Evaluation of Predictions of Land Subsidence due to Panel Caving at the Resolution Copper Mine, Arizona

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LIGHTNING SUMMARY

The prediction by Rio Tinto that land subsidence resulting from panel caving at the proposed Resolution Copper Mine, Arizona, will not affect the sacred escarpment of Apache Leap is based on questionable mapping of geologic faults, the false assumption that subsidence is always slow, and a lack of any error bounds. It can be shown that the probability that the subsidence zone will reach Apache Leap is at least 5.3%, which is generally recognized as an unacceptable risk for the destruction of irreplaceable cultural or religious heritage.

ABSTRACT

The Resolution Copper Mine that is being proposed by Rio Tinto in Arizona would process up to 150,000 metric tons of ore per day from an ore body at a depth of 5000-7000 feet. The mining would be carried out using block caving, a type of underground mining that involves controlled cave-ins of overlying rock. Panel caving, the particular variation of block caving that would be used at the Resolution Copper Mine, divides the ore body into smaller panels that are mined sequentially. Land subsidence is a typical consequence of block caving. Rio Tinto has predicted that the maximum depth of the crater will be 984 feet, but that the subsidence zone will reach only 1500 feet from the sacred escarpment of Apache Leap. Rio Tinto has provided a description of the types of data used to predict subsidence, but not the actual data or the details of the modeling. The only exception is a map of the geological faults, which are the most important structures that transmit deformation. In that case, it can be shown from satellite imagery and aerial photography that the West Boundary Fault, which connects the footprint of the ore body with Apache Leap, was mapped in the wrong location with an offset of 2000 feet. Rio Tinto has described an extensive program of subsidence monitoring that relies on the assumption that "subsidence is a slow and gradual process that is predicted…and controlled." However, unanticipated subsidence occurs in 20% of block caving projects and the manual relied upon by Rio Tinto emphasizes the known risks of rapid subsidence and rockbursts. No error bounds have been provided on the limits of the subsidence zone. However, based upon the uncertainty in the prediction of maximum crater depth (coefficient of variation = 20%), the probability that the subsidence zone will reach Apache Leap is 5.3%, not taking into account any incorrect data used by Rio Tinto. By any standards, this is regarded as an unacceptable risk for the destruction of irreplaceable cultural and religious heritage.

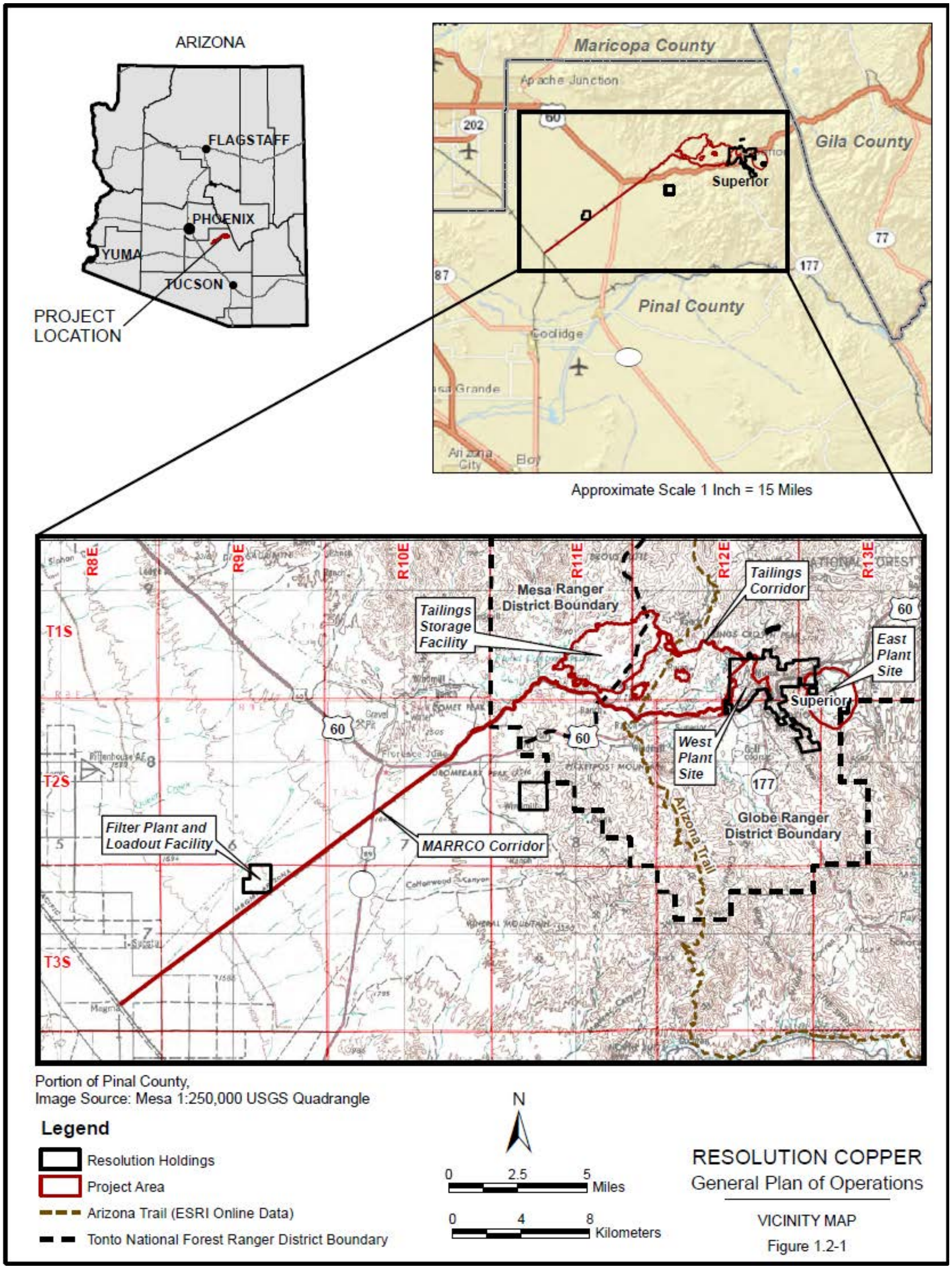

Figure 1. Rio Tinto has submitted a proposal for an underground copper mine, called the Resolution Copper Mine, within a mix of federal public land (Tonto National Forest), Arizona state trust land, and private land, which would process 120,000 metric tons of ore day with a maximum processing rate of 150,000 metric tons per day from an ore body that lies 5000-7000 feet below the surface. Figure from Resolution Copper Mining (2014b).

INTRODUCTION

Rio Tinto has submitted a proposal to the U.S. Forest Service for an underground copper mine in Arizona, called the Resolution Copper Mine (see Fig. 1). The porphyry copper deposit occurs 5000-7000 feet beneath the surface and has an inferred resource of 1790 million tons with a copper grade of 1.47% and molybdenum grade of 0.037% (Houston et al., 2010; Cherry, 2011; Hehnke et al., 2012). The ore processing rate is predicted to be 120,000 metric tons per day with a maximum processing rate of 150,000 metric tons per day. Process improvements over the anticipated 40-year life of the project could increase the ore processing rate by up to 25%, for a maximum throughput of 187,500 metric tons per day (Resolution Copper Mining, 2014a-c).

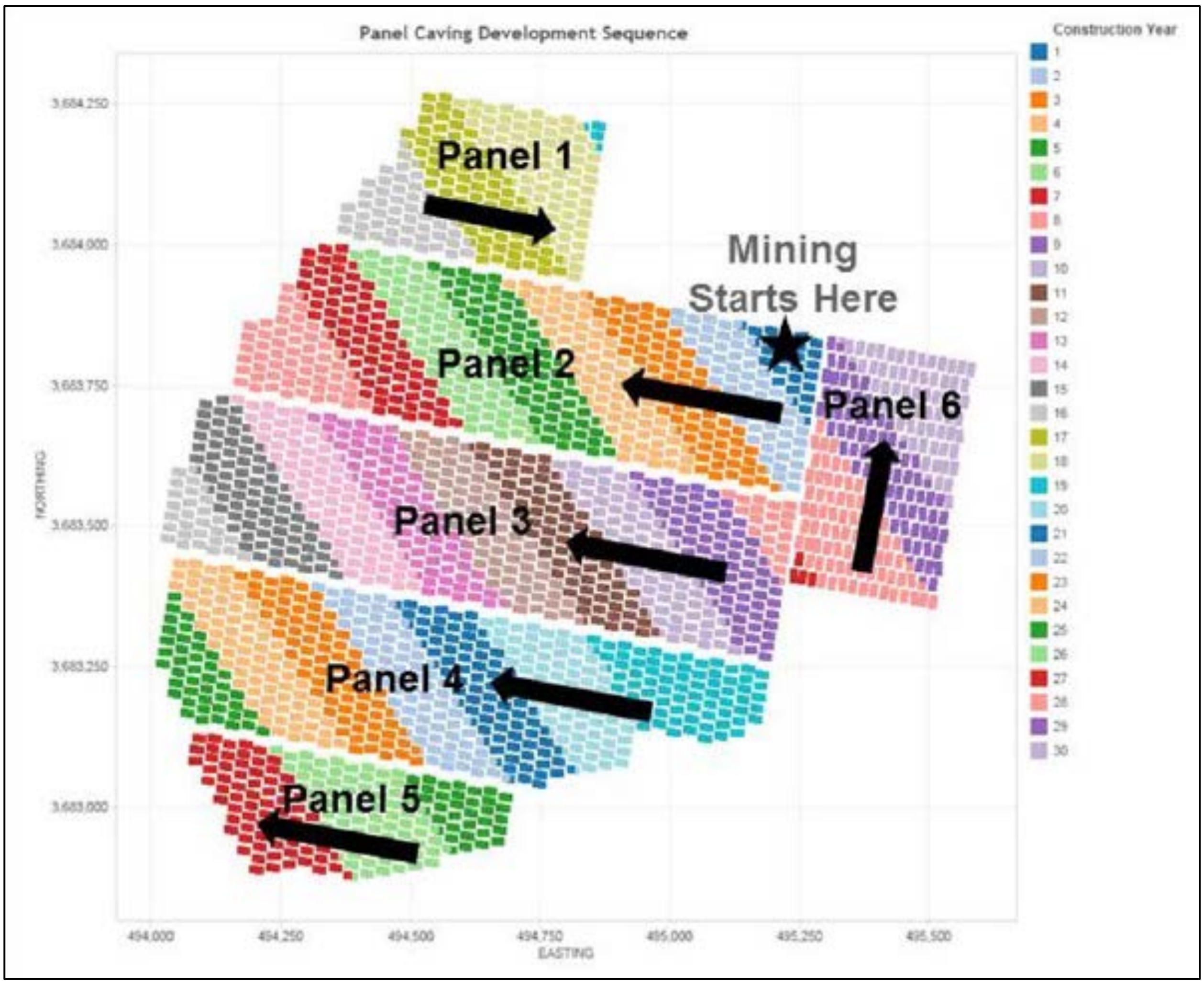

Figure 2. Block caving is a type of underground mining that involves controlled cave-ins of overlying rock. Panel caving, the variation of block caving that is planned at Resolution Copper Mine, involves dividing the ore body into smaller panels that are mined sequentially. Land subsidence is a typical consequence of block caving. Figure from Resolution Copper Mining (2014a).

The proposed mine is located within a mix of federal public land (Tonto National Forest), Arizona state trust land, and private land (Resolution Copper, 2018a). The proposal includes an exchange of 5344 acres of land privately held by Rio Tinto for 2422 acres of the Tonto National

Forest (Resolution Copper Mining, 2014a). The Arizona Mining Reform Coalition and 15 other organizations have submitted scoping comments to the U.S. Forest Service that describe a wide range of detrimental social and environmental impacts of the proposed copper project (Arizona Mining Reform Coalition et al., 2016). Those social and environmental impacts will not be reviewed or further developed in this study.

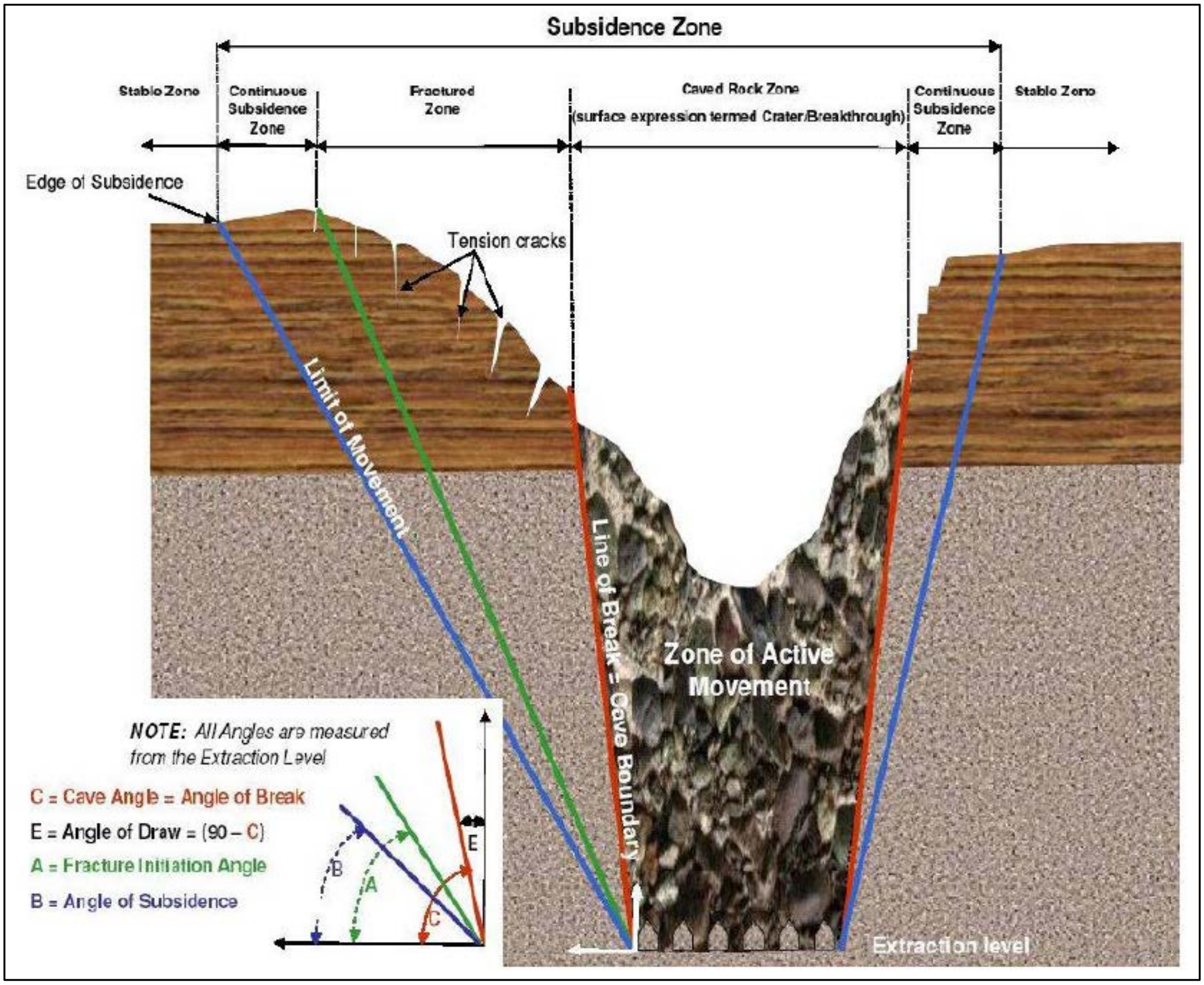

Figure 3. The subsidence zone can be divided into the caved rock zone, the fractured zone and the continuous subsidence zone. The caved rock zone is the zone of greatest vertical displacement and consists of fragmented rocks of all sizes. The fractured zone is the zone where visible deformation can be seen on the surface, including cracks and slumps. In the continuous subsidence zone, deformation can be detected only by high-resolution monitoring equipment. The region outside of the subsidence zone is called the stable zone. Figure from Resolution Copper Mining (2014c).

According to the proposal, mining will be carried out using block caving, a type of underground mining that involves controlled cave-ins of overlying rock (Resolution Copper Mining, 2014a,c). Panel caving, the variation of block caving that is planned at Resolution Copper Mine, involves dividing the ore body into smaller panels that are mined sequentially (see Fig. 2). As expected, land subsidence is a typical consequence of block caving. Since the overlying rock increases in volume from its *in situ* state as it collapse (a process called bulking or swelling), the land subsidence should be smaller than the thickness of the ore body that is mined.

Rio Tinto has predicted that the maximum land subsidence in the center of the crater that will form over the ore body will be 984 feet (Resolution Copper Mining, 2014a).

An important consideration is the lateral extent of the region that will be affected by land subsidence. The block caving vocabulary varies somewhat, but Fig. 3 explains the terminology used by Rio Tinto (Resolution Copper Mining, 2014c). The subsidence zone can be divided into the caved rock zone, the fractured zone and the continuous subsidence zone. The caved rock zone is the zone of greatest vertical displacement and consists of fragmented rocks of all sizes from boulders to clay-sized particles. The fractured zone is the zone where visible deformation can be seen on the surface, including cracks and slumps. In the continuous subsidence zone, deformation can be detected only by high-resolution monitoring equipment. The region outside of the subsidence zone is called the stable zone.

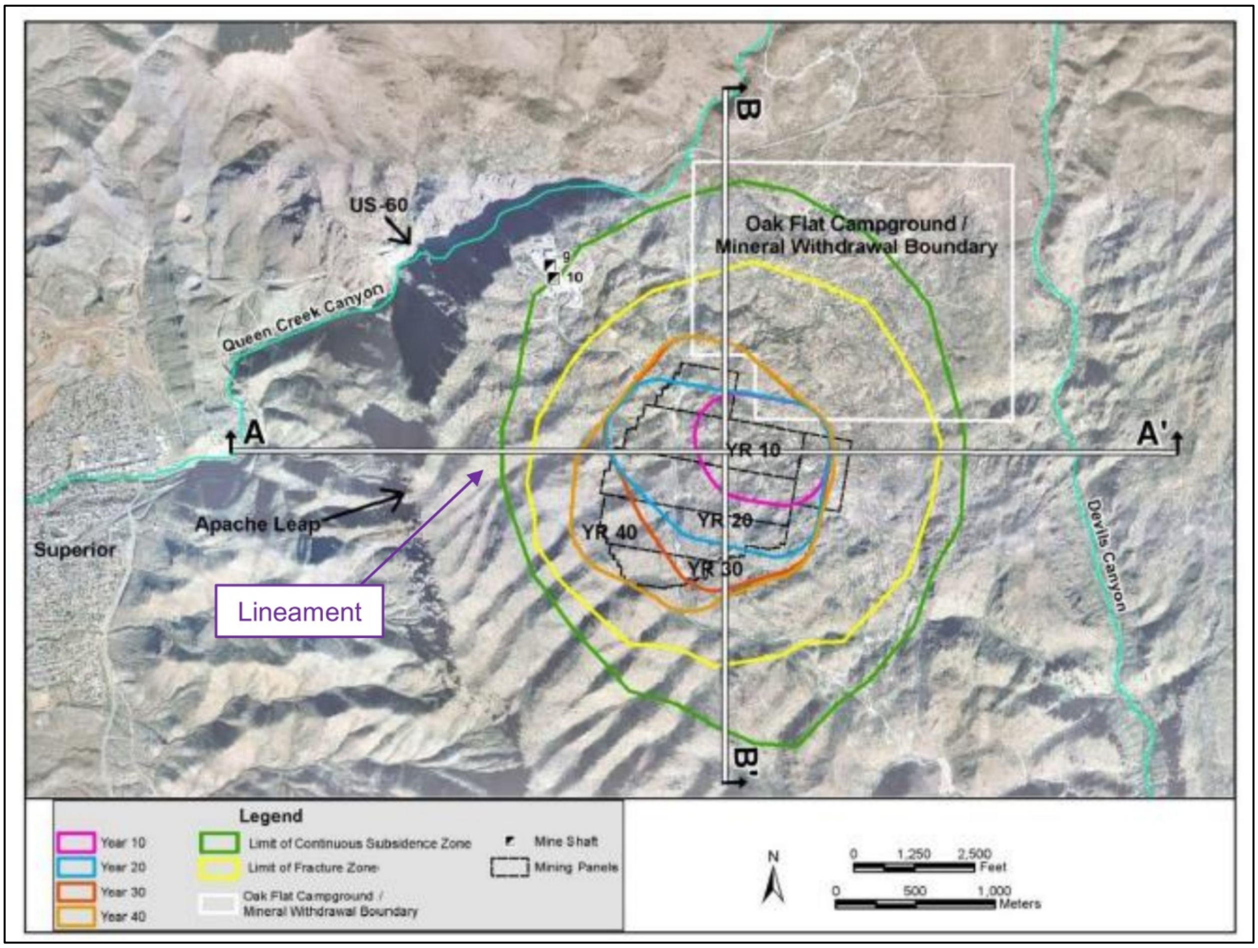

Figure 4a. According to modeling by Rio Tinto (Resolution Copper Mining, 2014a-c), the sacred escarpment of Apache Leap will be more than 1500 feet outside of the subsidence zone even after 40 years of panel cave mining. Fig. 4b shows a cross-section along line AA'. The contours marked by years indicate the limits of the caved rock zone after 10, 20, 30 and 40 years of mining. The lineament shown in Figs. 7a-b can be seen to intersect the caved rock zone in the above figure. Figure modified from Resolution Copper Mining (2014a).

The most important prediction is the probability that the subsidence zone will extend to the sacred escarpment of Apache Leap (see Figs. 4a-b). Apache Leap will remain within the Tonto National Forest and is not a part of the proposed land exchange with Rio Tinto. According to the modeling carried out by the consultants for Rio Tinto, the approach of the outer limit of the subsidence zone to Apache Leap at the end of the 40-year mining project will be more than 1500 feet (Resolution Copper Mining, 2014a,c; USDA Tonto National Forest, 2019a). The data that were input into the models came from surface mapping, core samples, and high-resolution photography from the No. 10 Shaft, the primary access shaft that was drilled to a depth of 6943 feet (Resolution Copper Mining, 2014c; Resolution Copper, 2018b). Data from the drill core samples included observations regarding major structures, total core recovery, artificial breaks, rock quality designation, solid core recovery, solid length, minor-defects, cemented joints, and open joints. Rock strength testing was also carried out on the drill core samples (Resolution Copper Mining, 2014c). The cave angle (see Fig. 3) was predicted using an empirical method developed by Laubscher (2000). The complete subsidence response to panel caving was predicted by Itasca Consulting Group using the FLAC3D (Fast Lagrangian Analysis of Continua) numerical modeling package and by Beck Engineering using a coupled DFE-NCA (Discontinuum Finite Element – Newtonian Cellular Automata) code (Resolution Copper Mining, 2014c).

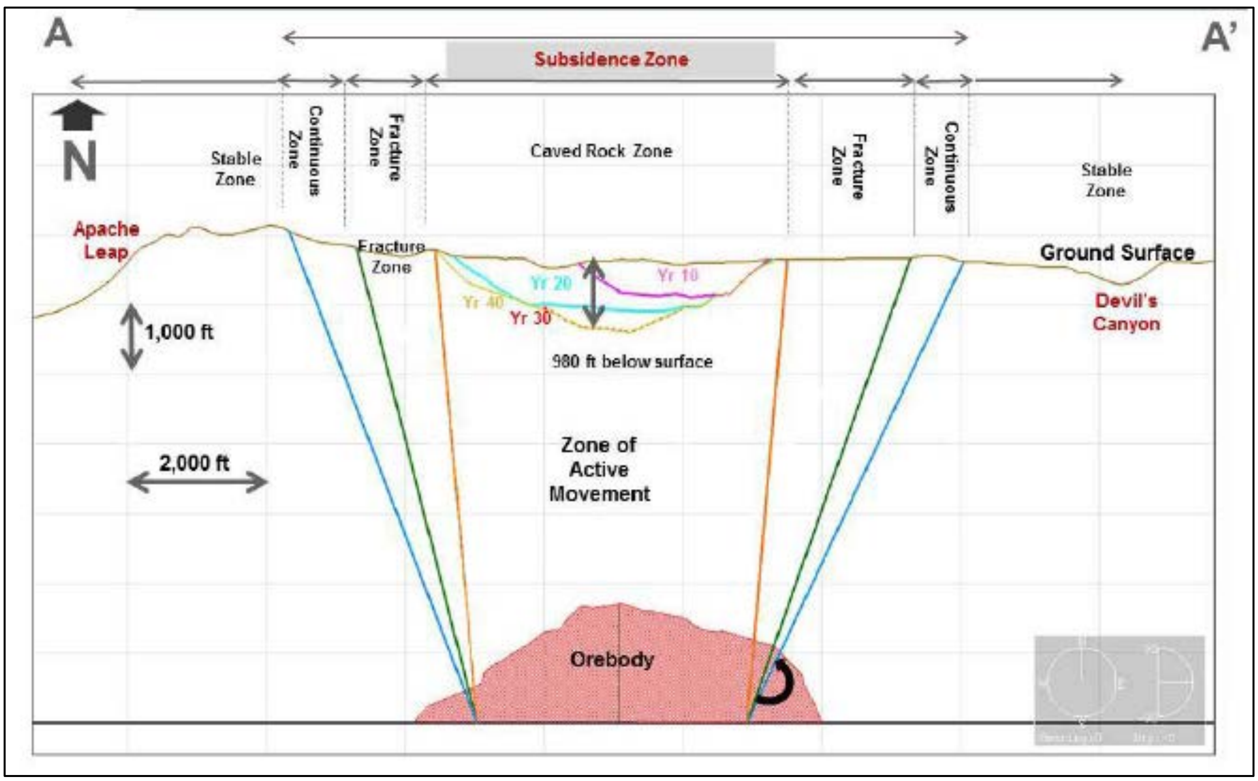

Figure 4b. According to modeling by Rio Tinto (Resolution Copper Mining, 2014a-c), the sacred escarpment of Apache Leap will be more than 1500 feet outside of the subsidence zone even after 40 years of panel cave mining. The same modeling shows that the maximum subsidence in the caved rock zone could be 984 feet. Fig. 4b shows a map view. Figure from Resolution Copper Mining (2014a).

The proposal also describes an extensive program of subsidence monitoring before, during and after the life of the mining project. The pre-mining monitoring involves baseline studies using terrestrial LIDAR scans and digital tilt meters. The monitoring during the mining project would include the use of extensometers, survey prisms, crack displacement monitors, aerial photography, interferometry synthetic aperture radar (INSAR), and a microseismic monitoring system. Post-mining monitoring would continue for at least 15 years after the cessation of mining under the assumption that the crater would reach equilibrium within five years after mining. The post-mining monitoring would be extended if the monitoring data were still showing movement at the end of 15 years.

The objective of this study is to address the following question: Has Rio Tinto correctly predicted the land subsidence that would result from panel caving at the proposed Resolution Copper Mine? Although this study has been prepared at the request of the Arizona Mining Reform Coalition, the intended audience is individuals or companies who might wish to invest in the copper project or the companies managing the copper project. For context, Resolution Copper Mining is owned 55% by Resolution Copper, a Rio Tinto subsidiary, and 45% by BHP Copper, a BHP-Billiton subsidiary (Rio Tinto, 2018). It might be assumed that the possible destruction of Apache Leap is more of a religious than a financial issue. However, anyone who honors the spiritual significance of Apache Leap has already made up his or her mind on this issue, just as all Jews and Moslems would be in full agreement on the wisdom of underground copper mining within a mile of the Western Wall and the Temple Mount in Jerusalem. On that basis, this study is aimed at those who would be concerned about the financial and reputational losses that could result from any adverse impact of the Resolution Copper Mine on Apache Leap. Previous reports concerning the financial viability of the Resolution Copper Mine include an evaluation of the impact of the discovery of geothermal water on the mining project (Emerman, 2018a) and the projected electricity and water consumption of the project (Emerman, 2019).

METHODOLOGY

The objective of this study can be subdivided into the following questions:

1) Did the prediction of subsidence use correct input data and was the modeling carried out correctly?
2) Does the mining project have an adequate subsidence monitoring program?
3) Do the predictions of the subsidence models have appropriate error bounds?

The questions were addressed by comparing the information in the proposal (Resolution Copper Mining, 2014a-c) with Google Earth images, the standard manual on block caving (Laubscher, 2000), and compilations of past experiences with land subsidence caused by block caving (Blodgett and Kuipers, 2002; Woo et al., 2013). Information on appropriate error bounds came from Canadian Dam Association (2013), which has considerable discussion on the impact of dam failure on cultural values that should be relevant to the possible failure of other types of mining infrastructure.

RESULTS

Correct Input Data and Modeling

The actual data that were used in the subsidence modeling are not presented in any documents that have been provided by Rio Tinto. The only information that has been provided are the types of data and, in some cases, statistical summaries of the data, such as the distribution of micro-defect frequencies in each geotechnical domain (Resolution Copper Mining, 2014c). On that basis, there is no way for anyone not affiliated with Rio Tinto to repeat the subsidence modeling or to carry out his or her own subsidence modeling. It is not even possible to predict the cave angle using the empirical method of Laubscher (2000), which would not require any numerical simulation.

Even the description of the data is inadequate for assessing the validity of the subsidence modeling. The most important information that is missing are the numbers of drill cores and the depths of the drill cores. Clearly, a valid subsidence model requires an adequate number and distribution of samples, which cannot be assessed. The geotechnical properties of the deepest layers (or geotechnical domains) can have a great influence on the extent of the subsidence zone on the surface (see Fig. 3). However, there is no information as to how many or whether any of the drill cores penetrated as deeply as the No. 10 Shaft (the 6943-foot deep primary access shaft).

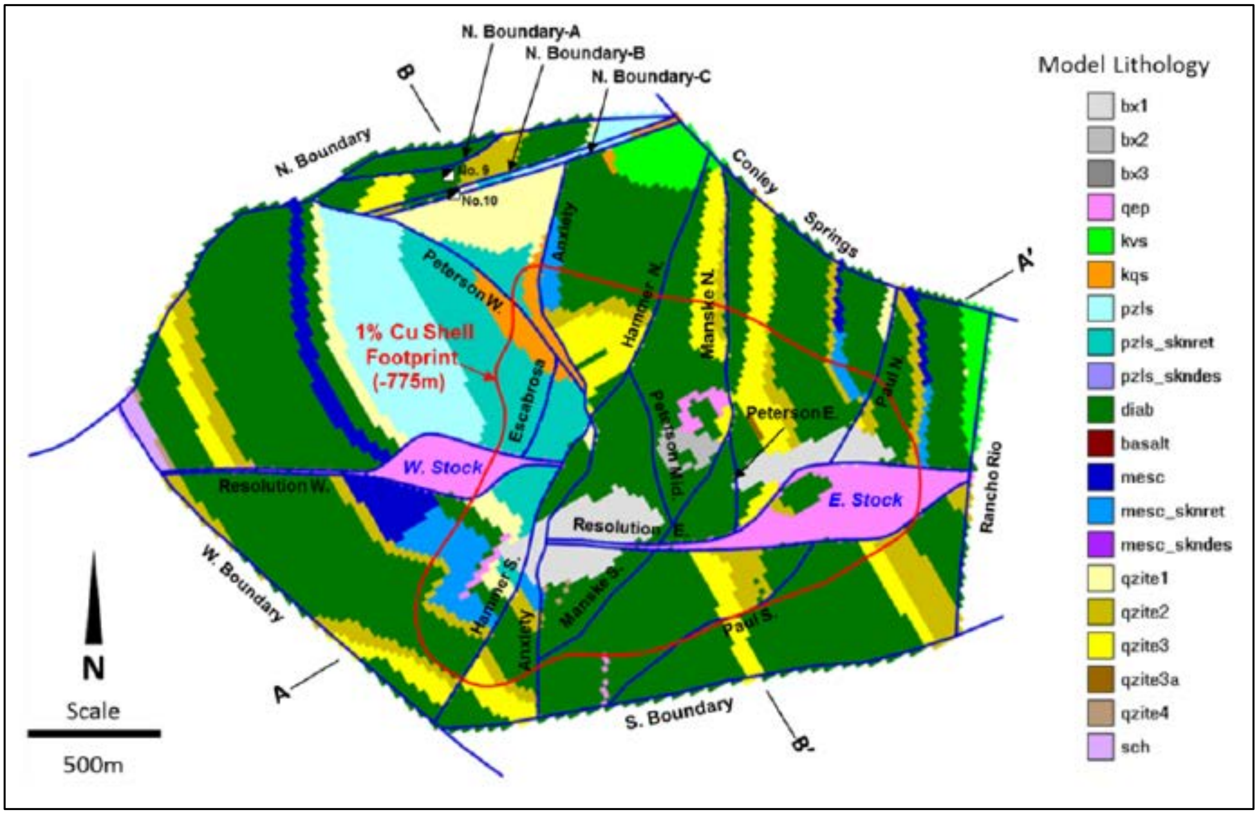

Figure 5. The most important structural controls on land subsidence caused by block caving are the locations and physical properties of geological faults. The above map shows the mapped faults that were used in the modeling (see Figs. 4a-b). For predicting the impact of panel caving on Apache Leap, the mapping of the West Boundary Fault is the most important since it connects the mining area with Apache Leap (see Fig. 7a). The above fault map can be located spatially by comparing the position of the footprint of the 1% Cu shell in Figs. 5 and 6. Figure from Resolution Copper Mining (2014c).

The only exception to the above-mentioned lack of input data is the map of the geological faults that were used in the subsidence modeling (see Fig. 5). The faults and other zones of weakness should be the primary control on the surface expression of subsidence. In particular, the primary control on the ability of the panel caving to transmit deformation to Apache Leap should be any faults that connect Apache Leap to the surface footprint of the panel caving area. From this perspective, the most important fault is the West Boundary Fault (see Fig. 5). The fault map is difficult to interpret because it does not include any geographical information (see Fig. 5). However, the fault map does include the outline of the 1% Cu shell (footprint of the volume within which the ore has a grade of greater than 1% copper), so that it can be aligned with the geological map from Resolution Copper Mining (2014c) that also includes the 1% Cu shell, as well as the footprint of the mining project area and other geographical information (see Fig. 6).

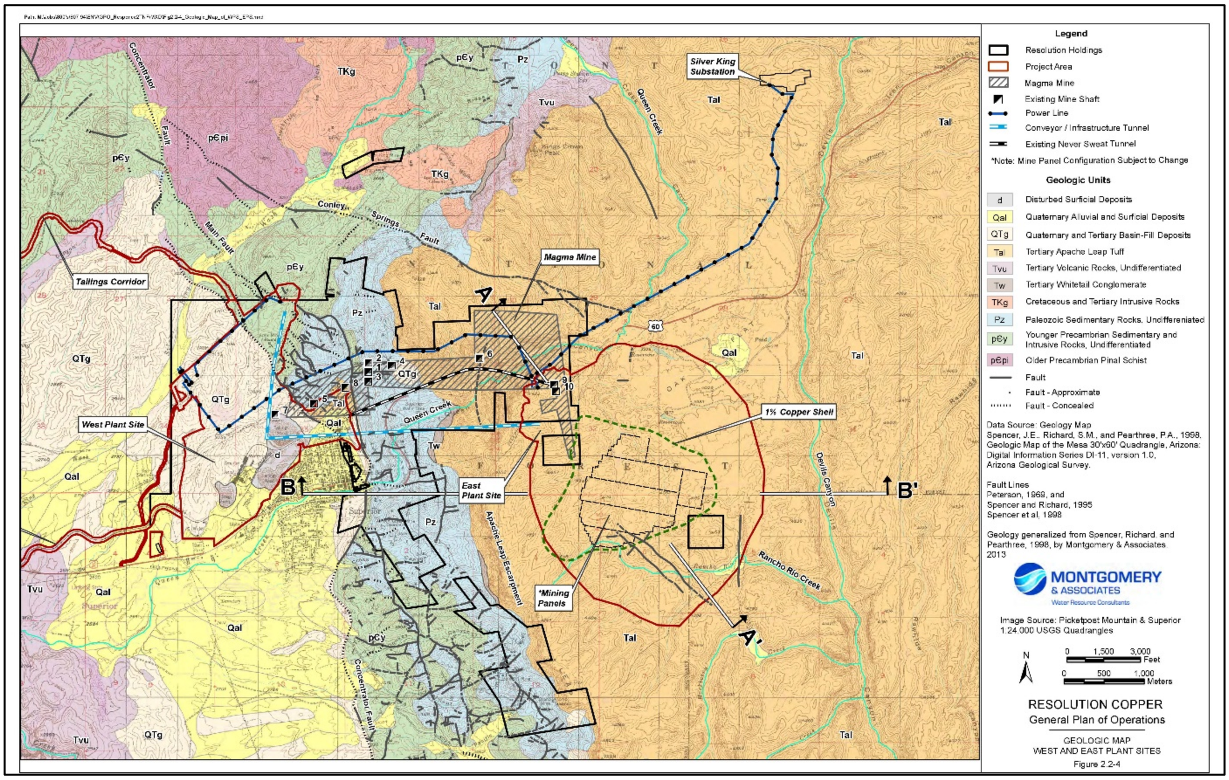

Figure 6. Since the above map includes both the footprint of the 1% Cu shell as well as other geographical information, it can be used to spatially locate the fault map in Fig. 5. Figure from Resolution Copper Mining (2014b).

The superposition of the West Boundary Fault (as mapped in Fig. 5) onto a Google Earth image (a seamless integration of aerial photography and satellite imagery) shows a pronounced surface feature (labeled as a lineament) that is subparallel to the West Boundary Fault and offset from the fault by about 2000 feet (see Figs. 7a-b). The lineament should not strictly be assumed to be a fault, but a fracture trace, that is a linear feature that is visible from aerial photography or satellite imagery (Fetter, 2001). (Lineaments are fracture traces that are longer than 1500 meters.) Lineaments may be surface expressions of deep-seated zones of structural weakness, such as geological faults, but that must be verified by surface or subsurface mapping. However, the nearly-parallel orientations of the West Boundary Fault and the lineament are certainly suggestive that the West Boundary Fault has been incorrectly mapped, and there is no other mapped fault that could be correspond to the lineament (Figs. 5, 7a-b). Unlike the mapped West Boundary Fault, the lineament intersects the caved rock zone (Fig. 4a), so that there is potential for deformation to be transmitted from the caved rock zone to Apache Leap if the lineament is indeed a plane of structural weakness, such as a fault. On this basis, there could have been an underestimation of the extent of the subsidence zone.

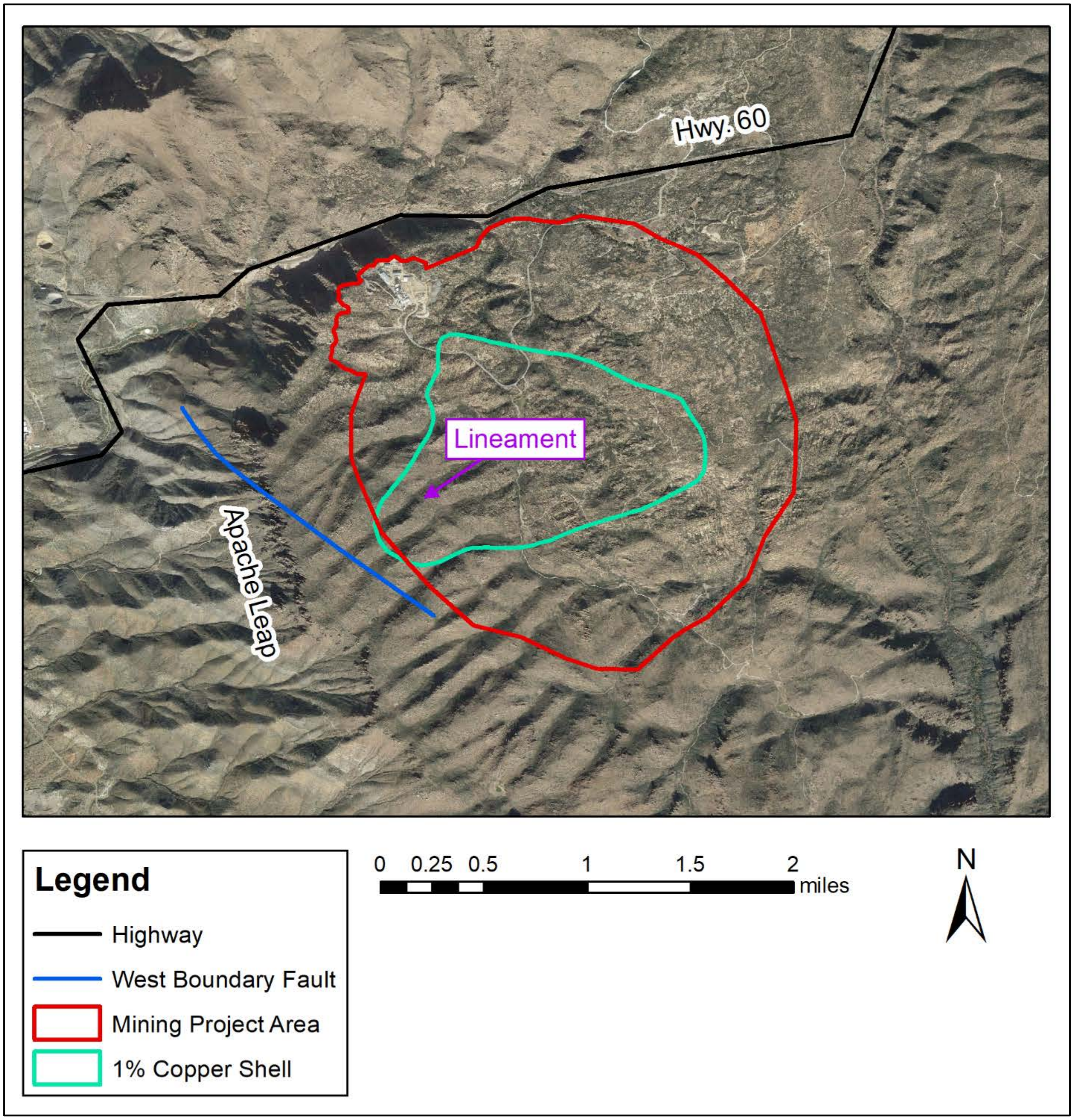

Figure 7a. The West Boundary Fault (see Fig. 5) is subparallel to and offset by 2000 feet from a pronounced lineament that is visible from aerial photography and satellite imagery. The lineament does not correspond to any other mapped fault that was used in the subsidence modeling (see Fig. 5), which suggests that not all geological faults have been correctly mapped. The faults and other zones of weakness that connect Apache Leap with the mining area are the most important in predicting the impact of the subsidence caused by panel caving on Apache Leap. The lineament has been traced in Fig. 7b. Outlines of the mining project area and the footprint of the 1% Cu shell are from Fig. 6. Google Earth imagery is from December 6, 2014.

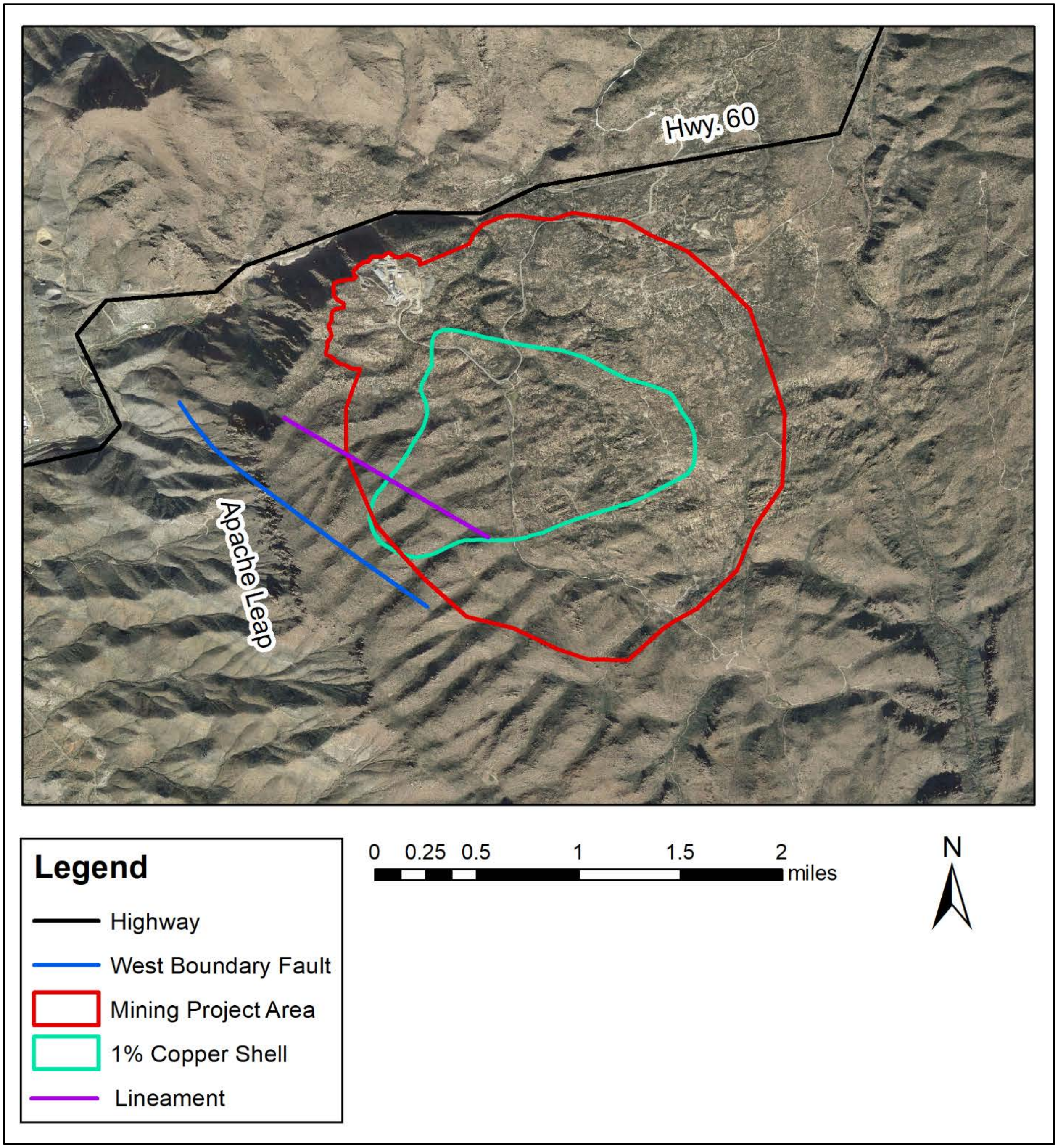

Figure 7b. The West Boundary Fault (see Fig. 5) is subparallel to and offset by 2000 feet from a pronounced lineament that is visible from aerial photography and satellite imagery. The lineament does not correspond to any other mapped fault that was used in the subsidence modeling (see Fig. 5), which suggests that not all geological faults have been correctly mapped. The faults and other zones of weakness that connect Apache Leap with the mining area are the most important in predicting the impact of the subsidence caused by panel caving on Apache Leap. The lineament without the trace on top can be seen in Fig. 7a. Outlines of the mining project area and the footprint of the 1% Cu shell are from Fig. 6. Google Earth imagery is from December 6, 2014.

Even if all of the input data were adequate, it would be difficult to assess the validity of the subsidence modeling since no details have been provided, except for the names of the consulting companies and their numerical codes. Not even the titles or the lengths of the consulting reports have been provided (Resolution Copper Mining, 2014c). The subsidence modeling was presumably carried out by competent engineers and computer programmers. However, I am very sorry to have to point out that Rio Tinto has a history of claiming that the reports from their consultants said the exact opposite of what they actually said. A particular example was documented by Emerman (2018b), based upon a comparison of a consulting report to Rio Tinto with Rio Tinto's summary of the report.

Adequate Subsidence Monitoring Program

The General Plan of Operations (Resolution Copper Mining, 2014a-c) does present an extensive program of subsidence monitoring, using a wide variety of instrumentation. However, the primary issue is not Rio Tinto's ability to document subsidence, but their ability to take appropriate action in response to unanticipated subsidence. A comprehensive database of subsidence caused by block caving reported that unanticipated subsidence has occurred in 20% of block caving projects with most of the anomalies being related to geological faults (Tetra Tech, Inc. and R Squared, Inc., 2006; Woo et al., 2013). The connection between observation and action is based on the explicit assumption that "Subsidence is a slow and gradual process that is predicted, closely monitored, and controlled" (Resolution Copper Mining, 2014a) and that "Subsidence is a rather slow and continuous process, and as such there would be time to apply an adaptive monitoring plan if required" (Resolution Copper Mining, 2014c). With regard to the latter quote, note that "monitoring" is not the same concept as "action."

Blodgett and Kuipers (2002) have documented numerous case studies of block caving projects at which land subsidence was both unanticipated and rapid. For example, at the Henderson Molybdenum Mine in Colorado, "The cave zone appeared on the surface as a steep-walled cavity…Although surface survey data revealed the development of a slight depression over the production area, a surface inspection by geologists three days before breaching resulted in no evidence of impending glory-hole development. Geologic factors such as rock contacts and alteration-zone boundaries had little influence on the location of the initial glory hole [mining excavation that breaches the surface]" (Blodgett and Kuipers, 2002). At the Miami Copper Mine in Arizona, "the average daily rate of subsidence was at least 2.4 feet (Blodgett and Kuipers, 2002). Finally, at the Athens Iron Mine in Michigan, "At 5 am…block 2, which was 250 feet thick, 350 feet wide, and 600 feet long, caved to the surface through 1900 feet of jasper (gossans cap) The mined-out area that collapsed was only one-tenth the thickness of the jasper cap. The cave-in occurred during a shift change and no injuries were reported. Immediate inspection revealed no evidence of inundation by water or sand, no crushing of drifts or workings, and no signs of an air blast" (Blodgett and Kuipers, 2002).

Rio Tinto seems to rely heavily on A Practical Manual on Block Caving (Laubscher, 2000), since this is the only reference on block caving that is cited in the General Plan of Operations (Resolution Copper Mining, 2014c). In fact, the manual has even been posted on the website that reports progress toward completion of the Environmental Impact Statement (USDA Tonto National Forest, 2019b). This same manual repeatedly draws attention to the dangers of both rapid subsidence and rockbursts. Some examples of the discussion of rapid subsidence are "Lateral extension or subsidence caving as it was previously described, occurs when adjacent mining has removed the lateral restraint on the block being caved. This can result in rapid propagation of the cave with limited bulking…There can be a rapid propagation of the cave with massive wedge failures if a well developed relaxation zone has formed ahead of the cave front" (Laubscher, 2000). Some examples of discussion of the related problem of rockbursts are "The potential effects of a block cave on installations located in the peripheries of the block include…shear displacements on faults and shear zones. These could produce rockbursts…Cave mining of deep, hard rock orebodies, involving removal of large volumes of rock, will inevitably lead to the generation of mining-induced seismicity, which may lead to rockbursts…The location of the source of the seismicity and the location of the rockburst damage may or may not be coincident. In the larger magnitude events, the separation of the two locations may be hundreds of meters…Rockbursts have become a major problem on block caving mines in competent rock, where the regional principal stress is > 35 MPa" (Laubscher, 2000).

If subsidence is sufficiently slow (as opposed to the rapid subsidence described above), it may be possible to take appropriate corrective action in terms of the planning for the next steps of panel caving. For example, Rio Tinto has emphasized that they will "start mining at a point far away from Apache Leap. The easement will allow many years to gather technical information to reassess the cave and subsidence angles" (Resolution Copper Mining, 2014c). (The preceding quote seems to be contradicted by Fig. 2, which shows the initiation of panel caving at the western edge of the mining project area, the edge closest to Apache Leap.) However, it is difficult to understand the purpose of the post-mining monitoring, at which point it will no longer be possible to correct the procedures of panel cave mining. This disconnect between observations and subsequent preplanned actions should be regarded as a misuse of the Observational Method, which is used implicitly throughout the General Plan of Operations (Resolution Copper Mining, 2014a-c). The Observational Method was both reviewed and critiqued by Independent Expert Engineering Investigation and Review Panel (2015), who investigated the causes of the 2014 tailings dam failure at the Mount Polley Mine in British Columbia. According to Expert Engineering Investigation and Review Panel (2015), the Observational Method "uses observed performance from instrumentation data for implementing preplanned design features or actions in response." However, the Observational Method is not simply a license to figure things out later. Expert Engineering Investigation and Review Panel (2015) concluded "the Observational Method is useless without a way to respond to the observations."

Appropriate Error Bounds on Subsidence Predictions

The predictions of the limits of the caved rock, fractured and continuous subsidence zones contain no uncertainties or error bounds of any kind (see Figs. 4a-b). Presumably, all predictions are simply the best estimates and not the worst-case scenarios. The only exception to the lack of error bounds in subsidence predictions are the predicted maximum depth of the crater above the ore body. According to Rio Tinto, "The depth of the crater has been estimated from numerical simulations and also from experience at other operations. As part of the Second International Caving Study a database of bulking factors was developed to assist in the estimation of bulking from the caving process. Based on this work the average life of mine bulking factor for Resolution Copper is expected to range between 8 and 12 percent. If these values are used to estimate the potential crater depth, the maximum depth is projected to range between 656 and 984 ft in depth. Numerical simulations both completed by Beck Engineering and Itasca Consulting also estimate that the crater depth could have a maximum value ranging from 656 to 984 ft" (Resolution Copper Mining, 2014c). It is surprising that the empirical method and the numerical simulations carried out by two different consulting companies using different numerical methodologies all arrived at the exact same range of depths. However, the above range of depths could be re-expressed as a predicted depth of 820 ± 164 feet. If the uncertainty (164 feet) is assumed to be the standard deviation (although that is not clear from the text), then the coefficient of variation (ratio of standard deviation to mean) of the predicted maximum depth is 20%. In the absence of other information, the same coefficient of variation could be assumed to apply to other aspects of the subsidence predictions.

Based on the uncertainty in the maximum crater depth, the uncertainty in the prediction of the approach of the subsidence zone to Apache Leap can also be assessed. Based on Fig. 4b, the predicted distance from the center of the ore body to the outer limit of the subsidence zone in the direction of Apache Leap is 4650 feet. Assuming a coefficient of variation of 20%, the standard deviation of that prediction is 930 feet. Since the closest approach of the subsidence zone to Apache Leap is 1500 feet (Resolution Copper Mining, 2014a,c; USDA Tonto National Forest, 2019a), the distance between the eastern edge of Apache Leap and the center of the ore body is 6150 feet. Then assuming that the population of predictions of the distance of the outer edge of the subsidence zone from the center of the ore body follows a normal distribution with mean equal to 4650 feet and standard deviation equal to 930 feet, the probability that the outer limit of the subsidence zone will extend onto Apache Leap or beyond is 5.3%.

The same logic can be used to estimate the probability that the eastern edge of Apache Leap is actually in the fracture zone of visible cracks and slumps (see Fig. 3). Based on measurements on Fig. 4b, the outer limit of the fracture zone from the center of the ore body is 3650 feet. Continuing the assumption that the coefficient of variation is 20%, the standard deviation of the prediction of the outer limit of the fracture zone is 508 feet. On the above basis, the probability that the outer limit of the fracture zone will extend onto Apache Leap or beyond is 0.03%.

DISCUSSION

A useful framework for discussing acceptable probabilities for destroying cultural and religious sites is found in the Dam Safety Guidelines of the Canadian Dam Association (2013). These guidelines explicitly include "cultural losses" with the explanation that "social impacts, such as damage to irreplaceable historic and cultural features that cannot be evaluated in economic terms, should be considered on a site-specific basis. Separate assessments should be made of potential damage to sites of cultural and historic value, taking into account the feasibility and practicality of restoration or compensation" (Canadian Dam Association, 2013). The Dam Safety Guidelines then classify dams into five categories, based upon the consequences of dam failure. In terms of cultural losses, a high-consequence dam corresponds to "restoration or compensation in kind highly possible," a very high-consequence dam corresponds to "restoration or compensation in kind possible but impractical," and an extreme-consequence dam corresponds to "restoration or compensation in kind impossible" (Canadian Dam Association, 2013). It should be clear that any mining infrastructure, for which the failure would result in the destruction of a landscape feature with profound spiritual significance, should be placed in the strictest category of "extreme consequences."

Having established that panel caving in the vicinity of an irreplaceable site of cultural and religious significance is an "extreme-consequence" activity, acceptable probabilities for the occurrence of those consequences can be considered. According to Canadian Dam Association (2013), dams whose failures would have either very high or extreme consequences should be designed to withstand 10,000-year events (such as the 10,000-year flood or the 10,000-year earthquake). These events have an annual exceedance probability of 0.01%. On this basis, probabilities that Apache Leap will be within the continuous subsidence zone or the fracture zone of 5.3% and 0.3%, respectively, should be regarded as completely unacceptable risks. Even a dam in the low-consequence category, defined as "no long-term [cultural loss]" should be able to withstand a 100-year event, corresponding to an annual exceedance probability of 1%.

CONCLUSIONS

The conclusions of this study can be summarized as follows:

1) The predictions of land subsidence due to panel caving at the proposed Resolution Copper Mine cannot be verified because Rio Tinto has provided neither the data, the details of the modeling, nor the reports from the consultants.
2) The only exception to the lack of data is the map of geological faults, which is inconsistent with the aerial photography and satellite imagery that show a pronounced lineament nearly parallel to and offset by 2000 feet from the mapped West Boundary Fault. This lineament would most likely be the zone of structural weakness that would transmit deformation from the caved rock zone to the sacred escarpment of Apache Leap.
3) The subsidence monitoring program proposed by Rio Tinto explicitly assumes that subsidence will be slow, predictable and controlled, which is inconsistent with the past history of block caving and authoritative manuals on block caving.
4) Rio Tinto has provided no error bounds on the predictions of the lateral extent of the subsidence zone.
5) Based on the range in predictions of the maximum depth of the subsidence crater, the probability that the subsidence zone would reach Apache Leap can be estimated as 5.3%. This probability is about 500 times greater than what would be generally regarded as an unacceptable risk for the loss of irreplaceable cultural and religious heritage.

RECOMMENDATIONS

It is recommended that potential investors in the Resolution Copper Mine seek clarification from Rio Tinto on the following questions:

1) Why has Rio Tinto not provided the reports on subsidence modeling from their consultants?
2) Why does Rio Tinto not recognize the pronounced lineament that connects Apache Leap with the caved rock zone as a geological fault or zone of structural weakness?
3) Why does Rio Tinto believe that rapid subsidence and rockbursts cannot occur, in opposition to the block caving manual that they rely upon?
4) Why has Rio Tinto not provided any error bounds on their predictions of the lateral extent of land subsidence?

ABOUT THE AUTHOR

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