscher and Jakubec (2001) approach to downgrade intact rock strength by taking into account the rock hardness range and fracture frequency (ff/m), a 0.85 factor would have been required which is less conservative than the 0.8 factor used.

Data gathered from SMART Multiple Point Borehole Extensometers at the No. 10 Shaft at Resolution Copper were used by RCM to back-analyze the performance of the rock mass and evaluate the appropriateness of the rock mass properties used for subsidence modeling. The Workgroup considers this a good practice that meets industry standards for characterizing rock mass strength at the No. 10 shaft.

2.3.2. Subsidence Modeling

There is no set standard or method that is applied to the evaluation of subsidence resulting from block caving, but rather evaluation relies on industry-accepted approaches. In general, estimates of subsidence consider major geological structures, rock mass strength, current in-situ and induced stresses, and the depth of mining. One empirical method often used during the early stages of block cave mine planning is based on Laubscher's MRMR system (Laubscher and

Jakubec, 2001; Laubscher, 2000; Brown 2003). This system considers the geological environment through Bieniawski's (1989) rock mass ratings, and then adjusts for the effect of the mining operation on the rock mass. The ratings and specifics of the mining operation and its impact on the surrounding geology are used to define the caveability, subsidence angles, fractured zones, fragmentation, undercut-face shape, cave-front orientation, undercutting sequence, overall mining sequence, and ground support design (Laubscher, 1994).

RCM has evaluated the proposed panel cave mining using this empirical approach and their results are reported summarized in Section 5.3. RCM notes that while such empirical methods largely account for macro deformations and provide a first approximation to the cave angle at early stages, they cannot properly account for anisotropy in the rock mass, the influence of large structures such as faults, varying topography, or the extent of fracturing and the continuous subsidence zone (Woo et al., 2013). The Workgroup agrees with this statement, and the results of this empirical assessment are further discussed in Section 5.3.

To address these limitations of the empirical approach, numerical analyses are typically performed in the later stages of mine planning, which better account for these complexities (Flores and Karzulovic, 2002; Sainsbury, 2010). These models are supported and informed by studies of other block caving mines and their subsidence patterns relative to site-specific rock mass properties, geological structures, and topography (Woo et al., 2009; 2013).

One program commonly used in numerical analyses, and generally considered to be an industry standard, is FLAC3D (Itasca, 2017). Specifically for use within FLAC3D, an algorithm to simulate mine cave growth was developed by Itasca and has been successfully compared with cave behavior at many other mines around the world, including Northparkes E26, Palabora, Grace Mine, Henderson Mine, Ghaghoo mine, and Henderson 7700SW (Itasca, July 17, 2017). This modeling approach was used by Itasca for the Resolution Copper Project and included sensitivity analyses to better understand the parameters with the largest influence on cave growth and subsidence specific to the Project site. The Workgroup concluded that this modeling approach, including use of FLAC3D, is appropriate and consistent with industry standards and best practice.

2.4. Data Validation Approach

Validation of the field program, laboratory testing, geological modeling, data analysis, and subsidence modeling was based on a phased approach. For the first phase, the Workgroup requested documentation from RCM on their internal data validation procedures, reviewed the received documents for adequacy, and reviewed the baseline data to see whether internal procedures were followed by RCM. Following the first review phase, some additional questions and uncertainty remained regarding the validity of the data and procedures used for the mine plan and subsidence evaluation. Therefore, a second phase was initiated, incorporating a more in depth review of coring and logging processes, database management and data analyses, the Vulcan 3D geologic model and geological interpretations, subsidence modeling (rock mass characterization, geotechnical domains and associated material properties, and geologic structures, hydrogeology, and other input parameters and assumptions), and internal validation and quality control procedures.

This second phase approach included:

- On-site visits and discussions with RCM staff (Brandt et al., July 7, 2017)
- On-site and direct observation of work procedures, processes, and results (e.g., core handling, logging, and storage)
- Virtual tours with RCM staff of the acQuire database, the Vulcan 3D geological model, the Itasca FLAC3D subsidence model, and the surface and groundwater models
- Reviewing subsidence modeling input parameters – for example, rock mass strength derivation methodology, and rock mass strength and fault modeling assumptions used in subsidence modeling, against measured field conditions
- A series of data requests from the Workgroup and TNF to RCM, and subsequent in-person and/or phone meetings with RCM, TNF, SWCA and Workgroup members from various supporting consulting firms to discuss the RCM's data responses. For example, this process resulted in multiple requests to clarify the methodology and criteria used in numerical modelling to estimate subsidence, as well as sensitivity analyses. This process helped the Workgroup better assess the validity of the subsidence predictions.

3.0 ADEQUACY OF RCM QA/QC PROCEDURES

This section summarizes the review of the adequacy of RCM's Quality Assurance and Quality Control (QA/QC) program for geotechnical data. An objective for acquiring this data is to adequately simulate surface subsidence caused by the proposed panel cave mining. Two cases, described in this report as "near case" and "far case", have been reviewed for data adequacy in meeting this objective using Data Quality Indicators (DQI) subject to achieving Data Quality Objectives (DQO). Seven DQIs were selected by the Workgroup as those that are universally recognized (and used) in determining the adequacy of RCM's sampling and testing program. The terms "near case" and "far case" are discussed in more detail below.

3.1. QA/QC, DQI and DQO

This section reviews the adequacy of QA/QC procedures, data quality indicators (DQI), and data quality objectives (DQO). On May 4 and 5, 2017, Workgroup members Laurie Brandt, Gastón González and Rex Bryan attended on-site field and office meetings with staff of RCM (Brandt et al., July 7, 2017). The purpose was to discuss the site geology, drilling programs, internal procedures for data validation, and QA/QC pertaining to their use in modeling subsidence. Other items reviewed included database management, input parameters/assumptions pertaining to rock mechanics assessments and geotechnical domains definition, geology, rock mass structure, hydrogeology, and the Vulcan 3D block model.

This section uses the terms: QA, QC, and DQO. According to the ISO 9000 (ISO, 2015), QA consists of that "part of quality management focused on providing confidence that quality requirements will be fulfilled." By contrast, QC is that "part of quality management focused on fulfilling quality requirements." In the context of geologic data management, QA identifies the right standard or procedure, whereas QC checks that the results are consistent with that standard. Put another way, QA "assures" that proper sampling will result in quality data, and QC "controls" quality by identifying and correcting poor quality data. The DQO method considers data to be of sufficient quality if it can successfully be applied to achieving a pre-defined objective (EPA, 2006).

Most of the sampling data collected at Resolution is derived from drill core. Their drilling program targeted areas that have the most promising economic viability, which is the mineralized zone (1% copper shell). As a consequence, this has produced a pattern of drill hole locations that may not be optimized for geotechnical data collection and subsequently for the modeling of surface subsidence. For modeling of the future block cave mine, RCM has used Vulcan, a sophisticated 3D mine modeling software. Vulcan's primary purpose is to produce a 3D block model which is used for mineral resource estimation and mine planning. It applies geostatistical theory to classify the mineral resource into indicated and inferred categories (RCM, March 24, 2017).

As described in Section 2.1, financial disclosure requirements for reporting of mineral resource and mineral reserve estimates require estimates to be based on an assessment by a "Qualified Person" or "Competent Person" (RCM, March 24, 2017; JORC, 2012, SEC, 2018). This includes discussion of the QA/QC results within the resource estimation process (RCM, March 24, 2017). To meet this requirement, RCM developed a comprehensive data quality assurance (DQA) plan

(RCM, March 24, 2017). RCM's modeling effort has been discussed by other authors such as Parker (March 14, 2017, March 7, 2018), Hart (2016) and Kloppenburg (2017). A list of geotechnical and geology data types is shown in Appendix B in Table B1. These data are measured according to classification (nominal), ranked lists (ordinal), ranked scale (interval) and graded values (ratios).

3.2. DQI and DQA: Adequacy of Sampling Rock Properties

RCM has developed a formal DQA project plan that details the necessary QA procedures, QC activities, and other technical activities that were implemented to ensure that the results will satisfy performance or acceptance criteria. A review of the DQA plan indicated the data possess seven critical DQIs including

- Precision
- Bias
- Accuracy
- Representativeness
- Comparability
- Completeness and sensitivity.

Their definitions and application are shown in Table B2 (Appendix B). A partial list of steps within the DQA and their DQIs that are affected is shown in Table B3 (Appendix B).

The steps that are needed to produce acceptable statistical adequacy and representativeness include items such as utilizing a third party of independent experts to periodically critique and refine sampling and data evaluation procedures. RCM has implemented a formal process of reviewing the base geotechnical information and its analysis by a third-party Geotechnical Review Board (GRB). The GRB and various experts and consulting companies are directed to challenge the process and review validation procedures and conclusions. The Workgroup determined that RCM continually adjusted its sampling protocols as recommended by the GRB. These adjustments are reflected in the current DQA project plan. The Workgroup noted that RCM has its own sampling protocols and methods of applying internal QA/QC procedures (RCM, March 24, 2017); RCM uses industry standard methods (such as those from ASTM, ISRM and industry best practice techniques, as noted previously) and implements its own internal data validation procedures, including peer review. In addition, a Competent Person oversees the entirety of the data acquisition program at RCM. Finally, outside consulting firms have been tasked to re-sample and re-analyze core data as a confirmatory check. The Workgroup concluded that the QA/QC program in general, and the DQIs specifically, are appropriate, rigorous and relevant.

3.3. Geotechnical Workflow Procedures

Figure 3-1 shows the geotechnical logging workflow and process control for the sampling program. Figure 3-2 shows some of the QC process control steps of the geotechnical logging that evaluate logging accuracy and consistency to identify discrepancies before input to the subsidence modeling. It requires the 3D data to be stored in Vulcan, such as position and characteristics of faults, rock strength properties and lithologic and geotechnical domains. RCM developed a detailed set of process control diagrams to maintain quality and consistency in data input (RCM, March 24, 2017). Typical industry standards used by RCM in the analysis of geotechnical and geologic data are presented in Table A2 (Appendix A).

Some of the process control steps follow ASTM standard analysis methods. For instance, Rock Quality Designation (RQD) measurements are taken using an ASTM method (Deere, 1989; Deere and Deere, 1988). RQD is a measure of core recovery and rock mass quality characteristics measured in percentages ranging from poor (<25%) to excellent (90-100%). Other measurements follow industry best practice protocols. For example, core recovery is estimated from driller blocks which is corroborated from detailed ABI logging (where possible) to generate a final core recovery number. Core orientation is also verified by ABI data, which is industry standard, when available. Various workflow diagrams, as shown in Figure 3-1 and Figure 3-2, incorporate process controls to find and correct errors in data.

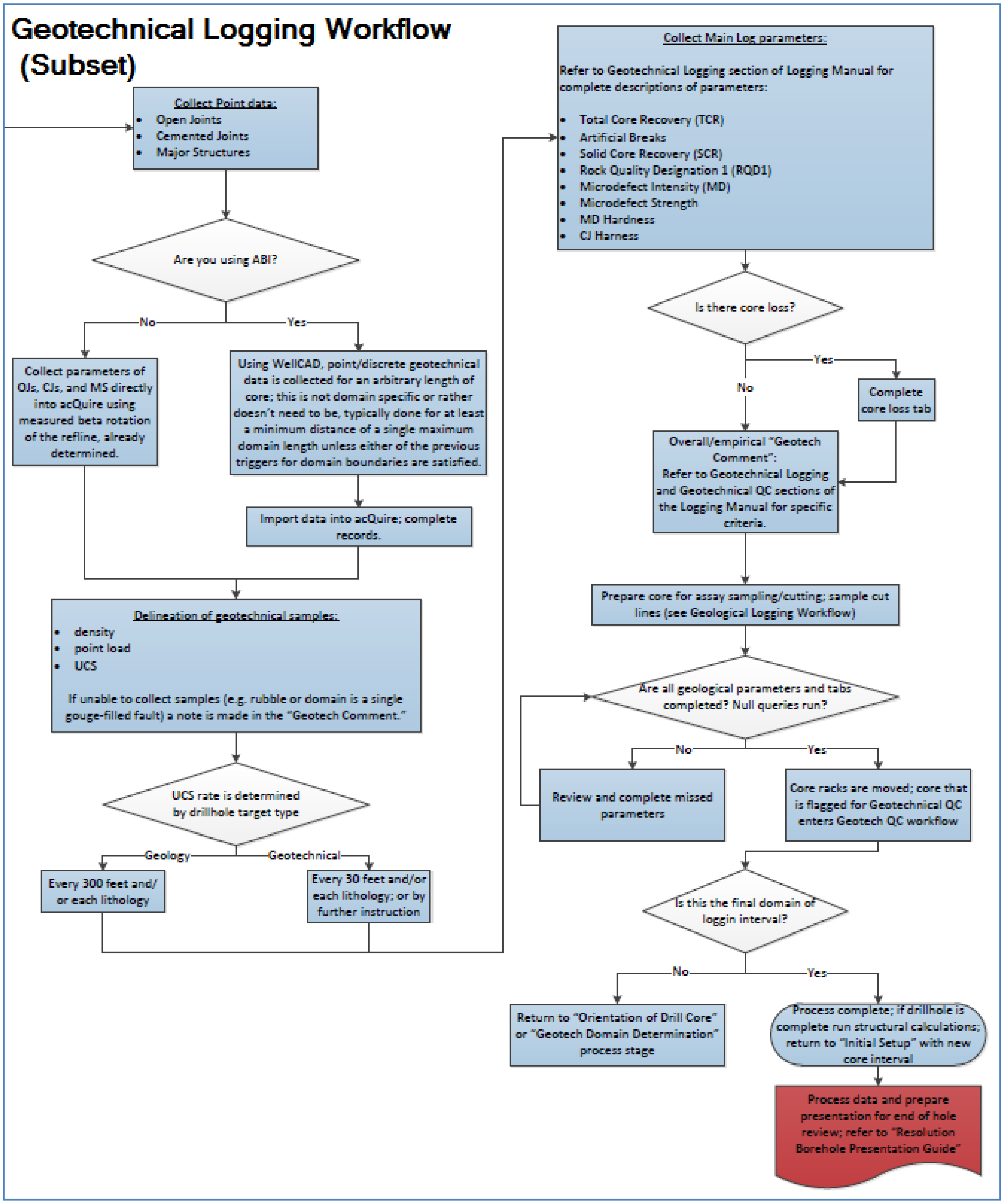


Figure 3-1. Portion of Geotechnical Logging Workflow (Subset) –Process control diagrams are a QA element in the RCM sampling program (RCM, March 24, 2017).

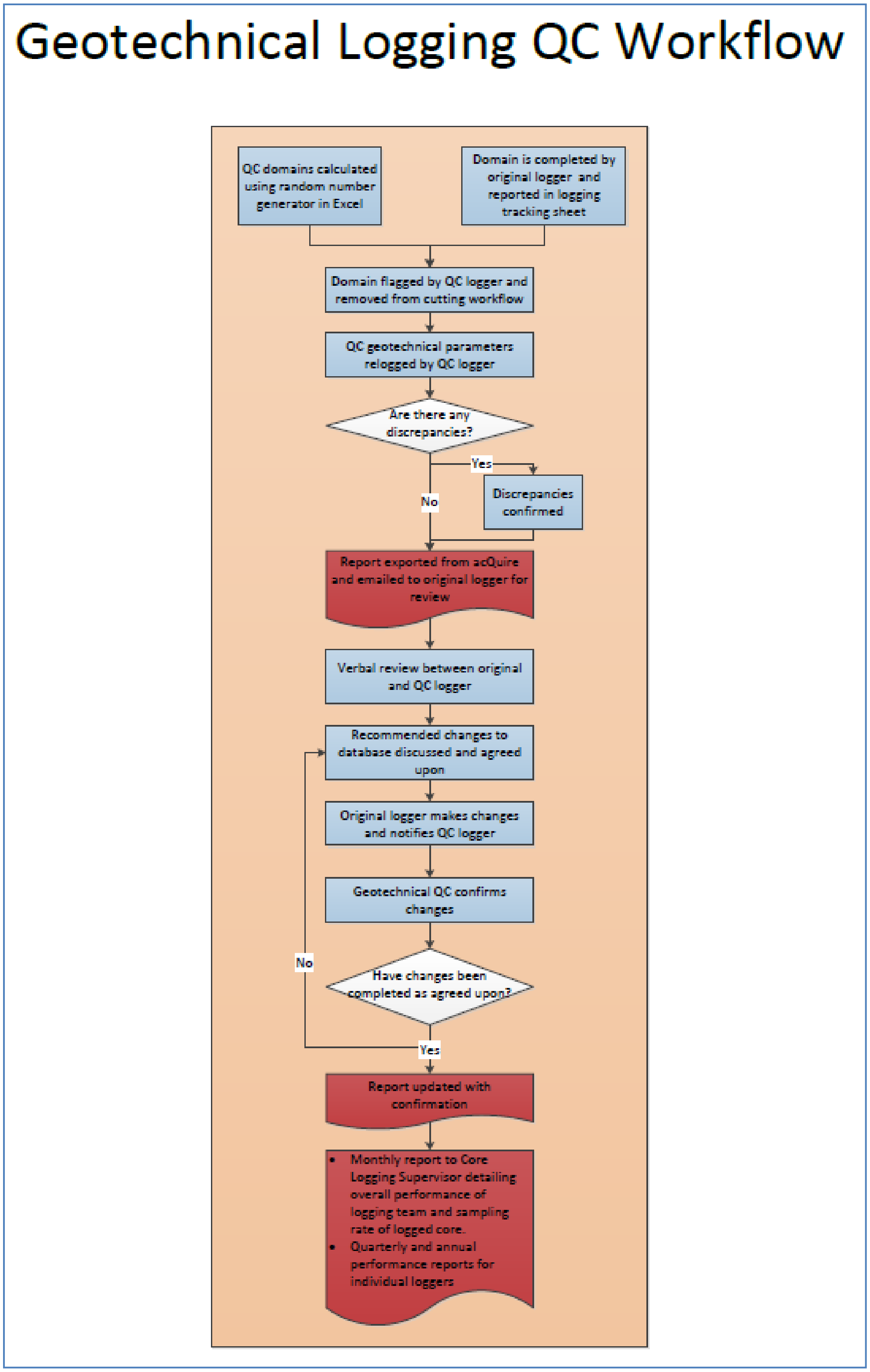


Figure 3-2. Geotechnical Logging QC Workflow (Subset) – Process control diagrams that provide additional detail on the model quality control (RCM, March 24, 2017).

3.4. acQuire Database: Analysis of Drill Hole Core Data

The primary source of geological, geotechnical, and metallurgical data for the Project is from the extensive analysis of drill core. The initial focus of the drilling was to develop a mineral resource model, with copper as the primary target. This has resulted in a higher density of drill holes within higher grade mineralized zones and less dense drilling in low-grade areas. External reviewers indicated that the database and the logging of lithology, alterations and mineralogy meets high industry standards (RCM, 2016a; 2016b; March 24, 2017; Parker, March 14, 2017; March 7, 2018).

RCM realizes several benefits in its use of a sophisticated, quantitative, digital logging system like acQuire. This geotechnical database program is designed to capture detailed lithology, alteration and mineralization attributes, as well as geotechnical data. To assure consistency, RCM has instituted a training program for their geologists and all loggers who are all degreed geologists. An important part of acQuire is the QC protocols designed to ensure consistency and accuracy for both geologic and geotechnical data. For this reason, geotechnical data entry templates are built within acQuire and embedded with the QC protocols to ensure data integrity, consistency and accuracy. The logged core data are entered into a separate database while logging and checked for QC before it is merged into the acQuire database that hosts the geotechnical data. The top figure in Figure C1 (Appendix C) shows the acQuire geotechnical logging template for data entry while logging core. The middle figure shows a borehole graphical log, built in WellCAD from an ABI survey, which illustrates the core information visually after logging is completed. The borehole log allows comparison of the various borehole information (for instance, RQD, ISRM strength, weathering, ABI image, etc.) along the hole. The bottom figure of Figure C1 shows a partial report of borehole data generated by a geomechanics reporting function in acQuire which demonstrates the core information in a series of histograms, cumulative graphs and pie charts that represent various core information (RQD, ISRM strength, fracture frequency, etc.). Figure C2 shows the arrival of the core in secured boxes and the warehouse where core is archived after logging. The top photo of Figure C3 shows a core during the logging process (Brandt et al., July 7, 2017) and the bottom photo shows a laptop computer used at the core logging station to input data directly into the acQuire database. The acQuire data entry template is also seen in Figure C3 being used in real time.

The sequence of how the core is logged is shown in Table 3-1. It illustrates a portion of the geotechnical logging workflow designed to assure sufficient data quality that will allow for future management and engineering decisions (RCM, 2016a; 2016b, March 24, 2017). Figure C2 in Appendix C has photos of step 1 (core delivery) and step 12 (secure archiving of core), while Figure C3 shows photos of step 6 (logging by geologist and real-time data entry).

Table 3-1. Geotechnical and geologic data input steps using acQuire (Pere et al., 2011).

Input Steps
1. Core delivery
2. Clean-up
3. Orientation
4. Preparation
5. Photography
6. Logging by geologist • Real-time data entry into acQuire template • Training and reference (chip-boards) to maintain consistency in lithologic description • Checking of logging by supervisor geologist • Ability to review and correct data entry in real time
7. Multiple test data entered into the acQuire database e.g., IR spectrometers, X-ray fluorescence meters, density, rock strength, ABI, etc.
8. Merge core data into the acQuire database
9. Statistical analysis and side-by-side data tables and charts of multiple data types
10. On-going data validation and secure error correction
11. Variance checks of re-logged data
12. Secure archiving of core

3.5. Near and Far Inference Cases

Two cases of data adequacy are considered using DQIs. The “near” and “far” cases consider how well sampling data can be used to infer the geotechnical properties of the in-place rock. As depicted in Figure 3-3, the near case (shown in green) is related to interpretation based on available information in the acQuire drill hole database, and the far case (shown in red) is related to the interpreted geology within the Vulcan wireframe model that is inferred by extrapolation. The bottom panel in Figure 3-3 shows an E-W cross section through the 2016 Resolution deposit model. Again, green signifies the area with interpolated data and dense drill sampling, whereas the red depicts the area where the geology has been extrapolated from more limited sampling.

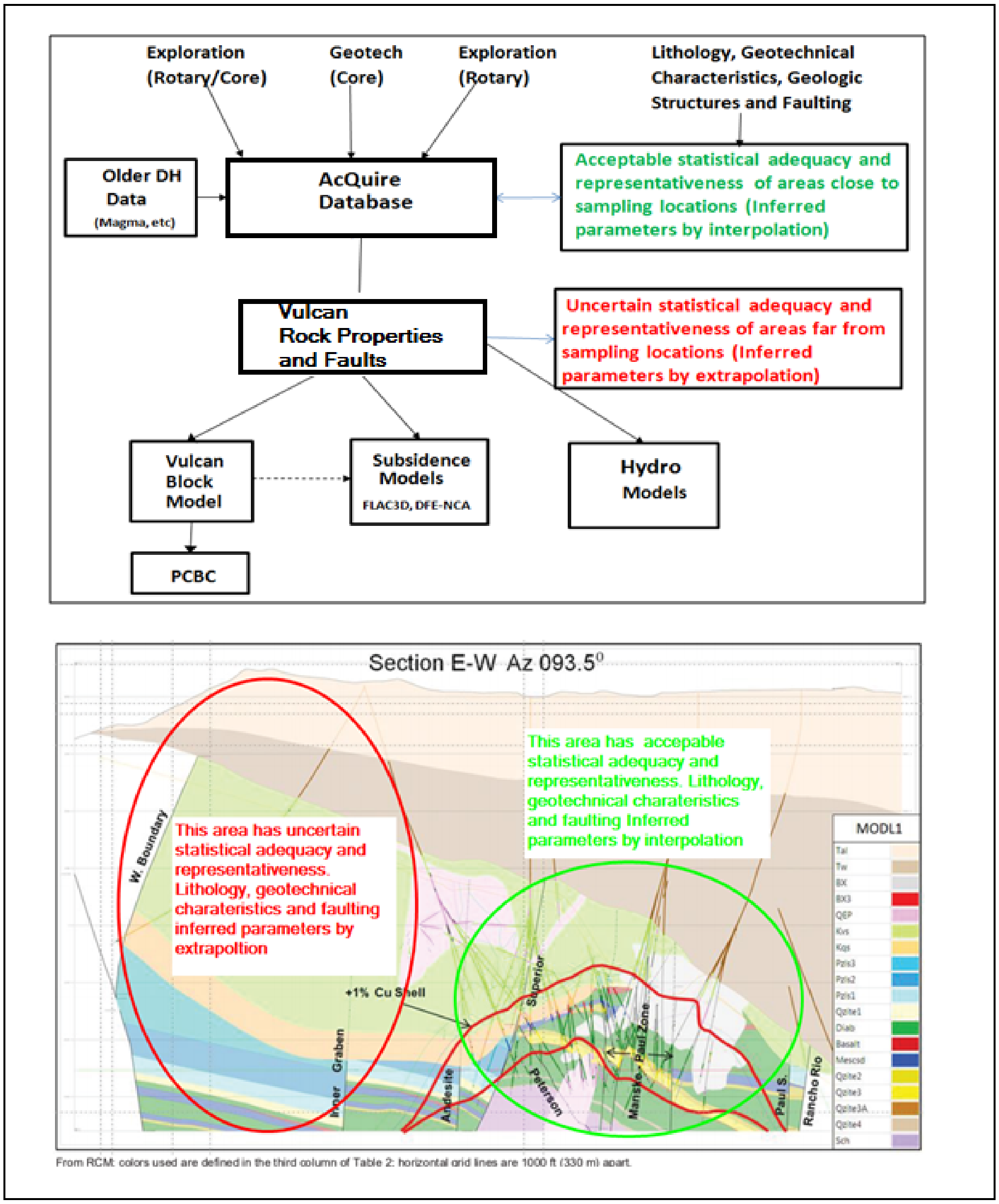


Figure 3-3. Top panel: Data flow from acQuire database to Vulcan model, rock properties and fault model (RCM Presentation during May 4-5, 2017 Site Visit). Bottom panel: Illustration of statistical adequacy of data in Vulcan model based on extrapolation distance. (Revised from RCM, March 24, 2017).

The near case considers whether there is acceptable statistical adequacy and representativeness of areas close to the sampling locations. This can be generalized as inferring data within the acQuire database to estimate in-situ rock properties by *interpolation***.** The far case can be considered as inferring data within the Vulcan model by *extrapolation*.

For the near case, the Workgroup concludes that RCM's program of logging drill hole geotechnical data meets and exceeds industry standards when checked against the seven DQIs (listed in Table

B2 (Appendix B)), as shown in Table B3 (Appendix B). These DQIs have been applied to the rock properties within the drill holes, such as lithology, fracture intensity, and rock strength (RCM, 2016c), as listed in Table B1 (Appendix B). DQI 4 (Representativeness) applies to how a sample is *statistically representative* of those parameters within the in-place rock being sampled. At the local scale, the Workgroup concludes that RCM's sampling program meets this DQI, that it is representative of the population. In addition to representativeness, the sampling program also meets the six other DQIs shown in Table B2 (precision, bias, accuracy, comparability, completeness, and sensitivity). This conclusion is supported by these observations:

1. The rock mass quality in the No. 10 shaft indicated that geotechnical data from drill hole cores are conservative (Itasca, February 21, 2011, RCM, August 5, 2018, Attachment 3).
2. Industry best practices and established standards and guidelines are applied to characterize the rock mass.
3. Historical mines within the same rock units have similar properties.
4. Multiple measurement methods produce confirmatory results.
5. Re-logging by different geologists produce similar results.

For the far case, the inference of geotechnical data becomes less certain as extrapolation distances increase. Observation of the drilling density indicates that most sampling occurs within the mineralized zone (1% copper shell). That is reasonable, as most drilling was completed to delineate the mineral resource. Outside the mineralized zone, sampling density falls, requiring sampled rock properties to be extrapolated over large distances. Visual inspection of the location of drill holes show large areas, including where subsidence is projected to occur, with limited or no sampling. These areas are outside of the mineralized zone and have rock properties extrapolated for distances of more than 1000 ft (305 m). In addition, fault positions are important as they can play an important role in the final shape of surface subsidence (Vyazmensky et al., 2010). Figure C4 (Appendix C) shows a cross section detailing a portion of the area within the 1% copper shell. This is the densest sampling at the Resolution deposit and illustrates a complexity of fault geometry that most likely exists at unsampled areas as well. A quote from an RCM consultant (Parker, March 14, 2017) describing the 2016 geologic and mineral resource model emphasizes how new drill holes in poorly sampled areas may change the interpretation of fault geometry:

> *"... the 2016 geologic model saw the addition of two new faults and significant revisions to five other faults, significant changes to the shapes and extents of the main Laramide intrusive and breccia bodies... Where substantial changes in the interpretation have occurred, these can be related to augmented interpretations based on new drill holes."*

With very limited data for the far case, the existence and/or position of a fault must be based on extrapolation of limited available data and professional judgement and not geostatistical analyses alone. This is where detailed surface mapping, an understanding of regional tectonics and faulting, and the application of structural geology principles are critical for proper fault interpretations.

3.6. Summary of Adequacy of RCM QA/QC Procedures and relevancy of DQIs.

This review of RCM's internal QA/QC procedures concludes that for the near case (the area of dense drill sampling in the mineralized zone), RCM's program of logged drill hole geotechnical data meets industry standards. The procedures were checked against seven DQIs selected by the Workgroup. These DQIs have been applied to the rock properties probed by the drill holes such as lithology, fracturing intensity, and rock strength (RCM, 2016c; October 5, 2017). These seven DQIs were used in determining that RCM's sampling and testing program was appropriately conducted. The Workgroup concludes that RCM's sampling program meets all seven DQIs for the near case.

For the far case (area outside of the mineralized zone), the Workgroup concludes that the extent of the extrapolation impacts fulfilment of the DQIs. Outside of the mineralized zone, sampling density falls rapidly, which requires rock properties to be extrapolated from fewer samples to greater distances. The Workgroup finds that these areas may not be representative based on data from a long distance away. This does not mean that the interpretations of rock properties and geologic data in the far case are wrong. Rather, it simply highlights that the rock property and fault information used in the subsidence modeling involved extrapolation of sampled data, and interpretation using professional judgement.

It is common, particularly for a project covering such a large area, to perform some extrapolation of sampled data to unsampled areas; there will generally be some level of extrapolation in such cases, as the subsurface in its entirety cannot be explicitly known and observed. The Workgroup finds that the interpretations of far case rock properties and assumptions are generally reasonable. Section 5.6 reviews the justification for extrapolating Tw rock mass properties that is back-analyzed using Tw rock unit behavior observed during the sinking of Shaft #10, to the entire mining area.

4.0 REVIEW OF RCM'S GEOLOGIC INTERPRETATIONS

This section provides a review of RCM's methodology for interpretation of geologic units (within fault blocks) and faults using drill hole data and geology mapping of surface structures. Beginning in 2002, RCM developed and revised a methodology and procedures for interpretation of geological structures and geological rock units (Parker, March 7, 2018). RCM has retained external consultants to review its geological and structural geology model to ensure it meets mineral resource and mineral reserve reporting standards.

The most recent updates to the structural and geological model were completed in 2014 and 2016 in which the data from the latest infill drilling were used to confirm the existing interpretation and/or to update the lithology and the fault model interpretations. The latest review of RCM geological and structural models was completed in March 2018 (Parker, March 7, 2018).

4.1. Geology and Geotechnical Database

The acQuire geology and geotechnical database contains data from 438 drill holes within the Resolution property, the majority of which are drilled within the 1% copper shell at depths targeting the ore body. As a result, the drill hole density is high within the 1% copper shell but is low away from the caving area and near the surface. Out of 438 drill holes, 135 holes (over 430,000 ft (131,000 m)) have been logged for geotechnical information (RCM, October 5, 2017). RCM has also conducted photogrammetric mapping of No. 10 shaft and its lateral developments during sinking and has information from historic surface mapping in the area and from the former Magma mine (RCM, October 5, 2017). Subsurface mapping provides information to further refine modelled geological units and structural geology (faults). This information has been used to interpret and develop geological units and structural geology models.

In interpreting geological units and structural geology, RCM divides the rock mass into several fault blocks. Each fault block refers to a volume of rock mass delineated by several faults and/or distinct boundaries or geological contacts. The rock mass within each fault block is further divided into layers of rock types that are interpreted based on the drill hole and surface mapping data and are separated by bedding planes.

4.2. Geologic Units Interpretation

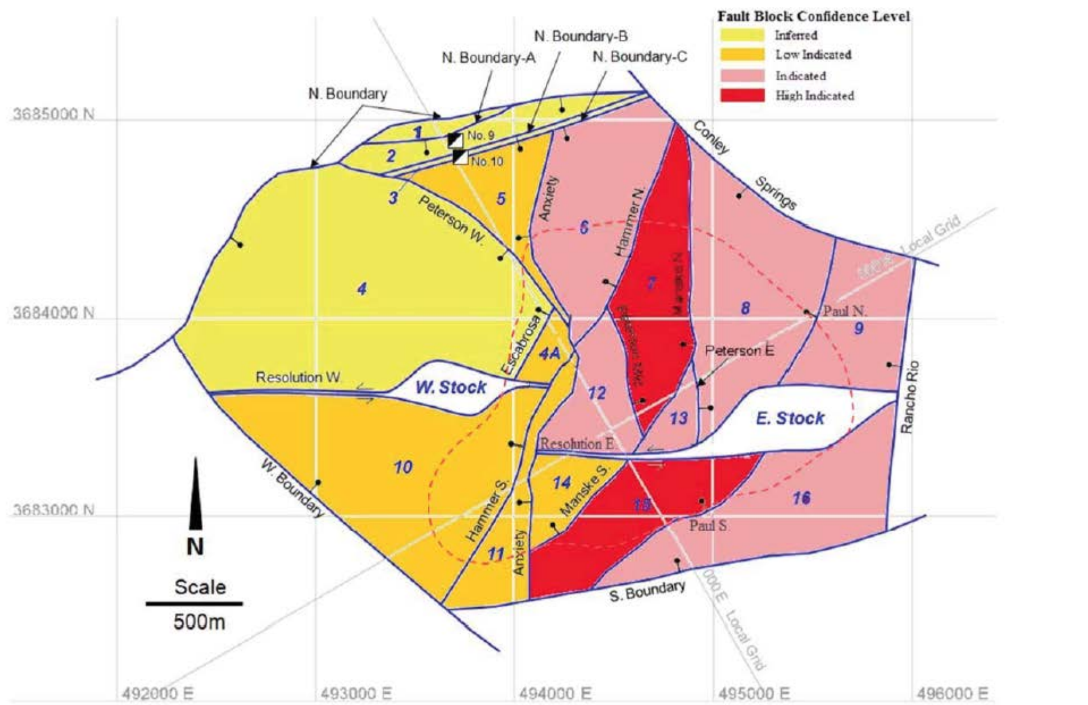
The ore grades at the Resolution Copper property are strongly controlled by lithology (RCM, March 24, 2017, Appendix 2). As such, RCM has incorporated the reliability of geological interpretation (lithology and faults) into mineral resource classification. This includes the confidence level in location, thickness, and elevation of the geological units, as well as the confidence in the interpreted faults that delineate various fault blocks.

The RCM lithology interpretation relies on bedding plane location and orientation. RCM uses a nine-step procedure to interpret lithological units within a fault block (Parker, March 7, 2018) beginning with identification of the bedding plane contacts on horizontal and vertical cross sections followed by developing contact surfaces from digitized contacts on multiple cross sections. This process is repeated, and contact surfaces of all lithologies are constructed.

Reference geology and contact surfaces and fault planes are used to delineate the extent of each fault block. As a check, RCM uses radial cross sections through each drill hole to confirm that the modeled (interpreted) contact surfaces correspond with the logged lithology contact in the core. RCM has applied this nine-step procedure to interpret lithology where there are sufficient drill hole or surface mapping data available.

Based on the level of confidence in Resolution's geological (rock type) interpretation within a fault block, the interpretation of that fault block is qualitatively rated by Amec Foster Wheeler as "Inferred", "Low Indicated", "Indicated", and "High Indicated" (Parker, March 7, 2018). These terms are used qualitatively by RCM, depending on the amount of geologic information available from drill holes within the fault blocks and based solely on professional judgement. This qualitative rating is dependent on the number of "significant" holes piercing through the fault block and the amount of information available from each hole to help geologists interpret the fault. A drill hole is generally considered significant if it pierces through multiple geological units within the same block. Fault blocks are interpreted as "Inferred" if there are less than three significant holes to characterize the lithology. Likewise, at least three significant holes are required to characterize the block as "Indicated". The "High" or "Low" prefix is assigned based on the number of significant holes and the geologic data available from the significant holes. The Workgroup finds that this approach to rating the confidence levels in fault block interpretations to be reasonable, with enough information for the reader to understand the assumptions behind these ratings.

Figure 4-1 shows a map indicating the confidence level in interpreting geological units in all fault blocks within the Resolution property (Parker, March 7, 2018). All blocks within the center of the caving operation are rated as Indicated or High-Indicated (fault blocks 7, 8, 12 and 13). The interpretation of several of the fault blocks outside this zone is considered Inferred based on limited core and mapping data, which could result in less certainty about the strike, dip, and position of the contacts and geological units.



Base from RCM. Confidence levels from Amec Foster Wheeler; the future mining area lies within red dashed line. Grid intervals are 1000 m (3300 ft).

Figure 4-1. Confidence level for fault blocks (geological units) (Parker, March 7, 2018).

RCM has also evaluated the uncertainty in elevation and thickness of the geological units using conditional simulation. In this approach, equi-probable images of the geological units and faults are simulated according to pre-defined uncertainty estimates provided by Resolution geologists. The simulated rock types within each fault block are compared with the modelled geological units and the perpendicular distance of the modelled unit to the simulated one is calculated on either side of the geological unit contact. In the simulation, the limit of variation for the geologic unit elevation was assessed to be ±100 ft (±30 m) and that for the geologic unit thickness was assessed as ±20% of the interpreted thickness (Verly et al., 2009). This variation limit represents variability within two standard deviations for each parameter. A comparison of the simulation volume with that of the interpreted model shows a change in volume of less than 2%, which is considered very good (Parker, March 7, 2018). The Workgroup agrees with Parker's (March 7, 2018) conclusions and considers that comparison to be a good fit.

4.3. Structures/Faults Interpretation

Faults are typically represented in the drill core as broken core zones with gouge infills of variable thickness. Slickensides are normally associated with faulting and displacement across a fault plane. Faults can also be identified from disruption in continuity of geologic units when projected across multiple drill holes. The fault orientation, thickness and depth along hole can be more accurately measured from ABI logs of the borehole walls.

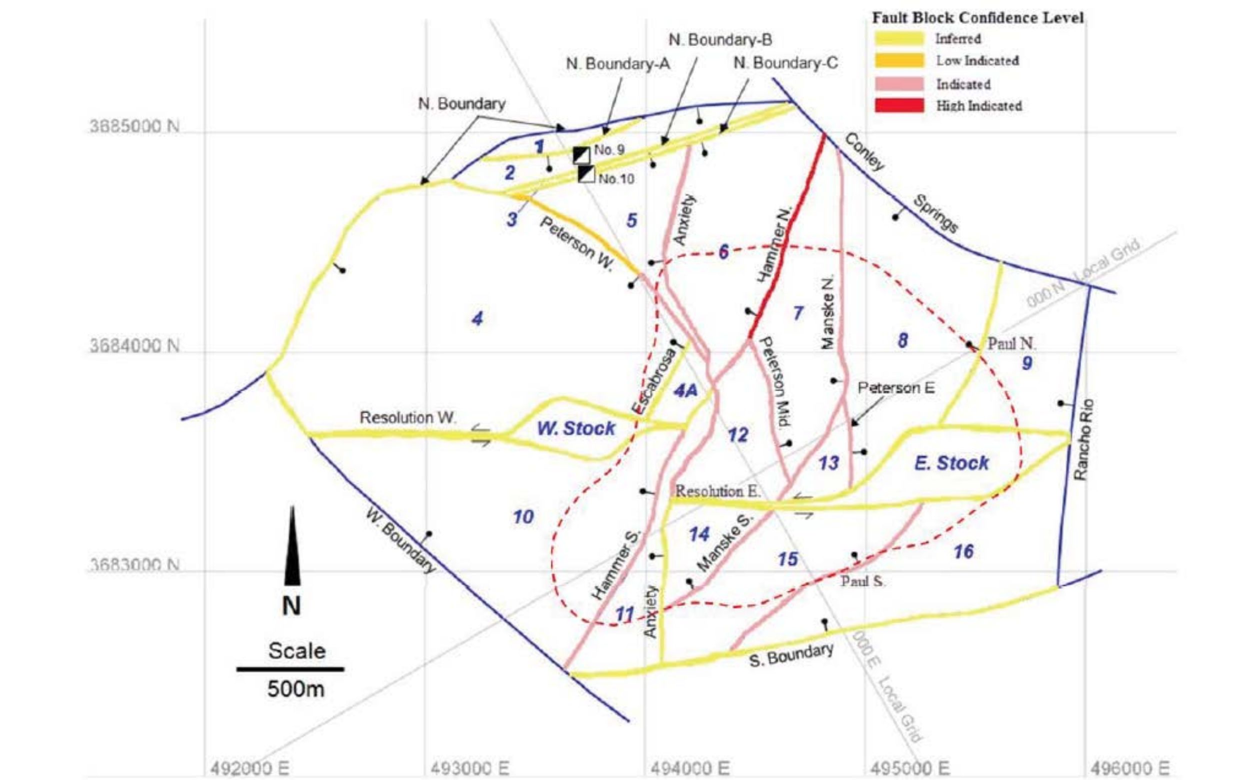
RCM used ABI logs, core data and core photos to identify and characterize faults and fault zones. As part of the structure picking process to orient the core, RCM measured fault surface orientation accurately from ABI logs. In addition to drill hole data, RCM mapped discontinuities including faults and fault zones in the lateral development and while sinking the No. 10 Shaft. The structural data was then plotted on a stereonet and key structural controls (faults, joint sets, etc.) were determined. RCM has associated major faults/fault zones to having a displacement (across fault plane) of greater than 50 ft (15 m) (Parker, May 7, 2018). Faults with displacements less than 50 ft (15 m) have not been considered by RCM as major structures. The Workgroup agrees that this is a reasonable cutoff for fault displacement used in modeling.

RCM has improved its fault model since 2012 with additional infill drilling. It has updated the interpretation of the existing faults and/or has identified new faults within the Resolution property. Through additional drilling, RCM has identified marker bedding planes (quartzites) within the stratigraphic sequence that can be used to confirm approximate bedding plane orientations measured from core (Parker, March 7, 2018). With the majority of drill holes targeting the orebody within the 1% copper shell, the faults and fault zones are well defined and characterized. Infill drilling after 2012 and 2014 programs has improved the fault interpretation in the outlying areas outside the 1% copper shell (Parker, March 7, 2018).

While televiewer data can be used to identify a fault and measure its orientation, the location of the fault can vary $\pm$50-200 ft (15-61 m). RCM has retained Amec Foster Wheeler to evaluate and develop a confidence level for each interpreted fault. Amec Foster Wheeler evaluated each fault separately using two adjacent intersecting fault blocks and associated drill holes that pierce through the fault plane (Parker, March 7, 2018).

Similar to fault blocks, Amec Foster Wheeler rated faults as Inferred, Low Indicated, Indicated, and High Indicated based on the number of holes that pierced through the fault plane (Parker, March 7, 2018). To rate a fault plane as Indicated, a minimum of three holes are required to pierce through the fault plane and confirm its orientation. The Low and High prefix refers to the length of the fault trace between fault blocks and the number of holes piercing the fault plane.

As reported by Parker (March 7, 2018), Amec Foster Wheeler evaluated all identified faults and created a color-coded map showing the confidence level used in interpretation of each fault (Figure 4-2). As shown, faults in the center of the mining area are considered to have Indicated or High Indicated confidence levels. It is notable that the faults in the perimeter of the map (colored in blue) were not rated at the time of the study due to a lack of drilling data. These faults, however, have been rated as Inferred based on the information from subsequent surface infill drilling programs.



From RCM. Confidence levels assigned by Amec Foster Wheeler; the future mining area lies within the red dashed line; grid intervals are 1000 m (3300 ft).

Figure 4-2. Confidence levels for faults (Parker, March 7, 2018).

The uncertainty about fault position has also been evaluated using conditional simulations (Verly, 2009; Parker, March 7, 2018). In a similar approach to geological unit position uncertainty, fault surfaces are interpreted and created from borehole data. Fault surfaces are then simulated based on the geologist's estimate of limit of variation of fault position (the standard deviation of the distance from the simulated fault plane to the modeled/interpreted fault plane). The latter is estimated for both sides of the fault plane and may not be the same on both sides. Close to drill hole pierce points the standard deviation of distance is low, but away from pierce points and where there are few holes, the standard deviation is high. The results indicate the average percent change between a simulated fault position and the corresponding modeled/interpreted fault position is reasonably low and unbiased (Verly, 2009; Parker, March 7, 2018).

The Camp and Gant faults, although important faults in the proposed subsidence zone, were not intersected with boreholes. The geological character of these faults has, however, been estimated by field mapping (RCM, June 28, 2018b). See Sections 5.5 for discussion of sensitivity analyses to evaluate a range of fault strength properties and their impacts on subsidence.

Following publication of the DEIS, some public comments noted the presence of lineament features observed on Google Earth imagery, in the vicinity of the modeled subsidence zone. These lineaments were determined by the Workgroup to represent the West Boundary Fault and the Gant Fault. Both the West Boundary and Gant faults were included in RCM's geologic model and subsidence model (RCM, February 26, 2020). This is further discussed below in Section 5.4.3

4.4. Geological Modeling and Interpretation

At Resolution, geologic modeling and interpretation has been informed by regional studies and mapping, site-specific mapping of lithology and faults, borehole data, and sound geological principles. Modeling and interpretation of mineralization and alteration has also been informed by classic porphyry copper deposit models (e.g., Lowell and Gilbert, 1970).

As is conventional in the mining industry, RCM uses the Vulcan software platform for three dimensional (3D) geologic modeling. The Vulcan geologic model uses faults, other structures, and lithologic and geotechnical domains to produce a structural wireframe model. The process of identifying and interpreting fault blocks, and fault structures, was reviewed in previous sections.

The Vulcan model is updated periodically with new borehole data. The resulting block model is based on each block representing a geotechnical domain with a characteristic lithology, rock strength, mineralization, and alteration. Finally, RCM confirms the interpreted geology and structural models by infill drilling in areas already drilled and used in the model (Parker, March 7, 2018), and by comparing the distribution of similar rock types to nearest-neighbor geology models (RCM, March 24, 2017). These practices are generally considered industry standard.

4.5. Summary of RCM's Geologic Interpretations

RCM has developed a robust and sophisticated process for data collection (core logging, ABI surveys, surface and underground/shaft mapping, and statistical methods) and interpretation of geological data, and has generated and refined geological and structural (faults) models for the Project. RCM has improved its geological and structural interpretations through continuing data collection programs and using industry-standard methodology and tools.

RCM has placed a strong emphasis on developing a reliable and accurate geological model because lithology is a key control on ore grade for mine planning. Various lithologies are identified and modeled using core and ABI data. RCM has also revised and updated its structural geology and fault block (geological units) models over the last several years. Faults are interpreted in the geological model where discontinuities are present indicating displacement of the marker bedding planes or contacts across fault planes. Many faults have been identified and interpreted within the Resolution property. Those faults pre-dating mineralization are strongly annealed by veins of hydrothermal quartz or anhydrite, and intrusive dikes and sills. The infill in some faults is stronger than the surrounding rock, increasing the rock mass strength (RCM, October 5, 2017). The post-mineralization faults are generally reported to be weaker. The majority of faults that are observed on surface and are mapped are post-mineralization. Surface subsidence may be impacted by post-mineralization faults located around the perimeter of the cave zone and may work to extend the subsidence zone laterally. Parker (March 7, 2018) states that RCM interpretations of faults and fault blocks are considered high quality and acceptable for subsequent geotechnical modeling, subsidence prediction and impact assessment.

The Workgroup finds that the interpreted structural and geologic models presented by RCM are reasonable and supported by adequate data collected according to industry-accepted methods, tools, and standards.

5.0 REVIEW OF THE SURFACE SUBSIDENCE MODEL

RCM retained Itasca to conduct an advanced 3D numerical modeling assessment of ground surface subsidence resulting from the proposed panel cave operations at the Resolution Copper property.

5.1. Review Scope

The main objectives of this review are to assess:

- Whether the methods used to evaluate surface subsidence are adequate and appropriate
- Whether the assumptions considered are reasonable and the subsidence criteria used to predict subsidence are valid and acceptable, based on industry practice
- Whether the rock mass and discontinuity strength properties used in the model are representative of the rock mass conditions at Resolution
- Whether the key faults/fault zones are included in the model
- Whether the cave mining operation and subsidence progression to surface are adequately simulated
- Whether the model appropriately and reliably predicts the potential impacts to Apache Leap, Highway US-60, and Devil's Canyon.

The RCM study also included an assessment of the potential impacts to mine infrastructure (shafts, surface facilities, etc.); however, these impacts fall outside the scope of this report. The subsidence impacts to mine infrastructure will therefore not be included herein.

Section 5.2 provides an overview of the cave-induced surface subsidence, and the spatial characteristics of the various subsidence zones defined by the magnitude of ground movements, and the extent of ground cracking as it applies to panel caving at Resolution. The latter definitions are based on accepted terminology currently used in the mining industry in practice.

Section 5.3 reviews and summarizes the results of an empirical assessment of the Resolution panel cave conducted by RCM and determined a first approximation of the cave angle. Section 5.4 summarizes the results of the review of Itasca's detailed 3D numerical assessment of the surface subsidence at Resolution. Section 5.5 summarizes the results of sensitivity analyses of various geotechnical parameters and in situ stress regime on the numerical assessment results. Section 5.6 discusses global rock mass strength properties of Tw and Tal rock units in more details.

5.2. Panel Cave Induced Surface Subsidence - Background

Itasca (June 18, 2018, August 1, 2018) described, in general terms, surface subsidence associated with block and panel cave operations, as well as the methodology, damage criteria and associated thresholds considered to predict the onset of subsidence-induced damage from the numerical model. RCM provided these memoranda to the Workgroup as part of its response to Data Request #9 (RCM, June 29, 2018) and clarifications to follow-up questions on RCM response to Data Request #9 (RCM, August 5, 2018). A summary of information provided in the

Itasca memoranda is presented here to establish background information on caving-induced surface subsidence.

Mining-induced subsidence is the settlement of the ground surface as a result of underground mining, particularly in cave mining operations where it can be pronounced. In caving operations, as ore is extracted at depth, voids are created and then filled by the overlying rock mass as it loosens and moves downward. As the cave propagates towards surface a characteristic depression is formed which is generally referred to as “discontinuous subsidence”. This is typically associated with large, discontinuous step-shaped vertical displacements (Brown, 2003). The extent and shape of the caving-induced surface subsidence can be influenced by many factors including (Brown, 2003):

- The dip of the orebody
- The shape of the orebody in plan
- The depth of mining and the associated *in-situ* stress field
- The strengths of both the caving rock mass and the rocks and soils closer to the surface
- The slope of the ground surface
- Major geological features such as faults and dykes intersecting the orebody and cap rock
- Prior surface mining
- The placement of fill in a pre-existing or the newly produced crater
- Nearby underground excavations.

Surface disturbances by block and panel caving have been described by Lupo (1998), Van As et. al. (2003) and Sainsbury et al. (2010) as zones characterized by the Crater, Large-Scale Surface Cracking (Fractured Zone), Small-Scale Displacement Zone (Continuous Subsidence Zone) and the Stable Zone. Van As et al. (2003) and Sainsbury et al. (2010) proposed the terminology shown in Figure 5-1 to describe caving-induced subsidence features.

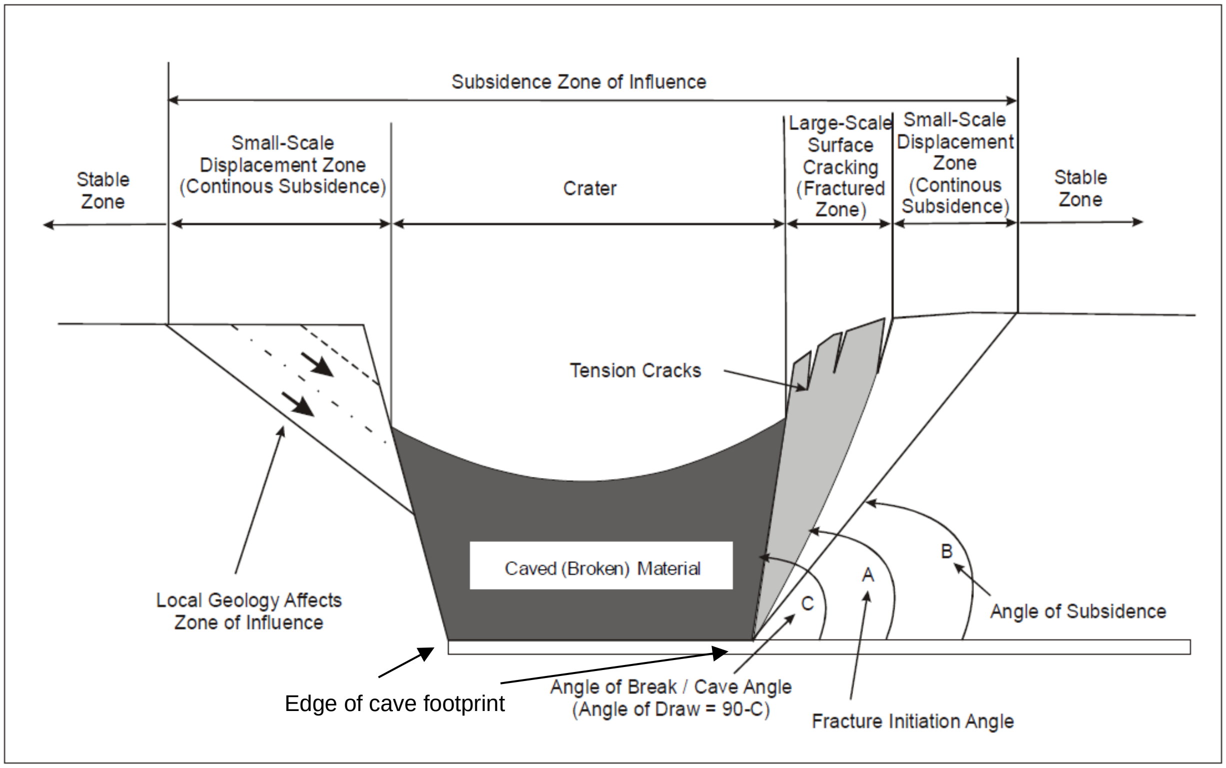


Figure 5-1. Terminology used to describe caving-induced surface subsidence features (Van As, et al., 2003, Sainsbury et al., 2010).

5.2.1. The Crater

The caved rock zone develops as the mobilized volume reaches the ground surface, causing the ground surface to both break up and subside a substantial amount. The outer limit of this zone is called the Crater Limit (Itasca, August 1, 2018). The Crater is located immediately above the undercut footprint in which the rock mass has experienced the greatest disturbance and is usually filled with broken irregular rocks (Woo et al., 2013). The magnitude of vertical displacement in the Crater, at maximum, is normally in hundreds to thousand feet (tens to hundreds of meters), depending on the size, shape and depth of the orebody.

5.2.2. Fractured Zone Limit

The Large-Scale Surface Cracking (Fractured Zone) is an area around the Crater and is characterized by open cracks with large vertical displacements and a step-shaped profile. The Fractured Zone Limit is the boundary between Fractured Zone and the Continuous Subsidence Zone (Figure 5-1). The primary failure mechanism associated with Fractured Zone is shear failure of the rock mass. Tensile failure and other modes of ground movement including toppling and block rotation are also present but appear to be secondary mechanisms (Itasca, June 18, 2018, Itasca, August 1, 2018). Hairline cracking within this zone is possible and can be correlated to total vertical displacement induced by caving. Ground monitoring at other sites (Clayton et al., 2018) has demonstrated that subsidence must reach a threshold before hairline cracks initiate on the ground surface. This threshold for crack initiation is site-specific and must be determined through instrumentation and monitoring once cave mining begins.

5.2.3. Continuous Subsidence Zone Limit

The Continuous Subsidence Zone is the area beyond the Fractured Zone Limit where ground movements occur without associated visible fracturing and can only be detected with high resolution instruments (LiDAR scan, ground survey, high resolution photogrammetry, etc.). The limit of the Continuous Subsidence Zone is not as well defined as the Fractured Zone Limit because delineation of this zone in practice is a function of the precision of the monitoring system used (Itasca, June 18, 2018, Itasca, August 1, 2018) and this varies between mine sites.

5.2.4. Cave Angle, Fracture Initiation Angle and Angle of Subsidence

Cave angle is defined as the angle from horizontal from the edge of the undercut level to the edge of the crater. Fracture initiation angle is defined as the angle from horizontal from the edge of the undercut level to the outer limit of the fractured zone (the boundary between the Fractured Zone and the Continuous Subsidence Zone) and angle of subsidence is the angle from horizontal from the edge of the undercut level to the outer limit of the Continuous Subsidence Zone. The Crater Angle, the Fractured Initiation Angle and the Angle of Subsidence are shown in Figure 5-1.

5.2.5. Mining-Induced Surface Displacements

Mining-induced surface displacements can be broken down into five major components (Harrison, 2011) including:

- Vertical displacement
- Horizontal displacement
- Tilting
- Horizontal strain
- Angular distortion.

According to Harrison (2011), uniform vertical and horizontal displacements alone do not generally cause damage to surface infrastructure. Itasca (June 18, 2018, August 1, 2018) referred to examples provided by Singh (2003) of an observation tower that sank 30 ft (9.2 m) in a coalfield, mining structures that subsided a similar amount around the sulfur mining areas off the coast of Louisiana and a church in a potash-mining district that settled 20 ft (6.2 m), all without significant damage.

Tilting is defined as the rigid body rotation of rock blocks/formations as a result of differential vertical displacements and can impact the stability of tall slender rock formations, such as those observed at Apache Leap. Turichshev et al. (2010) suggested that tall slender formations are susceptible to toppling at tilt angles greater than 7.5 degrees.

Strain is the relative change in shape or size resulting from applied forces (stresses). Horizontal strain is the ratio of horizontal displacement over horizontal length between two points. Angular distortion is the ratio of the differential settlement over horizontal length between two points (slope) minus the tilt angle, if the object has tilted (Laefer et al., 2010).

The limit of the Continuous Subsidence Zone associated with cave mining is normally related to strain (rather than displacement), as this is what causes damage to the surrounding rock mass and surface infrastructure (Itasca, June 18, 2018, Itasca, August 1, 2018, Harrison, 2011). Harrison (2011) suggested that serviceability governs whether subsidence can be tolerated, and that ground movement is tolerable if it does not require repair. The concept of tolerability of ground movements has led to the development of empirical classification schemes that correlate potential damage to infrastructure to the anticipated strain in the infrastructure. The application of one of these schemes to classify caving-induced damage to rock mass at Resolution is discussed in Section 5.4.

5.3. Block/Panel Cave Empirical Assessment

RCM evaluated initial deterministic estimates of subsidence cave angle using Laubscher's empirical method (Brown, 2003, Laubscher, 2000, Laubscher and Jakubec, 2001) introduced in Section 2.3.2. Laubscher's method is based on the MRMR ratings of the geotechnical domains (geologic units) at Resolution, height and density of the caved material, and the depth and span of the cave. The empirically derived deterministic cave angle ranged from 72º to 84º, with an average value of 76º (RCM, 2016b).

Itasca was retained by RCM to carry out a probabilistic assessment of Laubscher's empirical method to account for variability in rock mass properties on predicted cave angle (Itasca, May 16, 2019). The probabilistic assessment was carried out using a Monte Carlo simulation to estimate a distribution of cave angle over seven cross-sections. The cave angle distribution was simulated at both ends of each cross section resulting in fourteen cave angle distributions representing variability of cave angle across various geological units around the cave. The variability in geological units was represented by assigning a normal distribution to the in-situ rock mass rating (IRMR) of each geologic unit with mean and standard deviation obtained from core data (Itasca, July 17, 2017, RCM, October 5, 2017). Monte Carlo simulation was carried out for 10,000 iterations where at each iteration IRMR value was picked from corresponding distributions of each geologic unit and adjusted for the ratio of hoop stresses to global rock mass strength to obtain mining rock mass rating (MRMR). Cave angle distribution was then developed following the same procedure described above at each cross section. To account for rock mass variability along depth at each cross-section, each cross-section was divided into 33 ft (10 m) segments and MRMR was estimated for each segment. The results indicated that the average (mean value) cave angle around the cave at 14 locations varied from 74º to 79º with a standard deviation of 2º. This study suggested an average cave angle of 77º (Itasca, May 16, 2019), which is in close agreement with the deterministic empirical assessment result of 76º.

An empirical investigation was conducted by Woo et al. (2013), using observations from a large number of caving operations, to characterize caving-induced surface subsidence. A comprehensive database was developed from this study. In this work, the impact of depth of orebody and extraction level, geologic structures (faults), rock mass characteristics, topography, and in-situ stress distribution on surface subsidence, Fractured Zone Limit and cave angle was evaluated. Also, in this study, data from caving operations were plotted and the impact of each parameter on cave angle, Fractured Zone Limit and surface subsidence were evaluated. Figure 5-2 and Figure 5-3 show the empirical relationship between the cave angle and the fracture initiation angle with the undercut depth from caving operations included in the Woo et al. (2013) database. Each line segment in the figures represents the range in caving angles measured from different sides of the undercut. The increase in range of caving angle indicates a higher degree of asymmetry in surface subsidence. Although there are few cases in the database that were developed at depths greater than 3280 ft (1000 m), the empirically derived cave angle range of 68º-84º (minimum to maximum cave angle range) are generally in agreement with the cave angle ranges reported by Woo et al. (2013) even though the empirical method does not take into account topography, in situ stress distribution and presence of geological structures.

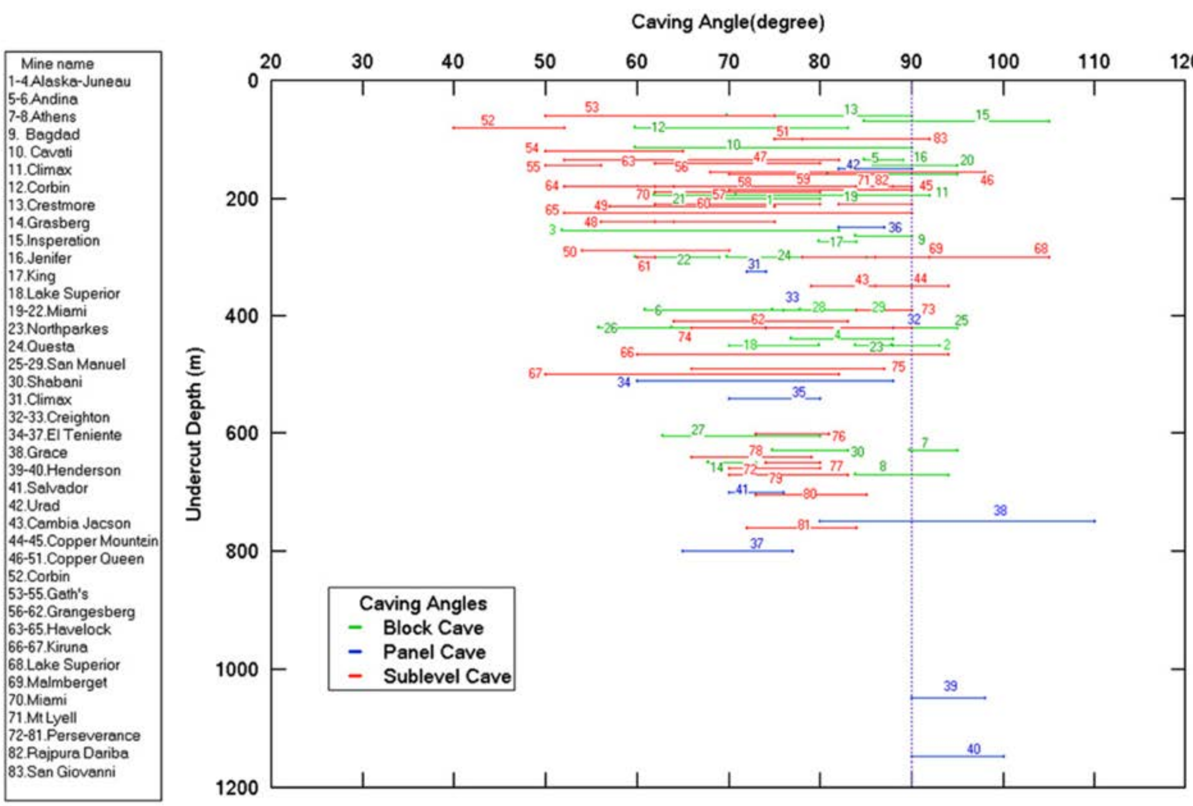


Figure 5-2. Empirical relationship between the cave angle and the undercut depth from caving operations included in the Woo et al. (2013) database.

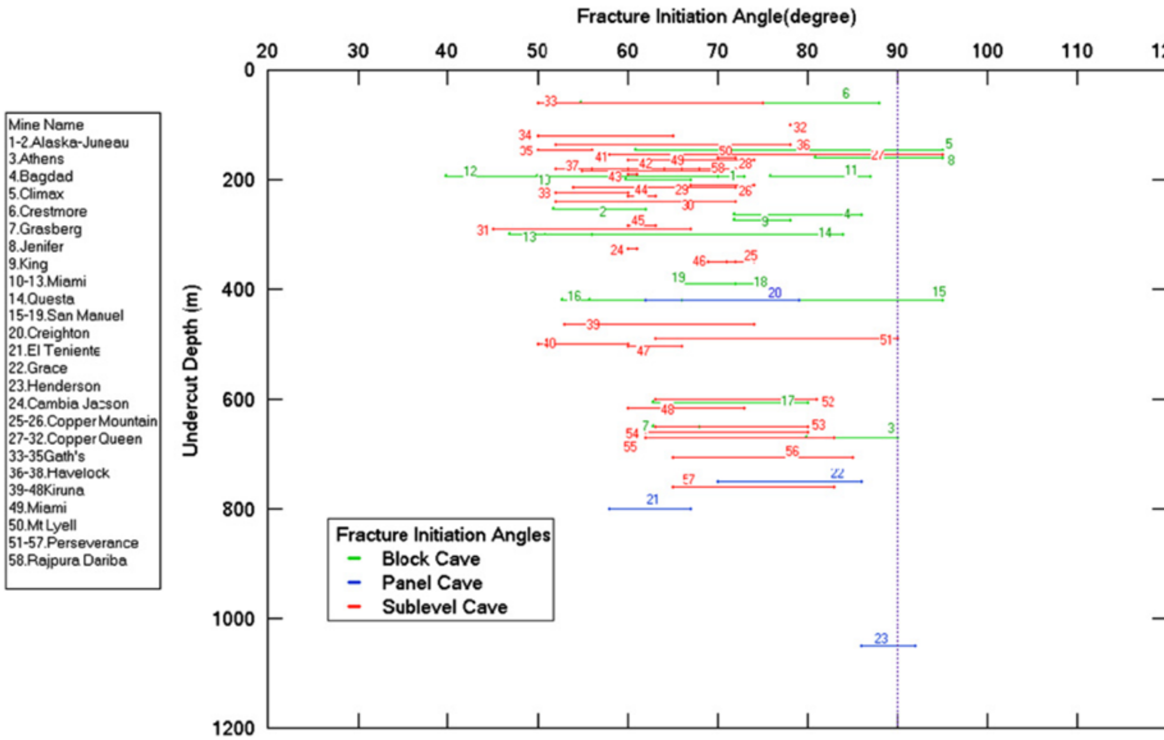


Figure 5-3. Empirical relationship between the fracture initiation angle and the undercut depth from caving operations included in the Woo et al. (2013) database.

It is important to note that empirical methods, while allowing for the prediction of key controlling factors on a cave operation (e.g., surface subsidence, cave angle) at early stages and with limited data, inherently include one or more assumptions that could impact the resulting surface subsidence and cave angle, and will likely ultimately contribute to uncertainties in the empirical cave design methodology and conclusions. These uncertainties should carefully be considered when an empirical approach is used. These uncertainties include, but are not limited to:

- Rock mass heterogeneity and strength properties, including spatial variability of rock mass properties
- Geological structures (fault/fault zones), their infill characteristics, spatial variabilities, and strength properties
- Local in-situ stress distribution including stress magnitude, orientation, and the stress ratio, which is a key factor in defining a local stress regime.

Considering the limitations above, RCM has used the empirical approach as a first approximation to estimate the cave angle and the Workgroup agrees with this approach. Proper assessment of the surface subsidence resulting from a caving operation requires detailed geological, structural, and geotechnical information within a detailed numerical assessment framework to adequately address these uncertainties mentioned above. The results of such assessment are discussed further in Section 5.4.

5.4. Surface Subsidence Prediction Model

A 3D numerical model was developed for the proposed RCM panel caving operation based on the Cave-Hoek constitutive model using FLAC3D finite difference code (Itasca, July 17, 2017; 2017). FLAC3D has been widely used to simulate block cave operations and has become an industry standard to predict the extent of ground surface subsidence from caving operations. The FLAC3D model simulates cave mining and predicts surface subsidence according to a mine production schedule.

RCM provided geologic units, a structural geology model, geotechnical domains and geotechnical properties associated with each domain, and the mine production schedule for input into the numerical model. The following assumptions were considered in the development of the numerical model (Itasca, July 17, 2017, Itasca, Aug. 3, 2018, Itasca, Aug. 29, 2018, RCM, June 28, 2018, RCM, Aug. 2, 2018).

5.4.1. Model Assumptions

- Faults were simulated implicitly as distinct weak rock masses rather than explicitly with interfaces. This assumption is considered reasonable because, at the Resolution property, faults are generally comprised of zones of relatively weaker rock mass (compared to the surrounding host rock) and are not necessarily discrete features.
- Geological Strength Index (GSI), which is a measure of the state of relative blocky-ness of the rock and joint surface conditions, was considered applicable to all rock mass domains to characterize rock mass structure. Typically, the application of a GSI value to a specific rock domain depends on the state of rock fracturing, the number of joint sets present in the rock mass and the joint sets persistence (continuity). Therefore, the global application of GSI to a rock domain at the Resolution site may result in underestimation of rock mass properties where this criterion is not applicable to a specific rock domain (i.e., Tw domain, because the interpreted GSI value would require three joint sets to be present and joints sets are presumed persistent).
- Only faults and faults zones are included in the model. Rock mass discontinuities (dominant joint sets) are not included in the model. Although they provide more flexibility to the rock mass to deform, discontinuities are at much smaller scale (rock fabric scale) compared to faults/fault zones and their impact on surface subsidence is more local and is strongly controlled by discontinuity orientation. In addition, RCM has downgraded UCS values obtained from PLT tests to account for the scale effect and the presence of defects in the rock mass.

The following sections summarize details on the numerical model geometry, structural geology model, and material properties used in the numerical model.

5.4.2. Subsidence Model Geometry

The subsidence model dimensions are approximately 9.4 mile x 7.9 mile x 1.9 mile (15.2 km x 12.6 km x 3 km), with the mine panel cave located in the center of the model. The model geometry was large to maintain model boundaries at a sufficient distance from the subsidence area to minimize boundary effects on the subsidence simulation. The mesh consists of 940,000 “zones”, with the smallest zone length, or element dimension, of 65 ft (20 m) applied to the extraction level, near ground surface areas, and near faults. The zone length is increased to 525 ft (160 m) at the limits of the model, away from the crater zone.

5.4.3. Geology and Structural Geology

The validity of procedures for interpretation of geological units and the structural geology (faults) model was discussed in Section 4.0. In this section, the geologic units and structural geology for input into the subsidence model are reviewed.

RCM provided the geologic units and structural geology model for the Resolution property in the form of a series of DXF wireframes and triangulated surfaces, respectively. The geologic units and faults were based on the latest model update in 2016. In the subsidence model, faults were modeled implicitly as a zone of weak rock mass, rather than as a planar interface. As stated previously, this is considered reasonable when faults are comprised of zones of weak rock mass rather than a distinct fault plane, with competent rock on either side.

As part of the interpretation, faults were characterized as strong, medium, or weak, based on the infill character:

- Strong – faults that are strongly annealed.
- Medium – faults described as mixed, with open and annealed shears with local gouge and local intense damage.
- Weak – faults described as slickensided shears, heavily damaged, brecciated and/or with gouge.

Among the faults that are observed on surface, only Monarch fault and Camp fault are rated by RCM as Strong and Medium faults, respectively. The remainder of the faults (exposed on ground surface) are modeled as Weak. Table 5-1 lists the qualitative ranking of the faults used in the subsidence model. Figure 5-4 shows the faults that are persistent to ground surface and their qualitative ranking (Itasca, July 17, 2017). The properties assigned to faults are indicated in brackets for each fault type in Table 5-1 and are discussed in Section 5.4.4 below.

Table 5-1. Qualitative ranking of the faults at Resolution used in the subsidence model (Itasca, July 17, 2017).

Strong (75 % σ_{cm}[1])	Medium (50 % σ_{cm})	Weak (Residual Properties)
Manske	Andesite	326 Pump Station
Monarch	Camp	Anxiety
MP-1	Hammer N	Concentrator
MP-2	Hammer S	Conley Spring
Mp-3	Hammer SW	Devil's 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	

[1]: σ_{cm} represents global strength of the host rock mass

Following issuing of the DEIS (TNF, 2019), the Gant W Fault was misidentified in a public comment (Malach, March 17, 2019) as the West Boundary Fault. Malach commented that the West Boundary Fault had been incorrectly mapped, potentially affecting the predicted subsidence towards Apache Leap. RCM (February 26, 2020) compared the misidentified fault with the Structural Geology Model and demonstrated that the misidentified fault is the Gant W fault and that West Boundary Fault has been correctly mapped.

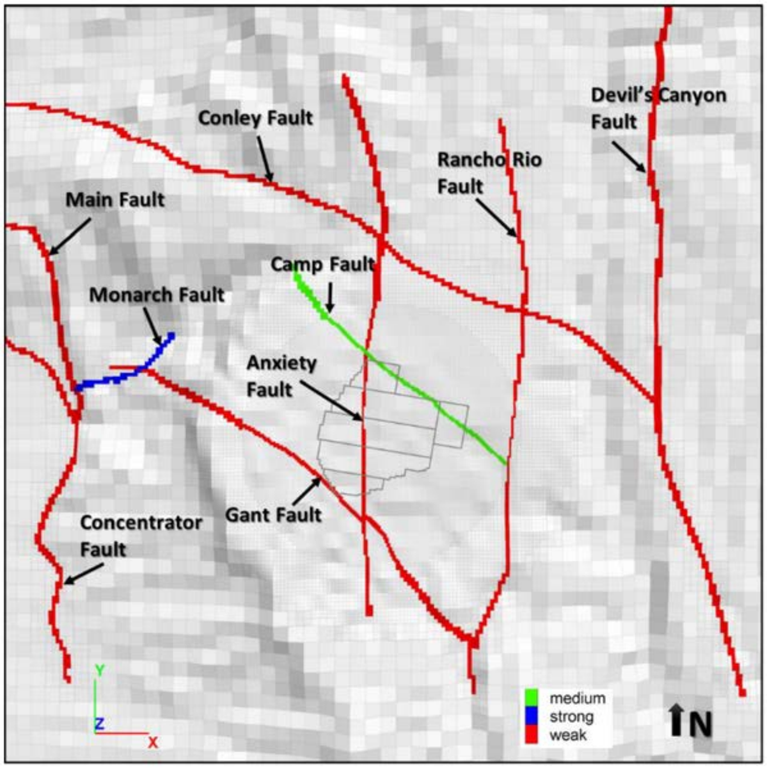


Figure 5-4. Fault zones persistent to ground surface and their associated strength ranking (Itasca, July 17, 2017).

5.4.4. Geotechnical Properties

5.4.4.1. Rock Mass Properties

The methodology used to develop rock mass properties meets industry best practice. Geotechnical properties of the rock mass within each geotechnical domain have been derived based on GSI rating, laboratory strength testing (UCS, TCS, DS etc.), including UCS correlated point load test results, and were input into the subsidence model.

Apache Leap Tuff (Tal) is the lithology observed at ground surface above the footprint of the proposed caving operations and overlies the Whitetail Conglomerate (Tw). The strength properties of these two units are key parameters in controlling the extent of subsidence near surface. Both units were characterized using the GSI system, which assumes three joint sets are present in the rock mass and that joint sets are persistent. Kaiser et al. (2015) discussed the challenges associated with the application of the GSI system for rock mass characterization for deep underground mines where the GSI system assumes joint sets are persistent along the length of the joints and that information about joint persistence cannot be determined from the core data. RCM has therefore, concluded that due to a lack of three joint sets in the Tw unit, and lack of information about joint set persistence in this rock unit, the application of GSI results in a "conservative" estimate of the Tw rock mass strength properties (Itasca, Aug, 29, 2018, Itasca, Feb. 21, 2011, Itasca, Aug, 3, 2018, RCM, June 28, 2018). The conservatism of Tw and Tal rock mass strengths is discussed in Section 5.6.

To adequately simulate the behavior of the rock mass adjacent to the cave (the rock mass within the Fractured Zone), where the rock mass is yielded, but not mobilized, the rock mass strength was reduced to residual strength. This was accomplished by applying a modified Hoek-Brown strain softening constitutive model in which peak rock mass strength is reduced to residual strength after a critical plastic strain has been accumulated. The critical plastic shear strain defines the brittleness of the rock mass failure. It is a subjective matter and is difficult to determine for a rock mass. Lorig and Varona (2000) reported that as part of the International Caving Study, a relationship was developed between the critical plastic strain and GSI, by back analysis of rock mass failure in caves and other openings. Itasca used this relationship to calculate an estimate of critical plastic strain (Itasca, July 17, 2017). When the critical plastic strain is reached, the strength of the rock mass within this zone is set to residual strength (i.e., zero cohesion, zero tensile strength and 50 degrees friction angle). The Workgroup agrees with the methodology used to obtain an estimate of the critical plastic shear strain.

5.4.4.2. Fault Strength Properties

As stated earlier, faults were modeled implicitly as zones of weak rock mass in FLAC3D. The strengths of the faults that were rated strong or medium were represented using 75% or 50%, respectively, of the global strength of the host rock mass (σ_{cm}). The weak faults were characterized by a frictional strength only (zero cohesion, zero tensile strength and a friction angle of 35 degrees).

The percentages used to characterize medium and strong faults represent a qualitative characterization of the possible fault strength relative to the host rock, and are considered by RCM to be conservative because:

1. Strong, annealed faults are generally stronger than the surrounding rock mass.
2. Modeled faults were assumed to be fully persistent (i.e., a continuous discontinuity for the full length of the fault). The Workgroup notes that this may not necessarily be the case, and this was also raised as a source of uncertainty by Kaiser et al. (2015).

As discussed in Section 5.4.3 and shown in Figure 5-4, with the exception of the Camp Fault and Monarch Fault, all other faults observed on ground surface have been characterized as “Weak”. These are faults with residual frictional strength, i.e. the mechanical strength of the weak faults is not considered proportional to the host rock mass global strength as in case of Strong and Medium Faults. The Camp and Monarch faults are located within the cave crater and only locally intersect the cave boundary. They are characterized as Medium and Strong faults and therefore, may only locally impact the extent of the Cave Crater and the Fractured Zone.

The Workgroup is not aware of any standard for assigning fault strengths without sampling and testing specific fault infill materials. The Workgroup therefore requested that RCM perform sensitivity analyses for all relative fault strengths to better evaluate the stated conservatism of the modeled fault strengths, and their impact on subsidence for a range of fault strength values (see Section 5.5.2).

5.4.5. In-situ Stresses

The in-situ stress regime was provided by RCM and is based on hydrofracturing tests completed at site. The in-situ stresses were simulated in the FLAC3D model with the major principal stress (σ_1) oriented vertical, the intermediate principal stress (σ_2) at 0.8 σ_1 and oriented north-south, and the minor principal stress (σ_3) at 0.5 σ_1 and oriented east-west.

5.4.6. Numerical Model Subsidence Criteria

Itasca considered the following criteria to determine Cave Crater Limit, Fractured Zone Limit, and Continuous Subsidence Zone Limit (Itasca, July 17, 2017).

- **Crater Limit** is defined as the area where vertical settlement exceeds 6.5 ft (2 m). This is also referred to as the mobilized zone in the subsidence report. This criterion has been used extensively and validated further through back-analysis of crater limits at other cave operations including Kiruna, Grace and Century Mines as well as Andina, Venetia, Pampa Escondida and La Encantada Mines (Itasca, August 1, 2018).
- **Fractured Zone Limit** is defined by the area where the total strain exceeds 0.5%. This criterion has been developed by back-analysis of the fracture limit induced by caving at the El Teniente mine (Cavieres et al., 2003). This analysis indicated that a total strain of 0.5% is a good indicator for delineation of Fractured Zone Limit in a numerical model. Although this criterion was developed through back-analysis of fracturing limit at one mine (El Teniente), it has been used extensively and has been validated further through back-analysis of Fractured Zone Limits at other cave operations including Kiruna, Grace, and Century mines, as well as Andina, Venetia, Pampa Escondida and La Encantada Mines, as reported by Itasca (August 1, 2018).
- **Continuous Subsidence Limit** is the area beyond the Fractured Zone Limit where the horizontal strain is greater than 0.2% and angular distortion[1] is greater than 0.3% (Itasca, July 17, 2017). Sainsbury and Lorig (2005) proposed this criterion, which provides an indication of the amount of settlement required to cause 'moderate to severe damage' to a masonry building during active subsidence. The strain values used to define the Continuous Subsidence Zone Limit are normally based on the damage they could cause to buildings. Even when no buildings are present on site, building damage is still a convenient means to convert strain values into real-world effects and appreciate the effects of different strain levels. It also represents a reasonable approach since buildings with concrete/masonry foundations are stiffer and hence more susceptible to damage than the rock mass itself (RCM, Mar. 13, 2020).

[1] Angular distortion is defined as the ratio of differential settlements over the distance between the two points under consideration. Distance refers to the spacing between point before ground settlement occurred (Negulescu and Foerster, 2010).

5.4.7. Base Case Surface Subsidence Model Results

As part of this review, the results of the base case FLAC3D model were reviewed by the Workgroup, and discussed in subsequent meetings with Resolution and their consultants. The Workgroup then requested further analyses to evaluate the sensitivity of the model to variations in several key parameters, including rock mass global strength properties and residual strength properties, fault strength properties, in-situ stress orientation and magnitude, and maximum bulking factor. The results of the base case analysis are presented below. The results of the requested sensitivity analyses are presented in the Section 5.5.

Based on the results of the base case subsidence model, RCM predicts no damage to Apache leap, Devil's Canyon, or to the serviceability of Highway (HW) 60 (Itasca, July 17, 2017). The base case model predicts the Fractured Zone Limit at Resolution is mainly controlled by the mine extraction level depth (6725 ft (2050 m) below ground surface) and shape of the panel cave footprint (Itasca, April 6, 2018). It also predicts good caveability with continuous upward cave growth that is estimated to break through the surface at year 6 of mine operations. Numerical simulation shows that while some faults serve as a limiting boundary for further cave growth, other faults at depth pull out the Fractured and Crater Zones outward, effectively increasing cave's footprint (Itasca, July 17, 2017). The model predicts a subsidence cave angle on the order of 70-78^{o}. This calculated cave angle compares reasonably well with the empirically derived cave angle of 72-84^{o}, discussed previously in Section 5.3. At the end of the proposed mine life, the Fractured Zone Limit (at the closest point) is predicted to be at approximately 1115 ft (340 m) from Apache Leap, and approximately 3450 ft (1050 m) from Devil's Canyon. The base case model also predicts the caving rate (defined as the ratio of the height of yielded zone above the footprint to the height of draw (height of solid rock pulled from draw points)) to vary between 5.8 and 16.8, which is within the range reported in the other caving operations around the world (Itasca, July 17, 2017). The bulking factor within the mobilized zone is also predicted to gradually increase from 11.4% in year 5 to 15.8% at year 41. The latter is also within the range observed in other caving operations (Itasca, July 17, 2017).

As part of the review, the Workgroup requested that RCM provide plots for several key ground deformation indicators in a plan view map, and along five cross-sections. Figure 5-5 shows the location of the cross-sections. These cross-sections were selected by the Workgroup and represent areas where the distance from the subsidence zone to key areas (Apache Leap, Devil's Canyon and HW 60) is perceived to be minimum. The key ground deformation indicators include predicted vertical and horizontal displacements, predicted angular distortion, predicted total strain along each cross section and predicted tilt angle. The angular distortion is used to identify the Continuous Subsidence Zone Limit, beyond which the predicted angular distortion and horizontal strains may not reach or exceed the damage threshold values that can cause 'moderate to severe damage' to the rock mass. The angular distortion and horizontal strains are discussed in Section 5.2 and the angular distortion threshold for identifying Continuous Subsidence Zone Limit is discussed in Section 5.4.6.

Key ground movement indicators, predicted from the FLAC3D numerical model, are reviewed and discussed in the following section.

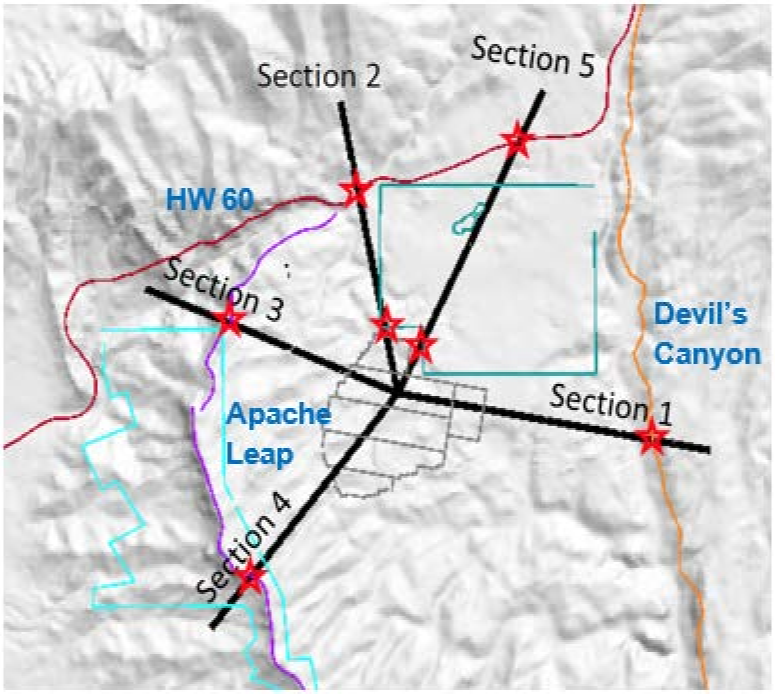


Figure 5-5. Locations of cross sections for review of subsidence model results.

Note: Stars indicate monitoring locations selected by the Workgroup to evaluate key ground movements parameters at Apache Leap, Devil's Canyon and at HW-60.

The angular distortion plot at the end of the proposed mine life (Year 41) along Cross Section 3 and Cross Section 4 are shown in Figure 5-6 and Figure 5-7, respectively. The plots show the angular distortion along the cross-section and are extended to the opposite side. Both plots in the base case analysis predict that the angular distortion at Apache Leap and Devil's Canyon, as well as at HW-60, is below 0.1%. This is well below the 0.3% threshold used for 'moderate to severe damage' to masonry buildings, which are typically more susceptible to damage than rock masses (RCM, March 13, 2020). Therefore, the base case analyses suggest that no damage is expected to occur at the Apache Leap, Devil's Canyon, or HW 60. The width of the undercut level along the cross-section is approximate.

The workgroup also reviewed the horizontal and vertical displacements near these areas. It is important to note that while horizontal and vertical movements are predicted to occur at these areas, as stated above, the predicted angular distortion is less than 0.1%, which is well below the 0.3% damage threshold. It is noteworthy that similar behavior reported by Singh (2003) has been observed at other mines where mining-induced settlement of up to 30 ft (9.2 m) did not cause significant damage to surrounding infrastructure. The Workgroup generally agrees with this conclusion.

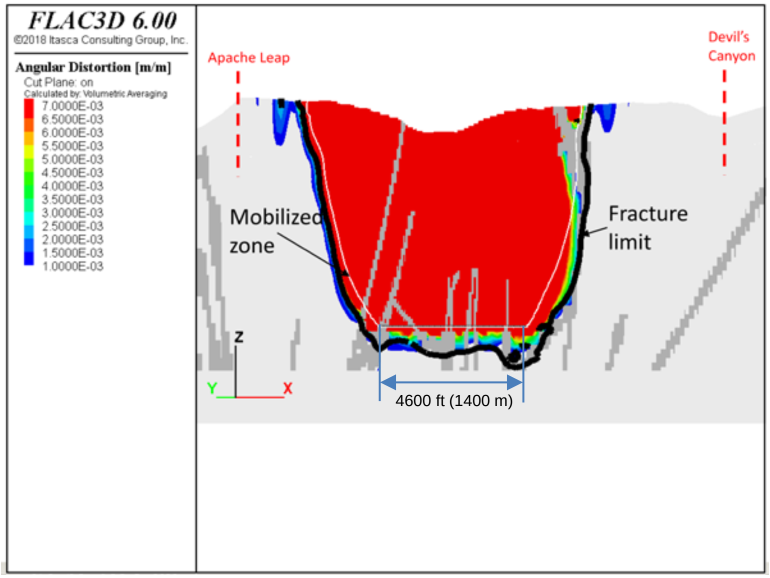


Figure 5-6. Angular distortion contours at Year 41 along Cross Section 3. The width of the undercut level at this cross section is approximate.

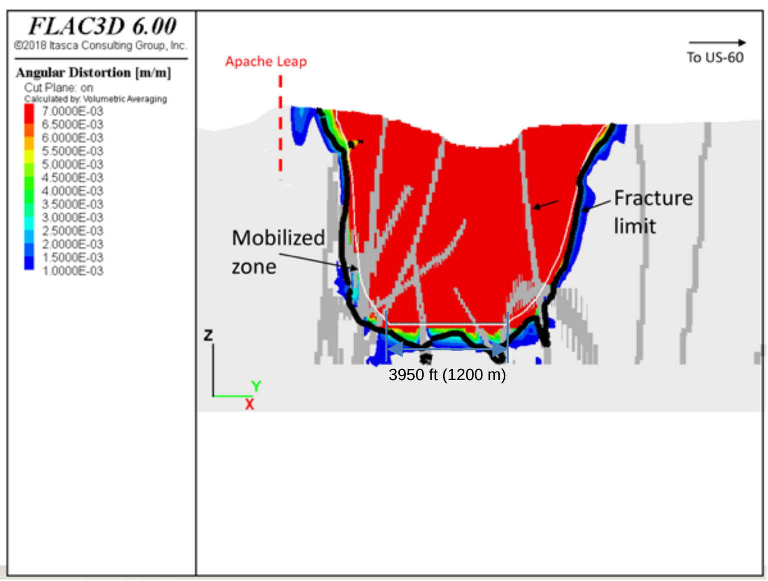


Figure 5-7. Angular distortion contours at Year 41 along Cross Section 4. The width of the undercut level at this cross section is approximate.

Stability of the tall slender rock formations at Apache Leap are controlled by tilting, which itself is controlled by differential settlement of the ground.

Figure 5-8 shows the predicted tilt angle of the ground above the cave footprint and at Apache Leap, Devil's Canyon, and HW 60. As shown on the figure, the tilt angle at these areas is less than 1º (one degree) which is far below the threshold value (7.5º) for toppling of the tall formations. The tilting threshold of 7.5º is based on the study completed by Turichshev et al. (2010). The results of the numerical assessment indicate that caving-induced ground deformations are unlikely to cause toppling of tall rock formations in these areas. However, any tall formation that is already tilted through natural causes (weathering, earthquake etc.) over time, may topple at lower angular distortions.

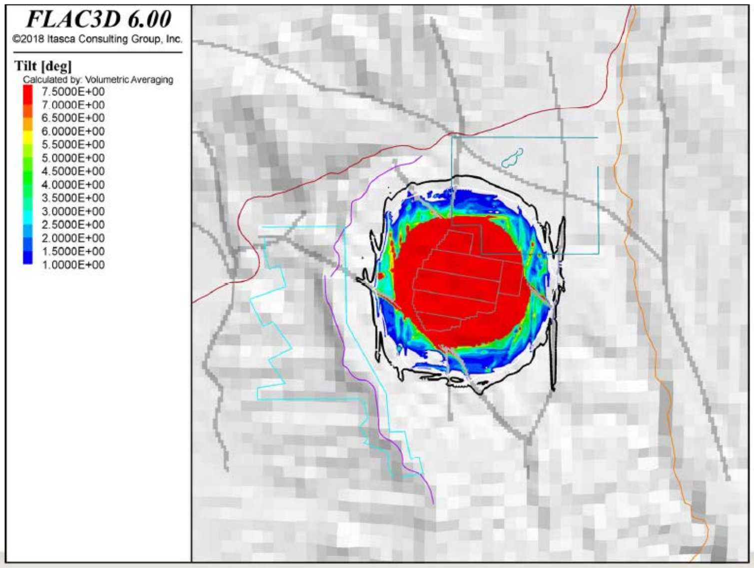


Figure 5-8. Predicted tilt angle at Year 41.

5.5. Sensitivity Analysis Results

Based on the results of the Resolution base case subsidence model, and findings from the Woo et al. (2013) study, RCM was requested by the Workgroup to carry out sensitivity analyses to assess the impact of variability in several model parameters. These included fault strength properties, rock mass global and residual strength properties, bulking factor, and in-situ stress distribution orientation and magnitude. Table 5-2 summarizes the sensitivity scenarios that were analyzed. In each scenario, the parameter subject to sensitivity analysis is shown in bold.

Table 5-2. Subsidence sensitivity analyses scenarios.

Sensitivity Scenario	Global Rock Mass Strength		Fault Strength[1]	Max. Caved Rock Porosity	In Situ Stress	
	Peak	Residual			K_0 Value	σ_H Orientation
Base Case	100% σ_{cm}	$\varphi = 50^o$	Base Case	40%	Base Case	N-S
Original Strong	100% σ_{cm}	$\varphi = 50^o$	**Strong Case**	40%	Base Case	N-S
Scenario 1	**75% σ_{cm}**	$\varphi = 50^o$	Base Case	40%	Base Case	N-S
Scenario 2	**125% σ_{cm}**	$\varphi = 50^o$	Base Case	40%	Base Case	N-S
Scenario 3	100% σ_{cm}	$\varphi = 50^o$	**Weak Case**	40%	Base Case	N-S
Scenario 4	100% σ_{cm}	**$\varphi = 43^o$**	Base Case	40%	Base Case	N-S
Scenario 5	100% σ_{cm}	$\varphi = 50^o$	Base Case	**30%**	Base Case	N-S
Scenario 6	100% σ_{cm}	$\varphi = 50^o$	Base Case	40%	**125% K_0**	N-S
Scenario 7	100% σ_{cm}	$\varphi = 50^o$	Base Case	40%	**75% K_0**	N-S
Scenario 8	100% σ_{cm}	$\varphi = 50^o$	Base Case	40%	Base Case	**E-W**

Note:

1. Under Scenario 1 and Scenario 2 (global rock mass strength sensitivity cases), the strength of the Strong and Medium strength faults are varied because the strength of Strong and Medium faults is a function of global strength of the host rock.

RCM has considered a range of ±25% for sensitivity analyses of peak global rock mass strength, which is based on the factor of safety acceptance criteria as stated in the *Guidelines for Open Pit Slope Design Study* (Read and Stacey, 2009, Itasca, Aug. 3, 2018). This range addresses the long-term stability with an associated high consequence of failure. While there are a limited number of published recommended design acceptance levels for factors of safety in the mining industry, the Workgroup believes that this sensitivity range is acceptable for the target level of confidence in the geotechnical data, and the expected consequence of ground instability at the current level of study of the Resolution project.

In each sensitivity analysis scenario, only one parameter was varied, and all other parameters were kept at the base case value. The only exception was the strength properties of the Strong and Medium strength faults, where fault strength is a function of the rock mass global strength properties and was therefore changed when rock mass strength was changed for the sensitivity analyses.

RCM used Fractured Zone Limit as one of the key metrics (instead of Continuous Subsidence Zone Limit) to assess the impact of each parameter variation on the model predictions because the Fractured Zone Limit, which is the limit of visible fracturing on the ground, can be readily observed in the field without the need for high-resolution instruments. The Continuous Subsidence Zone Limit, on the other hand, is difficult to identify and requires high-resolution instruments to determine the boundary beyond which the mining-induced damage is less than the 'medium to severe damage' threshold based on combination of angular distortion and horizontal strain on the ground (the Continuous Subsidence Zone Limit).

Overall, based on sensitivity analyses results, RCM concluded that the Fractured Zone Limit distance to key areas, crater depth, and cave angle were not significantly impacted by the parameter modifications imposed under each sensitivity scenario (Itasca, Apr. 6, 2018). RCM further stated during the Workgroup meeting of March 16, 2018 that ground monitoring will be implemented to track ground movements during operations (SWCA, Mar. 16, 2018). The latter has been included in the RCM's proposed Ground Monitoring and Management Plan (RCM, August 2020) and is reviewed in Section 6.0. Table 5-3 summarizes the results of the base case and sensitivity analyses in terms of distance from Fracture Zone Limit to the key areas (Apache Leap, Devil's Canyon and HW-60). The results of the sensitivity analyses are examined further in detail in the following sections.

Table 5-3. Base Case and Sensitivity Analyses Summary of Results

	Fracture Zone Limit - Approximate Distance to Key Areas				
	Cross Section 1	Cross Section 2		Cross Section 3	Cross Section 4
Scenario	**Distance to Devil's Canyon ft (m)**	**Distance to Apache Leap ft (m)**	**Distance to HW-60 ft (m)**	**Distance to Apache Leap ft (m)**	**Distance to Apache Leap ft (m)**
Base Case	3700 (1130)	1115 (340)	1560 (475)	1115 (340)	1310 (400)
Scenario 1	3250 (990)	890 (270)	1430 (435)	590 (180)	445 (135)
Scenario 2	3900 (1190)	1200 (365)	1575 (480)	1300 (395)	1312 (400)
Scenario 3	3700 (1130)	850 (260)	1280 (390)	740 (225)	850 (260)
Scenario 4	4185 (1275)	1360 (415)	1590 (485)	920 (280)	850 (260)
Scenario 5	3700 (1130)	1100 (335)	1560 (475)	1085 (330)	1310 (400)
Scenario 6	3675 (1120)	870 (265)	1215 (370)	1050 (320)	935 (285)
Scenario 7	3700 (1130)	1100 (335)	1560 (475)	1085 (330)	1310 (400)
Scenario 8	3790 (1155)	1460 (445)	1855 (565)	1050 (320)	1510 (460)

5.5.1. Rock Mass Strength Properties

In sensitivity analyses Scenario 1 and Scenario 2, the subsidence was simulated using 75% and 125% of the global rock mass strength properties used in the base case, and varied for the rock mass in all domains, accordingly. Simulation results indicated that the Fractured Zone Limit expands further in all directions under lower global rock mass strength case (Scenario 1) compared to the base case analysis (Itasca, April 6, 2018) (Table 5-3, Figure 5-9). In this scenario, the Fractured Zone Limit may reach to within 445 ft (135 m), 590 ft (180 m) and 890 ft (270 m) from Apache Leap in the southwest, west and northwest corner of the subsidence zone, respectively.

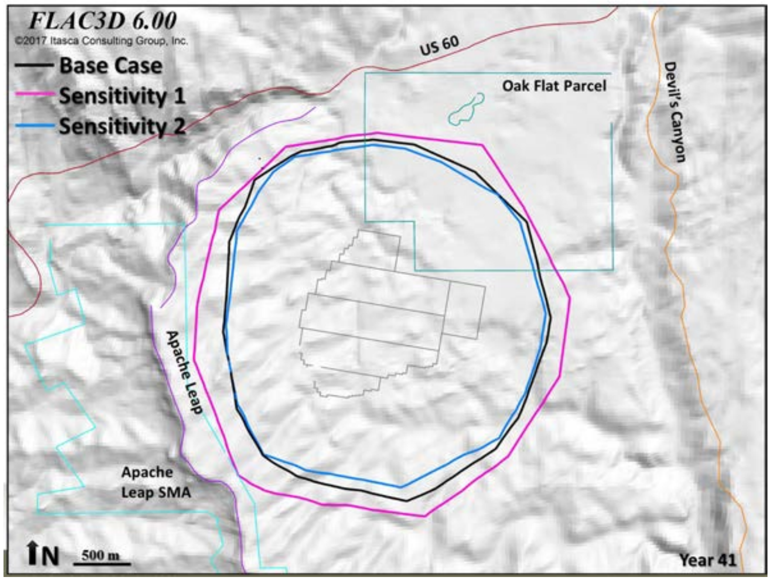


Figure 5-9. Fractured Zone Limit for Sensitivity Analyses Scenario 1 and Scenario 2

From sensitivity analyses results it can be inferred that although the Tw global rock mass strength values for the base case and sensitivity Scenario 1 are consistent with published values and measured performance at Shaft No. 10, there is the potential that the Fractured Zone Limit approaches Apache Leap, should the global rock mass strength actually be lower than estimated. This may result in toppling or failure of rock formations within the areas of interest that might already be tilted due to natural processes. The Fracture Zone Limit distance to key areas under Scenario 2 (the case of upper rock mass strength) is similar to further away as the base case. The uncertainty in rock mass strength properties is discussed in Section 5.6, where the results of key sensitivity cases are reviewed.

5.5.2. Fault Strength

Faults were modeled in FLAC3D as "Strong", "Medium", or "Weak" in the base case analysis, as described earlier. For the purposes of the sensitivity analyses, two other scenarios were considered (Table 5-4).

Table 5-4. Fault strength for base case and sensitivity analyses scenarios.

Fault Category	Base Case Scenario	Sensitivity Analyses	
		Original Strong Scenario	Weak Scenario (Scenario 3)
Strong	75% σ_{cm}	88% σ_{cm}	50% σ_{cm}
Medium	50% σ_{cm}	72% σ_{cm}	25% σ_{cm}
Weak	Cohesion = 0 Tensile Strength = 0 Friction Angle (φ)= 35^o	Cohesion = 0 Tensile Strength = 0 Friction Angle (φ)= 35^o	Cohesion = 0 Tensile Strength = 0 Friction Angle (φ)= 25^o

The Original Strong case refers to the upper fault strength scenario which is increased from the base case as shown in Table 5-4. Scenario 3 refers to the lower fault strength case where the strength of the Strong, Medium, and Weak Faults was reduced from the base case to 50% of global rock mass strength, 25% of global rock mass strength, and to a friction angle of 25^o, respectively.

Based on the sensitivity analyses results, for the upper fault strength (Original Strong case) the Fractured Zone Limit is not impacted or contracts in some areas (northwest and northeast of subsidence zone) by the increased fault strength, but in the lower fault strength case (Scenario 3), the Fractured Zone Limit expands towards west and southwest to within 740 ft (225 m) and 850 ft (270 m) from Apache Leap along Cross Sections 3 and 4, respectively, due to the lower frictional strength of the Gant fault, which is located in this area (Itasca, April 6, 2018) (Table 5-3, Figure 5-10).

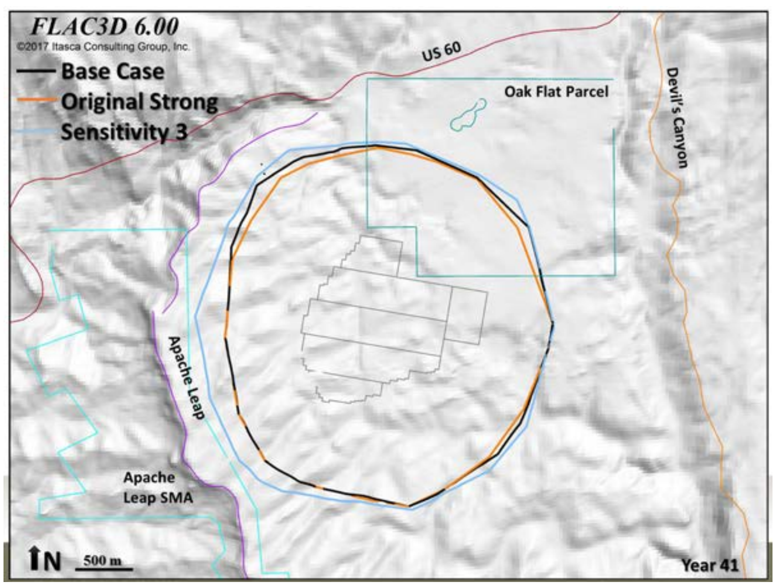


Figure 5-10. Fractured Zone Limit for Sensitivity Analyses "Original Strong" and Scenario 3.

5.5.3. Rock Mass Residual Strength

The sensitivity of the surface subsidence to rock mass residual strength was assessed by reducing the residual friction angle to 43 degrees (Scenario 4) from the base case. Model results show no significant change to the extent of the Fractured Zone Limit in comparison to the base case results, with the exception of the south side of the cave where Fractured Zone Limit extends further to the south and southwest along Cross Section 4 towards Apache Leap (Itasca, April 6, 2018) (Table 5-3, Figure 5-11).

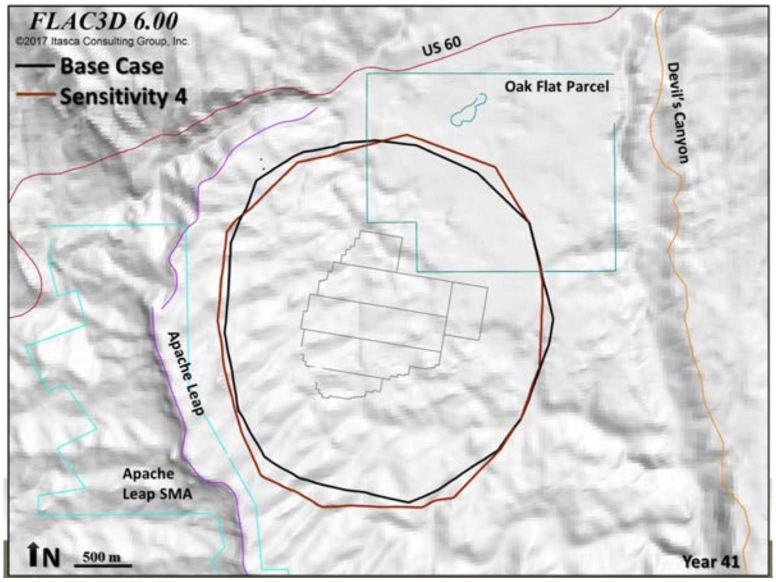


Figure 5-11. Fractured Zone Limit for Sensitivity Analysis Scenario 4

5.5.4. Caved Rock Maximum Porosity

Sensitivity analysis Scenario 5 considered a lower porosity of 30% for the caved rock. Results of this analysis show that a lower porosity does not impact the extent of the Fractured Zone Limit (Itasca, April 6, 2018) (Table 5-3, Figure 5-12).

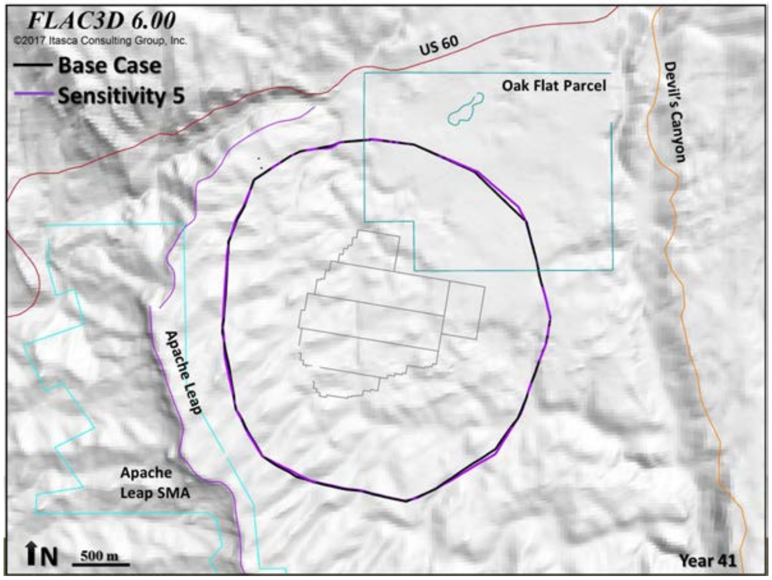


Figure 5-12. Fractured Zone Limit for Sensitivity Analysis Scenario 5

5.5.5. In-situ Stress Ratio (K_0)

Sensitivity analysis Scenario 6 and Scenario 7 represent the impact on Fractured Zone Limit of the lower- and upper horizontal to vertical stress ratio (K_0) by varying the base case ratio by ±25%. Results show limited impact on the extent of the Fractured Zone Limit in Scenario 6 in the west and southwest areas and no impact from Scenario 7 (Itasca, April 6, 2018) (Table 5-3, Figure 5-13). Itasca relates this behavior to the absence of locked-in stresses at the ground surface, and little difference in the stress regime in the near surface.

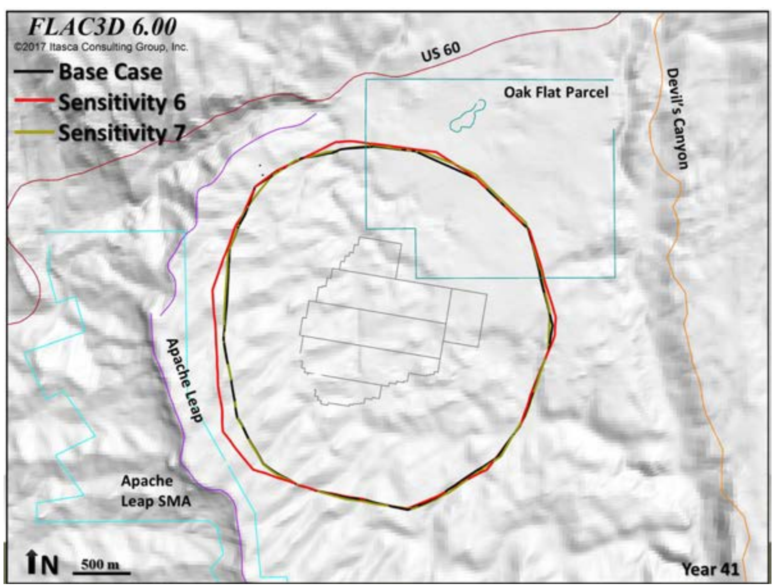


Figure 5-13. Fractured Zone Limit for Sensitivity Analyses Scenario 6 and Scenario 7

5.5.6. Horizontal Principal Stresses Orientation

In sensitivity analysis Scenario 8, the orientation of the horizontal principal stresses was rotated by 90°, while the magnitude of all stress components was kept the same as in the base case. This resulted in a rotation of the long axis of the Fractured Zone Limit from N-S to E-W. As a result, the Fractured Zone Limit extended in the west slightly closer to Apache Leap, and further away from HW-60 in the north (Table 5-3, Figure 5-14). Itasca (April 6, 2018) concluded that this slight extension does not increase the impact on Apache Leap or Devil's Canyon.

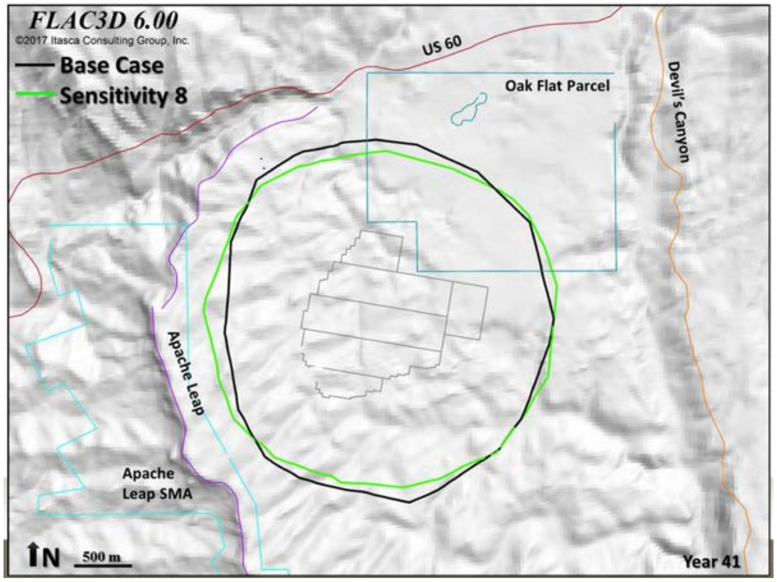


Figure 5-14. Fractured Zone Limit for Sensitivity Analysis Scenario 8

To address the uncertainty in the rock mass strength properties, rock mass residual strength properties and fault strength properties which impact the subsidence predictions, RCM is planning to establish a monitoring program to identify any potential acceleration of ground movements. RCM's proposed Subsidence Monitoring and Management Plan (RCM, August 2020) is reviewed and discussed briefly in Section 6.0.

Malach (March 17. 2019) commented that no error bounds were considered in the predictions of cave angle, crater depth, fracture limit, and continuous subsidence zone limit and that all predictions were best estimates. The Workgroup requested RCM to conduct sensitivity analyses on a number of key model parameters, including global rock mass and fault strength properties, rock mass residual strength property, in-situ stress magnitude and orientation and bulking factor. The Workgroup reviewed these sensitivity analyses and their impact on subsidence predictions. Further details of Malach's public comments and the Workgroup's review are provided in BGC (July 21, 2020).

5.6. Review of Tal and Tw Global Rock Mass Strength

A review of UCS data for all rock mass domains (RCM, October 5, 2017, Figure 1-16) indicates that the Tw rock domain is a relatively weak geologic unit and therefore the subsidence crater and Fractured Zone Limit could potentially extend laterally within this unit. Any instability in the Tw unit could also extend into the Tal unit, stratigraphically located immediately above. RCM claims that the Tw rock mass property is underestimated because not all conditions presumed in the GSI system are met when characterizing the Tw rock unit. As such, it is important to understand the level of conservatism in strength properties of the Tal and Tw rock units used in the subsidence model.

As discussed in Section 5.4.1, RCM notes that the application of GSI to the Tw unit results in conservative rock mass properties for this unit because GSI inherently assumes there are at least three joint sets in the Tw unit to form blocks in this rock mass, and that the joint sets are fully persistent (RCM, June 28, 2018, Itasca, August 3, 2018, Itasca, August 29, 2018). However, rock mass structure measurements in the Tw unit indicates that there is only one joint set present within this rock domain and no information on joint set continuity (persistence) can be obtained from the available drill core data. This may have resulted in underestimation of GSI for the Tw unit. Kaiser et al., (2015) states that the assumption of fully persistent joint sets adds to the uncertainty as the GSI system is not applicable to discontinuously jointed or highly interlocked rock masses, and that the information on joint trace length and large scale waviness is not known when GSI is estimated from borehole data (Itasca, Aug. 29, 2018).

During the sinking of Shaft No. 10, RCM carried out geotechnical instrumentation and monitoring to evaluate rock mass behavior in the Tw unit (RCM, Oct. 5, 2017, RCM, June 28, 2018, Itasca, Aug. 29, 2018). RCM used borehole camera surveys of probe holes drilled ahead of the advancing face and installed extensometers in the shaft wall along about 1312 ft (400 m) of shaft length from 1706 ft (520 m) to 3018 ft (920 m) depth. Borehole camera surveys of probe holes indicated no signs of stress damage within the Tw rock unit. RCM used this monitoring and observational information to conduct a back-analysis and to demonstrate the Tw rock mass properties in the model are underestimated.

To investigate the level of conservatism in the rock mass properties of Tw and Tal rock units used in the subsidence base case analysis, RCM conducted statistical “Monte Carlo” simulations of the global rock mass strength properties for these geologic units. To achieve this, RCM developed a cumulative distribution of global rock mass strength properties for each domain by randomly sampling the input distributions of GSI and UCS, and then calculating the global rock mass strength using Generalized Hoek-Brown failure criteria (Hoek et al., 2002). The UCS distribution was developed using point load test data correlated to UCS and then downgraded by 20% to account for differences between “sample sizes” between the laboratory and the site-wide rock mass and the impact of micro-fracturing, weathering and alteration on the intact rock strength. The rationale for application of 20% downgrade to UCS of rock mass domains was discussed in Section 2.3.1. The GSI distribution was estimated based on block volume using the methodology proposed by Cai et al. (2004). Block volume was estimated from core data using both apparent spacing and the joint weighted density methodology by Palmstrom (2005). Figure 5-15 shows the UCS and GSI distributions and the resulting global rock mass strength (σ_{cm}) cumulative distribution for the Tw rock mass domain (Itasca, April 6, 2018; March 16, 2018; RCM, June 29, 2018, Appendix A1). The base case (deterministic) UCS and GSI values of 23 MPa and 73, respectively, as well as the base case and lower sensitivity rock mass strength values (labeled as scm) are shown in Figure 5-15.

Using the experience gained during shaft sinking, as well as the Tw rock mass strength distribution from the Monte Carlo simulation, RCM carried out a numerical back-analysis to determine the impact of varying rock mass properties on the shaft behavior (Itasca, Feb. 21, 2011). In this study, Tw rock mass strength values representing a range from 10th to 70th percentiles of the cumulative global rock mass strength distribution were used, and rock mass deformation in the shaft was estimated. While ground monitoring during shaft sinking indicated zero deformation in the Tw unit, numerical modeling estimated a minimum of 1.7 m deformation in the Tw unit at the highest rock mass strength modeled (70th percentile). RCM therefore concluded that the Tw global rock mass strength must be greater than the 70th percentile value. The Workgroup agrees with this conclusion.

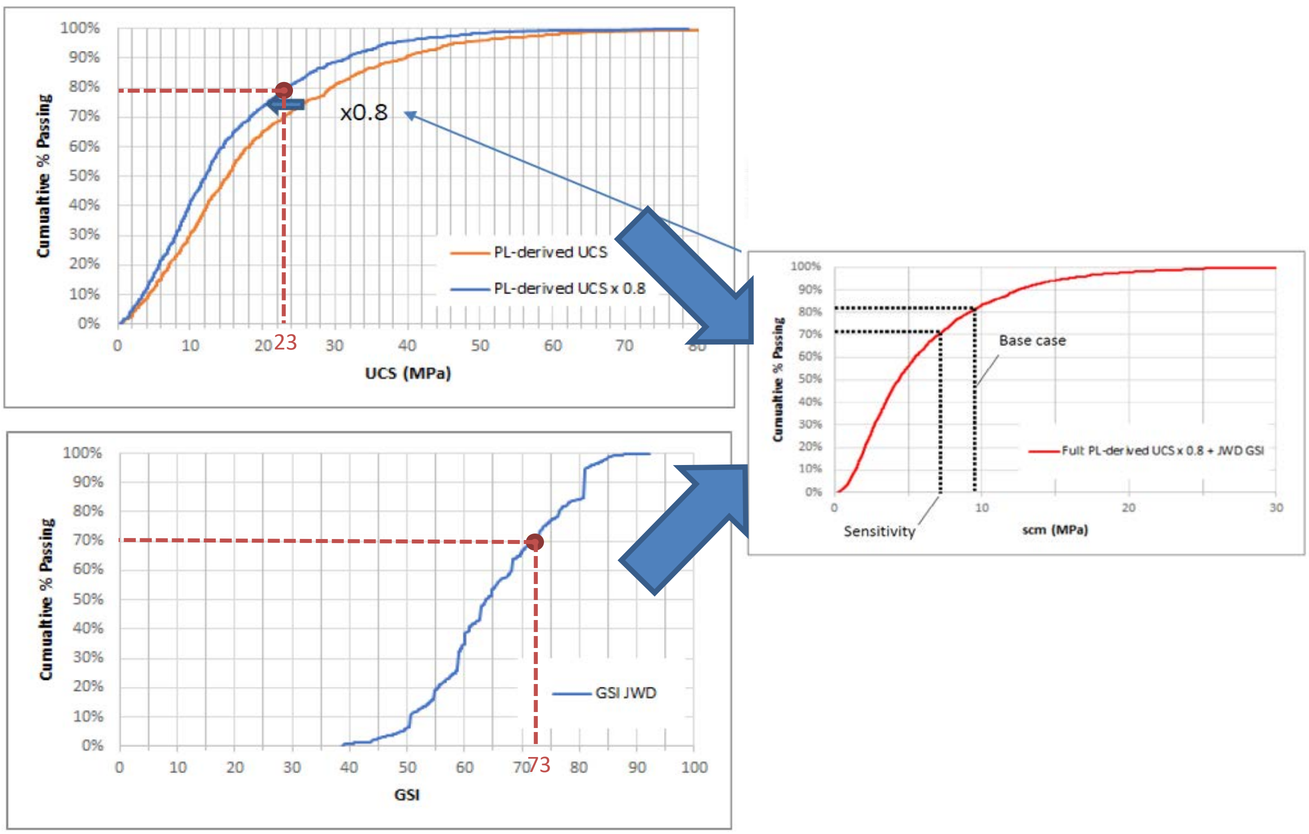


Figure 5-15. UCS and GSI distributions and the resulting global rock mass strength (labeled by scm) cumulative distribution for Whitetail Conglomerate (Tw) rock mass domain (Itasca, April 6, 2018; March 16, 2018; RCM, June 29, 2018, Appendix A1).

As can be seen in Figure 5-15, the input UCS (23 MPa) and GSI (73) for the base case analysis are at 79th percentile and 70th percentile, respectively, on their respective cumulative distributions. The calculated global rock mass strength for the Tw unit for the base case, σ_{cm}, is 9.6 MPa, which corresponds to the 82nd percentile on the global rock mass strength cumulative distribution chart. Although the base case UCS and GSI and the resulting global rock mass strength of the Tw unit fall on the upper range of their respective distributions (greater than 70th percentile), RCM considered the Tw base case global strength is underestimated, based on the results of the back-analysis and considering no deformation was observed during the shaft sinking within this rock unit (RCM, February 21, 2011, RCM, October, 6, 2017, RCM, June 28, 2018).

For the Tw unit lower sensitivity Scenario 1 (75% σ_{cm}), the Tw global rock mass strength is 7.2 MPa, which falls just above the 70th percentile on the cumulative distribution chart (Figure 5-15); as discussed above, RCM considered this is also underestimated based on ground observations during sinking of the No. 10 Shaft.

Itasca (April 6, 2018) states that, according to Pierce (2010) and Rafiei Renani et al. (2018), a conservative global rock mass strength between the 30th and 40th percentiles on a cumulative global rock mass strength distribution is typically considered in cave-scale simulations. Itasca (April 6, 2018), however, states that, in the case of the Tw geologic unit, due to underestimation of GSI (because GSI presumes three fully persistent joint sets as opposed to one joint set observed in the core), adopting GSI and UCS values at 30th to 40th percentiles would result in extremely low strength properties that would not be representative of the Tw ground conditions observed in Shaft No. 10. Considering the available monitoring and observational information from Shaft No. 10, the Workgroup agrees with this conclusion.

The shaft observations and monitoring data justify the application of the Tw rock mass properties, used in the base case, in the vicinity of Shaft No. 10. However, to justify extrapolation and application of the Tw base case properties to the entire mining area, RCM retained Itasca to carry out an assessment of the spatial variability of the Tw intact rock properties (UCS) (Itasca, September 10, 2018). For this assessment, Itasca compared the range of the point load strength data collected from the Tw unit within the entire mining (cave) area with those from the Tw unit collected from the RES-008 hole (Shaft No. 10 pilot hole). The comparison indicated that while the mean point load strength data of the Tw unit from the RES-008 hole was higher than from the entire mining area by 30%, the strength range of the samples collected and tested from the RES-008 hole extended the full spectrum of point load test results obtained from the entire mining area. Itasca demonstrated that the variability of the Tw UCS within the entire Resolution property corresponds with its variability around the Shaft No. 10 and therefore concluded that the Tw base case properties (calibrated with back-analysis) can be used in the subsidence model to represent the Tw unit in the entire mining area.

Based on the discussions above, knowing Tw rock mass properties are underestimated (based on observations in Tw unit in the Shaft No. 10), the properties used for the Tw unit in the base case analysis are considered appropriate for subsidence prediction considering the site-wide uncertainty in Tw rock mass properties.

Similar analyses were carried out for the Tal rock unit (Itasca, April 6, 2018; March 16, 2018). Figure 5-16 shows the UCS and GSI cumulative distributions and the resulting global rock mass strength cumulative distribution for the Tal rock mass domain. The base case (deterministic) UCS and GSI values of 66 MPa and 64, respectively, are shown as well as the base case and lower sensitivity rock mass strength values (labeled as scm). Also shown on Figure 5-16 is the UCS cumulative plot downgraded by a factor 0.8 to account for sample size, micro-fracturing, weathering and alteration on intact rock strength.

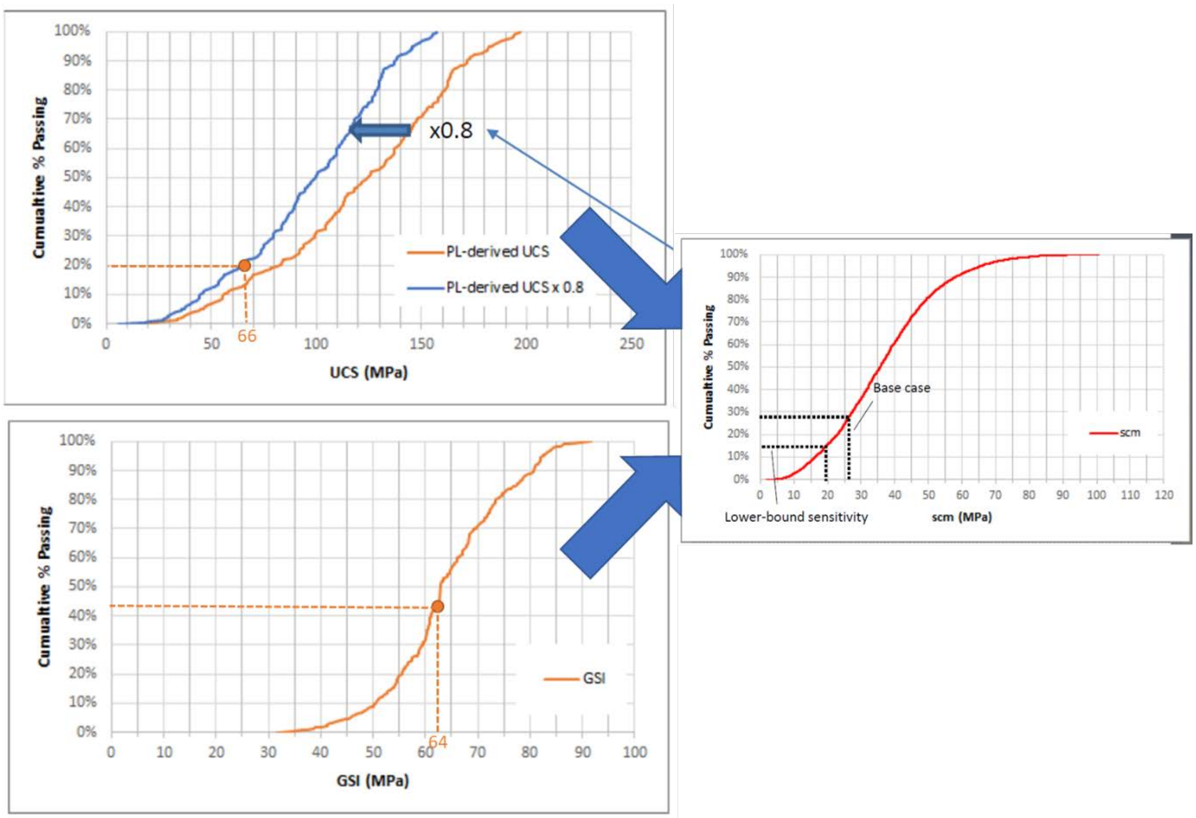


Figure 5-16. UCS and GSI distribution and the resulting global rock mass strength (labeled by scm) cumulative distribution for the Apache Leap Tuff (Tal) rock mass domain (Itasca, April 6, 2018; March 16, 2018).

The Tal rock mass domain UCS (66 MPa) and GSI (64) for the base case analysis are at 20th percentile and 42nd percentile, respectively, on their respective cumulative distributions (Figure 5-16). The calculated global rock mass strength for this domain for the base case is 26 MPa, which corresponds to the 27th percentile on the global rock mass strength cumulative distribution. The calculated base case Tal global strength is within the lower end of the recommended 30th to 40th percentile of the cumulative global rock mass strength (Pierce (2010), and Rafiei Renani et al. (2018)) and is therefore considered by RCM to be conservative (Itasca, April 6, 2018). It is however possible that the base case global strength value may found to be lower than will be experienced during the mine development, which would likely lead to a reduced fracture limit and subsidence crater, and a cave angle similar to, or possibly steeper than, the base case.

The global rock mass strength of the Tal unit for sensitivity Scenario 1 (75% σ_{cm}) is also plotted on the cumulative distribution chart (Figure 5-16). The global rock mass strength of 19.5 MPa for this case corresponds to the 15th percentile on the cumulative distribution plot. Looking at the upper sensitivity Scenario 2 (125%σ_{cm}), the global rock mass strength for the Tal unit is 32.4 MPa, corresponding to the 38th percentile on the cumulative global strength distribution plot (Figure 5-16). Itasca concluded that the calculated global rock mass strength for the Tal unit is close to the 30th percentile on the global rock mass strength cumulative distribution, and is within the recommended range stated for cave-scale simulations by Pierce (2010), Lorig et al. (2018), and Rafiei Renani et al. (2018).

The uncertainties associated with several geologic and material properties, and their potential impact on predicted surface subsidence were reviewed and discussed in this section. These uncertainties are associated with the density of geotechnical data collected and used in the subsidence assessments and predictions. The adequacy of RCM data collection and QA/QC procedures were reviewed and discussed in Section 2.3 and Section 3.0. While data density is adequate within the mineralized zone, the data density is lower outside the mineralized zone leading to more uncertainty in rock mass properties, because rock mass properties are estimated from fewer data and based on professional engineering judgement. RCM conducted sensitivity analyses to account for these uncertainties and to estimate their impact on predicted subsidence were reported earlier in this section. RCM is proposing to address the uncertainties associated with geologic information as well as rock mass and fault strength properties through Subsidence Monitoring and Management Plan (August 2020) which includes a network of aerial, surface and subsurface instrumentation and a trigger action response plan (TARP) that will be initiated prior to initiation of caving and will be active throughout mining operation and during post-mining. The Workgroup agrees with this approach.

6.0 RCM SUBSIDENCE MONITORING AND MANAGEMENT PLAN

RCM is planning on implementing a ground monitoring and instrumentation program at Resolution site to account for uncertainties in the geologic information, as well as rock mass and fault strength properties. This program would also include a plan of actions through a Trigger Action Response Plan (TARP), should the measured ground movements be greater than predicted movements. The *Subsidence Monitoring and Management Plan* (RCM, August 2020) outlines the methodologies and planned strategies to ensure that the impact of subsidence is continuously monitored, managed and communicated throughout the life of the mine.

RCM's overall strategies for subsidence monitoring and management include:

- Subsidence monitoring methodology subdivides the monitoring plan into multiple phases of instrument installations and will be subject to time dependencies as the mining progresses with subsequent growth in the surface subsidence footprint.
- Subsidence management methodology will rely on predictions from the EIS subsidence impact analysis (Itasca, July 17, 2017) on surface subsidence for the operation, in conjunction with actual field measurements obtained from instrumentation. A graphical comparative tracking tool will be used to measure and track actual data to modeled data. This will provide valuable early trends and projections on subsidence progression and rates of growth, and if required, implementation of any mitigation strategies.

6.1. Subsidence Monitoring

RCM proposes to use a network of aerial, surface and subsurface instruments to monitor ground movements. Monitoring is divided into several phases including Pre-Caving, Cave Tracking to Surface, Cave Maturation, and Post Caving. Proposed instrumentation includes:

- Aerial: InSAR, and aerial photogrammetry
- Surface: LiDAR, robotic prism network, surface monuments and crack mapping
- Subsurface: Time Domain Reflectometers (TDRs), cave smart markers and beacons with detectors, wireless in-ground monitoring (Geo4Sight), inclinometers, and soil extensometers.

The details of the RCM Subsidence Monitoring and Management Plan are provided in RCM (August 2020).

6.2. Subsidence Management

RCM will use the monitoring plan, and data obtained from instrumentation, in the overall management of subsidence. RCM plans to track ground movements against predicted states of subsidence (Itasca, July 17, 2017) in order to understand the trends, and to allow for projections and implementation of any early mitigation measures, if required.

RCM plans to use the masonry building damage criterion (combination of angular distortion and horizontal strain) discussed in Section 5.2 and Section 5.4 to compare the measured angular distortion and horizontal strains against the predicted values (RCM, August 2020).

RCM's TARP is based on the distance of the measured limit of building damage against the predicted distance. RCM's TARP is associated with a response plan that provides a step-by-step guideline which includes confirming instrument data, notifying all stakeholders including the USFS of the occurrence of exceedance level, checking of mining sequence and production data and determine if deviation is required and take appropriate actions. RCM's subsidence management and TARP are discussed in detail in RCM (August 2020).

6.3. Reporting to USFS

RCM will compile and submit instrumentation and system status, data trends, and tracking behavior data to the USFS at each phase of mining. Details of the reporting schedule and reporting frequency are provided in RCM (August 2020).

Several public comments were submitted on the DEIS related to subsidence monitoring and management. These comments have been addressed in RCM's Subsidence Monitoring and Management Plan (August 2020). Specifically, Malach (March 17, 2019) provided public comments on RCM's proposed monitoring plan and ability to address potential ground movement. Malach's comments were based on review of the original GPO (RCM, 2014), and not the current Subsidence Monitoring and Management Plan. BGC conducted a detailed review of Malach's comments and provided responses in BGC (July 21, 2020).

7.0 SUMMARY OF SURFACE SUBSIDENCE MODEL REVIEW

A 3D numerical assessment was completed for RCM by Itasca to evaluate the impact of the proposed panel caving operations, including the extent of ground surface subsidence, the limit of fracturing, and the potential impact on Apache Leap, Devil's Canyon, and HW 60.

7.1. Summary of Assumptions

The following summarizes the assumptions in the subsidence model:

- Faults were simulated implicitly as distinct weak rock masses rather than interfaces because, at the Resolution property, faults generally consist of zones of relatively weaker rock mass (compared to the surrounding host rock) and are not necessarily discrete features.
- Geological Strength Index (GSI), which is a measure of the relative blocky-ness of the rock and joint surface conditions, was considered applicable to all rock mass domains to characterize rock mass structure. Typically, the application of a GSI value to a specific rock domain depends on the state of rock fracturing and the number of joint sets present in the rock mass and assumes joints sets are fully persistent. Therefore, the global application of GSI to a rock domain at the site may underestimate rock mass properties where this criterion is not applicable to a specific rock domain (i.e., Tw domain for the interpreted GSI value where three fully persistent joint sets are assumed).
- Only faults and fault zones are included in the model. Rock mass discontinuities (dominant joint sets) are not included in the model.

The damage criteria used to define Fracture Zone Limit and Continuous Subsidence Zone were discussed in Section 5.4.6 and are summarized below:

- A minimum vertical settlement of 6.5 ft (2 m) is used to define the boundary of the cave crater.
- A total strain criterion of 0.5% has been used to define the extent of the Fractured Zone Limit.
- A minimum 0.2% horizontal strain and 0.3% angular distortion are used to define the extent of the Continuous Subsidence Zone. The latter criterion corresponds to "moderate to severe damage" to masonry buildings. The strain values used to define the limits of subsidence are normally based on the damage they could cause to buildings. Even when no buildings are present on site, building damage criteria is still a convenient means to convert strain values into real-world effects and appreciate the effects of different strain levels. It also represents a reasonable approach since buildings with concrete/masonry foundations are stiffer and hence more susceptible to damage than the rock mass itself (RCM, Mar. 13, 2020).

7.2. Summary and Conclusions of Surface Subsidence Model Review

The following summarizes the findings from this review:

- The RCM numerical model simulates the caving operation to predict ground subsidence at Resolution. Cave angle can be calculated from the numerical results.

- FLAC3D, which is a commonly used code to simulate caving-induced subsidence in the mining industry, has been used to simulate panel caving at Resolution.
- RCM's methodology to interpret faults, geological units and rock mass domains is consistent with established industry best practices and standards.
- RCM characterizes faults in the model as Strong, Medium, or Weak, based on the characteristics of their infill material. Faults are rated Strong if they are strongly annealed; Medium strength if they are a combination of open and annealed, with local gouge and local intense damage; and Weak if they contain slickensided shears, are heavily damaged, brecciated and/or infilled with gouge.
- GSI has been assumed to be applicable to all rock mass domains. Because the Tw unit has fewer than three joint sets and that they are presumed to be fully persistent by GSI, RCM considers that the Tw strength properties are underestimated.
- While the average point load strength of the Tw unit at the Shaft No. 10 pilot hole (RES-008) is about 30% higher than the average from the Tw unit across the entire project area, the ranges of point load strengths from the two populations are similar. Therefore, RCM assumed that the applied UCS value of the Tw unit in the subsidence model is representative of the Tw unit in the project.
- Numerical back-analysis of the Tw rock mass response predicted 1.7 m deformation in the Tw unit for a global rock mass strength corresponding to the 70th percentile, while ground monitoring during sinking of the Shaft No. 10 indicated no deformation in this geologic unit (RCM, February 21, 2011, RCM, October, 6, 2017, RCM, June 28, 2018).
- Based on the experience gained from shaft sinking and the results of the back-analysis, RCM concluded that the input strength properties for the Tw unit for the base case and for sensitivity Scenario 1 (lower strength) are underestimated. As such, RCM concluded the global rock mass strength of the Tw unit used in the base case analysis and in the sensitivity Scenario 1 case are also underestimated.
- The total strain threshold (0.5% of total strain) used to define the Fractured Zone Limit is consistent with industry practice. It has been used in cave analyses for many caving operations and its reasonableness has been validated (see Section 5.4.6 for references). Nonetheless, the Fractured Zone Limit is very sensitive to this criterion. Considering the variability in the rock mass properties, there is some remaining uncertainty as to whether the fracture limit could extend closer to Apache Leap.
- The threshold used to define the Continuous Subsidence Zone is considered reasonable for rock formations such as those at Apache Leap.
- Based on the base case analysis, RCM concluded that although block cave operations may cause deformation at Apache Leap, Devil's Canyon, and at HW 60, the resulting strains in terms of angular distortion and horizontal strain is predicted below the damage threshold that could cause "moderate to severe damage" to the rock mass. Sensitivity analyses, however, indicate that the Fractured Zone Limit is impacted by reductions in rock mass and fault strength properties, as described below:
    - Fractured Zone Limit is extended outward in all directions, including towards Apache Leap, when rock mass strength properties of the Tal and Tw units were reduced by 25% (sensitivity Scenario 1) from the base case.

- The Fractured Zone Limit is also sensitive to reductions in fault strength. Sensitivity analysis indicates that the Fractured Zone Limit is closer to Apache Leap at lower fault strengths, compared to the base case.
- The Fractured Zone Limit is less sensitive to reductions in rock mass residual strength. Sensitivity analysis indicates that the Fractured Zone Limit is slightly closer to Apache Leap at lower residual strength values, but unlikely to impact subsidence.

The base case analysis shows that cave-induced ground deformations occur at or near Apache Leap, Devil's Canyon, or HW 60, but the predicted angular distortion is below the damage threshold that would cause "moderate to severe damage" in the rock mass. From sensitivity analyses it can be inferred that although the Tw global rock mass strength values for the base case and sensitivity Scenario 1 are consistent with published values and measured performance at Shaft No. 10, there is the potential that the Fractured Zone Limit approaches Apache Leap, should the global rock mass strength actually be lower than the values currently estimated for the base case and for sensitivity Scenario 1. This may result in toppling or failure of rock formations that might already be tilted due to natural processes.

8.0 CONCLUSIONS BY THE GEOLOGY AND SUBSIDENCE WORKGROUP

As stated in Section 1.0, the purpose of the Geology and Subsidence Workgroup was to review RCM's procedures and geologic and geotechnical baseline documents to answer five basic questions regarding the methods, interpretations, QA/QC, and other procedures employed by RCM. Table 8-1 summarizes the key parameters and factors affecting the subsidence analysis and the related data quality available for this investigation.

Table 8-1. Key input parameters impacting surface subsidence and the quality of the associated data.

Input Parameters	Direct/Indirect Impact	Relative Significance on Subsidence Model	Relative Quality of Data
Methodology Used to Collect and Document Geologic Data			
Geologic Data Collection	Indirect	Medium	High
Sample Recovery	Indirect	Medium	High
Core Logging	Indirect	Medium	High
Laboratory Testing	Indirect	Medium	High
Data Management	Indirect	Medium to Low	High
Interpretations of Geologic Structures, Rock Properties and Geotechnical Data			
GSI	Indirect	Medium	High
UCS	Indirect	Medium	High
Geologic Structures, Faults	Direct	High	High
Geotechnical Data Quality	Indirect	Medium	High
Key Model Inputs (Including Uncertainties)			
Rock Mass Quality	Indirect	Medium	High at depth within 1% copper shell, Medium to low outside 1% copper shell
Rock Mass Strength Properties	Direct	High	Medium to High
Fault Strength Properties	Direct	High	Medium to High
Rock Mass Damage Criteria	Direct	High	Medium
Peak to Post-Peak Rock Mass Criterion	Direct	High	Medium

These five questions are discussed in detail within this report and are summarized below.

1. Determine whether the methods employed by RCM in collecting and documenting geologic data were appropriate, adequate, and according to industry standards. In other words, does the data and analytical approach meet the current industry standard-of-practice?

   Conclusion: As discussed in previous sections, geologic data collection including drilling, sample recovery, core logging, data management, laboratory testing, analysis, interpretation, and modeling meets or exceeds industry standards. Generally, the Workgroup finds that RCM's geologic program meets or exceeds the industry standard-of-practice.

2. Determine whether RCM's interpretations of geologic structures, faults, rock properties, geotechnical data, and assumptions are reasonable.

   Conclusion: As discussed in Sections 3.0 and 4.0, internal RCM procedures require intensive evaluation of results in the acQuire geotechnical database system, assigning of geotechnical domains, interpretation of structures, faults, and lithologic units, and geologic model interpretation. Updates to the geologic model occur periodically to incorporate new borehole data, laboratory results, and field mapping. Internal QA/QC review is extensive and robust and occurs throughout the data acquisition, interpretation, and modeling processes. External review of interpretations by a Geotechnical Review Board and others provides adequate scrutiny of input data, interpretations, and assumptions. Therefore, the Workgroup finds RCM's interpretations of geologic structures, faults, rock properties, geotechnical data, and assumptions to be reasonable.

3. Identify any data gaps. In other words, are there weaknesses in the analysis?

   Conclusion: As discussed in Section 3.0, at the local scale, RCM's sampling program meets all seven DQIs for the near case because of the dense sampling within the 1% copper shell mineralized zone. Therefore, the samples are representative of the population. However, for the far case (i.e. those areas outside of the mineralized zone), the extent of the extrapolation reduces DQIs because, outside the mineralized zone, sampling density is much lower. Rock properties, faults, and lithologic boundaries in these areas are extrapolated over large areas. This extrapolation does not represent a "data gap", but rather it represents an area with less certainty in the interpretations of that data.

   As discussed in Sections 4.2 and 4.3, there are many fault blocks and faults, especially on the west side of the ore body that are "inferred" to "low indicated," which indicates the data do not support higher levels of confidence on this area. This has implications that, although the quality of the data is high (meaning the data is properly acquired, reviewed, and verified), the spatial distribution of the data is low or minimal. Two particular faults (Camp and Gant) were not intersected with drill holes. These are potentially important west boundary faults in the proposed cave zone. However, there has been extensive field mapping (RCM, June 28, 2018b) of these faults.

Therefore, the Workgroup concludes that geologic data outside of the mineralized zone, as well as for the Camp and Gant faults, is not as well represented as in the mineralized zone. Modeling assumptions and sensitivity analyses have been used to account for sparse data in these areas. However, the interpretation of surface subsidence, as described in the EIS, includes areas of data uncertainty.

4. Identify how much uncertainty exists with these interpretations, with consideration of data gaps. What data and assumptions have the most influence on subsidence and the model?

Conclusion: As discussed in Sections 3.0, 4.0 and 5.0, there is a great deal of interpretation required in the entire process of estimating the amount and extent of subsidence, from data collection to testing and analysis, to model input and interpretations, and sensitivity runs. There are two approaches to consider the certainty of the geologic and subsidence models. One approach is empirical, which compares the model results with a conceptual model of the cave geometry based on what has been observed at other similar mines with similar geologic settings. The other is to change input parameters to reasonable limits to see the resulting cave geometric response (i.e. sensitivity analyses). Each approach is discussed below.

Base case model results predicted that the Fractured Zone Limit at Resolution is mainly controlled by the extraction level depth (6725 ft (2050 m) below ground surface) and shape of the footprint (Itasca, April 6, 2018). For comparison with existing panel cave mines, the Woo et al. (2013) database of cave operations was consulted. Although very few cave operations have been included in the database with undercut depth greater than 3280 ft (1000 m), the results of the base case simulation of the Resolution panel cave are generally in agreement with other cases in that database. However, it is important to note that there are uncertainties associated with the use of empirical methods to estimate the cave angle. These include variability in rock mass strength and fault strength properties, and local in-situ stress distribution. These uncertainties are discussed in Section 5.0. Proper assessment of surface subsidence resulting from a caving operation requires detailed geological, structural, geotechnical and numerical assessments to adequately address these uncertainties.

The numerical simulations of the Resolution panel cave considered a set of geological, geotechnical, and structural conditions representative of the Resolution property, and used a widely accepted, commonly used numerical tool to predict ground surface subsidence at the Resolution property. Sensitivity analyses were performed to assess impact of uncertainty and variability in several input parameters on the subsidence model predictions. The uncertainties explored using sensitivity studies included:

- Rock mass quality and intact rock strength properties – there are uncertainties associated with spatial variability of the rock mass properties, particularly in the Tw geologic unit, which is a relatively weak rock mass situated immediately below the Tal unit. The UCS values were derived from point load tests that were completed on core samples obtained from diamond drill cores, where available. As a limited number of holes have been drilled in the Tw unit, the spatial variability of UCS data could result in uncertainty in estimated global rock mass strength. There is also uncertainty in global rock mass strength in the Tw unit due to limitations in applying GSI to this unit. Application of GSI to the Tw unit at its interpreted value implies that there are three joint sets in the rock mass and that joint sets are fully persistent. The rock mass structure assessment, however, only indicated one joint set in the Tw unit and no information on joint persistence can be obtained from core data, hence GSI is underestimated and results in low global strength for this rock unit.

- Fault strength properties – fault strength properties have been estimated based on infill characteristics, and as such, have been classified as Strong, Medium, or Weak. Fault infill characteristics have been provided by RCM geologist and are mainly based on detailed logging of core and mapping of fault exposures on surface. Considering the limited amount of core and mapping data available from fault intercepts compared to the extent and depth of the faults that have been identified within the Resolution property, there is uncertainty associated with the fault characterization and the associated material properties assigned to each fault category. This has more effect in the case of faults that are positioned near the perimeter of the subsidence crater and Fractured Zone Limit, which is where drilling data are less abundant.
- Fractured Zone Limit criterion (total strain limit at 0.5%) – determination of Fractured Zone Limit from FLAC3D numerical model is directly dependent on the Fractured Zone Limit fracture limit criterion used. This criterion is empirical and has been used in and validated by its successful application to other cave operations (see Section 5.4.6 for references). Numerical results, however, have shown that total predicted strain may vary locally. The empirical nature and total strain sensitivity creates a level of uncertainty in the predicted total strain and the resulting Fractured Zone Limit. At this time, there is no explicit way to calibrate the model and to refine the Fractured Zone Limit criterion to address this uncertainty.
- Critical plastic strain threshold as a criterion to reduce peak rock mass strength to residual– an empirically calculated critical plastic strain has been used in FLAC3D to determine at what stage peak rock mass properties are reduced to residual strength to determine the Fractured Zone Limit. As discussed in Section 5.4.4, Lorig and Varina (2000) reported that, as part of the International Caving Study, an empirical relationship was developed between critical plastic strain and GSI by back analysis of rock mass failure in caves and other openings, and was used to determine an approximation of the critical plastic strain for each rock mass domain. Considering the GSI assigned to the Tw unit may be underestimated, as discussed earlier, this introduces a level of uncertainty into the calculated critical plastic strain used in the model, which could impact the extent of Fractured Zone Limit predicted by the subsidence model.

5. Determine if there are cases where RCM's interpretations are not considered reasonable and, if so, provide alternative interpretations and supporting rationale.

Conclusion: Overall, the Workgroup concludes that RCM's interpretations are reasonable, and that the geologic data and modeling results represent the best available science for determining and disclosing subsidence impacts. Therefore, we do not propose alternative interpretations. However, as described in the previous sections, there are numerous input variables and several layers of interpretation involved in the modeling of surface subsidence. Therefore, it is important to disclose these areas of uncertainty, areas of sparse or missing data, and that actual surface subsidence could vary from the modeled results.

9.0 CREDENTIALS OF REVIEWERS

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Laurie is a Certified Professional Geologist (AIPG) with a B.S. in Geography/Geology from the Pennsylvania State University (1984) and an M.S. in Remote Sensing/Geology from Cornell University (1986). She has worked for over 20 years in engineering geology and specializes in geotechnical site assessments, mineral resource evaluations, geologic hazards, and mine reclamation. Laurie is both MSHA and HAZWOPER certified and has been involved with Environmental Impact Statements (EIS) and Environmental Assessments (EA) in Colorado, California, and Arizona for mines, powerlines and Resource Management Plans (RMP). Laurie is also a Lecturer of Geology at the Montrose Campus of Colorado Mesa University where she has been teaching classes since 2000.

Robert (Nick) Enos, M.Sc., CPG

Nick is a Principal Geoscientist with BGC Engineering, and a Certified Professional Geologist (AIPG). He has a B.S. in Geology from California State University Chico (1988) and an M.S. in Geosciences from Oregon State University (1992), where his graduate research focused on structural geology, tectonics, and geophysics. Nick has over 28 years of experience in the mineral industry, with an emphasis on geosciences, environmental permitting, Environmental Impact Statement (EIS) and National Environmental Policy Act (NEPA) review, integrated environmental baseline studies, and mine closure planning.

Amir Karami, PhD, P.Eng (BC, NS)

Amir is a Senior Geotechnical Engineer with BGC Engineering, specializing in rock mechanics in underground and open pit geotechnical engineering. He has a Ph.D. in Rock Mechanics from University of Alberta (2002). Amir has been involved in many mining projects in Canada, the US, and overseas. Amir has been involved in 2D and 3D numerical investigations for a number of open pit and underground mine development projects. Amir has several years of underground mine operations experience and was the lead geotechnical engineer to support mine operations and mine technical services teams. Amir has been involved in geotechnical investigations, numerical modeling, ground control management plan development, geotechnical monitoring and instrumentation, geotechnical audits and geotechnical incident investigations in consulting and/or at mine operations.

Diana Cook, Ph.D., PE

Ms. Cook is a Senior Geological Engineer with BGC Engineering with approximately fifteen years of experience in geotechnical and geological engineering, including design of earthen and rockfill dams, heap leach pads, tailings impoundments, pit stability analyses, and waste containment for mining projects. Ms. Cook has a Ph.D. in Geological Engineering from Colorado School of Mines (2009). Ms. Cook has worked on site-specific seismic hazard analyses for several mines around the world and has also performed liquefaction studies for sites in the U.S., South America, and

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Mr. Henderson has extensive experience providing civil and geotechnical engineering design. He has a M.Sc. in Civil Engineering from University of Pittsburgh (1984) and has completed post-graduate studies in Geotechnical Engineering from University of Nevada and Colorado State University. Mike is responsible for senior review and leadership on a wide range of engineering projects, including underground mines, tailings impoundments, water storage reservoirs, heap leach facilities, and mine planning. Mike's technical background relating to designing mining facilities includes design-engineering experience on a wide range of projects in the US and overseas, operations experience at several large mines, mine and energy research for the US Bureau of Mines and Department of Energy, and expert witness testimony related to mining issues.

Rex Bryan, Ph.D.

Dr. Rex Bryan has a PhD in Mineral Economics from the Colorado School of Mines and a geology degree from Brown University. He has been a mining consultant for over forty years specializing in geostatistics. He has consulted to both the mining and environmental industries on sampling, geological computer modeling and resource estimation. He is a Qualified Person for mineral resource estimation. He has authored EPA guidance documents on sampling methods and statistics analysis for the Data Quality Objective process.

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APPENDIX A
TABLES A1-A2

Table A1

Summary of Key Activities & Data Submittals for Geology & Subsidence Workgroup

As of 12/15/2020

Date	**Activity**	**Details**
11/15-16/16	Site visit by EIS team to Superior, AZ	RCM hosted the site visit that involved presentations (such as site geology and geologic model by B. Hart), field trips on surface and underground, and meetings to discuss the proposed project
1/25/17	Internal memo from BGC to SWCA - Summary of Geotechnical Reports for the Resolution Copper Mine	Initial comments based on review of documents available to date regarding data gaps and methodology adequacy for Subsidence Management Plan, Rock Types Characteristics and Rock Mass Characterization, Seismic Hazard Analysis, and other areas with data gaps.
1/27/17	Internal memo from DOWL to SWCA – Draft review of baseline documents relating to geology	Initial comments based on review of documents available to date regarding data gaps and methodology adequacy for geologic modeling, affected minerals, geophysical data, molybdenum development, geologic data, alternative collapse modeling, seismic hazard, geologic hazards, and QA/QC procedures.
3/3/17	Baseline Data Request #1 sent to RCM	1B – Internal Quality Procedures – Geology 1C – Geologic Framework Report
3/24/17	RCM response to Baseline Data Request #1 for Item 1B	Attachment 1: 2015 annual report 2015 inferred resource Attachment 2: A description of quality assurance program for the geologic model describing the data inputs, the QA/QC process, modeling Attachment 3: Process control diagrams Attachment 4: A letter from the third party competent and qualified person (H. Parker 3/14/17 letter) describing the 2016 geologic and mineral resource model and validation process
5/4-5/17	Field visit to observe logging procedures and Vulcan data	L. Brandt, R. Bryan and G. Gonzales toured the EPS; field trips to see faults, existing and proposed operations, and drilling locations; tour of core shed and logging/testing procedures; meetings for explanations of logging, QA/QC, data entry, testing, modeling, etc.
5/12/17	RCM response to Baseline Data Request #1 for Item 1C	4D Geo Applied Structural Geology. "Summary of geologic information relevant to development of the porphyry Cu-Mo Resolution deposit, Arizona". May 2017 (00001347.pdf)
6/2/17	Internal workgroup call re: additional data requests	Topics for next data request memo – internal RCM QC procedures, data gaps outside ore body, faults, sensitivity analysis in model, rock properties, cross-sections, geologic map update
6/22/17	Baseline Data Request #3 sent to RCM	Request for Apache Leap LIDAR data

Date	Activity	Details
6/26/17	Extraction of hi-res geology map from original PDF file	"20161231_Hart RCM Geologic Map of the Resolution Project Area extracted from 1347.pdf"
6/30/18	Internal memo from BGC to SWCA -	List of data base, model and raw data information needed for cave project evaluation and criteria used for strength and other model parameters.
7/7/17	Summary of field visit May 4-5 by L. Brandt, G. Gonzalez, R. Bryan	Describes the site visits and meetings hosted by RCM to show and explain procedures for logging and testing samples, geologic interpretation, characterizing faults, etc. Contains conclusions and recommendations for further information.
7/11/17	RCM response to Baseline Data Request #3	Resolution_Movement_Monitoring_v2.pdf Resolution Report March 2012.pdf Apache Leap Report April 2014.pdf Apache Leap Report November 2014.pdf 2015_11 Maptek Change Detection Report.pdf Change Detection Report April 2016.pdf RCML GTC 2017 01 MAPTEK Change Detection Report January 2017.pdf
7/17/17	RCM submittal of Itasca subsidence report	Itasca Consulting Group. "Assessment of Surface Subsidence Associated with Caving: Resolution Copper Mine Plan of Operations". July 17, 2017
7/28/17	Internal workgroup call re: Itasca report review and additional data requests	Recognize need for report to bridge the gap between the GPO and the subsidence report. Need more info/properties of overburden units (Tw, Tal). Possible bias towards strong materials.
7/31/17	Informal request for Itasca subsidence shapefiles; internal comparison of GPO and new Itasca contours	
8/3/17	RCM submittal of Itasca subsidence shapefiles, with evolution over time	"Sub_Files_Fig17_Itasca_2017 Report.zip"
8/16/17	Geology/Subsidence Workgroup draft data request memo of geology, geotechnical considerations and subsidence modeling Provided to RCM in preparation for 9/13 meeting	"Data Request Memo - Geology Geotechnical Subsidence Info DRAFT 8-16-17_v1.docx"
9/13/17	**Workgroup Meeting #1**	"20170913_Subsidence KO Meeting-minutes-pkg.pdf"
9/14/17	Internal workgroup call re: additional data requests	Need for more graphics of boreholes and cross-sections, sensitivity analysis, geotech characterization and subsidence modeling reports, more fault info.

Date	Activity	Details
10/12/17	Baseline Data Request #4 sent to RCM	A. (1-6) 3D Visualizations B. (1-8) Sensitivity Analysis of the Subsidence Model Report C. (1-13) Geotechnical Characterization Report. D. (1-4) General Subsidence Modeling Tech Memo or Report. E. (1-3) Fault Data Tech Memo. F. (1-2) Vibration Report.
1/10/18	RCM provides Geotech Rock Characterization Report	"Geotechnical Characterization Report-Jan-10-2018" dated October 5, 2017
10/18/17	Baseline Data Request #5 sent to RCM	Request for Queen Creek and Oak Flat LiDAR data
10/18/17	RCM submittal of revised geology report (data request #1C)	"P1259 Res NEPA EIS geology 201705.pdf"
10/31/17	Informal request for clarification of subsidence contours overlapping EPS infrastructure	Email from Donna Morey to Vicky Peacey asking for Resolution to confirm the DXF files and project for the data received for Itasca's July 2017 report.
11/7/17	Clarification provided to RCM on spacing for Data Request #4	Email from Donna to Resolution (Cameo Flood) stating that the group feels "300 or 500' spacing but 100' spacing as you come near each fault, then back to 300-500'" would be appropriate for the Data Request #4
11/29/17	**Workgroup Meeting #2**	"20171129_Geology Workgroup Meeting notes-pkg.pdf"
12/15/17	RCM confirms that subsidence contours overlap EPS infrastructure	
1/9/18	1st RCM response to Baseline Data Request #4 – Geologic/Geotechnical	"Letter to USFS - RC Response to Baseline #4.pdf" A_1: Sections A_2: Drilling Spreadsheet A_3: 3D PDF Viewer A_4: Table of Drill Holes Intersecting Faults B_1: Alteration Logging Process C_1: Block Caving Database Reference Updated GPO Appendix F
1/18/18	Internal workgroup call to discuss submittal	
1/25/18	2nd RCM response to Baseline Data Request #4	E3. Lettis Consultants International, Inc. (LCI): "Final Report Site-Specific Seismic Hazard Evaluation for the Proposed Resolution Copper Mine, Southern Arizona". January 23, 2018.
1/26/18	**Workgroup Meeting #3**	"20180126_Subsidence Meeting_Minutes_pkg.pdf"
2/15/18	RCM response to Baseline Data Request #5	3v Geomatics, Inc. "InSAR Monitoring at Rio Tinto Resolution Copper Mine In Arizona, US". October 21, 2016.
3/14/18	3rd RCM response to Baseline Data Request #4	Amec Foster Wheeler (Dr. Parker): "Review of Geological and Structural Models at Resolution Copper Project", March 7, 2017 [Note incorrect date]

Date	Activity	Details
3/15/18	RCM submits PPT with initial sensitivity output	"Cave Model Sensitivity Resolution MPO_15Mar2018.pdf"
3/16/18	**Workgroup Meeting #4**	"20180316_SubsidenceMeeting_notes_pkg.pdf" and received presentation by M. Pierce "Sensitivity Study of Model Parameters in the Caving Predictions for Resolution Copper Mine."
3/16/18	Internal input from P. Werner	Email from Peter Werner on 3/15 - questions on distribution samples
3/19/18	Confirmation of incorrect date on new Parker report submitted 3/14	Chris checked with Vicky on 3/19 by phone to ensure date - then emailed the Forest and SWCA subcontractors with the confirmation & disseminating the report
3/19/18	Internal comparison and discussion of Itasca vs. Beck models	Email from Nick Enos to Chris Garrett & BGC Team on 3/19/18
3/27/18	Internal input from P. Werner	Email from Peter Werner to Chris Garrett with his thoughts on subsidence modeling, included some other papers for consideration
4/9/18	Obtain Parker report reference	"263171926-Geological-Model-Simulation.pdf"
4/10/18	4th RCM response to Baseline Data Request #4	Itasca Consulting Group. "Subsidence Impact Analysis – Sensitivity Study, Addendum to Itasca Report "Assessment of Surface Subsidence Associated with Caving"". April 6, 2018.
4/17/18	RCM internal memo from J. Tshisens to V. Peacey for distribution to Geology Workgroup	"3D PDF Legend, Recovery Table and Sections Explanations"
4/19/18	Internal workgroup call re: final data request	Itemize what is lacking from the subsidence sensitivity report; fault descriptions and strength; rock mass global strength, model results
4/19/18	RCM response to 1/26 workgroup meeting action items	"Response to 1-26-18 Action Items - Geology-Geotechnical.pdf"
4/20/18	RCM response to 3/16 workgroup meeting action items	Itasca Model History Plots (email with attachments); "Displacements through sections Base Case.pptx"
4/23/18	Internal outline and plan for Geology Data Validation Report circulated	
4/26/18	Internal compilation of geology/subsidence reference list	"Geology-Subsidence references.docx"

Date	Activity	Details
4/30/18	Clarification received from RCM on available fault analysis memos	Confirmed that there are three memos: 1) "Wickham memo" (related to hydrology, not yet submitted); 2) 1/23/18 Lettis report; 3) 3/7/18 AMEC/Parker report
4/30/18	RCM submittal of revised Parker geology report with correct date	E2. AMEC Foster Wheeler (Dr. Parker). "Review of Geological and Structural Models at Resolution Copper Project". March 7, 2018 [This version has correct date and replaces version provided 3/14/18]
5/2/18	RCM response to workgroup action items	Itasca Consulting Group. "Answers to Questions Raised in March 16, 2018 Review of Itasca Analysis of Resolution Subsidence". May 2, 2018. (2-4208-04-18TM15.pdf)
5/9/18	Internal workgroup call to discuss final data request	Master list needed of requests and responses; more fault info; statistical analysis data needs.
5/16/18	**Workgroup Meeting #5**	20180516_Geology_MtgNotes_pkg.pdf
5/13/18	Internal circulation of final data request to FS specialists	Email from Donna Morey to internal team
5/14/18	Internal input from P. Werner	Sensitivity ranges, spatial distribution, point histories and Apache Leap
5/15/18	Internal workgroup call to discuss final data request	Point histories, fracture limits, rock mass strength, sensitivity analyses, etc.
5/29/18	Baseline Data Request #9 sent to RCM (draft)	A. Rock Mass Strength A1. Monte Carlo for Tw A2. # of samples on figures/tables A3. Discussion of spatial distribution; statistics supporting assumption that rock properties vary by lithology and not by location A4. Rationale for base-case strength value A5. Rationale for sensitivity based on factor of safety concept B. Faults B1. Gant and Camp fault data B2. Additional cross sections B3. Resolution fault confirmation B4. Verify Parker-Verly numbering B5. GIS layer for faults C. Model Results C1. Add yielded zone/fracture limit to sections C2. Additional line plots C3. Contour plots D. Sensitivity Report D1. Rationale for total strain threshold value D2. Provide CODELCO reference

Date	Activity	Details
		E. Additional documentation for using the "continuous subsidence limit" as the basis for the limit of impacts
6/12/18	**Workgroup Meeting #6**	20180612_GeologyWG6_minutes_pkg.pdf
6/29/18	RCM submittal of Subsidence Monitoring Plan	Resolution Copper. "Draft Subsidence Monitoring Plan". May 5, 2018.
6/29/18	RCM response to Baseline Data Request #9 – Geotechnical data for subsidence model review	Provided in letter response (rock mass strength, faults, model results, sensitivity impact analysis), point loads, Tw strength info, wireframes of faults (dxf), line plots, tilt plots, video of W Boundary fault, Gant and Camp fault descriptions, Itasca Caving Predictions for RCM at YR 41, Itasca Surface Subsidence Cave Operations.
7/9/18	Internal memo from BGC to SWCA	"Mining-Induced Seismicity: Causes and Possible Impacts – Final"
7/23/18	Informal (email) request for clarifications on Data Request #9	A1. Rock Mass Strength – Request for further discussion about Tw conservativeness via dated addendum A3. Rock Mass Strength – Request for spatial variability statistical analysis A4. Rock Mass Strength – Request for rationale for base case, Tal and Tw both A4. Rock Mass Strength – Request for additional sensitivity run A5. Rock Mass Strength – Request for discussion about factor of safety C1. Model Results – Request for additional output D. Sensitivity analysis – Request for rationale for selecting strain threshold
8/3/18	RCM response to 7/23/18 clarification requests	A1. Response included in Attachment 1 A3. No additional data available provided A4. Response included in Attachment 2. Attachment 3provides additional reference on base case selection. A4. No additional sensitivity run provided. A5. Attachments 1 and 3 C1. No additional output provided, citing June 12 meeting discussion. D. Itasca memo updated and provided as Attachment 4
8/7/18	Internal geo/subsidence workgroup phone conference call	Prior to meeting with RCM, workgroup discussed topics that needed to be covered tomorrow. The group clarified requests to RCM for data or explanations that were still needed.
8/8/18	**Workgroup Meeting #7**	20180818_GeologyWG7_minutes_pkg.pdf
8/18/18	Combined FS comments on Draft Geologic Data Subsidence Modeling Evaluation Report	Itemized comments from Mary Rasmussen and Peter Werner.

Date	Activity	Details
9/5/18	RCM response to geology workgroup email questions	Email with attachment from V. Peacey, which has responses from M. Pierce (Itasca) and the reference "Probabilistic stability analysis of slopes in highly heterogeneous rock masses" attached.
9/14/18	Emailed partial response from RCM for 8/8/18 meeting data request	D. Morey (SWCA) sent the Geology/Subsidence Workgroup an email containing two files from RCM relating to the 8/8 request: 1. Technical memo from Itasca explaining representativeness of data from Shaft #10 for the Whitetail Conglomerate. 2. Updated Figures 16 and 21 from H. Parker report.
10/12/18	Internal geo/subsidence workgroup phone conference call	To discuss details of a Standards table (ASTM, ISRM, etc.), as requested by the FS. Should include lab testing, field and lab core logging, modeling and interpretation.
10/25/18	Email data request for RCM's evaluation/ comments of Standards Table A2	Chris Garrett sent an email with Table A2 attached to V. Peacey of RCM requesting their comments and edits to the table so that it is most accurate for the standards followed by RCM.
11/5/18	Email response from RCM with modeling references	V. Peacey of RCM email to C. Garrett of SWCA forwarding a list of references from M. Pierce of Itasca for subsidence modeling and rock mass strength as model input.
12/1/18	Completion of Geologic Data and Subsidence Modeling Evaluation Report	N. Enos on behalf of Geology/Subsidence Workgroup email to C. Garrett, submitted revised Geologic Data and Subsidence Modeling Evaluation Report (rev 6, dated 11/30/2018).
12/27/18	Email summary of remaining subsidence clarification by A. Karami for RCM	A. Karami/N. Enos email to C. Garrett with a summary list of 5 remaining requests for RCM related to subsidence modeling. These were later included as part of the Geology/Subsidence/Seismicity Workgroup action item #GS-7.
8/19/19	**Publication of DEIS**	**The Tonto National Forest published the Draft EIS on August 9, 2019.**
11/7/19	End of DEIS public comment period	The Draft EIS public comment period closed November 7, 2019.
12/11/19	Distribution of Chambers and Emerman public comment letters regarding subsidence, seismic design, and seismicity	C. Garrett email to Workgroup providing Dr. Chambers Appendix A – Comments from the Center for Science in Public Participation (10/28/19) regarding subsidence and seismic design; and Dr. Emerman – letters commenting on seismicity for the tailings storage facilities (3/27/2019) and subsidence (3/17/19)
1/21/20	**Workgroup Meeting #8**	Overview of public comments related to geology, subsidence, alternative mining methods, and seismicity received on the DEIS. Review of EIS Team "Charter" with plan on addressing comments for the FEIS.
1/21/20	Development of 12 action items for Workgroup to address DEIS comments	C. Garrett email to Geology/Subsidence/Seismicity Workgroup summarizing 12 action items (GS-1 through GS-12) for Workgroup and RCM to address.

1/21/20	Email summary of all RCM responses addressing GS-7	C. Garrett email to Geology/Subsidence/Seismicity Workgroup summarizing all responses and items received from RCM addressing GS-7.
2/2/20	Dr. Kliche response to Chamber's comments re underground mining techniques (GS-1).	Documentation received by SWCA on 1/29/20. Note that documentation regarding Alternative Mining Techniques provided in 9/11/20 Process Memorandum to File: Post-DEIS Review of Alternative Mining Techniques.
2/11/20	**Workgroup Meeting #9**	Workgroup status review of Action Items GS-1 through GS-12. Specific discussion related to Emerman subsidence report and subsidence disclosure, alternative mining techniques, subsidence monitoring plan, and seismic analysis. Workgroup identified 4 additional action items (GS-13 through GS-16).
2/26/20	RCM response to GS-2, addressing specific assumptions made by Chambers related to the ore deposit	V. Peacey (RCM) letter to M. Rasmussen (USFS) responding to GS-2, including response memo from RCM consultants Itasca Consulting Group and Pierce Engineering.
2/26/20	RCM response to GS-4, addressing faults incorporated into the subsidence model	V. Peacey (RCM) letter to M. Rasmussen (USFS) responding to GS-4, including response details on how faults are incorporated into subsidence modeling from RCM consultants Itasca Consulting Group.
2/26/20	RCM response to GS-5, addressing uncertainty in subsidence modeling	V. Peacey (RCM) letter to M. Rasmussen (USFS) responding to GS-5, including response memo from RCM consultants Itasca Consulting Group and Pierce Engineering, which provides input on uncertainty in subsidence modeling.
2/26/20	RCM response to GS-9, providing 2018 Subsidence Monitoring Plan.	V. Peacey (RCM) to M. Rasmussen (USFS) providing a copy of the 2018 Subsidence Monitoring Plan, in response to GS-9.
3/3/20	Email summary of RCM data responses to GS-2, GS-4, GS-5, and GS-9.	C. Garrett email to Workgroup summarizing RCM's data responses to Workgroup action items GS-2, GS-4, GS-5, and GS-9.
3/13/20	Itasca info addressing GS-11, on describing subsidence displacement and tilt	V. Peacey (RCM) email to M. Rasmussen (USFS), providing information from M. Pierce (Itasca) on how subsidence model output (displacement, tilt, differential movement) can be translated into real-world effects.
3/18/20	Itasca presentation summarizing alternative mining techniques (GS-3b and GS-11)	Itasca and RCM provided a PowerPoint presentation summarizing a literature review of possible alternative mining techniques, forming a partial response to Action Item GS-3B. Action Item GS-3A, assigned to the TNF, determined the appraisal document was not relevant or needed. GS-11 was also addressed with discussions of displacement/tilt and analogs.

3/19/20	BGC memo assessing investigations of surface faulting at Skunk Camp (GS-12a)	N. Enos email to C. Garrett submitting BGC's (M. Zelman/D.Cook) memo assessing RCM's previous investigations of surface faulting at the Skunk Camp TSF location. Action item GS-12a.
3/24/20	RCM responses regarding seismic hazard and design for TSF (GS-2 and GS-10)	C. Garrett email to Workgroup forwarding V. Peacey (RCM) email and letter responses to GS-2 and GS-10, regarding seismic hazard and design criteria for the tailings storage facility, including KCM memo: Skunk Camp Tailings Storage Facility Response to Geo-Subsidence/Seismic Working Group Action Items #GS-2 and #GS-12 Related to Seismicity.
3/24/20	**Workgroup Meeting #10**	RCM presentation of, and Workgroup review of, 2018 Subsidence Monitoring Plan, with discussion of revised plan for FEIS.
3/26/20	RCM provides additional information on alternative mining techniques (GS-3b)	V. Peacey (RCM) email to M. Rasmussen (USFS), providing additional information on alternative mining techniques, responding to GS-3b. Included is a 3/24 memo by Pierce Engineering addressing Safety Considerations in Mining Method Selection at Resolution.
3/27/20	BGC review comments on the TARP section of RCM's 2018 Subsidence Monitoring Plan	C. Garrett email to Workgroup with A. Karami's (BGC) review comments on the Trigger Action Reponses Plan (TARP) section of the 2018 Resolution Subsidence Monitoring Plan.
4/17/20	RCM responses regarding induced seismicity, addressing GS-16	C. Garrett email to Workgroup with V. Peacey letter with two reports – Tech Memo by Itasca (10/1/19) "Assessment of Potential for Caving-Induced Fault Slop Seismicity at RCM" and Tech Memo by Lettis Consultants (4/13/20) relating to induced earthquake potential and failure modes.
6/19/20	RCM responses to GS-17, including an updated Subsidence Monitoring & Management Plan	V. Peacey (RCM) email to M. Rasmussen (USFS) providing responses to GS-17, including an updated Subsidence Monitoring & Management Plan. Forwarded to the Workgroup for review on 6/22.
7/13/20	BGC review comments on updated Subsidence Monitoring & Management Plan	C. Garrett (SWCA) email to V. Peacey (RCM) requesting responses to BGC's 7/10 comments on the updated Subsidence Monitoring & Management Plan.
7/17/20	RCM responses to GS-18 and DEIS comments on subsidence monitoring	V. Peacey (RCM) email to M. Rasmussen (USFS) providing responses to GS-18 and recommendations for baseline or continual monitoring using baseline features (SRP transmission poles, ADOT Queen Creek Bridge, ADOT Queen Creek Tunnel, AWC Water Tank); Includes responses to related DEIS comments on subsidence monitoring.
8/6/20	RCM responses to BGC's comments on updated Subsidence Monitoring &	V. Peacey (RCM) email to C. Garrett (SWCA) with responses to BGC's 7/10 comments on the updated Subsidence Monitoring & Management Plan from Andy Davies (Principal Geotechnical Engineer – Underground, Rio Tinto, Copper & Diamonds).

9/11/20	Process memo addressing GS-1 and Alternative Mining Techniques	Process Memorandum to File: Post-DEIS Review of Alternative Mining Techniques, prepared by C. Garrett (SWCA).

Table A2: Reference standards applicable to geologic interpretation, laboratory testing, subsidence modeling, and geotech data		
Reference Standard(s)	**IS THIS REFERENCE STANDARD APPLICABLE?**	**WHAT ASPECTS OF THE ANALYSIS IS THIS REFERENCE STANDARD APPLICABLE TO?**
FIELD TESTING		
ASTM D5434 - Guide for Field Logging of Subsurface Explorations of Soil and Rock	yes	Field logging of rock core sampling protocol
ASTM 5781, D5782, D5783, D5784, D5872, D5875 and D5876 - Drilling method guidelines	yes	Field logging of rock core sampling protocol
ASTM D2113 - Standard Practice for Rock Core Drilling and Sampling of Rock for Site Investigation	yes	Field logging of rock core sampling protocol
ASTM D6169/D6169M - Standard Guide for Selection of Soil and Rock Sampling Devices Used with Drill Rigs for Environmental Investigations	yes, where applicable	Field logging of rock core sampling protocol
ASTM D653 - Terminology Relating to Soil, Rock, and Contained Fluids	yes	Field logging of rock core sampling protocol
ASTM D5079 and D4220 - Practices for Preserving and Transporting Rock Core and soil samples	yes	Field preserving and transporting rock and soil samples protocol
ASTM D5783 - Guide for Use of Direct Rotary Drilling with Water-Based Drilling Fluid for Geoenvironmental Exploration and the Installation of Subsurface Water-Quality Monitoring Devices	yes, where applicable	Field logging of rock core sampling protocol
ASTM D5876 - Guide for Use of Direct Rotary Wireline Casing Advancement Drilling Methods for Geoenvironmental Exploration and Installation of Subsurface Water-Quality Monitoring Devices	yes	Field logging of rock core sampling protocol
ASTM D6032 - Test Method for Determining Rock Quality Designation (RQD) of Rock Core	yes	Field logging of rock core sampling protocol
ASTM D6429-99(2011)e1 - Standard Guide for Selecting Surface Geophysical Methods	yes	Field geologic analysis
ISRM Suggested Method for Rock Fractures Observations Using a Borehole Digital Optical Televiewer.	yes	Field geologic analysis
ISRM (1981) Suggested Method for Geophysical Logging of Boreholes	yes	Field logging of rock core sampling protocol
ISRM (1978) Suggested Method for Determining Sound Velocity	no	Field logging of rock core sampling protocol
ISRM (1987) Suggested Method for In-Situ Rock Stress Determination	yes	rock characterization
ISRM (2003) Suggested Method for In-Situ Rock Stress Estimation	yes	rock characterization
ISRM (2006) Suggested Method for Borehole Geophysics in Rock Engineering	yes	rock characterization
ISRM (1978) Suggested Method for Monitoring Rock Movements Using Borehole Extensometers	yes	monitoring
GEOTECHNICAL CHARACTERIZATION & SUBSIDENCE MODELING		
ASTM D5878 - Standard Guide for Using Rock-Mass Classification Systems for Engineering Purposes	yes	subsidence modeling
ASTM Special Publication 984 - Rock Classification Systems for Engineering Purposes	yes	rock characterization
ISRM (2007-2014) Suggested Methods for Rock Stress Estimation—Part 5: Establishing a Model for the In Situ Stress at a Given Site	yes	rock characterization
ISRM (2007-2014) Suggested Methods for Rock Failure Criteria - General information, Mohr-Coulomb Failure Criterion, Hoek-Brown Failure Criterion, 3D Failure based on Hoek-Brown, Drucker-Prager Criterion, True Triaxial Testing Failure Criterion	yes, Mohr-Coulomb Failure Criterion and Hoek-Brown Failure Criterion no, Drucker-Prager Criterion and True Triaxial Testing Failure Criterion	rock characterization

ISRM (2007-2014) Lade and Modified Lade 3D Rock Strength Criteria	no	rock characterization
ISRM (1978) Suggested Method for Quantitative Description of Discontinuities in Rock Masses	yes	rock characterization
ISRM (1978) Suggested Method for Petrographic Description of Rocks	yes	rock characterization
ISRM (1999) Suggested Method for the Complete Stress-Strain Curve for Intact Rock in Uniaxial Compression	yes	rock characterization
LABORATORY TESTING		
ASTM D5607 - Standard Test Method for Performing Laboratory Direct Shear Strength Tests of Rock Specimens Under Constrnt Normal Force	no	Lab testing of rock core samples
ASTM D5731-05 - Standard Test Method for Determining of the Point Load Strength Index of Rock and Application to Rock Strength Classifications. Determines point load strength index for strength classification of rock materials.	yes	Lab testing of rock core samples
ASTM D7012 - Standard Test Methods for Uniaxial Compressive Strength (UCS) and Elastic Moduli of Rock Core Specimens under Varying States of Stress and Temperatures. Determines the compressive strength of rock core samples.	yes	Lab testing of rock core samples
ASTM D4543 - Standard Practices for Preparing Rock Core as Cylindrical Test Specimens and Verifying Conformace to Dimensional and Shape Tolerances	yes	Lab testing of rock core samples
ISRM (2007-2014) Suggested Method for the Determination of Mode II Fracture Toughness	no	Lab testing of rock core samples
ISRM (2007-2014) Suggested Method for Determination of the Schmidt Hammer Rebound Hardness: Revised Version.	yes	Lab testing of rock core samples
ISRM (2007-2014) Suggested Methods for Determining the Dynamic Strength Parameters and Mode-I Fracture - Toughness of Rock Materials.	no	Lab testing of rock core samples
ISRM (2007-2014) Suggested Method for the Determination of Mode II Fracture Toughness.	no	Lab testing of rock core samples
ISRM (2007-2014) Suggested Method for Reporting Rock Laboratory Test Data in Electronic Format.	yes	Lab testing of rock core samples
Upgraded ISRM (2007-2014) Suggested Method for Determining Sound Velocity by Ultrasonic Pulse Transmission Technique.	yes	Lab testing of rock core samples
ISRM (2007-2014) Suggested Method for Laboratory Determination of the Shear Strength of Rock Joints: Revised Version.	no	Lab testing of rock core samples
ISRM (1978) Suggested Method for Petrographic Description of Rocks	yes	Rock characterization in lab
ISRM (1985) Suggested Method for Determining Point Load Strength	yes	Rock characterization in lab
ISRM (1979) Suggested Method for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials	yes	Lab testing of rock core samples
ISRM (1978) Suggested Mehotd for Determining the Strength of Rock Materials in Triaxial Compression	yes	Lab testing of rock core samples
ISRM (1974) Suggested Method for Determining Shear Strength	no	Lab testing of rock core samples
ISRM (1978) Suggested Method for Determining Tensile Strength of Rock Materials	yes	Lab testing of rock core samples

APPENDIX B
TABLES B1-B3

Table B1. List of Geotechnical data types.

Drill hole metadata (name, date, survey datum, collar coordinates, type, driller name, etc.)
Core depth and orientation
Acoustic Borehole Imaging (ABI)
Major Structures recorded
Total core recovery (1 cm or 0.4inch accuracy).
Artificial breaks recorded.
Rock quality designation (1 cm or 0.4-inch accuracy).
Solid core recovery (1 cm or 0.4-inch accuracy
Solid length (1 cm 0.4-inch accuracy).
Micro-defects (intensity, hardness and strength).
Cemented joints.
Open joints.
Photogrammetry of No. 10 shaft.
Within Geotechnical Domain Delineation
lithology
mineralogy
intensity of fracturing
orientation of fracturing
rock strength
Geotechnical Structures with Domains
open joints
intensity of fracturing
orientation of fracturing
rock strength
artificial breaks
intensity of fracturing
cemented joints or veins
micro-defects
Rock Strength Tests
UCS testing
Point Load Test
Triaxial and Uniaxial Strength Tests

☐ *Brazilian Test*
☐ *Acoustic Velocity Test*
☐ *Rock Tunnel Quality Index (Q')*
☐ *Rock Mass Rating (RMR)*
☐ *Geologic Strength Index (GSI)*
☐ *Mining Rock Mass Rating (MRMR)*

Table B2. DQI definitions.

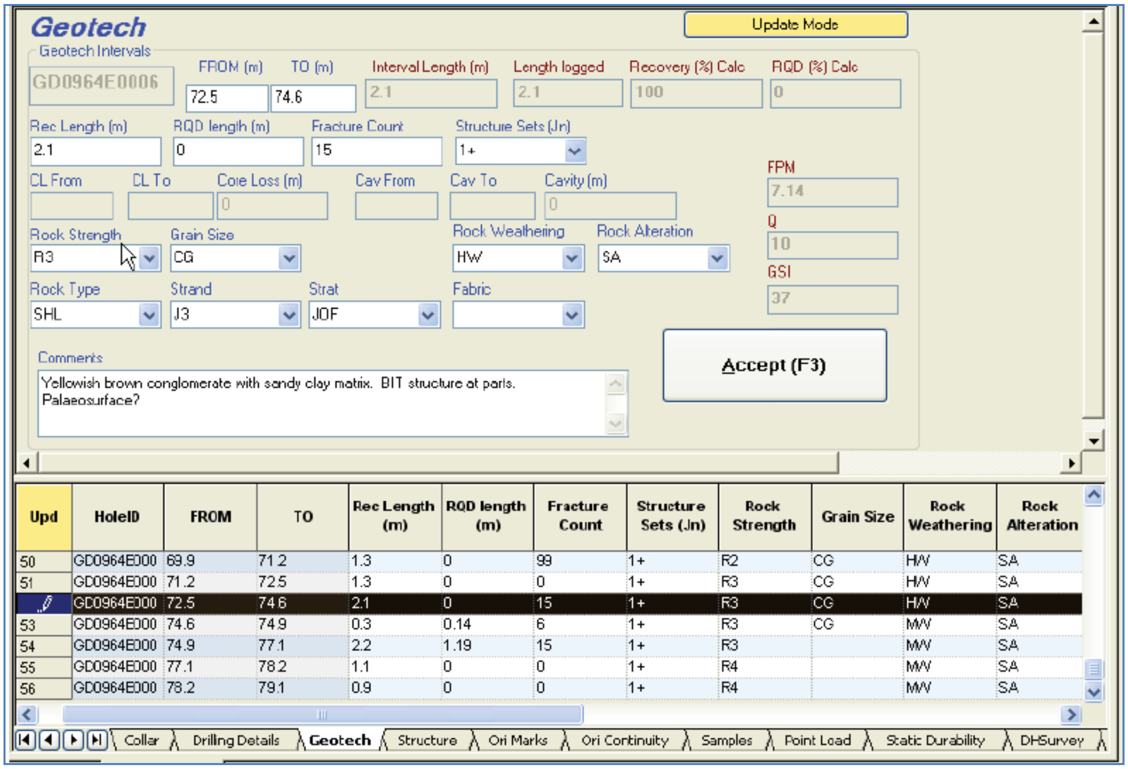
Data Quality Indicator (DQI)		Description
1	**Precision**	The measure of agreement among repeated measurements of the same property under substantially similar conditions.
2	**Bias**	The systematic or persistent distortion of a measurement or observation that deviates in one direction.
3	**Accuracy**	A measure of the overall agreement of a measurement to a known value or an observation to known condition. Contains a combination of random error (precision) and systematic error (bias).
4	**Representativeness**	A qualitative term that expresses "the degree to which data accurately and precisely represent a characteristic of a population.
5	**Comparability**	A qualitative term that expresses the measure of confidence that one data set can be compared to another and can be combined for the decision(s) to be made.
6	**Completeness**	A measure of the amount of valid data needed to be obtained from a measurement system.
7	**Sensitivity**	The capability of a method or instrument to discriminate between measurement responses or observations representing different levels of the variables of interest. (Analytical instrument design parameters or the skill and experience of the observer).

Table B3. Checklist of DQI steps in producing acceptable statistical adequacy and representativeness.

Steps	DQI						
	1	2	3	4	5	6	7
- An integrated system of management activities involving planning, implementation, assessment, reporting, to assure that information derived is of sufficient quality for use in making decisions.				x		x	x
- QA project plan: A formal document describing in comprehensive detail the necessary quality assurance procedures, quality control activities, and other technical activities that need to be implemented to ensure that the results will satisfy performance or acceptance criteria.	x	x	x	x	x	x	x
- Integrated data base and plotting and analysis program (acQuire) to allow for real-time data entry, review, and analysis. Correlation between multiple measurements. Weight-of-evidence approach.		x	x	x		x	
- Intergraded 3D geologic modeling software (Vulcan) allowing for visualization of the geologic and analytical data. Visual correlation between numerous 3D data. Weight-of-evidence approach.				x		x	
- Guidance: a suggested practice that is not mandatory, intended as an aid or example in complying with a standard, specification or "best practice".	x	x	x				x
- RCM's base geotechnical information and analysis are also reviewed and amended by a third-party Geotechnical Review Board (GRB) and various individuals and companies who challenge the process and review validation procedures and conclusions. RCC's internal data validation procedures with peer review and internal QA/QC along this process.	x	x	x	x	x	x	x
- Overall responsibility of data acquisition process under the supervision of a competent person.				x	x	x	
- Used the same analytical instrument or observation to make repeated analysis on the same sample.	x	x	x				
- Use of reference standards and state-of-practice" or "industry best practice" (See standards section)	x	x	x		x		x
- Compared the of analysis of reference materials or lead logger with the results of an outside laboratory or reviewer.	x	x	x		x		x
- Random review by the lead logger of a domain once a week.		x			x		
- Evaluated current industry "Best Practice" on whether physical samples, measurements, or observations appropriately reflect the condition of the population				x	x		
- Compared the number of valid measurements or observations with the project's established performance/acceptance criteria.						x	
- Used outside consultants to select the appropriate analytical instrument with the appropriate sensitivity of instrument.							x

Steps	DQI						
	1	2	3	4	5	6	7
- Safeguards in place to reduce data processing errors, minimize data transcription errors and to prevent unauthorized changes to the data.		x					
- Routine monitoring to reduce estimation and measurement error, limit bias.	x	x	x				
- Relevant training for project personnel in making appropriate observations along with continual feedback from lead logger.		x			x		
- Describe how and when internal data quality assessments will be implemented.	x	x	x				x
- Routine cross-checking protocols					x	x	
- Regular verification of consistency and compliance with methods and protocols	x	x	x				x
- Archival of in a secure location for future re-analysis.					x		
- The overall system of technical activities that measure the attributes and performance of a process against defined standards or industry best practices that fulfill the specifications of the required level of quality.							
- Low turn-over of logging staff					x		
- Maintaining consistency in lithologic description					x		

APPENDIX C
PHOTOS AND GRAPHICS



Upd	HoleID	FROM	TO	Rec Length (m)	RQD length (m)	Fracture Count	Structure Sets (Jn)	Rock Strength	Grain Size	Rock Weathering	Rock Alteration
50	GD0964E000	69.9	71.2	1.3	0	99	1+	R2	CG	HW	SA
51	GD0964E000	71.2	72.5	1.3	0	0	1+	R3	CG	HW	SA
	GD0964E000	72.5	74.6	2.1	0	15	1+	R3	CG	HW	SA
53	GD0964E000	74.6	74.9	0.3	0.14	6	1+	R3	CG	MW	SA
54	GD0964E000	74.9	77.1	2.2	1.19	15	1+	R3		MW	SA
55	GD0964E000	77.1	78.2	1.1	0	0	1+	R4		MW	SA
56	GD0964E000	78.2	79.1	0.9	0	0	1+	R4		MW	SA

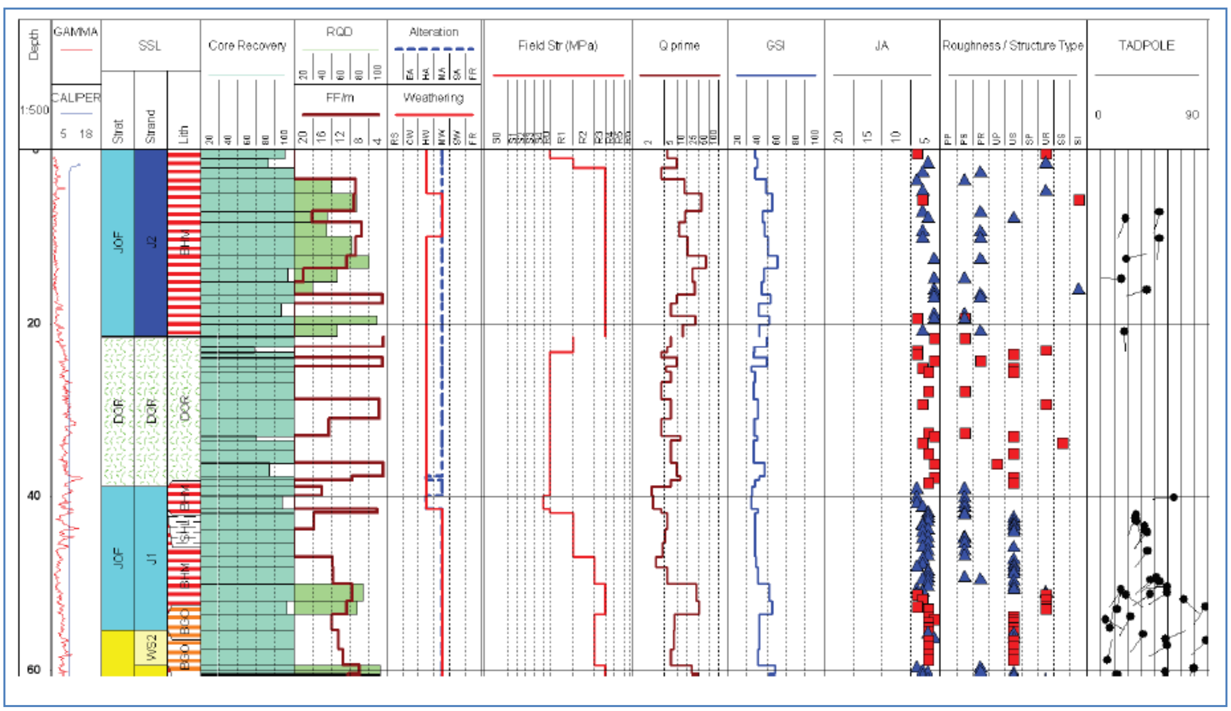


Figure C1. Example output from acQuire. Data entry panels (top graphic), simultaneous down-hole charts (center graphic) and statistical analysis graphs (bottom graphic) are designed to help maintain quality of a drill hole database (Pere et al., 2011).

Figure C2. Top photo: Drill core arriving for logging sequence in secure boxes. Bottom photo: Drill core archived after logging in secure facility. (Field visit to Resolution Copper by authors of Brandt et al., 2017)

Figure C3. Core being logged (upper photo) and real-time data entry into acQuire software on a laptop at a geologist's core logging station (lower photo). [Brandt et al., 2017; Pere et al., 2011]

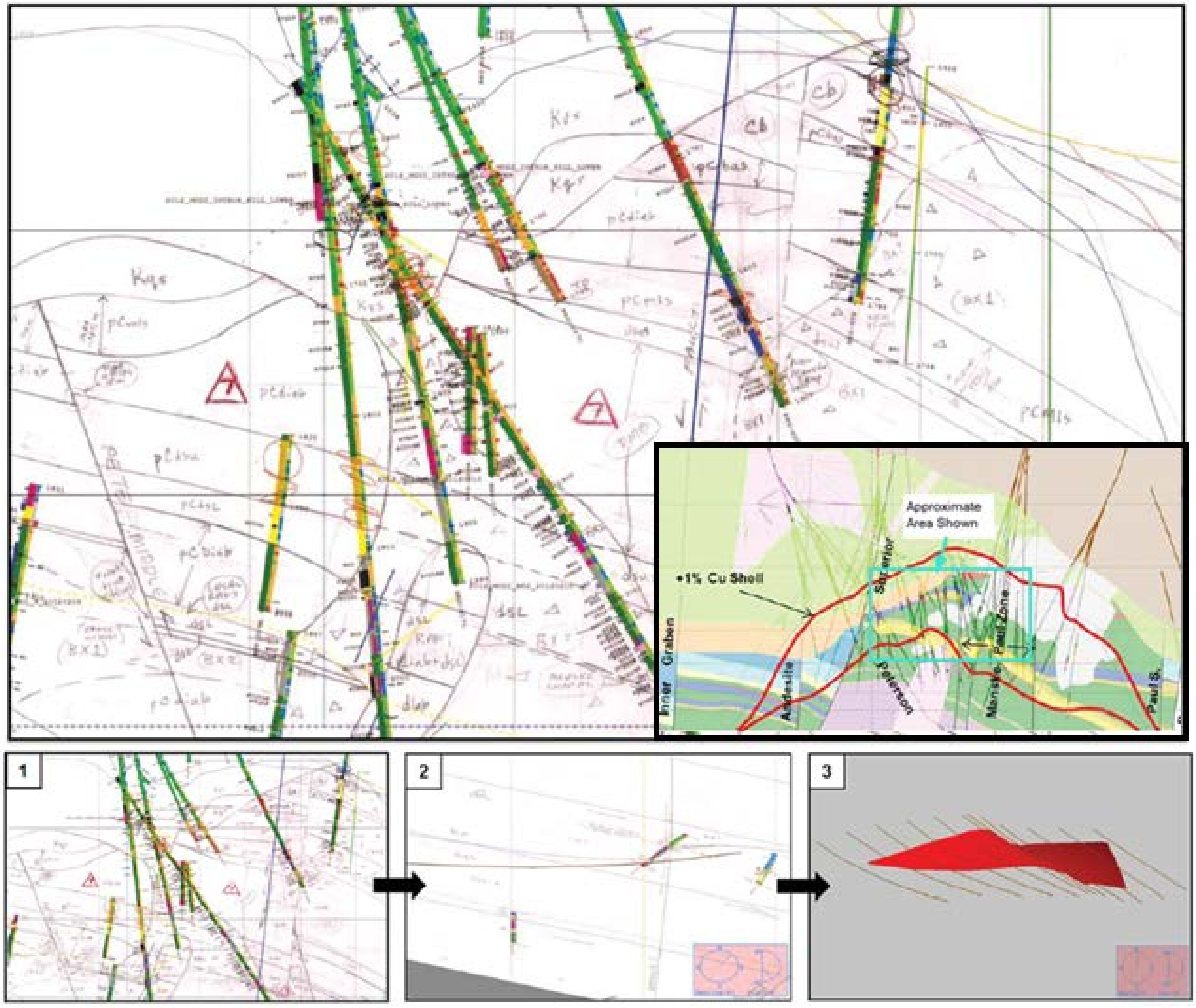


Figure C4. Composite figure showing the complexity of faulting within the 1% Copper Envelope (Parker, March 14, 2017).