TECHNICAL MEMORANDUM

TO: Resolution Copper Project Record
Attn: Chris Garrett, SWCA Project Manager

FROM: Charles A. Kliche, P.E., PhD

DATE: November 1, 2017

RE: **Technical Memorandum for Alternative Mining Methods, Resolution Copper Mining, LLC, Superior, AZ**

INTRODUCTION

Resolution Copper Mining (RCM) is a limited liability company owned 55 per cent by Resolution Copper Company, a Rio Tinto PLC subsidiary, and 45 per cent by BHP Copper, Inc., a BHP-Billiton PLC subsidiary. The Resolution Project will be managed by Resolution Copper Mining, LLC, through its majority member, Resolution Copper Company, a wholly owned subsidiary of Rio Tinto.

The project targets a deep-seated porphyry copper deposit located adjacent to and beneath the now inactive Magma Mine. Rio Tinto has reported an indicated plus inferred resource of 1.969 billion short tons containing 1.54 percent copper and 0.035 percent molybdenum at depths exceeding between -500 and -2,500 ft below MSL[1] (5,000 to 7,000 ft below the surface).

Resolution Copper proposes to use an underground mining method known as *panel caving*, which is a variation of *block caving*. Panel caving allows for the mining of very large relatively low-grade underground ore bodies by dividing the deposit into smaller strips, or panels, so that the ore can be removed by a safe and efficient manner[2].

Because of the depth of the orebody, RCM maintains that an open pit mine is not economically or logically feasible. Furthermore, because of this great depth of the orebody, relatively low grade of the resource, and disseminated nature of the copper within the orebody, the only real feasible mining method which could maximize extraction of the copper-bearing ore deposit, is *Block Caving*, or a variation thereof.

The scope of the review for this memorandum included:

- a comprehensive review and classification of underground stoping methods which may be applicable as an alternative to block caving;
- a review of literature to estimate an Operating Cost per ton (or per tonne) for the more feasible alternatives to block caving;
- a review of other pertinent block caving operations world-wide;
- a meeting with RCM personnel (Mses. Vicky Peacy and Kim Heuther, and Mr. Bill Hart) on 3/23/17 to discuss information needs to complete this assessment;
- develop an estimate, based on limited information provided by RCM, of the total tons of potentially mineable material above a cut-off grade of 2% which lies at or above the -2,500 ft level;

[1] Parker, Harry M. 2017. *Geologic and Mineral Resource Model - Suitability for Declaration of Mineral Resources and Support for Mine Plans to Develop a Block or Panel Cave Mine*, Letter prepared exclusively for Resolution Copper Mining (RCM), by Amec Foster Wheeler E&C Services Inc. March 14, 2017.

[2] RCM. 2016. *General Plan of Operations - Resolution Copper Mining,* Section 1.5 "Proposed Operations."

- project the tons vs cut-off grade (COG) line to other COGs to estimate the tons available if the COG were to rise due to utilizing a more expensive alternative mining method; and
- discuss possible realistic alternative mining methods which may be utilized instead of block caving.

REVIEW AND CLASSIFICATION OF STOPING METHODS

In mining, it is most desirable to select the appropriate mining method which will yield the largest net return. The method employed must be safe and must also permit optimum extraction under the particular geologic conditions encountered[3].

An initial classification of stoping methods was developed and adopted by the U.S. Bureau of Mines, and was devised largely on the basis of rock stability[4].

Lewis and Clark[3] took Jackson and Gardner's work and developed it further, primarily from a structural engineering point of view; and Hustrulid[5] added to and modernized the Lewis and Clark's classification. Basically, Lewis and Clark determined that the following characteristics were the most important for selecting the most applicable underground mining method: (1) the size and shape of the orebody; (2) the depth and type of overburden; (3) the location, strike and dip of the deposit; (4) the strength and physical character of the ore; (5) the strength and physical character of the surrounding rock; (6) water and drainage, that is, the presence or absence of aquifers; (7) grade and type of ore and other economic factors. Furthermore, as an aid for the classification of stoping methods, Lewis and Clark developed four (4) overall general classifications based upon the principles of rock stability: (1) stopes naturally supported; (2) stopes artificially supported; (3) caved stopes; and (4) combination of supported and caved stopes. Hustrulid expanded classification #4 further to include such methods as Longwall Mining, Shortwall Mining and VCR stoping.

Presented below in Table 1 is Lewis and Clark's classification[3] as modified by Hustrulid[5];

[3] Lewis, Robert S. and G.B. Clark. 1964. *Elements of Mining.* Chapter XII - Underground Mining Methods Selection. John Wiley & Sons, New York.
[4] Jackson, C.F. and E.D. Gardner, 1936. *Stoping Methods and Costs,* USBM Bull. 390.
[5] Hustrulid, W.A., ed. 1982. *Underground Mining Methods Handbook.* Society of Mining Engineers of The American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York.

Table 1. ***Classification of stoping methods adopted by the U.S. Bureau of Mines (adapted from Lewis & Clark, 1964; and Hustrulid, 1982)***

	Important Characteristics from a Structural Geological Engineering Point of View:						
Classification of Stoping Methods	***Size & Shape of the Orebody***	***Depth and Type of Overburden***	***Location, Strike and Dip of the Deposit***	***Strength and Physical Character of the Ore***	***Strength and Physical Character of the Surrounding Rock***	***Water and Drainage (presence or absence of aquifers)***	***Grade and Type of Ore, and other Econ Factors***
A. Stopes naturally supported							
1. Open stoping	Stoping in which no regular artificial method of support is employed, although occasional props or cribs may be used to hold local patches of insecure ground. The walls and roof are self-supporting and open stopes can be used only where the ore and wall rocks are firm (*Dictionary of Mining, Mineral, and Related Terms,* 1997)						
- Open stopes in small orebodies	Small	Strong. Not an issue	Flat-lying to steeply-dipping	Strong ore	Strong surrounding rock	Not an issue	High grade pockets of ore
- Sublevel stoping	Large orebodies desirable; well-defined; regular in shape; steeply dipping (> 20 ft thick)	Strong. Not an issue	Steeply inclined deposits (dip > 55°)	Strong ore; not subjected to fracturing is best (> 14,000 psi)	Strong wall rock (> 14,000 psi)	Water might be an issue in sulfide ore, causing oxidation	Reqs extensive ore body development with rel high cap expenditures. Prod costs are comparatively low
2. Open stopes with pillar supports	Pillars of ore are left to support the back of stopes in deposits of uniformly low-grade ore, generally extending over a large area and either horizontal or flat-dipping, in which it is cheaper to leave pillars of ore than to use artificial support (Lewis & Clark, 1964)						
- Casual pillars (random pillars)	Uniformly low-grade ore, generally extending over a large area	Competent	Horizontal or flat-dipping (Dip < 35°)	Strong; walls and roof self-supporting	Strong; walls and roof self-supporting	Not an issue, but dry is best	Low to moderately low; pillars of waste within the ore left to support the back
- Room (or stope) and pillar (reg. arrangement)	Uniformly moderate grade extending over a large area (< 30 ft thick for R&P; < 150 ft thick for S&P)	Competent	Horizontal or flat-dipping (dip < 35°)	Strong; walls and roof self-supporting (> 14,000 psi)	Strong; walls and roof self-supporting (> 14,000 psi)	Not an issue, but dry is best	Pillars regularly spaced within the orebody left to support the back. Often robbed.

Classification of Stoping Methods	Important Characteristics from a Structural Geological Engineering Point of View:						
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B. Stopes artificially supported							
3. Shrinkage stoping	A vertical, overhand mining method whereby most of the broken ore remains in the stope to form a working floor for the miners. Another reason to leave the broken ore in the stope is to provide additional wall support until the stope is completed and ready for drawdown. Stopes are mined upward in horizontal slices. Normally, about 35% of the ore derived from the stope cuts (the swell) can be drawn off ("shrunk") as mining progresses. [classified by some as an open stope method and by others as a supported stope method]						
- With pillars	Narrow to wide (4 to 100 ft thick)	Not an issue	Must be greater than angle of repose to facilitate drawing of ore (Dip > 55°)	Should be strong (> 14,000 psi)	Weaker than those mined by sub-level stoping and shrinkage w/o pillars (> 14,000 psi)	Water might be an issue in sulfide ore, causing oxidation	Much ore tied up in inventory in the stope until final drawing of the ore
- Without pillars	Narrow to wide (4 to 100 ft thick)	Not an issue	Must be greater than angle of repose to facilitate drawing of ore (Dip > 55°)	Should be strong (> 14,000 psi)	Weaker than those mined by sub-level stoping (> 14,000 psi)	Water might be an issue in sulfide ore, causing oxidation	Much ore tied up in inventory in the stope until final drawing of the ore
- With subsequent waste filling	Narrow to wide (4 to 100 ft thick)	Not an issue	Must be greater than angle of repose to facilitate drawing of ore	Should be strong (> 14,000 psi)	Weaker than those mined by sub-level stoping (> 14,000 psi)	Water might be an issue in sulfide ore, causing oxidation	Better long-term stability. Oxidation may be an issue for sulfides
4. Cut-and-fill stoping	A method of underground mining used in vertical stopes and in mining high-grade irregular ore bodies. The rock mass surrounding the ore deposit is also usually weak—unable to support loads over an extended stoping height. As the name of the method implies, successive cutting of the ore into horizontal slices is carried out starting from the bottom of the stope and progressing upwards towards the surface (or, starting from the top and progressing downwards, as in Underhand C-and-F). This horizontal slicing leaves a void that is backfilled with material to provide support until all the ore is extracted from the mine.						
- Overhand cut-and-fill	Narrow to wide; steeply dipping to low dips (> 6 ft thick)	Not an issue	Steep to flat. Draw chutes must be greater than angle of repose (Dip* > 45°)	Should be strong (> 8,000 psi)	Weak. Supported immediately by fill (6,000 – 14,000 psi)	Fill usually placed wet. Can be an issue for sulfide waste when it dries	Higher grade since filling is expensive; cost of mining greater than for shrinkage
- Underhand cut-and-fill	Narrow to wide; steeply dipping to low dips (> 6 ft thick)	Not an issue	Steep to flat. Draw chutes must be greater than angle of repose (Dip* > 45°)	Should be strong (> 8,000 psi)	Weak. Supported immediately by fill (6,000 – 14,000 psi)	Fill usually placed wet. Can be an issue for sulfide waste when it dries	Higher grade since filling is expensive; cost of mining greater than for shrinkage

* Any, if thick

	Important Characteristics from a Structural Geological Engineering Point of View:						
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5. Stulled stopes in narrow veins	The walls of narrow veins frequently are supported by stull timbers placed between the foot and hanging walls, which constitute the only artificial support provided during the excavation of the stopes. Stulls may be placed at irregular intervals to support local patches of insecure ground, in which case the stopes are virtually open stopes. Sometimes the stulls are placed at regular intervals both along the stope and vertically, in which case stull stoping should be considered a distinctive method.						
"	Narrow vein; steep to low dips (10° to 45°)	Not an issue	Narrow vein, usually less than 12 ft. Steep or flat.	strong to weak	Competent hanging and footwall rock	Not an issue	High grade as stull timbers or steel supports are expensive
6. Square-set stoping	This method is most applicable in mining deposits in which the ore is structurally weak. Also, the surrounding rock may be fractured, faulted and altered to such an extent that it is also very weak. The geometry of the deposit is such, and the value of the ore is of sufficient magnitude, that caving methods may not be employed. The method is flexible in that sets can be extended in any direction or can be terminated as irregularities in the shape of the orebody are encountered. The sets can be filled with waste or tailings for additional support and to stop oxidation of exposed sulfide materials.						
"	Narrow vein to massive; wider than for stulls. Useful for irregular-shaped orebodies	Not an issue	Too deep may have serious ground pressure issues; shallow to deep	Weak; running ground;	Weak	Water can be introduced if backfilled with tailings	Very expensive; high grade ore a necessity. Need a ready source of timber. Labor intensive.
7 Modified Mitchell Stoping	Vein, chimneys to massive deposits	Weak or strong OB		Weak	Weak to moderately strong		May not need quite so much timber as Sq Set
C. Caved stopes							
1. Caving (ore broken by induced caving)	There are two distinct types of caved stopes: In the first, the ore is broken by caving induced by undercutting a block of ore. In the second, the ore itself is removed by excavating a series of horizontal or inclines slices, while the overlying capping is allowed to cave and fill the space occupied previously by the ore.						
- Block caving	Block caving is most applicable to large orebodies which have a capping which may be caved. Development consists of driving a series of evenly spaced crosscuts below the bottom of the ore, from which main, branch, and finger raises are driven up to the ore. The ore is then undercut, and the weight of the ore plus the capping is employed to force the ore to crush, run down through the raises and thus mine itself. ***The most ideal conditions for block caving are found in the porphyry copper deposits where both the ore and capping are weak.***						
"	(> 100 ft thick). Massive. Outlines of orebody fairly regular and the sides should dip steeply.	Very weak OB which caves. Breaks into lg pieces & resists attrition as the block is drawn. Some dilution inevitable.	(Dip^{v}* > 55°). Lg orebodies with a capping which may be caved.	(> 6,000 psi**) Proper fracture pattern (several sets with various orientations and will break into sizes & shapes that can pass thru the drawpoints).	(6,000 – 18,000 psi**). Strong wall rock preferable to limit dilution.	Should limit water into the caved muck & capping to minimize acid or metals production.	Large, massive orebodies. Disseminated ore grades. High to low grades, but usually applied to low grade deposits. Porphyry Cu.

* Any, if thick ** Caveable

^{v}* Any, if very thick

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Classification of Stoping Methods	***Size & Shape of the Orebody***	***Depth and Type of Overburden***	***Location, Strike and Dip of the Deposit***	***Strength and Physical Character of the Ore***	***Strength and Physical Character of the Surrounding Rock***	***Water and Drainage (presence or absence of aquifers)***	***Grade and Type of Ore, and other Econ Factors***
- Sublevel caving	Sublevel caving is very similar to top slicing. The general plan of operation is to mine every other slice, permitting the weight of the capping to assist in mining of the ore. The capping should be somewhat stronger than that in which top slicing is applicable. ***For both top-slicing and sublevel methods of mining, it is absolutely essential that the capping be weak enough to cave when it is undermined.***						
"	(> 20 ft thick). Can yield lower recoveries in some longitudinal layouts	No longer requires weak, caveable OB as the ore between sublevels is drilled & blasted. Can blast down the OB.	(Dip* > 50°) Can mine shallower dips but may get low recoveries	(> 14,000 psi) Moderately strong ore; drilled & blasted.	(6,000 – 18,000 psi**) Caveable waste rock.	Good drainage is essential to provide good roadbeds	Can be applied to hard & moderately weak ground; also to irreg orebodies & wide or narrow orebodies
2. Top slicing	A method of stoping in which the ore is extracted by excavating a series of horizontal (sometimes inclined) timbered slices alongside each other, beginning at the top of the orebody and working progressively downward; the slices are caved by blasting out the timbers, bringing the capping or overburden down upon the bottom of the slices that have been previously covered with a floor or mat of timber to separate the caved material from the solid ore beneath. Succeedingly lower slices are mined in a similar manner up to the overlying mat or gob, which consists of an accumulation of broken timbers and lagging from the upper slices and of caved capping.						
"	Fairly wide to massive orebodies	Weak capping material. Should not bridge or arch during caving	Moderately deep to deep; flat to steep to massive.	Weak ore	weak to strong	Water in the caved material can be an issue—may produce acid & bad air	Plentiful & relatively cheap timber required
D. Combination of supported and caved stopes							
E. Others							
- Longwall mining	(< 30 ft thick) Deposits up to 200 ft thick have been mined successfully	200 to 2000 ft Caveable.	(Dip < 15°)	Coal & trona, mainly. Trona ≈ 6600 psi;	Moderately strong to strong floor. Caveable roof.	Water-filled Cavities or mined out areas can cause major probs.	All types of coal; trona; Others: potash, iron, copper, uranium, gold
- Shortwall mining	3.5 to +12 ft thick seams	200 to 2000 ft; Reasonable strong roof, supportable by roofbolting,	Dip no steeper than what mobile equip or continuous miner can handle	Coal, mainly.	Firm floor, preferable;	Wet floor can be a prob for mobile equip.	All types of coal, trona, other soft rocks.
- VCR stoping	(> 40 ft thick)	Any depth.	(Dip > 45°)	(> 14,000 psi); widths > 12 to 15 m. May or may not be backfilled.	(> 14,000 psi); strong enough to blast against w/o adding much dilution	Oxidizing ore mined relatively quickly.	Strong ore. Good grades. Gold (HMCo) has been mined this way.
F. Resolution Copper deposit[6]	Very large; massive & thick	Deep. Weak to moderate. Highly jointed.	Deep; flat-lying to steeply-dipping	Weak to moderate	Weak to moderate; very thick; uniform	Much very hot water present	Large tonnage of low-grade ore. Porphyry copper deposit

[6] Taken from "Resolution Copper Mining, LLC - Mine Plan of Operations and Land Exchange - Follow-up Alternatives Information;" August 14, 2017; Ms. Vicky Peacey to Ms. Mary Rasmussen. Project Record #0001734.

ESTIMATE OF COSTS FOR VARIOUS UNDERGROUND MINING METHODS

Edumine, which provides a source for education and training through a set of on-line and short courses, developed a table[7] of underground mining costs based upon 2010 dollars. The authors of the table used a publication developed by CostMine (a division of InfoMine) titled Mining Cost Service[8] to estimate the costs (Table 2).

Mining Cost Service is the industry standard for mine cost estimating. It is a 2-volume loose-leaf system which includes information on the following topics:

- Mine and Mill Cost Models
- Smelting
- Mining Taxes
- Mine and Mill Equipment Costs
- Electric Power Costs
- Metal Prices
- Transportation Costs
- Cost Indexes
- Labor Costs
- Mine and Mill Supply Costs
- Development Costs
- Natural Gas Costs

Table 2. ***For a shaft entry underground mine, the approximate total operating costs (in dollars per tonne ore) and the total capital costs (millions of dollars).***

U/G Mining Method	Production Rate (t/day)	Op Cost ($/t)	Cap Cost ($M)
Cut & Fill	1,000	68.03	32.7
Mechanized Cut & Fill	1,000	52.48	68.4
Shrinkage	1,000	51.49	31.5
End Slice	2,000	25.58	45.0
Vertical Crater Retreat	2,000	40.36	66.8
Sublevel Longhole	4,000	19.02	63.7
Room & Pillar	8,000	20.83	118.2
Sublevel Caving	8,000	21.99	142.6
Block Caving	30,000	9.10	163.7

A similar table of relative operating cost per tonne of ore vs underground mining method is presented below within Figure 1[9]. This figure shows that a mining method such as Cut-and-Fill mining can be 20, or more, times as expensive per ton (tonne) as a bulk method such as Block Caving.

[7] Hem, Priyadarshi, G. Fenrick and J. Caldwell. rev 2011. *Underground Mining Methods.* http://technology.infomine.com/reviews/UgMiningMethods/welcome.asp?view=full Accessed 7/7/2017.
[8] http://costs.infomine.com/miningcostservice/ Accessed 7/7/2017.
[9] Moss, Allan. 2011. *An Introduction to Block and Panel Caving.* BMO Capital Markets 2011 Global Metals and Mining Conference. https://www.scribd.com/document/217853788/Introduction-to-Panel-Caving

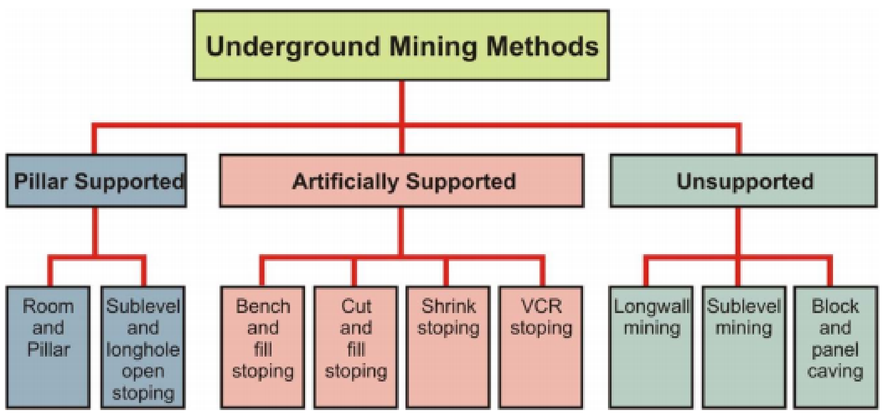
It is important at this point to discuss the concept of **Cutoff Grade** as it pertains to mining. The cutoff grade is defined as the lowest grade of mineralized material that qualifies as ore in a given deposit[10]. That is, the cutoff grade is the lowest grade of ore-type material that, at the current price and mill recovery, just equals the cost of stripping, drilling & blasting (ore & waste), mining (ore & waste), hauling (ore & waste), crushing, processing, G&A, applicable taxes, and other associated costs to produce 1 ton (tonne) of ore.

For a copper porphyry deposit, it can be written in simple form as:

Cutoff Grade (decimal form) =

$$\frac{(\text{mining cost/ton of ore}) + (\text{haulage cost/ton of ore}) + (\text{milling cost/ton of ore}) + (\text{applicable taxes/ton of ore}) + (\text{G \& A/ton of ore})}{\text{anticipated price (\$/lb of Cu)} \times \left(\frac{2000\ \text{lb}}{\text{ton}}\right) \times \left(\frac{\%\ \text{mill recovery}}{100}\right)}$$

So, it can be seen that with a more expensive mining technique that, as the cost of mining goes up, and with the copper price and metal recovery from the mill remaining the same, then the cutoff grade also goes up.



Method	T / Manshift	Avg. T / Day	Relative Operating Cost per tonne
Resuing	0.2 - 0.5	50 - 100+	70+
Cut and Fill	12 - 48	500 – 1,500	20 to 70
Shrinkage	20 - 28	200 - 800	20 to 50
Room and Pillar	15 - 150	1,500 – 10,000	7 to 20
Open Stoping	20 - 115	1,500 – 25,000	7 to 25
Sub-level Caving	65 - 180	1,500 – 50,000	7 to 17
Block Caving	300 - 2000	10,000 – 100,000	1 to 2.5

Figure 1. ***Relative operating cost for various stoping and caving underground mining methods.***

[10] American Geological Institute. 1997. *Dictionary of Mining, Mineral, and Related Terms,* American Geological Institute in cooperation with the Society for Mining, Metallurgy, and Exploration, Inc., Alexandria, VA.

REVIEW OF BLOCK CAVING OPERATIONS WORLDWIDE

General Characteristics of Block Caving

As summarized in Table 1, block caving is most applicable to large ore bodies which have a capping which may be caved.

Tobie and Julin (1982)[11] state some of the requirements for a successful block caving application as: *Included as a necessary characteristic in an ore body suited to a successful block caving operation is a proper fracture pattern. Ore hardness should be another governing factor, and the toughness or softness of the ore should be considered. There must be sufficient horizontal area available for expansion of the undercut, if necessary to start the caving process. Large, massive orebodies usually meet these conditions.*

Furthermore, they state: *In block caving, a fairly uniform distribution of values in the ore is necessary. Grade values may range from low grade to high grade, but most often the system is applied to low-grade ores. The ore must be such that it can be supported while blocks are being developed and undercut, but breaks up readily when caved. Some applications include porphyry copper….*

Outline of the orebody should be fairly regular, and the sides of the orebody should dip steeply. It may not be economical to mine small portions of the ore extending into the walls of the deposit, and low-grade inclusions in the ore cannot be left unmined.

The intensity of the (rock) fracture pattern is a critical parameter to be analyzed (to determine a deposit's suitability for caving). Several sets of fractures are essential to promote good caving. Ideally, two vertical sets at nearly right angles to each other and a third set nearly horizontal are required to insure a good caving ore body.

Additional considerations include[3]:

- *Some dilution of the ore with waste and some loss of ore always occur when this system of mining is used. It is important to know the grade of the ore before selecting the method by which the ore is to be mined. If the loss of from 12 to 15% of the ore is of more importance than the additional cost of mining by the other method, caving would not be used.*
- *In general, an ore body must be of large size to justify the expense of the haulage drifts, rises and other development work (high capital cost).*
- *The thickness of the capping is the most important factor in deciding whether the mine should be worked by the open-cut method or by caving*. Some sort of method must be used to determine the break-even stripping ratio between surface mining and underground (block caving) mining. If the stripping ratio via proposed open pit mining exceeds this break-even ratio, then underground mining (block caving) is an alternative.

Table 3 below lists some of the more important advantages and disadvantages of block caving[12].

Summarizing for block caving: Where applicable, it is a mining alternative with a high initial capital investment cost, but low operating cost per ton of ore (see Table 2).

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[11] Tobie, Ray L and Douglas E Julian. 1982. *Block Caving,* In Underground Mining Methods Handbook. Hustrulid, W.A., ed. Society of Mining Engineers of The American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York.

[12] Source: http://minewiki.engineering.queensu.ca/mediawiki/index.php/Block_caving

Table 3. ***Advantages/disadvantages of block/panel caving.***

Parameter	Advantage	Disadvantage
Cost	• Low unit cost ($/ton ore) ➢ Little to no drill and blast • Can be profitable even with relatively low grade ore bodies	• High capital cost ➢ Development infrastructure needs to be in place before first ore ton produced
Safety	• Inherent safety • No large open stopes standing • High degree of mechanization possible	• Poor ground conditions during development • Explosive handling could be an issue for draw point blasting
Production & Development	• High productivity ➢ Centralized, one level production ➢ Few workers required to muck all ore • Fewer active areas allows for easier ventilation	• Long time for development, construction, commissioning ➢ Required to reach bottom production level to develop haulage infrastructure and drawpoints • High dilution ➢ From hanging wall ➢ When overburden fragmentation is higher than expected • Low recovery • Risk of subsidence (must be able to predict) ➢ Potential to damage surface infrastructure • Uncertainty ➢ Limited draw control ➢ Lower selectivity at ore face

Hem (2012)[10] compiled a list of developing, producing and closed (one on the list) block caving mines worldwide (Table 4). A mine added to Table 4 by Dr. C. Kliche is the San Manuel mine outside of Tucson, AZ, which closed in 2003.

Figure 2 shows a map of many of the planned and operating block caving mines around the world.

Table 4. ***Block caving mines worldwide***[13]

Mine	**Location**	**Commodity**	**Status**
Northparks	Australia	Cu, Au	Production
Jeffrey	Canada	Asbestos	Closed (2012)
New Afton	Canada	Au	Development
Andina (Rio Blanco)	Chile	Cu	Production
Chuquicamata (Subterranea)	Chile	Cu	Development
El Teniente	Chile	Cu	Production
El Salvador	Chile	Cu	Production
Tongkuangya	China	Cu	Production
Freeport DOZ	Indonesia	Cu	Development
Grasberg Block Cave	Indonesia	Cu	Development
Oyu Tolgoi (Hugo North Deposit)	Mongolia	Cu, Au	Development
Cullinan	South Africa	Diamond	Production
Finsch	South Africa	Diamond	Production
Kimberley	South Africa	Diamond	Production
Koffiefontein	South Africa	Diamond	Production
Palabora	South Africa	Cu	Production
Bingham Canyon	USA	Cu	Development
Climax	USA	Mo	Production
Henderson	USA	Mo	Production
Resolution	USA	Cu, Mo	Development
San Manuel	USA	Cu	Closed (2003)
Questa	USA	Mo	Production
Shabani	Zimbabwe	Asbestos	Production

Figure 2. ***Map of block cave mines around the world***[14]

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[13] Hem, Priyadarshi. 2012. *Block Caving.* InfoMine. Located at: https://queensminedesign.miningexcellence.ca/index.php/Block_caving
[14] TechnoMine. *Block Caving*. http://technology.infomine.com/reviews/Blockcaving/welcome.asp?view=full Accessed 7/7/2017.

Discussion of Selected Block Caving Operations

1. Codelco's El Teniente

Location[15]**:** El Teniente ("The Lieutenant") is an underground copper mine in the Chilean commune of Machalí in Cachapoal Province, Libertador General Bernardo O'Higgins Region, near the town of Sewell, 2,300 m (7,500 ft) above mean sea level in the Andes.

Coordinates: 34°05′16″S 70°23′15″W

Facts:

- El Teniente is the world's largest underground copper operation and the sixth biggest copper mine by reserve size.
- El Teniente is owned and operated by Codelco, the state-owned copper miner and the world's largest copper producer (Codelco also owns Chuquicamata, the world's largest open pit mine).
- The El Teniente mine extracts the porphyry copper deposit, located 2,500m above sea level in the core of a volcanic mountain in the Libertador General Bernardo O'Higgins region in the Andes. Mining is carried out at different levels around a non-mineralised formation called the Braden Pipe that houses mining infrastructure of each level.
- The underground mine was estimated to contain 15.2 million tonnes of fine copper (1,538 million tonnes of ore grading 0.99% copper) in proven and probable reserves at the beginning of 2013.
- Located 80km south of Santiago, in the Andes mountain range, El Teniente is undergoing an extensive $5.4bn expansion project called New Mine Level project, which will extend the mine's production life by 50 years.
- The New Mine Level project will access approximately 2.02 billion tonnes of ore reserves (grading 0.86% copper) lying at about 350 metres below the existing undercut level of the mine.
- The massive deposit was discovered in the early 19th century and has been operational since 1905, when U.S.-based Braden Copper Company began operations.
- Block caving is used for extracting ore. More than 2,400km of underground drifts and in excess of 1,500km of underground road have been developed in the mine since it began operations.
- The mine is accessed by a 3.5km tunnel and the ore is hauled to the surface through a railroad system. The hauled ore is sent to the crushing plants on surface from where it is conveyed to a concentrator and the produced copper concentrate is sent to nearby smelter.
- El Teniente employs 4,000 staff workers and about 11,000 contractors.
- The El Teniente mine produced 450,000t of copper in 2013 compared with 417,000t in 2012, becoming Codelco's biggest copper producing mine during the year.
- It will process approximately 137,000t of ore per day and maintain El Teniente's the existing production level for a period of 50 years. The project also keeps the option open to expand the mine's ore output capacity to 180,000t per day.

[15] https://en.wikipedia.org/
(NOTE: Wiki was used **only** for location data for the block caving mines discussed)

Figure 3. ***El Teniente from Codelco Annual Report, 2015***

Figure 4. ***Google Earth image of same area as shown above (Red pin is located at 34°05'16"S 70°23'15"W).***

2. Magma Copper's (later BHP Billiton's) San Manuel

Location[14]**:** The San Manuel Copper Mine was a surface and underground porphyry copper mine located in San Manuel, Pinal County, Arizona.

Coordinates: 32°41′46″N 110°41′22″W

Facts[16]**:**

- The San Manuel group of mining claims was located in the 1920s and '30s.
- The San Manual Copper Corp. formed as a subsidiary of the Magma Copper Co. to carry on the exploration, revealing reserve estimates for copper ore that totaled 30 million tons, averaging 0.80 percent copper.

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[16] Most San Manuel facts from: Ascarza, Wm. 2014. "Mine Tales: San Manuel was once world's largest underground copper mine," *Arizona Daily Star.* http://tucson.com/news/local/mine-tales-san-manuel-was-once-world-s-largest-underground/article_cbe2c60f-9516-520d-bcd3-b58679c1435d.html

- Development of the San Manuel ore deposit — 7,700 feet long, 3,500 wide and up to 2,700 feet deep — began in 1952 with the approval of a $94 million loan by the Reconstruction Finance Corp. to the Magma Copper Corp.
- By the 1980s, the San Manuel mine was the largest underground copper mine in the world in terms of production capacity, size of the ore body and infrastructure. It also included the similarly sized "Kalamazoo" ore body a mile to the west, which was a faulted segment of the San Manuel ore body.
- Mining operations during the 44-year life of the mine included underground block-caving methods that extracted more than 700 million tons of sulfide ore that was processed at the mill, smelter and refinery. Open-pit mining and a heap leach facility were initiated in 1985 to extract and process 93 million tons of oxide ore over 10 years
- Between 1955 and 1999, copper concentrates, finished and unfinished copper, ore and sulfuric acid were shipped 30 miles via the San Manuel Arizona Railroad Company from the San Manuel Mine and smelter to an interchange at Hayden with the Southern Pacific and later the Copper Basin Railway, a Southern Pacific spinoff railroad.
- BHP Billiton acquired the property through a merger with Magma in 1996. Mining operations ended in 1999 due to the decline in mineable ore reserves, along with sinking copper prices from a high of $1.39 per pound in 1995 to 65 cents in 1999. The mine, closed in 2003, holds the distinction of being the largest open-pit reclamation project undertaken in Arizona history, completed in 2006.
- The underground mine at San Manuel was first established in the 1940s and in 1952 Magma Copper Company constructed the mine, plant and railroads and started developing the community of San Manuel. By 1972, the mine mill was processing more than 60,000 tons of ore per day. The development of the open pit mining operations began in 1985. By the 1990s, the operation included an open pit, solvent extraction-electrowinning operation, an in-situ leaching process and underground sulfide mine. Prior to being placed on care and maintenance in 1999, the San Manuel Mine produced a world record 703 million tons of ore hoisted.

Figure 5. ***Aerial view of the San Manuel mill and smelter*[15]*.***

Figure 6[17] ***Open pit at San Manuel, looking south toward Santa Catalina Mountains on skyline. Broken ground in the far wall resulted from the collapse of surface exposures above the underground block caving operation.***

[17] Briggs, David F. 2014. *History of the San Manuel-Kalamazoo Mine, Pinal County, Arizona.* Contributed Report CR-14-A, Arizona Geological Survey.

Figure 7. ***Google Earth of the San Manuel Mine. Where's the subsidence?***

Figure 8. ***Zoomed in on the Magma Copper Open Pit/Mammoth Gold Mine. Subsidence visible in the foreground and on the left side of the open pit.***

3. Freeport's Henderson

Location[14]**:**

The Henderson molybdenum mine is a large underground molybdenum mine west of the town of Empire in Clear Creek County, Colorado, USA. The Henderson mine, which has produced molybdenum since 1976, is owned by Freeport-McMoRan.

Coordinates: 39°46′13″N 105°50′00″W

Facts[14] **:**

- The Henderson molybdenum mine is just east of the snow-capped continental divide
- The Henderson mine is North America's largest producer of primary molybdenum. 2007 production was 40 million pounds of molybdenum, with a value of $1.1 billion.
- The Henderson mine is near the Urad mine, which produced molybdenum from 1914 to the 1960s, before exhausting its orebody. The owner, Climax Molybdenum Co., recognized the potential for deeper orebodies in the area, and discovered the Henderson deposit in 1964. The mine was named after mining engineer Robert Henderson.
- Production began in 1976, and, on Jan. 4, 2010, the workers mined the billionth pound of molybdenum. In 2006, remaining ore reserves were estimated to be 500 million pounds of recoverable molybdenum.
- The deposit is a porphyry-type deposit consisting of a stockwork of small veins of molybdenite in rhyolite porphyries of Tertiary age that intrude into Precambrian Silver Plume granite. The ore averages 0.2% molybdenum. The molybdenite is associated with pyrite and quartz. The deposit is similar to other porphyry molybdenum deposits such as the Climax mine in Colorado and the Questa mine in New Mexico.
- Mining is done by block caving. In 1980 the cavity produced by the panel caving broke through to the surface, producing a large glory hole (subsidence) on the side of Bartlett Mountain.
- The ore is carried by a 15-mile conveyor belt system through a tunnel beneath the Continental Divide to the ore processing mill near Parshall, Colorado. The ore is treated by froth flotation to obtain molybdenite concentrate, which is shipped to a plant in Fort Madison, Iowa for further processing.

Figure 9. ***Henderson Mine glory hole (subsidence crater).***

Figure 10. ***Henderson Mine subsidence crater as viewed with Google Earth.***

4. Petra Diamond's Cullinan

<u>Location</u>:

The Premier Mine is an underground diamond mine owned by Petra Diamonds. It is situated in the town of Cullinan, 40 kilometers (25 mi) east of Pretoria, Gauteng Province, South Africa.

Coordinates: 25°40′S 28°30′E

<u>Facts</u>:

- Cullinan Diamond Mine is a carrot shaped volcanic pipe and has a surface area of 32 hectares (79 acres).
- On 22 November 2007, De Beers, the world's largest diamond producer, sold its historic Cullinan mine to Petra Diamonds Cullinan Consortium (PDCC), a consortium led by Petra Diamonds.
- The mine rose to prominence in 1905, when the Cullinan Diamond — the largest rough diamond of gem quality ever found — was discovered there. The mine has produced over 750 stones that are greater than 100 carats and more than a quarter of all the world's diamonds that are greater than 400 carats. It is also the only significant source of blue diamonds in the world.
- Ownership: Petra Diamonds Limited: 74%
  Kago Diamonds (Pty) Ltd: 14%
  Itumeleng Petra Diamonds Employee Trust: 12%
- Current depth of Resources : 1,073m
- Depth of current mining: 747m
- Mining Method: Block cave
- Potential Mine Life: +50 years

- Reserves & Resources[18]:

Category	Gross		
	Tonnes (millions)	Grade (cpht)	Contained Diamonds (Mcts)
Reserves			
Proved	-	-	-
Probable	47.8	45.1	21.59
Sub-total	47.8	45.1	21.59
Resources			
Measured	-	-	-
Indicated	251.5	70.3	176.88
Inferred	171.2	10.1	17.29
Sub-total	422.7	45.9	194.17

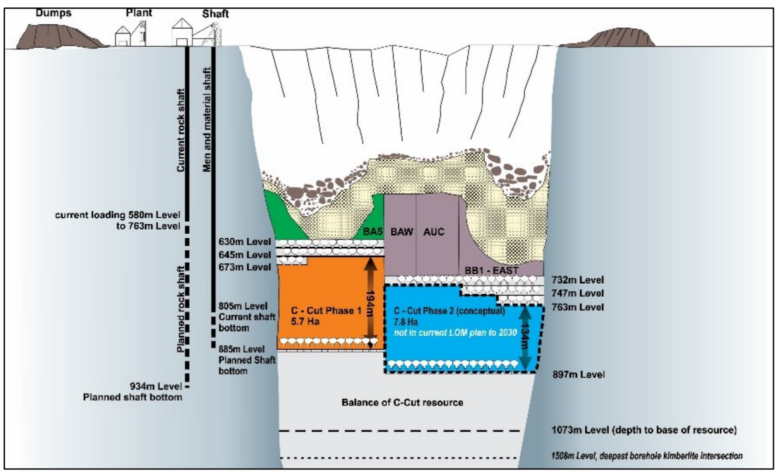

Figure 11. ***The orange block demonstrates both the* C-Cut *Phase 1 block cave that will be brought into production from* FY *2016 onwards. The blue block represents* C-Cut *Phase 2 which is available for mining post the end of the current mine plan (2030).***

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[18] Petra Diamonds Limited, 2016 Resource Statement, pg 2. https://www.petradiamonds.com/wp-content/uploads/Petra-Diamonds-2016-Resource-Statement-FINAL-1.pdf

Figure 12. ***The pit at the Premier Mine, Cullinan, Gauteng, South Africa. The cross-sectional area of the 190 meter deep pit at its surface is about 32 hectares. The mine was the source of the 3106 carat Cullinan Diamond, the largest diamond ever found.***

5. Northparkes

Location[19]**:**

CMOC-Northparkes Mines (Northparkes) is a copper and gold mine located 27 kilometres north west of Parkes in the Central West of New South Wales, Australia. Northparkes is a joint venture between China Molybdenum Co., Ltd (CMOC) (80%) and the Sumitomo Groups (20%).

Coordinates: 33°08′16″S 148°10′29″E

Facts:

- The mine was originally started in 1994 using open pit mining, with underground mining using the block caving method starting in 1997.
- The mine has an operational capacity to process six million tonnes of ore per year, containing roughly 60,000 tonnes of copper and 50,000 ounces of gold. Economic viability of the mine is projected to extend at least to the year 2032.
- In 2006 Northparkes began construction of a new block cave mine on the E48 copper/gold deposit with production officially commencing in September 2010. In 2012, the joint venture partners approved a $35.6 million extension of the E48 block cave mine, extending the life of mine by approximately two years. Recently Northparkes' Environmental Assessment was approved by government taking Northparkes' mine life to 2032.
- The Northparkes deposits occur within the Ordovician Goonumbla Volcanics, part of a volcanic belt in the Central Lachlan Orogen of NSW. The ore deposits are typical copper-gold porphyry systems; the highest grades associated with the most intense stockwork veining. Sulphide species in the systems are zoned from bornite-dominant cores, through a chalcopyrite-dominant zone to minor distal pyrite.

[19] http://www.mining-technology.com/projects/goonumbla/

- The porphyry copper deposits at Northparkes are typically narrow but extend to great depths. The E26 and E48 deposits range from 200 to 400m in diameter (>0.5% copper) and extend vertically for more than 1,000m.
- Northparkes currently holds ~1,000 km^2 of Exploration leases around the Northparkes Mines.

Figure 13. ***Google Earth image of Northparkes Mine. Subsidence crater in the foreground, mine pit at top left.***

Figure 14. ***Subsidence crater at Northparkes Mines.***

6. Palabora Copper (Pty) Ltd, a subsidiary of Palabora Mining Company.

Location:

Palabora Copper (Pty) Limited, a subsidiary of Palabora Mining Company Ltd, is a copper mine that also operates a smelter and refinery complex based in the town of Phalaborwa, in South Africa's Limpopo Province. The mine owes its origins to a unique rock formation in the region known as the Palabora Igneous Complex.

Coordinates: 23°56′S 31°7′E

Facts[20]**:**

- Palabora has been operational since its incorporation in 1956 and is the country's major producer of refined copper, producing approximately 45,000 tonnes of copper per annum. Palabora Copper is South Africa's sole producer of refined copper, which it supplies mainly to the local market and export the balance. Whilst copper forms the base-load of its business, Palabora also mines and exports other by-products such as Magnetite, Vermiculite Sulphuric acid, anode slimes and nickel sulphate.
- The company owes its origin to the unique formation known as the Palabora Igneous Complex. Nowhere else is copper known to occur in carbonitites as is the case at Palabora, and a host of other minerals such as phosphates, vermiculite, phlogopite, magnetite, nickel, gold, silver, platinum and palladium also occur.
- Palabora operates a large block cave copper mine and smelter complex employing approximately 2,200 people. The refinery produces continuous cast rod for the domestic market and cathodes for export. Useful byproduct metals and minerals include zirconium chemicals, magnetite and nickel sulphate as well as small quantities of gold, silver and platinum. Palabora has developed a US$410 million underground mine with a production capacity of 30,000 tonnes of ore per day.
- Palabora Mining Company operates a successful underground block-cave mine, producing 80,000 tonnes of copper ore per annum.
- The construction of the underground mine was completed in October 2004 when the 20th cross-cut was brought into full production. By May, 2005 the mine was consistently achieving 30,000 tonnes per day - one of the fastest ramp-ups to full production in the world.
- During 2006, Palabora treated 10.7Mt of ore grading 0.71% copper, giving an output of 61,500t of copper in concentrates. While production in the early stages of the underground operation had been hampered by problems with fragmentation in the block cave and secondary breaking systems, these seem to have been overcome in the past two-to-three years. The Palabora smelter produced 81,200t of copper metal, compared with 80,300t in 2005.
- The underground mine has been developed on a proven reserve of 225Mt at 0.7% copper, plus an additional probable reserve of 16Mt grading 0.49% copper. By the end of 2005, proven and probable reserves totaled 112Mt grading 0.56% copper, representing a significant reduction from the tonnage and grade cited the year before. Rio Tinto recorded a US$161m asset write-down in its 2005 accounts to reflect this

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[20] PMC Palabora Mining Company http://www.palabora.com/

Figure 15. ***Palabora mine pit. Caved area from UG block caving operations on the left.***

Figure 16. ***Palabora pit showing subsidence from UG block caving operation.***

Figure 17. ***Google Earth image of Palabora, SA.***

7. Freeport's DOZ

Location: The Deep Ore Zone (DOZ) Mine is in the Ertsberg Mining District in Papua, Indonesia. The operation is run by P.T. Freeport Indonesia (PTFI) under contract to the Republic of Indonesia. The PTFI project site is located approximately 4º-6'S latitude, 137º-7'E longitude, in the Sudirman Mountain range of Papua, the eastern most province of Indonesia which occupies the western half of the island of New Guinea.

The ore deposits, discovered in 1936 and then acquired and developed by PTFI beginning in 1967, are located approximately 96 kilometers north from the southwest coast, between elevations of 2900m and 4000m above sea level. Access to the project is through the PTFI portsite of Amamapare on the Tipoeka River, and from the international airport of Timika, some 43 kilometers north of Amamapare. The mine site is 118 kilometers from Amamapare. An access road to the mine project site connects the portsite to the mill, passing by the Timika airport en route.

Facts[21]**:**

- Ownership: 90.64% FCX (including 9.36% owned through their wholly owned subsidiary, PT Indocopper Investama); 9.36% the Government of Indonesia (Freeport recently has agreed to sell 41.64 percent of PT-FI to the Indonesian government, adding to the 9.36 percent share the government already holds, to reach the divestment target of 51% ownership by the government).
- DOZ is a copper-gold skarn deposit located on the northeast flank of the Ertsberg diorite intrusive body. It comprises the lower elevations of the East Ertsberg Skarn System (EESS). The EESS outcropped on surface at about 4000 meters, and the DOZ lift of the EESS is located on the 3100 meter level.
- Current operations in the district include the Grasberg open pit (200,000 tpd ore) and the DOZ block cave mine (40,000 tpd).
- The DOZ mine is a mechanized block caving operation. The DOZ is the third lift of the block cave mine that has exploited the East Ertsberg Skarn complex since 1980, and design and operation has benefited from the previous experience gained while mining the upper lift (GBT)

[21] FCX Freeport-McMoRan http://www.fcx.com/operations/grascomplx.htm

and the intermediate lift (IOZ). There are four main levels at the DOZ mine, from top to bottom they are; undercut level, extraction level, exhaust level, and the truck haulage level. An advanced undercutting system is employed at DOZ.

- Freeport Indonesia's first block caving operations began in 1980 with the Gunung Bijih Timur – East Ertsberg (GBT) mine. This achieved a maximum production rate of 28,000 t/d and was depleted in 1994. The IOZ mine began production in 1994 and ramped up to a maximum production rate of 32,000 t/d.
- It was in 1997 that the pre-production development of the DOZ block cave mine began, and caving was initiated in November 2001. That same year the combined Grasberg/Ertsberg District operations achieved new record copper production of over 1,640M lb of copper. In 2002 the record was raised to over 1,800M lb of copper and DOZ achieved a sustainable production rate of 25,000 t/d. In 2003 the DOZ expansion to 35,000 t/d was approved and completed. The following year DOZ operated at 43,600 t/d, over 8,000 t/d above design-capacity and expansion to 50,000 t/d was approved. Today the mine has reached a sustained production rate of 80,000 t/d – the 80K project.
- DOZ is the third level of block caving to exploit the copper-gold Ertsberg East Skarn System.

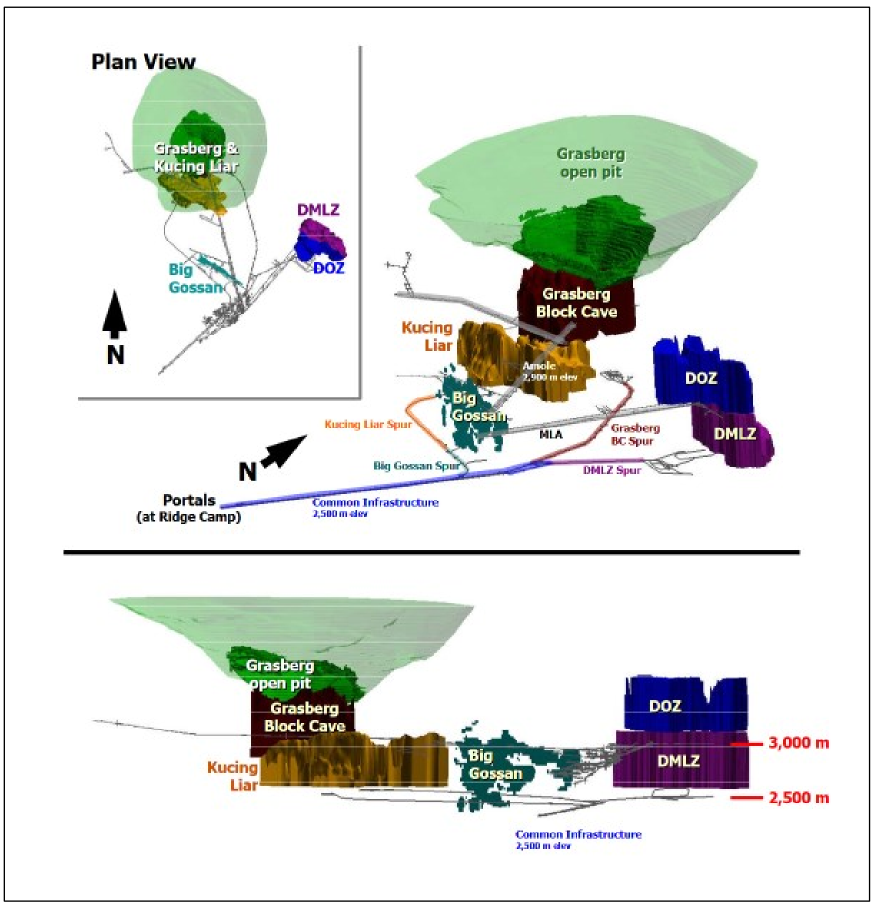

Figure 18. ***Grasberg District ore bodies*[22].**

[22] Brannon, C.A., M.W. Patton, R. Toba and G.A. Williams. 2012. Grasberg Block Cave: Logistical Support System Design. *Proceedings of the MassMin Conference,* Sudbury, Ont, Canada. 10 - 14 June 2012.

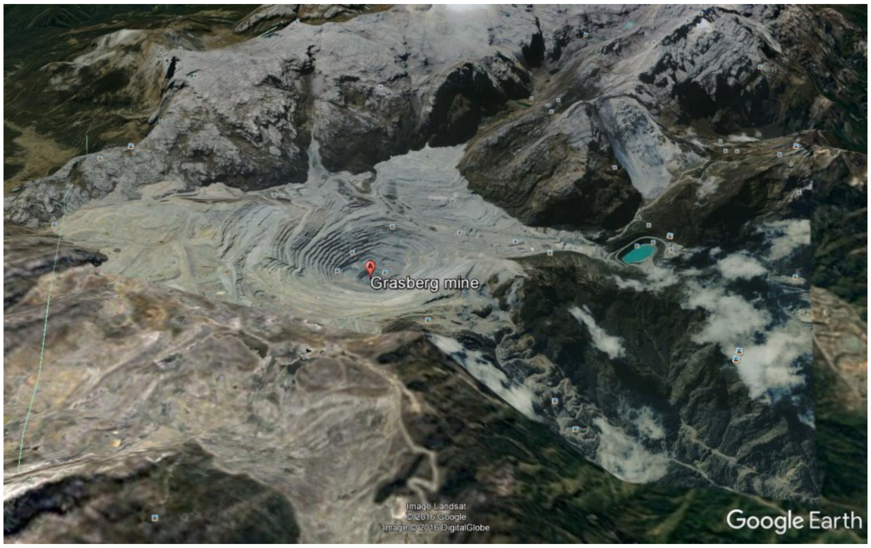

Figure 19. ***Google Earth image of the Grasberg Mine. So, where is the subsidence area?***

8. Resolution Copper

Location: Resolution Copper (RCM) is a joint venture owned by Rio Tinto and BHP Billiton formed to develop and operate an underground copper mine near Superior, Arizona, U.S. The project targets a deep-seated porphyry copper deposit located under the now inactive Magma Mine.

Coordinates: 33° 17' 57.2676" N   111° 5' 56.7708" W

Facts:

- Resolution Copper has a reported[1] mineral resource within a 1% Cu shell (implied COG of 1%) of 1,969M st at 1.54% Cu and 0.035% Mo.
- The project targets a deep-seated porphyry copper deposit located under the now inactive Magma Mine.
- The Resolution Copper deposit is located in an area that has a long history of use by Native Americans including the Salt River Pima Maricopa Indian Community, the Gila River Indian Community, the Pueblo of Zuni, the Yavapai Prescott Indian Tribe, the Yavapai-Apache Nation, the Hopi Tribe, the San Carlos Apache Tribe, the Tonto Apache Tribe, and the White Mountain Apache Tribe.
- In December 2014, Congress passed, and the president signed, the Carl Levin and Howard P. 'Buck' McKeon National Defense Authorization Act (NDAA) for Fiscal Year 2015. Section 3003 of this federal law authorizes and directs the exchange of land between Resolution Copper and the United States.

  The NDAA authorizes and directs the exchange of 2,422 acres of national forest lands located east of Superior, Arizona. In exchange, 5,344 acres of high priority conservation lands would be transferred to the Forest Service and Bureau of Land Management in Arizona, and other lands would be transferred to the Town of Superior.

Opponents (of the land swap) — including Native American tribes, officials and former miners in Superior, and conservationists — say the bill could not have passed Congress on its own merits.

- Through 2012 Resolution Copper had invested almost a billion dollars in the Superior project, and planned a $6 billion investment to develop the mine, if the Federal land exchange is approved. Pending approval, the project budget was cut from about $200 million in 2012 to $50 million in 2013.

  Resolution Copper also owns the mineral rights acquired from ASARCO to the Superior East deposit which is another deep seated porphyry deposit within a mile to the east.

- The mine is expected to take 10 years to construct, have a 40 year operational life, followed by 5-10 years of reclamation.

- Mining would use an underground mining technique known as panel caving. Using this process, a network of shafts and tunnels is constructed below the ore body. Access to the infrastructure associated with the panel caving would be from vertical shafts in an area known as the East Plant Site, near Oak Flat. Using the panel caving technique, ore is fractured using explosives, moves downward by gravity, and then is removed from below. As the ore moves downward and is removed, the land surface above the ore body subsides, or moves downwards. At the surface, a subsidence zone is expected to develop near Oak Flat, with potential downward movement of up to 1,000 feet.

- Crushed ore would be transported underground to an area known as the West Plant Site for processing. The West Plant Site is the location of the old Magma Mine in Superior. Processing would utilize a flotation process.

- Once processed, copper concentrate would be pumped as a slurry about 22 miles to a filter/loadout facility near Magma, Arizona. The slurry pipelines would follow an existing right-of-way known as the Magma Arizona Railroad Company (MARRCO) corridor. The MARRCO corridor would also include: an upgraded rail line, new water pipelines, new utility lines, several intermediate pump stations, and an estimated 30 new groundwater wells. From the filter/loadout facility, copper concentrate would be sent to market using rail or trucks.

- Tailings—the waste material left over after processing—would be pumped as a slurry 4.7 miles from the West Plant Site to a tailings disposal facility located on national forest land. The tailings facility would grow in phases, and eventually occupy about 4,400 acres (including associated structures) of national forest land.

Figure 20. ***Aerial view of Resolution Copper area showing the town of Superior, AZ, Queen Creek Canyon, Oak Flats and Apache Leap[23].***

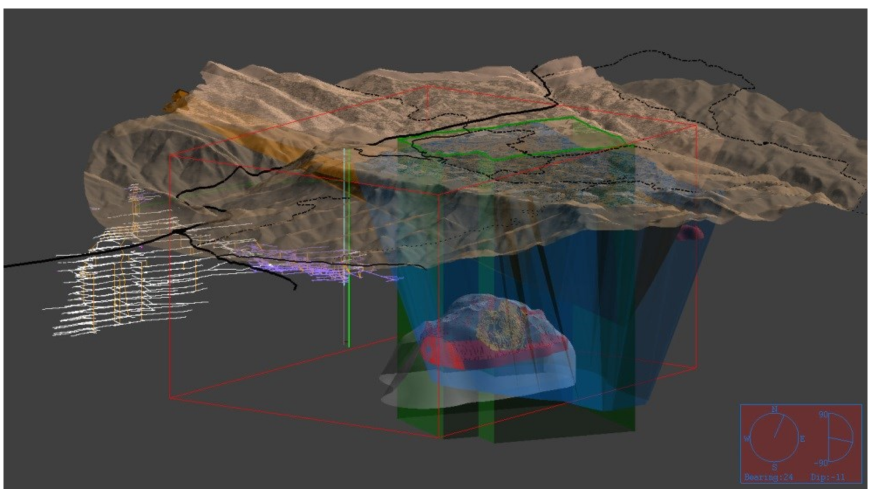

Figure 21. ***3-D view of Resolution Copper area in approximately the same direction as Figure 20 showing the Resolution deposit, the topography above the deposit and the Magma Mine workings.[24]***

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[23] Author: zeesstof from The Woodlands, TX, USA; https://www.flickr.com/people/35041397@N00

[24] Courtesy: Resolution Copper, (3/25/2017).

Table 5. ***Summary of important attributes of the block caving mines featured above.***

Mine	**Location**	**Commodity**	**Mining Method**	**Production (year)**	**Ore Mat'l**	**OB/Waste Mat'l**	**Ore Depth (Shallow (S): Depth ≤ 300m; Medium (M): 300m < Depth ≤ 1000m Deep (D): 100 m < Depth < ∞)**
Northparks	Australia	Cu, Au	Block caving	60,000 tonnes Cu/50,000 oz Au	Copper-gold porphyry	porphyry	M: 850m below surface
El Teniente	Chile	Cu	Block caving	450,000 t Cu	Copper porphyry	porphyry	New Mine Level (M: appx 400m below original workings)
Freeport DOZ	Indonesia	Cu	Mechanized block caving	80,000 tpd	Copper-gold skarn	diorite	Production level of DOZ (D: 1200m below surface)[25]
Cullinan	South Africa	Diamonds	Block caving	920,000 ct to 2.2M ct	Kimberlite	?	M: depth of current mining is 747m. Current depth of resources is 1,073m
Palabora	South Africa	Cu	Block caving	45,000 tonnes Cu per year	Carbonitites	Palabora Igneous Complex	D: 500m below the pit bottom; 1,280m -deep shaft.
Henderson	USA	Mo	Block caving	40 million lb molybdenum	Molybdenite porphyry	rhyolite porphyry	M to D
Resolution	USA	Cu, Mo	Panel caving		Porphyry copper	Porphyry granite	D: orebody is 5,000 ft to 7,000 ft below surface
San Manuel Closed (2003)	USA	Cu	Block caving	60,000 tons ore per day	Porphyry copper	Porphyry granite	M to D (depths from 0 to 2,700 ft for Magma deposit; 2,500 ft to 4,600 ft for Kalamazoo)

ALTERNATIVES TO BLOCK CAVE MINING AT RESOLUTION

The potential alternatives to block cave mining for RCM can be boiled down to:

1. Do not mine
2. Open pit mining
3. Non-caved stopes underground mining (see Table 1: Naturally supported and Artificially supported stopes)

Do Not Mine Alternative. The "Do Not Mine" alternative is beyond the scope of this Technical Memorandum, but will likely be discussed in detail in the Draft EIS.

[25] Operation Focus - Indonesia, *DOZ mine*, International Mining, January 2010, pp 12 - 24.

<u>Open Pit Mine Alternative</u>. When determining whether or not a deposit might be amenable to open pit mining, a well-established process should be followed. Basically what is done is to divide the deposit and surrounding rock mass into cells (blocks), each having a net value (positive, null or negative) based upon the present worth of the commodity contained within the block less all costs associated with removing and processing that block. A sample level map from the Resolution deposit showing color-coded average copper values within each block is shown in Figure 22. The objective is to devise a mining sequence that maximizes the total net undiscounted profit, yet following certain specific rules.

Simply stated, the open pit mining rules and basic assumptions are (Lerchs & Grossmann, 1965[26]; and modified by Caccetta & Giannini, 1986[27]):

Assumptions:

1. The cost of mining each block does not depend on the sequence of mining.
2. The desired wall slopes and pit outlines can be approximated by removed blocks.
3. The objective of the optimization is to maximize total undiscounted profit.

Rule:

1. In order for a block to be considered ***ore***, it must have a value sufficient to pay for its own mining and processing costs <u>plus</u> the cost of mining the waste blocks above it, at the chosen pit slope angle.

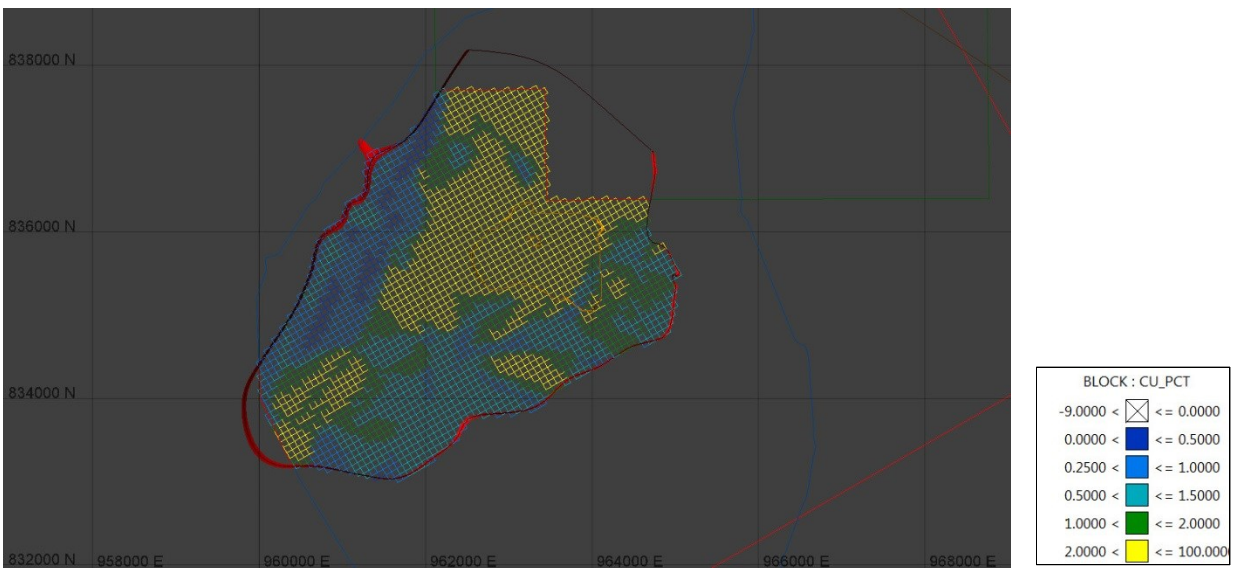


Figure 22. ***Slice through the -1600 level of the Resolution deposit showing block distribution by grade classes.***

[26] Lerchs, H., & Grossmann, I. (1965). Optimum Design of Open-Pit Mines. Transactions, C.I.M. Volume LXVII, 17-24.
[27] Caccetta, L., & Giannini, L. (1986). Optimisation Techniques for the Open Pit Limit Problem. Bull. Proc. Australas. Inst. Min. Metall, Volume 291, No 8.

With these assumptions and the above-stated rule in mind the Lerchs-Grossmann algorithm assigns a cell value (block value) based on the unit of the mineral assessed. A cell is defined as ore if[28]:

Grade x tonnage x Dollar value per unit x recovery - mining cost ≥ profit cut-off

This generates a cut-off grade for the bench. Processing costs are then applied to ore cells after the cut-off is defined. If the resultant cell value is less than the cut-off value, after mining costs are removed, then the waste removal cost is assigned to the cell to indicate that it is waste. If more than one ore type (mineral type) is extracted, the cumulative value is used.

Assay cut-offs/block dollar values are determined by the equations below:

Equation 1: Calculation of grade cut-off
Grade Cut-off (unit/t) = Processing cost (\$/t) / Recovery (%) x Ore Price (\$/unit)

Equation 2: Calculation of raw cell value
Raw Cell Value (\$) = [Assay (unit/t) x Tonnes (t) x Recovery (%) x Ore Price (\$/unit) x Ore Proportion (%)] – Modifiers (\$/T)

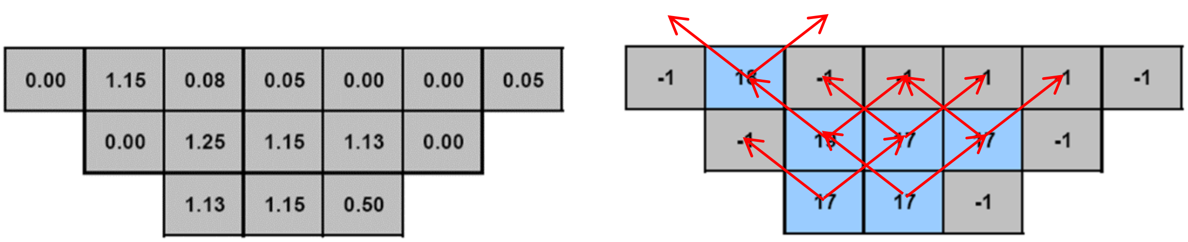
Equation 3: Calculation of cell processing
Cell Processing (\$) = [Tonnes (t) x Processing cost (\$/t)]

Equation 4: Calculation of cell value
Cell Value (\$) = Raw Cell Value (\$) - Cell Processing Value (\$)

Equation 5: Calculation of final cell value
Final Cell (\$) = Cell Value (\$) – [Tonnes (t) x Ore Mining Cost (\$/t)]

If *Final Cell ≤ Tonnes x Waste Mining Cost,* then the cell is assigned the value of *Tonnes x Waste Mining Cost* (i.e. a model cell cannot cost more to mine than the basic cost of mining).

Figure 23 illustrates how the Lerchs-Grossmann technique (or other optimization technique for open pit mining) works. Red arrows indicate ore blocks which can be mined, removing the associated waste blocks above (Rule 1).



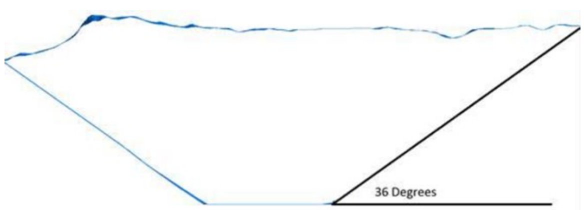
Geologic Model, Copper Grades (lb/ton) Economic Model, Value per block (\$/ton)

Figure 23. ***Deposit representation orebody model.***

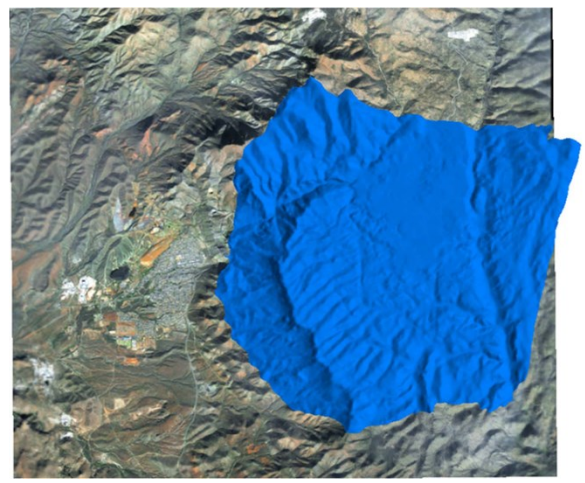
The open pit alternative to developing the Resolution Copper deposit would result in an extremely large volume of waste rock being removed, plus a very large surface footprint of the pit perimeter, plus required storage of the large volume of waste rock in waste repositories. Summarizing[29]:

[28] Mart, W.S. and G. Markey. 2013. *Intelligent Mining Software "Solutions" IMS - Lerch-Grossmann Pit Optimization.* For MineMap Pty Ltd.
[29] Email from Ms. Vicky Peacey, April 7, 2017. Project Record #0001316.

- Overall pit slope of 36° (Figure 24A)
- Overall strip ratio of 35:1
- Footprint of the open pit would be approximately 10,000 acres and would result in the removal of all of Oak Flat, all of Apache Leap, approximately 4 miles of Hwy 60, approximately 3 miles of Queen Creek, and approximately 3 miles of Devils Canyon (Figure 24B)
- Disturbance from an open pit would be approximately 8 times larger than the projected maximum disturbance from subsidence (approximately 1200 acres)
- Estimated volume of waste rock from an open pit would be over 100 times more volume than the projected volume for tailings.
- Results in approximately 205 billion tons of waste rock.



A. Cross-section showing overall open pit slope angle.



B. Approximate open pit disturbance.

Figure 24. ***Cross-section (A) and plan view (B) of the open pit option for the Resolution copper deposit.***

<u>Non-Caved Stopes Underground Mining Alternatives</u>.

The grade - tonnage relationship is widely used in the mining industry. Once modeled for a deposit, it is probably one of the most important tools for representing the variation in tonnage available within a deposit above various cutoff grades. It is especially important for low-grade porphyry copper deposits.

A problem with the grade - tonnage relationship curve, though, is the questionable continuity of grade zones. Depending on the geological characteristics of the deposit and the grade distribution, significant changes in the geometry of a deposit can occur due to variations in the cutoff grade. The grade tonnage curve calculation which is based on a block model counts every single block irrespective of its location and relationship to neighboring blocks, ie, without any consideration of continuity. A block or group of blocks separated from the mineable areas will still be counted and added to the tonnage totals in spite of their isolation and the fact that these blocks will have less probability of being mined if utilizing some sort of selective mining technique.

The grade - tonnage curve, therefore, shows the “best case” scenario, ie, at any cutoff grade the curve assumes implicitly total continuity of the mineralization and every block is considered as equally available to be mined. An example of the above is shown on Figure 22, which is a block representation of the -1600 level of the Resolution deposit. High grade zones are in yellow. If, based upon some constraints, the operator was required to mine only the material above a cutoff of 2% (the yellow zones), then that operator would have great difficulty devising a mining technique to recover all of the +2% material.

Some of the earliest work on the subject of tonnage - grade relationships for the prediction of ore reserves was conducted by Lasky[30] (1950). Lasky found that within porphyries the cumulative tonnage increases at a constant geometric rate as the grade decreases at an arithmetic rate.

Other early researchers in the field of tonnage - grade relationships among copper deposits, including porphyry copper were Singer, Cox and Drew[31] from the US Geological Survey who found a lack of correlation of tonnage and grade amongst deposits for both strata-bound and porphyry deposits. Their conclusions were: (1) Geologic factors influencing tonnage of a particular deposit type are probably distinct from those influencing grade; (2) frequency distributions of tonnages and grades approximate lognormality, making it possible to predict probability of various tonnage-grade classes and to test correlation between variables; (3) no significant correlation was found between tonnage and grade for porphyry or strata-bound deposits; (4) significant negative correlation between tonnage and grade was found for the massive sulfide subset, probably reflecting a mixture of high-grade low-tonnage massive ores, low-grade high-tonnage stockwork, and disseminated ores characteristic of some massive sulfide deposits; (5) significant negative correlation was found between tonnage and grade for the mixture of deposit types in the whole sample.

Given the above discussion, it is worthwhile to attempt to estimate the amount of mineable material which could be available to RCM if they were to opt for a more expensive underground mining technique. This is where the development and utilization of a grade - tonnage relationship for the Resolution copper deposit has value.

Basically, what these researchers, and others (Harris[32], 1984, for example) found for porphyry-type copper deposits was an inverse tonnage - grade relationship within a deposit, but no real relationship amongst deposits. That is, for a given deposit, as the cut-off grade rises, the tonnage available above that cut-off grade decreases by some definable exponential function.

Two charts below (Figures 25 and 26)[33] help determine which underground mining methods may be best suited as alternatives for the Resolution copper deposit. The first one (Figure 25) plots Ore stability vs Ore value; the second one plots Walls stability vs Ore stability.

From Figure 25, it can be seen that for deposits of low value and low ore stability, block caving is the most suitable method. It must also be noted that block caving requires an overlying material (overburden) that will cave.

Figure 26 is appropriate because if one of the non-caving underground stoping methods were to be utilized due to factors such as requiring the tailings material to be repositioned underground in mined-out stopes, then, instead of a massive, disseminated, low-grade deposit, the Resolution deposit would be broken up into smaller higher-grade deposits. This is due to the raising of the cutoff grade, thus lowering the tonnage available above said cutoff grade, by imposing some higher cost mining method (Tables 2 and 3 above). These several higher-grade deposits may or, more likely, may not be contiguous and may not constitute a mineable unit together by the alternative method. Therefore, additional non-contiguous potentially mineable material may be lost by imposing some higher-cost alternative stoping method.

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[30] Lasky, S.G. 1950. How tonnage and grade relations help predict ore reserves: Eng, and Mining JHour., v. 151, no. 4, p 81 - 85.

[31] Singer, D.A., D.P. Cox and L.J. Drew. 1975. *Grade and Tonnage Relationships Among Copper Deposits.* Geological Survey Professional Paper 907-A. US Government Printing Office, Washington, DC.

[32] Harris, D.P. 1984. *Mineral Resources Appraisal: Mineral Endowment, Resources, and Potential Supply: Concepts, Methods and Cases*. Oxford Press.

[33] Author unknown. https://www.slideshare.net/smhhs/mining-methods

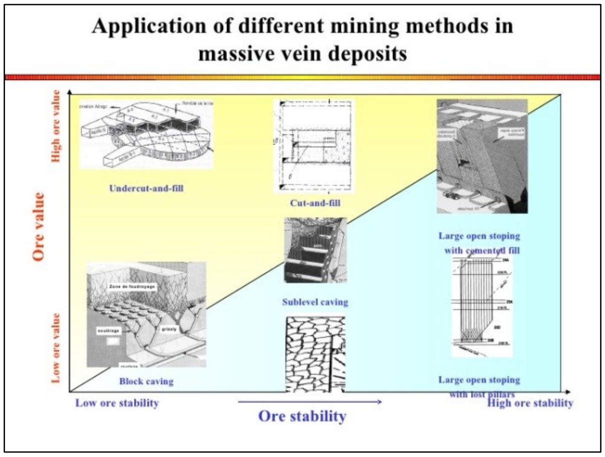

Figure 25.

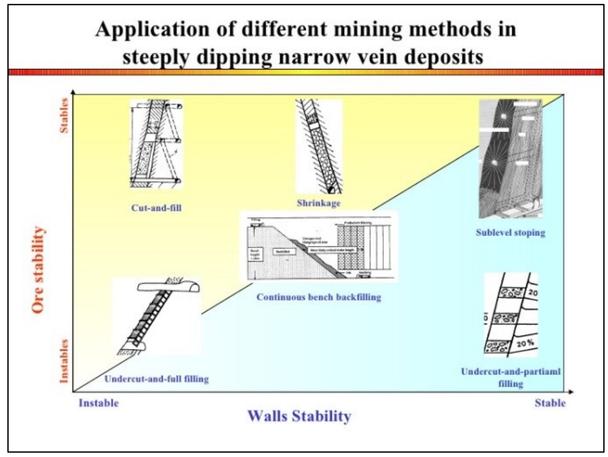

Figure 26.

The most probable mining method which could be imposed and which would allow for the repositioning of mill tailings material back underground is the "cut-and-fill" method. From Figure 26, it can be seen that cut-and-fill stoping is most applicable for material with low wall stability but with somewhat high ore stability; and from Figure 25, it can be seen that cut-and-fill stoping is appropriate for ore of high value (material above a higher cutoff grade).

Upon reviewing Table 1, it can be seen that other non-caving stoping underground mining methods may be applicable to the Resolution deposit. These would include: open stoping, open stoping with pillar support, shrinkage stoping, and VCR stoping.

Open stoping requires strong ore and strong surrounding rock; open stoping with pillars (either regular or random) requires strong ore and somewhat weaker surrounding rock. Generally, open stoping with pillar support is utilized in flat-lying deposits, but it has been used successfully in steeply dipping vein-type or bed-type deposits. Leaving pillars as support results in a loss of ore which is left in place, unless "robbed." Robbing the pillars at the end of mining the stope results in eventual collapse (caving) of the stope, unless backfilled.

Shrinkage stoping requires: (a) steeply dipping ore zones; (b) somewhat strong ore, but weaker wall rock; (c) steeply dipping (60° to 90°) tabular or lenticular ore deposit; (d) uniform ore; and (e) fairly high grade ore. A major drawback to the method, and one from which the method gets its name, is that a large proportion of ore is left in place within the stope to provide wall support as mining progresses upward, and only enough ore is "shrunk" (or withdrawn) out of the stope to allow for a safe working platform for the working personnel in the stope. If the ore material is sulfide in composition and oxidizes, then heat, fire, low oxygen and high noxious fumes (H_2S, amongst others) can be a problem in the stope. Another problem with shrinkage is that a large proportion of the ore is tied up in inventory within the stope until mining is complete within the stope and the ore is shrunk off (withdrawn). After shrinking of the stope, it can be backfilled with tailings or some sort of tailings paste mixture. If not backfilled, collapse (caving) can occur.

VCR (Vertical Crater Retreat) stoping requires both moderate-to-strong ore (> 14,000 psi) and moderate-to-strong waste (> 14,000 psi). VCR mining also requires a fairly thick (> 40 ft), steeply dipping (Dip > 45°; or greater than the angle of repose of the broken material) ore bed of sufficient height and uniformity to justify the method. It is a bulk mining method.

In a nutshell, VCR stopes are developed at some relatively large height, top to bottom. As an example, say 150 ft. A chamber is excavated at the top of the stope of large enough height to accommodate a drill with mast extended. Drill holes are often around 6 inches in diameter. Drill mast heights for underground drills capable of drilling 6 inch diameter holes are around 10 to 15 ft. Another chamber is excavated, along with draw points, at the bottom of the ore zone. This chamber must be of sufficient volume to accommodate the broken ore from a blast round, swelled. A pattern is laid out on the top of the ore zone at some pre-determined burden and spacing. Holes are drilled from the top of the ore zone through the ore zone until they punch out at the bottom of the zone. Deviation of the drilled holes should be minimized. Explosives are loaded at some pre-determined location at the bottom of the ore zone and sequentially blasted in order to drop a slice of the material into the excavated chamber at the bottom of the ore zone. This broken material is withdrawn out of the chamber using appropriate excavators. Another slice is loaded in the same way as the first and blasted into the void. This continues (the retreat up the ore zone) slice by slice until a final top sill of material of sufficient thickness to support blast loading operations remains at the top of the ore zone (usually 2 or 3 times the thickness of each mined slice). This final top sill is taken down in one large blast.

After the stope is blasted and the material is removed, a large void remains. This void can be backfilled with mill tailings or a paste made from the mill tailings to support the walls of the stope.

The name of the method comes from:

V (Vertical): the stope should be near-vertical (or Dip > 45°)
C (Crater): the blasting theory applied to break the material in the ore zone slice by slice (Livinston's Cratering Theory[34])
R (Retreat): Blasting slice by slice retreats up the stope bottom to top.

In order to determine the tonnages available within the Resolution copper deposit above various cutoff grades, it became necessary to estimate the tonnages available at, at least, two known points. The first point was given by RCM in the Parker report of reference 1. The second point was estimated utilizing the level maps provided by RCM (levels -500 to -2500, in steps of 100 ft) similar to Figure 22. All yellow blocks on said level maps were counted and the tonnage per level above the 2% COG was determined. A tonnage factor of 12.5 ft^3/st was used for the porphyry[35].

Tallying the tonnage per level resulted in the tonnage above a COG of 2% as shown in Table 6.

A plot of the two COG vs tonnage points on a semi-logarithmic scale is shown in Figure 27. And Figure 28 shows the same COG vs tonnage plot, but with the addition of the projected tonnage above COGs of 3%, 4% and 5%. It is apparent from Figure 28 that raising the COG lowers substantially the ore grade material available above that cutoff grade. It should be noted that plotted in Figures 27 and 28 is ALL material within the 1% shell above the cutoff grades, and NOT the mineable material. The difference is that some (or in some cases, MUCH) of the ore-grade material may not be mineable via the technique chosen.

[34] Livingston, C.W., 1956. Fundamentals of Rock Failure, *Quarterly of the Colorado School of Mines*, 51 (3).
[35] Private conversation with Ms. Nichole King, Sr. Geotechnical Engineer, Haile Gold Mine. Formerly at the Freeport-McMoRan Tyrone Mine)

Table 6. ***Total tons (above the -2500 level) within the Resolution copper deposit above a COG of 2%.***

Level	Tons	Level	Tons
-500	0	-1600	40,590,000
-600	0	-1700	41,355,000
-700	675,000	-1800	44,325,000
-800	1,890,000	-1900	30,757,500
-900	2,880,000	-2000	29,700,000
-1000	12,577,500	-2100	23,265,000
-1100	14,040,000	-2200	16,740,000
-1200	13,185,000	-2300	12,870,000
-1300	17,955,000	-2400	7,875,000
-1400	32,175,000	-2500	7,245,000
-1500	36,337,500		
Total = 386,437,500			

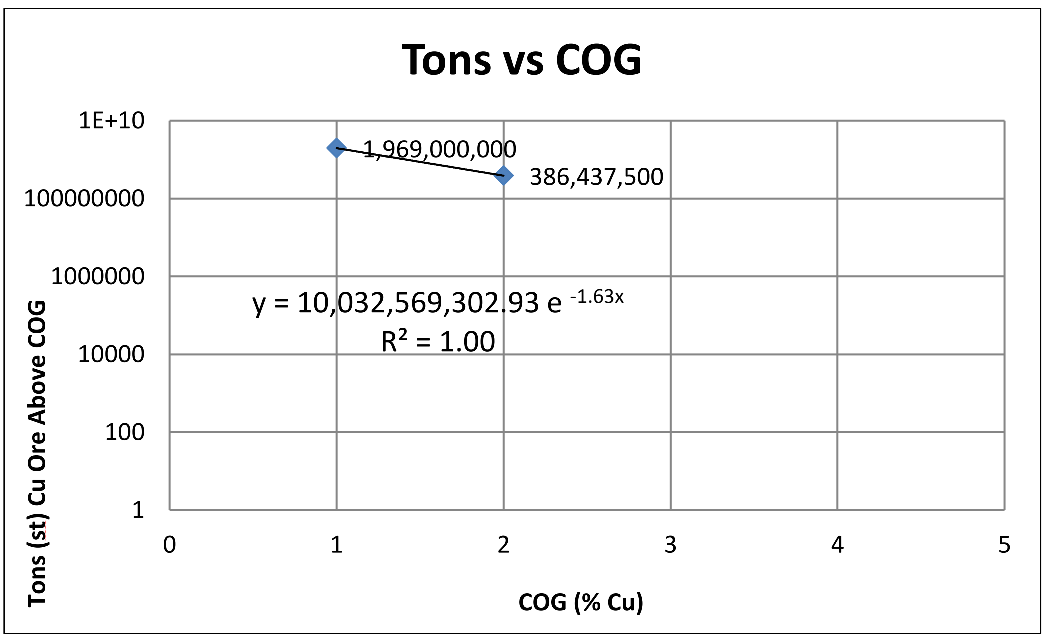

Figure 27. ***Plot of COG vs tonnage for points (1%; 1,969,000,000) and (2%; 386,437,500) for the Resolution copper deposit***[36]

[36] The second point was estimated utilizing the level maps provided by RCM (levels -500 to -2500, in steps of 100 ft) similar to Figure 20. Project Records #0001320 and #0001321.

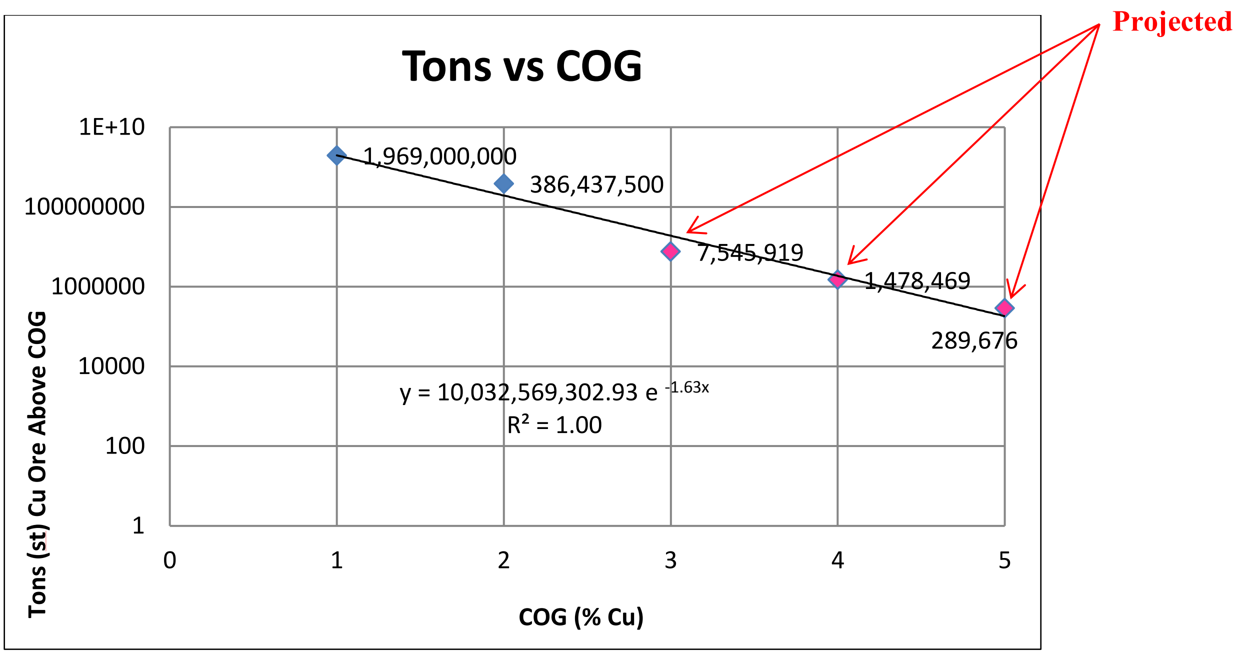

Figure 28. ***Plot of COG vs tonnage for points (1%; 1,969,000,000) and (2%; 386,437,500) for the Resolution copper deposit, plus the extension of the least squares best fit line through 3%, 4% and 5% COG.***

CONCLUSIONS

Block cave mining is by no means new. In the United States, it was used at the Miami Mine (Miami Copper Company, Gila County, AZ), the Climax Mine (Climax Molybdenum, Lake and Summit Counties, CO), Inspiration Mine (Inspiration Consol. Copper Co., Gila County, AZ), Questa Mine (Chevron Mining, Taos County, NM) and others[3]. It is a mass mining method that allows for the bulk mining of large, relatively lower grade, orebodies. This method is increasingly being proposed for a number of deposits worldwide. In general terms block cave mining is characterized by caving and extraction of a massive volume of rock which potentially translates into the formation of a surface depression whose morphology depends on the characteristics of the mining, the rock mass, and the topography of the ground surface.

Block cave mining can be used on any orebody that is sufficiently massive and fractured; a major challenge at the mine design stage is to predict how specific orebodies will cave depending on the various geometry of the undercut.

Other underground stoping mining methods may be substituted for block caving, then backfilled with tailings or a tailings paste mixture, thusly possibly eliminating all or a portion of the subsidence associated with caving. However, this would normally come at a substantial price: higher mining cost and the high cost associated with a tailings batch and pumping plant, resulting in a higher cut-off grade, which in turn results in the loss of block cave mineable resources. As the tons-grade relationship has been shown to be logarithmic[30, 31, 32], substantial low grade material may be lost, and these resources may be lost for good. A stope mining method, however, could allow for more selectivity of mining as only the higher grade material would be selected.

Without data for the copper grade of each block utilized to crate Figures 27 and 28, it is impossible to estimate the amount of actual recoverable copper at a 2% or 3% or other percent cut-off grade. Simply, one cannot estimate the average grade of the potentially mineable material above a given cut-off grade without knowing at least the average grade of the material left after deleting the material below the cut-off grade. This data was not provided by RCM.

In the final analysis, it can be seen from Table 6 and Figure 28 that a substantial amount of potentially mineable resources may be lost by choosing a higher cost mining method over the lower cost bulk method of block caving. The higher operating cost of one of the underground stoping methods results in a raised cutoff grade and, correspondingly, a lowered amount of available mineable material. If maximization of the recovery of the available resource is a priority, this then can be a large problem and can also be unacceptable to whoever owns the resource.