Relationships between Geology, Ore-body Genesis, and Rock Mass Characteristics in Block Caving Mines

by

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Abstract:

As Block Caving Mining becomes a more widely used method of extracting ore from deep, low-grade, weak, disseminated ore-bodies, it becomes important to understand the negative side effects associated with this mining method. One of the greatest side effects of concern is subsidence that results from the removal of material at depth. In order to better understand the processes affecting subsidence it is vital to first get an idea of the geological conditions that influence these subsidence inducing processes. Therefore it is the aim of this paper to shed some light on the various geological environments in which block caving is used to help single out the most important geological features, with respect to subsidence, that exist within each specific mining environment. Examples of important geological features would be ore-body dimensions and depth, the nature of the site specific rock units (ie. sedimentary or volcanic rocks of varying strengths), and the overall structural regime of the host geological environment (folding, faulting, shearing). Relationships that exist between geological characteristics at various mines will also be explored in the hope of finding similarities that can be used to link different mines and their corresponding subsidence responses. This will prove beneficial when attempting to find explanations as to why subsidence occurs in the manner that it does at a specific mine.

Thesis Objective:

To find relationships between geology, ore-body genesis, and rock mass characteristics in mines that employ block caving mining techniques in order to better understand the geological factors that influence subsidence resulting from block caving at depth.

1.0 Introduction:

Currently, there are over 80 mines worldwide that have either used or plan to use block caving mining methods to extract ore from massive, weak, low-grade ore-bodies. Many of these mines were once open pit projects that have eventually transitioned to block caving techniques as open pit techniques became impractical. Open-pit expansion is often not feasible for several reasons, ranging from being to expensive to expand the pit to there being spatial constraints present that would prevent further pit expansion (eg. Palabora). Therefore many companies have decided to explore and implement block caving techniques to increase the productive lifetime of their mine/ore-body in a manner which is as cost-efficient as possible.

As block caving becomes more widely used it becomes important to understand the mechanisms involved within this mining method, along with the impacts that this method has on its surroundings. One major impact of concern is subsidence due to the removal of material at depth. In order for engineers and geologists to better understand the phenomenon of subsidence due to block caving they need not only study the overall engineering mechanics of the mine, but they also need to consider the geological conditions that could impact the failure/caving mechanisms that lead to subsidence. Therefore it is the aim of this paper to find any relationships between geology, ore-body genesis, and rock mass characteristics in existing or past block caving mines to aid in the study of subsidence related problems created by the use of this mass mining technique.

There are two types of subsidence that can result from subsurface block cave mining. The first possible type of subsidence is continuous or trough subsidence, a process that involves the formation of a smooth surface subsidence profile that is free of step changes (Brady and Brown, 2005). This type of subsidence is typically associated with the extraction of thin, horizontal or flat-dipping orebodies that are overlain by weak sedimentary strata (eg. longwall mining of coal). The other type is discontinuous subsidence, characterized by large surface displacements over limited surface areas and the formation of steps or discontinuities in the surface profile (Brady and Brown, 2005).

Discontinuous subsidence can be associated with a number of mining methods, and can occur over a range of scales. It can also develop suddenly or progressively, something that is extremely important when assessing possible side effects created by subsidence (eg. air blasting associated with sudden subsidence). There are several kinds of discontinuous sudsidence, including crown holes, pillar collapse, chimney caving, piping or funnelling. Chimney caving is one of the most common types of discontinuous subsidence that results from block cave mining at depth. It involves the progressive migration of an unsupported mining cavity through the overlying material to the surface (Brady and Brown, 2005). The surface subsidence expression may be of a similar shape and area to the subsurface excavation, or it may differ depending on the structural geology of the overlying material. Chimney caves may form in weak overburden materials (eg. Zambian copperbelt), either in previously caved material or in regularly jointed rock which progressively unravels. Chimney caves have also been known to propagate upwards to the surface through several hundreds of metres of overburden. A more sudden type of chimney caving, known as plug subsidence, has some extremely dangerous side effects that accompany the sudden subsidence. One side effect that has led to fatalities is air blasting, which results from the sudden collapse of a plug or chimney of material. These are the types of subsidence related problems that can hopefully be avoided by completing a more in depth study of the geological characteristics that impact the extent of subsidence that results from block cave mining.

Determining the regional geology around each block caving project is a crucial part of understanding why side effects such as subsidence occur. Specific discontinuities within mine areas near the block caving operation are one way that geology is likely to influence the occurrence of subsidence, whether it be by creating boundaries for crack propagation or as conduits for further material failure (discontinuous subsidence). Discontinuities such as faults and joints also contribute to the fractured and weakened nature of both the ore and the host rocks in the environment surrounding the block caving operation. Other features of the geology that are important to subsidence in block caving mines are the depth of the ore-body below surface level, shape of the ore-body, and dip of the ore-body. All three of these ore-body properties will determine the area to be mined out by block caving, as well as the areas within the vicinity of the ore-body that will be first to cave once an opening has been created. With all this being said, the most important component of the geological setting within the mine has to be the types of host and ore rocks that are present in the subsurface (ie. sedimentary, volcanic, or metamorphic rocks). This is because the given rock type ultimately determines the strength, structural characteristics and rock mass properties of the subsurface environment around the mine, especially in the formations that are more susceptible to failure or caving. Features within specific rock types that influence the competency of the rock would include bedding planes in sedimentary rocks, foliations in metamorphic rocks, and fracture sets in any rock types. Compressive and tensile strength of the rocks and their corresponding rock mass characteristics will also impact their propensity for failure in and around an opening at depth, not to mention that the extent of alteration within host rocks will impact their individual rock mass properties. Therefore it is important to search for any geological similarities between different mines, as by searching for similarities/connections between mines and their individual subsidence profiles it may be possible to gather valuable information that can be used in the planning or prevention stages of future block caving mining projects.

To better understand the mining method being discussed in this paper a brief description of the process will be given. Block Caving is defined as a ‘distinct caving method applied mostly to large, massive ore bodies because of its inherent low cost and high production capabilities’ (Ratan and Ratan, 2005). It is carried out by undercutting large areas of a low-grade ore-body so that it can naturally cave into the underground mine. The caved material is then removed by collecting it at drawpoints so that the ore can be taken for processing. As the ore is continually removed the overlying material will continue to cave into the cut until all of the overlying material has caved in. Because many of these ore-bodies are located at great depths this continual caving is likely to cause overlying material to subside as the entire rock mass fails into the mine opening. From this definition of block cave mining it becomes evident that the rock masses associated with block caving mines are extremely weak and readily broken down. The reasons as to why the rock mass is weak will be explored in more depth along with the geological conditions which create the corresponding weak rock conditions.

2.0 Distribution of Past, Present and Future Block Caving Mines:

Block cave mines are located throughout the world in vastly differing geological settings to extract various mineral commodities (copper, gold, asbestos, diamonds, iron, cement and molybdenum). Each of these specific mineral commodities can be classified in terms of the ore-body generating processes that led to their mineralization. The major orebody genesis processes that have led to the creation of ore-bodies that can be mined using block caving techniques include kimberlite pipes (Type I and II), skarn deposits, porphyry deposits (molybdenum, copper, gold), asbestos deposits in peridotitic rock, iron ore deposits, and stratified sedimentary horizons of either Sedimentary Exhalative (SEDEX) or Volcanogenic Massive Sulphide (VMS) origin (Table 1).

Porphyry Deposits			
Chile:	*Arizona and New Mexico:*	*Phillipines:*	*Others:*
Chuquicamata	Lakeshore	Didipio	Palabora
El Salvador	Bagdad	Padcal	Oyu Tolgoi
Rio Blanco	Johnson Camp	Philex	Resolution
El Teniente	Miami	Santo Thomas	Tongkuangyu
	Inspiration	Lutopan	Craigmont
	Ray		Bingham Canyon
	San Manuel		Emma Nevada
Molybdenum:	*Australia:*		
Climax	Cadia East		
Henderson	Northparkes		
Questa	Mt Lyell		
Urad	Ridgeway		

Kimberlite Deposits			
Southern Africa:		*Canada:*	*Australia:*
Kimberley	Finsch	Ekati	Argyle
De Beers	Venetia		
Bultfontein	Koffiefontein		
Cullinan (Premier)	Jwaneng (Debswana)		

Skarn and Porphyry Related Deposits		
Ertsberg East Skarn System:	*Canada:*	*Japan:*
DOM Block A	Gaspe	Kamioka
DOZ (Deep Ore Zone)		
Ertsberg East		
Grasberg (Papua)		

Asbestos Mines			
Southern Quebec:		*Southern Africa:*	
Asbestos Corp Blk 20		Havelock Asbestos	
Johnson	King	KingSection, Gaths Mine	
Bell	King-Beaver	Shabani	
Johnson	Thetford		

Iron Ore Deposits			
United States:	*Sweden:*	*China:*	
Cornwall	Kirunavaara	Haolaigou	
Grace			
Mather			
Sunrise			

SEDEX, VMS and Stratiform Deposits:			
Canada:	*Zambian Copperbelt:*	*Australia:*	*United States:*
Creighton	Nchanga	Mt Isa Copper	Bunker Hill
Errington	Nkana		
Granduc (BC)		*India:*	
Stobie		Rajpura Dariba	

Other Deposits			
Australia:	*Bolivia:*	*United States:*	
Big Bell	Bolivian	Crestmore	
Mt Keith	Cangalli		
Perseverance			

Table 1. Distribution of Block Caving Mines by Deposit Type

It will be revealed later on that the ore-body generating processes are tremendously important to the subsidence that results from block caving. Also to be explored in the sections to come is that each ore deposit type tends to form within specific geographic regions of the world under unique geological settings. Examples of this would be the fact that kimberlite pipes form in old Archean rock, while porphyry deposits and skarn deposits form in younger convergent zones throughout the globe. An in depth look into each type of deposit and its associated mines will be completed to see if any patterns emerge that can explain why subsidence occurs in the manner that it does at certain mines.

3.0 Porphyry Deposits:

Porphyry deposits are defined as large, low- to medium-grade deposits in which primary (hypogene) ore minerals are structurally controlled, in addition to spatially and genetically related to, felsic to intermediate porphyritic intrusions (Kirkham, 1972). These kinds of porphry deposits occur throughout the world in a series of extensive, relatively narrow, linear metallogenic provinces (Fig.1: Sinclair, 2007).

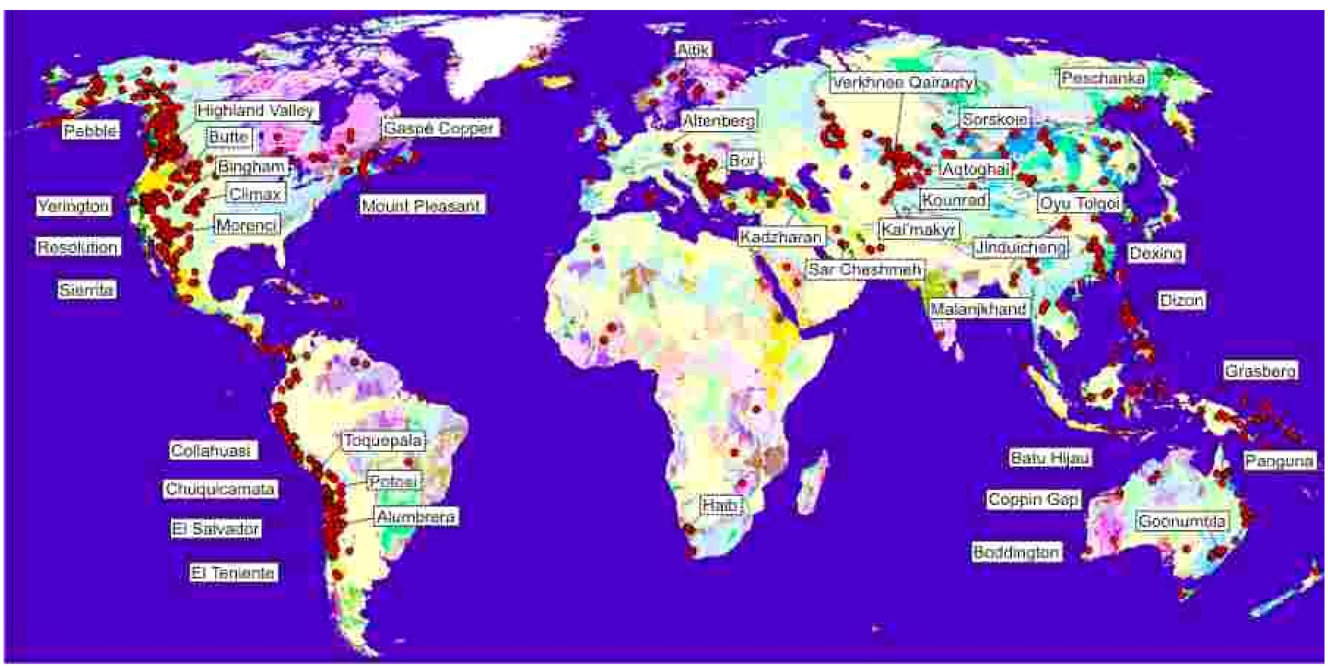


Figure 1. Distribution of Porphyry Deposits throughout the World

These metallogenic provinces can occur in several different geological settings, whether it be in sedimentary sequences like in New Mexico and Arizona, or in igneous sequences in areas like the Phillipines and the Andes of Chile. Of the over 80 mines that have used, are currently using, or plan to use block caving techniques, over half can be classified as porphyry deposits. The majority of these porphyry deposits tend to use block caving to mine world class copper and molybdenum deposits, with another few containing mineable reserves of gold, tin, and silver on top of the copper or molybdenum.

The type of host rock that the deposit occurs within is extremely important when attempting to understand the mechanisms associated with subsidence in porphyry related block caving mines. This is because host rock type plays a major role in the possible discontinuous propagation of subsidence related to cracks/fractures in and around areas mined by block caving at depth. Metamorphism of host rock due to the emplacement of these porphyritic intrusions, or just metamorphism of the host rock on a regional scale is also influential to the ultimate subsidence that can occur around a block caving operation. In the following sections the geological environment of each different type of porphyry deposit will be examined in more detail to determine the most important geological features that exist within each mine complex and if there are any discernable relationships between mines in different parts of the world.

3.1 Copper Porphyry Deposits:

There are over twenty mines in the world that have chosen to use block caving mining methods to mine copper from a large copper-porphry deposit. The subsequent sections will provide information on each of these major copper porphyry provinces.

3.1.1 Chilean Copper Porphyry Region:

One geographical region that hosts several large copper porphyry deposits is the Andean Cordillera in Northern Chile.

Figure 2. Map of the Chilean Copper Mines

Of the four major mines located in this region all can be classified as giant porphyry complexes. These four mines listed from north to south are Chuquicamata, El Salvador, Rio Blanco, and El Teniente (Fig. 2). The host rocks at each of the four mines include some form of mine andesite, whether they are described simply as mine andesites (El Teniente or Rio Blanco), or cretaceous andesitic flows (El Salvador; Figure 3). These andesitic host rocks can have considerable strength, however in these four mines the andesites have been highly altered and fractured. Examples of the alteration style would be the pervasive biotite alteration at El Teniente, which creates rock with weak cleavage planes along which the entire rock mass can fail (Cannell et al., 2005).

In other mines such as El Salvador the alteration is so great that it is impossible to differentiate between igneous and clastic rock units, thus leading to all of the host rock within the area simply being known as an 'andesite' (Gustafson and Hunt, 1975). There are also a few sedimentary rock sequences in this region, for example at El Salvador, where there are andesitic conglomerates and sandstones that are overlain unconformably by Lower Tertiary Volcanics (Gustafson and Hunt, 1975). Other weak rock units in and around the mines include a 400m thick layer of siliceous ignimbrites over the El Salvador ore-body. In each of the mines one can also find breccias that are either intercalated with andesitic flows, or merely occurring as rock units created by hydrothermal alteration.

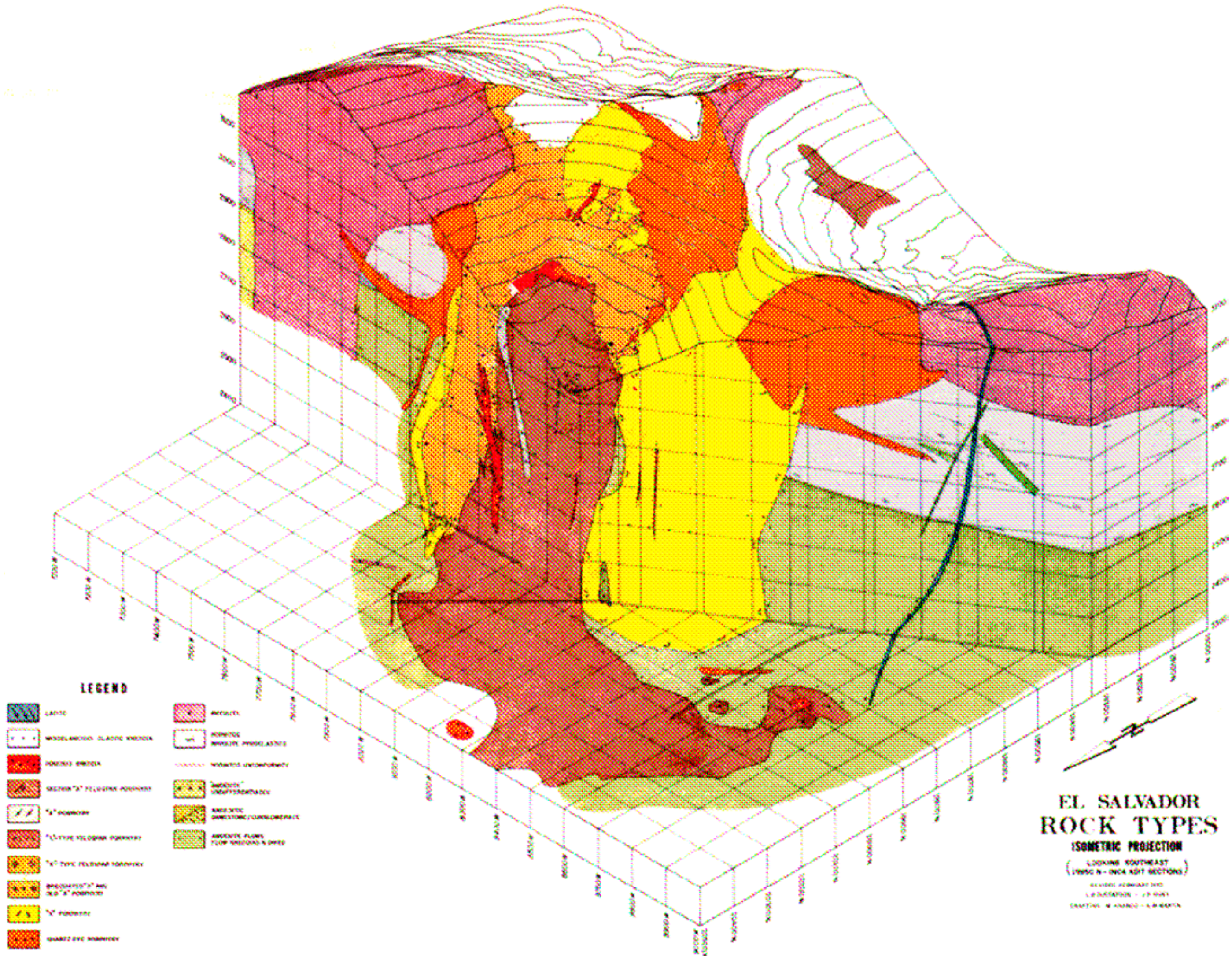


Figure 3. Geology of El Salvador Mine

The structural geology at each mine is also very important, as bedding planes, fracture orientations, and faults within the region impact the surface expression that subsidence creates. The fact that each of these mines has also been mined by open pit techniques prior to commencing underground block caving operations is important when assessing the possible extent of expected surface subsidence in the vicinity of the mine. In the El Teniente Esmeralda ore-body there are five predominant structural joint sets which contribute to rock fracturing. All of these joint sets lead to decreased rock mass quality and strength, making it vulnerable to caving and subsequent subsidence. The affect that jointing and fracturing has on other ore-bodies within this region such as the Rio Blanco mine are emphasized by the medium to poor rock quality of the host andesites and granodiorites which have RQD values of less than 25% (Warnaars et al., 1985). Also impacting possible subsidence is the shape and dip of the ore-body, as this is the material that will be removed by block caving. Each of the ore-bodies in this region have irregular shapes, such as the kidney shaped ore-body at El Teniente, which means that the surface at each of the mines is likely to show irregularly shaped expressions created by subsidence. This is not always the case however, as will be seen later in the section on Kimberlite pipes.

One last thing affecting the extent of subsidence above these block caving mines is the dip of the adjacent host rocks. This is simply because any failed rock will tend to follow the bedding planes or fracture surfaces which are already pre-existent within the mine area. One last feature of these mines that needs mentioning is the fact that there is little difference between the ore-body rock and host rocks (both being igneous rocks), which could lead to a larger subsidence surface profile, as subsidence would not be restricted to the surface area covered by weaker rock as it is in kimberlites. Now that the major geological features of the copper porphyry mines in Chile have been examined the next step is to do the same for copper porphyries in other regions of the world to see if they are impacted by similar features or by features that are geologically specific to that region.

3.1.2 Arizona and New Mexico Copper Porphyry Province:

Another region that has several large mines that use block cave mining methods to extract copper ore from porphyry deposits extends across Arizona and New Mexico. This region is important for studying how geology relates to subsidence as each of these seven copper porphyry deposits have been emplaced into sedimentary or metamorphic host rock sequences. These sedimentary host rocks are vital to the surface expression of subsidence that results from mining at depth as they contain several key failure impacting geological features. These features include, but are not limited to: rock mass strength, orientation of bedding planes, existence of fracturing and faulting, and alteration caused by the intrusion of the ore-bearing porphyritic bodies. The seven mines, shown on the following map, are Lakeshore, Bagdad, Johnson Camp, Miami, Inspiration, Ray, and San Manuel. The rest of this section will be dedicated to taking a more in depth look into the specific geological features that are critical to the type of surface expression caused by subsidence in these mines.

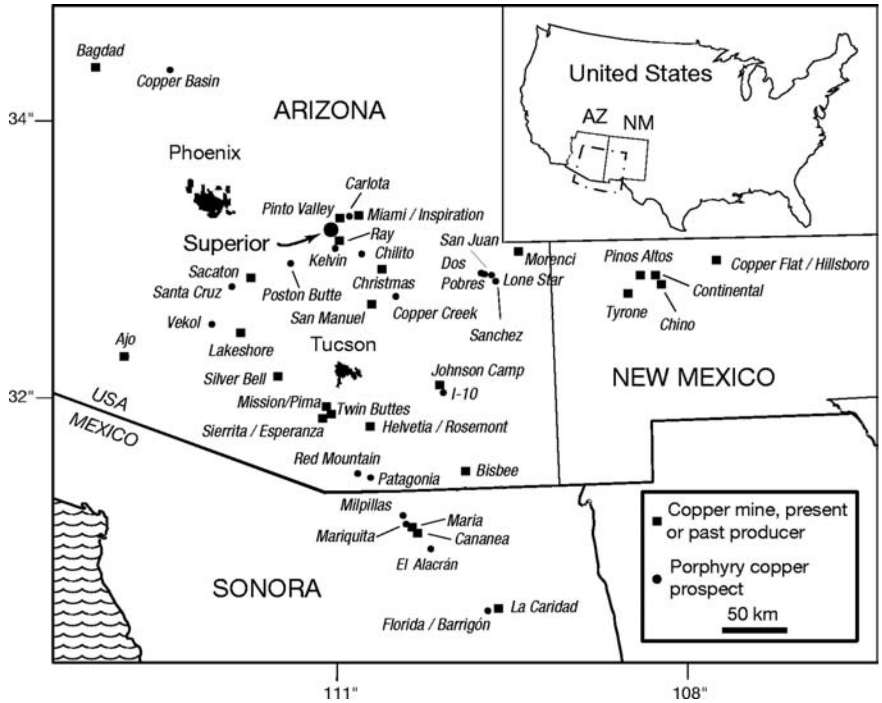


Figure 4. Location of Porphyry Copper Mines in Arizona and New Mexico

One very important rock unit that can be found in the vicinity of many of these mines is the Gila Conglomerate. This rock unit is extremely important as it makes up the capping rock for several of the deposits (Miami, Inspiration, Bagdad, San Manuel). In some mines such as San Manuel the Gila Conglomerate can be up to 1000 feet thick, which is substantial when considering how large of an impact capping material can have on subsidence. In regions where block caving is prevalent it is likely that these Conglomerate rocks are highly fractured, altered, weathered, or a combination of all three. The San Manuel mine is a very good example of how great an impact the Gila Conglomerate and its subsequent fracture intensity can have on the extent of subsidence that results from removing material at depth. This particular mine also illustrates the overall effect that intersecting low-angle and high-angle faults can have on surface subsidence, as such a fault regime has led to a high amount of subsidence. Ulitmately intense fracturing and faulting of host rocks in this region is a major reason why these ore-bodies are suited for block caving, and why a significant degree of subsidence can be expected.

Many of the mines in this region are also located within schistose rock units, varying from Pinal Schists at several of the mines to silicified or kaolinized schist at just a few. The foliations within these schistose units can become planes of weakness, especially in cases where the schist has been altered to sericite, kaolinite or clay along the foliations. It has been proven again and again within the rock in this area that where sericite is present the rock is extremely weak, to the point where it breaks readily. This problem of sericite weakening the rocks is only further amplified in mines like San Manuel where the structural integrity of certain sedimentary units such as the conglomerate have been weakened by poorly bedded contacts at bedding planes that separate local intercalated tuffs with the surrounding rock (Wilson, 1957). Since foliations, bedding planes, and fractures can act as planes of weakness, the dips and orientations of these structural features are important to the magnitude of subsidence and piping in the area. One final thing to consider when assessing the possible extent of subsidence are the geological barriers surrounding the mine in the form of major faults or shear zones. In mines like Inspiration not only is the ore-body restricted by major regional faults, but the boundaries of surface subsidence will also be dictated by these faults. This also rings true in the San Manuel and Lakeshore mining areas as both are cut by major faults (the low-angle reverse fault at San Manuel and the normal fault at Lakeshore (Cook, 1988)). One thing that is similar between the mines in this region and in Chile is that the actual ore-bodies take on quite irregular shapes, something that is rather consistent throughout all porphyry deposits. These are the many important geological factors that will dictate the extent of surficial subsidence in and around the mines in this copper porphyry province that is composed mainly of sedimentary rock sequences, metamorphic rock sequences, and igneous bedded flow sequences.

3.1.3 Phillipine Porphyry Deposits:

The Phillipines is another region that hosts several porphyry based block caving operations. The porphyry deposits in this area contain several different types of economic metals ranging from gold, to silver, to copper. These deposits are part of an island arc convergent setting where several porphyry and other such deposits have formed due to convergent tectonic activity. The five mines that use block caving techniques in the Phillipines are Didipio, Padcal, Philex, Santo Thomas, and Lutopan. For the purposes of this paper just the Didipio mine will be looked at in depth as it has the most available information.

The Didipio mine extracts ore from the Dinkidi gold-copper porphyry in Northern Luzon. The given porphyry has a very complex geology which consists of dioritic and monzonitic intrusions that have invaded volcanic host rocks (Figure 5). The dominant host volcanic rock is a diorite, which has been emplaced by a vertically stretching porphyry complex of monzonitic porphyries and dikes (OceanaGold Corporation, 2008). Mineralization in and around these porphyritic intrusions occur concentrically outwards from the core intrusion depending on the amount of hydrothermal alteration resulting from the invasion of the monzonitic porphyry. As can be seen in the corresponding cross section of this deposit, the ore zone is cut by a large post mineral shear (Figure 5). This shear is no doubt important to the subsidence associated with mining this deposit. The other key geological factors impacting subsidence above this deposit are the extent to which hydrothermal alteration has affected the volcanic rock in close proximity to the ore-body, much like in all of the other mines discussed to this point.

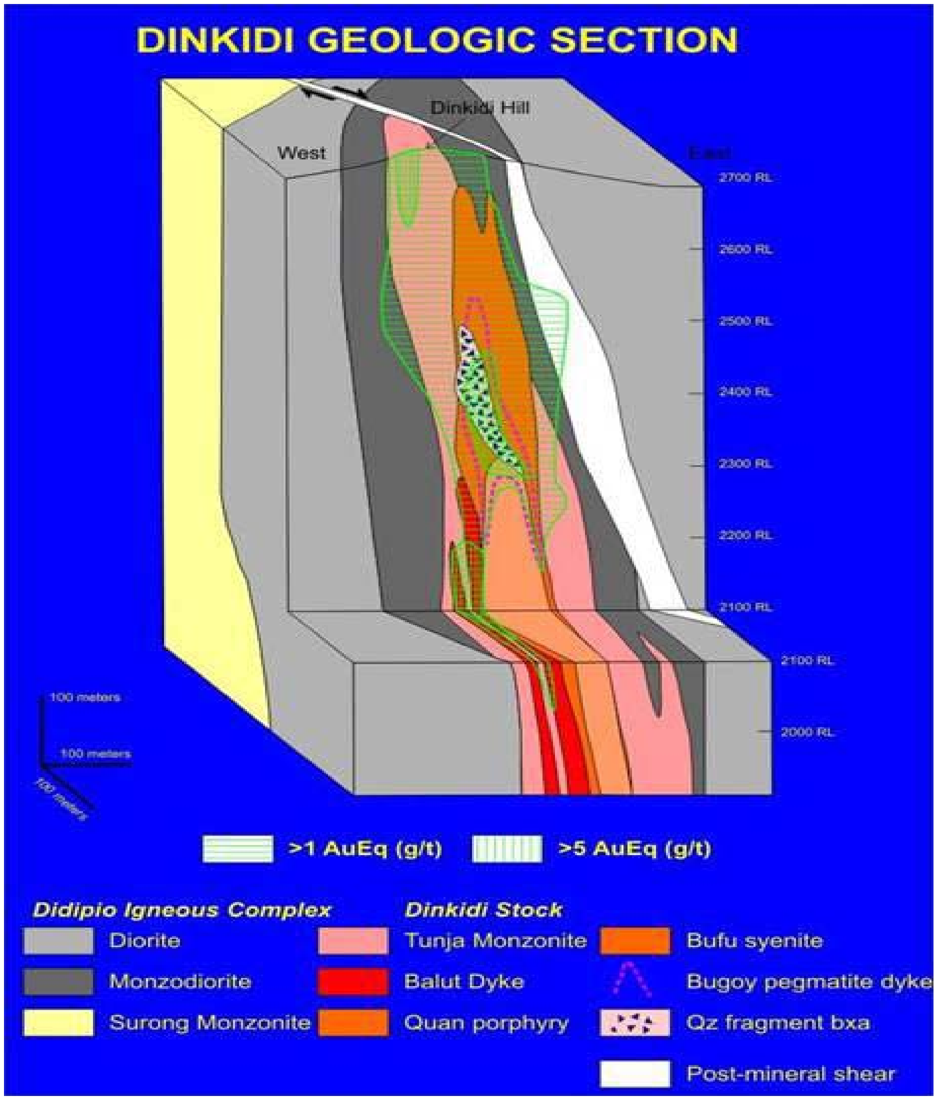


Figure 5. Geological Section of Dinkidi Cu-Au Porphyry

3.1.4 Australian Porphyry Deposits:

There are four copper, and copper-gold porphyry deposits located within Australia that use block cave mining methods to extract ore at depth. There are also two gold mines and two nickel mines in Australia that use block caving techniques, however these deposists are likely to vary in geological composition and setting from the porphyry deposits.

The four porphyry deposits being mined in Australia by block caving are Northparkes, Mt Lyell, Ridgeway, and Cadia East. The Northparkes gold-copper porphyry deposit has formed within a sequence of high-K calc-alkaline volcaniclastic rocks that range from basaltic andesites to trachyte (Arundell, 2004). There is also a thin weak ignimbrite layer higher in the stratigraphy, though this layer is not as important as the previously mentioned volcaniclastic rocks and their associated structural features. One structural feature of the volcaniclastic host rocks that is paramount to their strength and consistency is gypsum veining that has taken place throughout the rock's fractures (House et al., 2001).

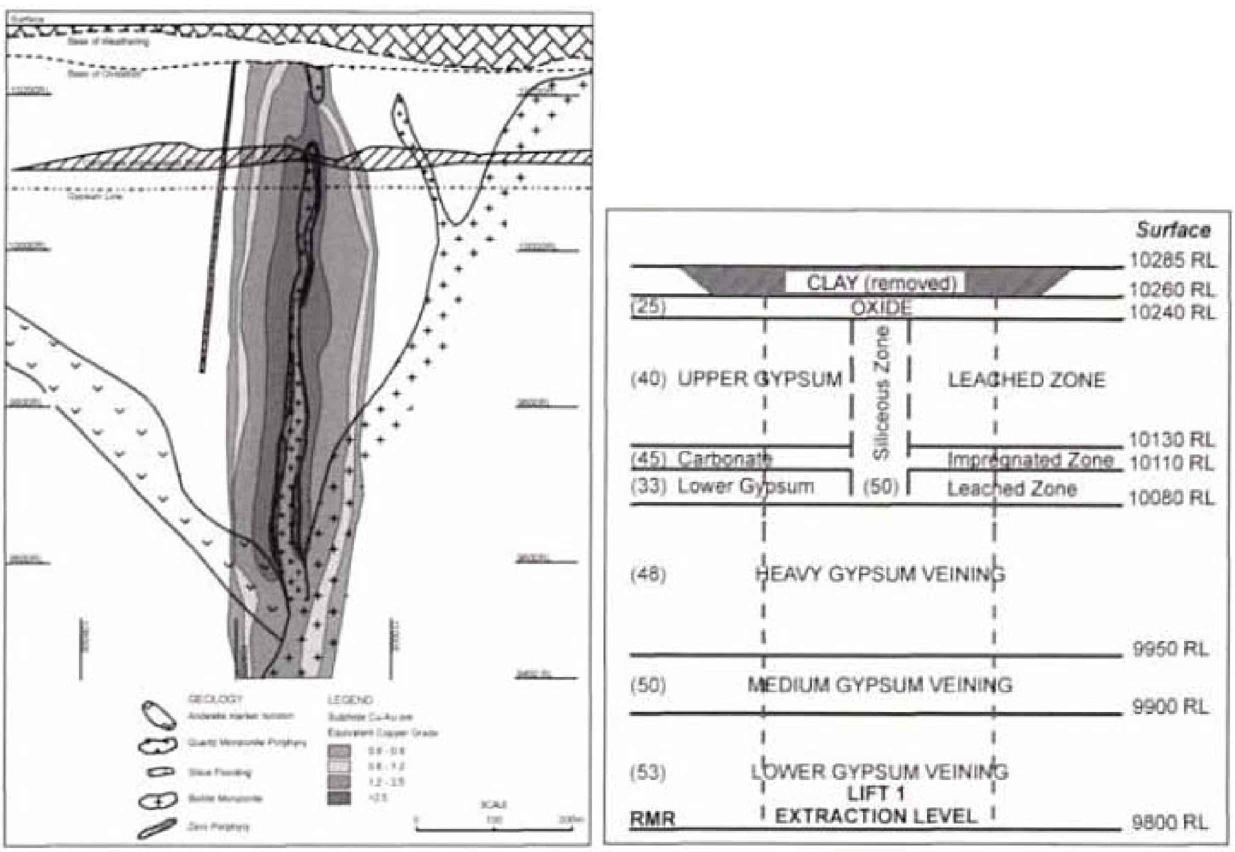


Figure 6. Cross Sections through the Northparkes Cu-Au Porphyry Deposit

This jointing and fracturing has created zones with extremely weak gypsum and calcite filled veins that are likely to break down and cave. The depth of the ore-body and corresponding gypsum vein intensity will affect the extent to which material will cave into the mine opening. This no doubt will impact the kind of surface subsidence occurring at this site.

Cadia East and Ridgeway are two other porphyry deposits being mined by block caving methods in Australia. Both are part of the Cadia mineralized corridor of western Australia. These two deposits can be described as sub-vertical ore zones located within quartz monzonite porphrytic intrusions that have invaded a sequence of Ordovician sediments and volcanics (http://www.newcrest.com.au/operations.asp?category=1). The geological settings of these mines are quite similar to the Arizona and New Mexico porphyries that have intruded sequences of sedimentary and volcanic rocks. However upon further review it is evident that they vary from the Arizona and New Mexico porphyries in terms of their site specific structural geological conditions (faulting, ore depth, ore shape).

Mt. Lyell is the final Australian porphyry. It, like the other Australian porphyry deposits, has formed within a geological environment that is different from any of the other deposits. At Mt. Lyell the porphyry deposit has invaded a complex sequence of silicic volcanic rocks up to 800 m thick that includes laterally impersistent lavas, ash-flow and ash-fall deposits, and abundant open-framework volcanic mass-flow breccias (Cox, 1981). Therefore subsidence occurring at this mine due to block caving will be controlled by the nature of these volcanic sequences rather than sedimentary sequences or gypsum-faulted volcaniclastic rocks like at the other Australian mines.

3.1.5 Other Worldwide Porphyry Deposits:

There are several other copper porphyry deposits located worldwide that use block cave mining methods that cannot be placed within any of the groups previously discussed. Major deposits include Palabora in South Africa, Oyu Tolgoi in Mongolia, Tongkuangyu in China, Craigmont in Canada, and the Bingham Canyon, Emma Nevada, and Resolution mines in the USA.

Palabora is one of the better known mines in the world to switch to block caving methods once the open pit had reached the end of its profitable life-time. The main host rock units within this mine are transgressive and banded carbonatites that have been steeply cut by several barren dolerite dykes (Fig. 7). The occurrence of dikes within the ore rock has led to a rock mass that is highly jointed and fractured. Along with these dikes, there are also some faults and shears that cross-cut the ore deposit. These faults and shears are important as they can create failure planes along which the ore and host rock can fail. Other rock units within the vicinity of this mine include granitic gneisses that formed prior to the creation of the carbonatite pipe deposit (Calder et al., 2001). These units have the potential to affect subsidence in the mine area if the edges of the open pit mine start to expand outwards to the point where they reach the gneisses.

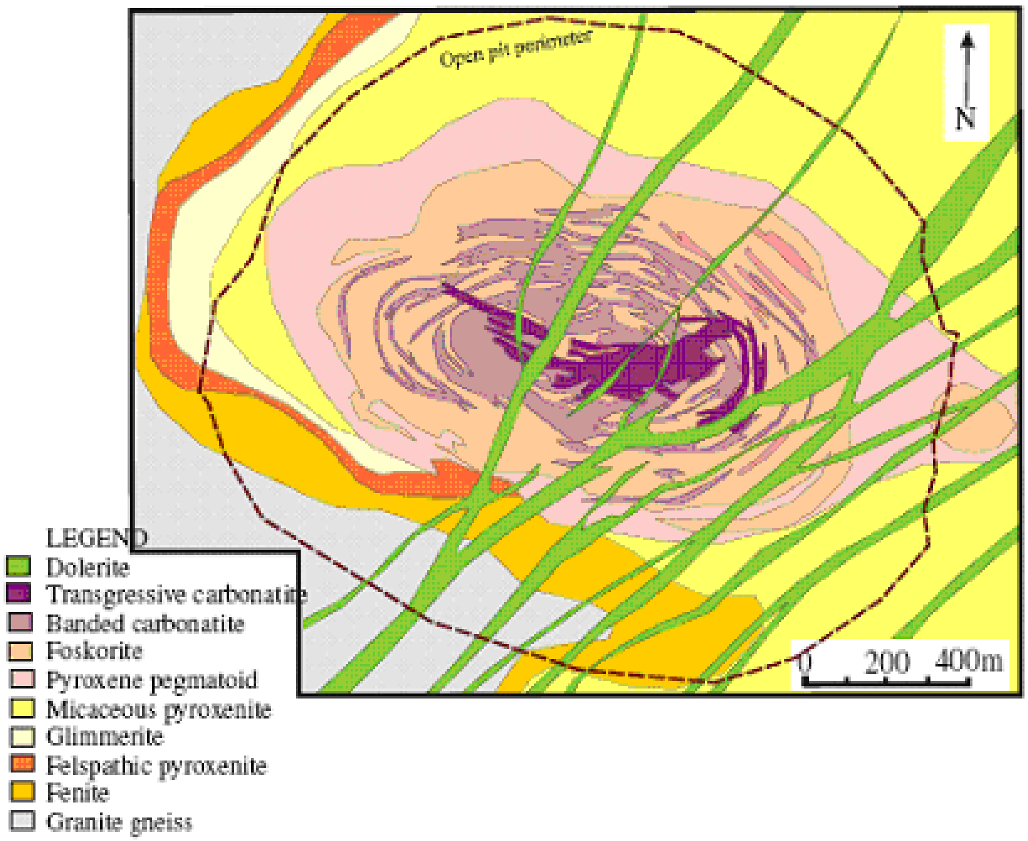


Figure 7. Geologic map of the Loolekop Carbonatite Pipe (Palabora)

It is important that expansion of the surface subsidence expression does not occur at this mine because mine facilities and infrastructure have been developed right up to the edges of the open pit. Therefore it is essential that all of the factors affecting possible subsidence around this mine, including its geology, be understood so that future problems related to expansion of the open pit either by slope failures or subsidence can be prevented.

Oyu Tolgoi in Mongolia is a large copper-porphyry deposit in the early stages of becoming a block caving operation. The group of deposits at this mine are similar in many ways to those located within Arizona and New Mexico in the United States. This is because the deposits occur as a group of quartz monozonite porphyries and post mineralization dikes that have intruded a sequence of basalts, tuffs, and sedimentary rocks (Haines et al., 2007). The post mineralization dikes and porphyritic intrusions at Oyu Tolgoi have created a highly fractured and faulted host rock mass that has very low rock mass ratings of 20-45 (Haines et al., 2007). The specific ore deposits that have had block caving chosen as their primary method of extraction are also located at considerable depth, which combined with the weak rock mass properties makes the overlying host rock even more susceptible to high degrees of subsidence.

Bingham Canyon is another isolated copper porphyry deposit, being located in Utah. The Bingham stock deposits have intruded a sequence of highly folded sedimentary rocks, again similar to the deposits located to the south in Arizona and New Mexico. Rocks in this region are predominantly feldspathic orthoquartzite and calcareous quartzite with interbeds of arenaceous limestone and calcareous sandstone (Lanier et al., 1978). These rocks have also been described as being locally argillaceous, silty, cherty, and fossiliferous. Structurally the area is highly folded and faulted with left-lateral tear faults cutting through the entire region, leading to a very weak rock mass. All of these geological features will affect any subsidence that occurs due to block caving, much like how the geology in the Arizona and New Mexico porphyries affects subsidence.

3.2 Molybdenum Porphyries:

There are currently four world class molybdenum ore deposits that utilize block cave mining techniques to extract ore. All four of these deposits are located in the mid-western United States and can be classified as Climax-type molybdenum deposits. Two of the ore bodies, Henderson and Urad, are located within the same geological complex in Colorado. Henderson is a prime example of the how block caving techniques can be used to process large quantities of highly disseminated ore, and how this extraction of ore by block caving can affect the surface profile above. Other Climax-type molybdenum deposits to be discussed include the Climax Molybdenum Mine in Colorado, and Questa Mine in New Mexico.

Both the Urad and Henderson ore bodies are located within the same porphyry system that intruded the local 1.4 Ga Silver Plume biotite-muscovite granite. The Urad ore body is near surface and related to the Red Mountain Porphyry intrusion, while the Henderson ore body is located entirely within the Urad Porphyry around 1050 m below surface level (Fig. 8: Shannon et al., 2004). The Henderson ore-body, which is shaped like an inverted bowl (Figs. 8 and 9), consists of stockworks of molybdenite-bearing quartz veins at the apex of a sequence of highly evolved silica-rich, subalkaline leucorhyolite/leucogranite porphyries (Shannon et al., 2004).

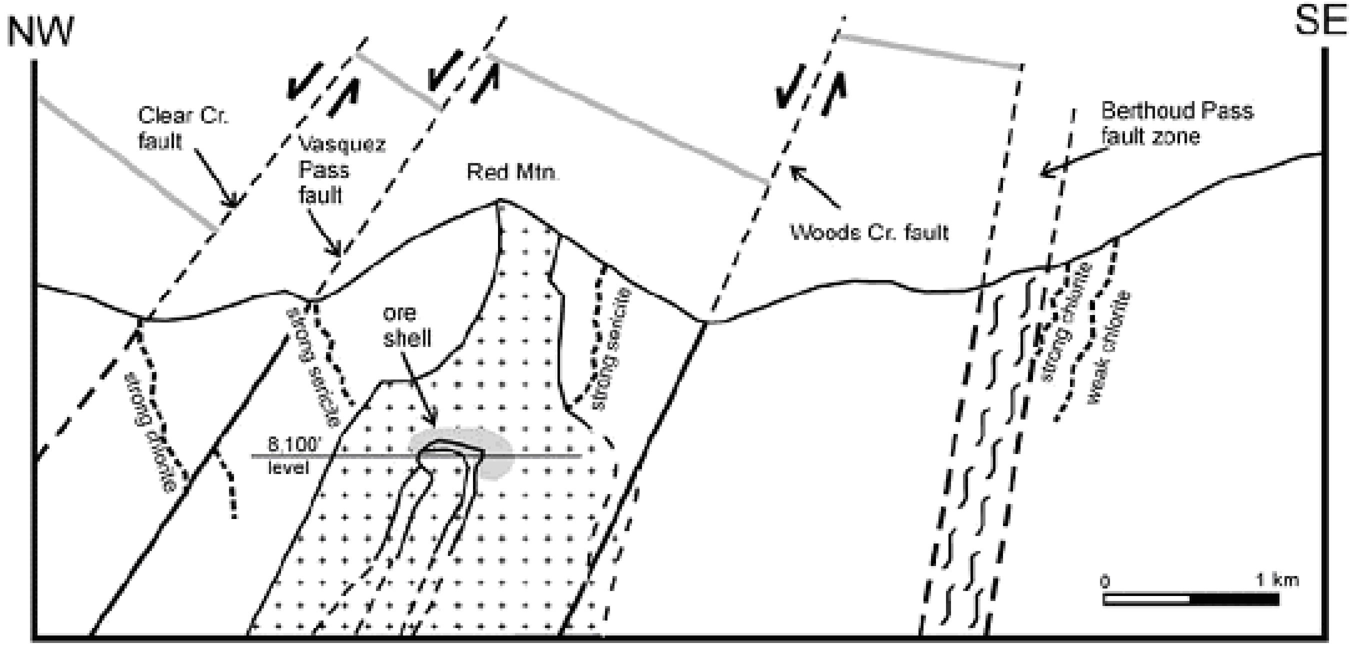


Figure 8. Cross Section through the Henderson Ore Deposit Region

The molybdenite within the ore-body is structurally controlled by the "main fissure" and subsidiary structures in the Tungsten Slide Complex pictured above. This entire system is controlled by several shear zones and faults, with the faults dipping at an angle of 65° as can be seen in Fig. 8. The faulting and tilting of rock units here is because the deposit was emplaced in Precambrian country rock that is located within a mile of two converging major fault zones. The ore-body rock at Henderson is also extremely weak, having an RQD average of 49 and RMR values that range from 27 to 60 (Rech et al, 2001). All three of these factors combined (irregular shape, consistent regional faulting, and weak ore-body rock) will likely create a subsidence profile that is irregular in shape and possibly asymmetrical in the direction of the regional faults.

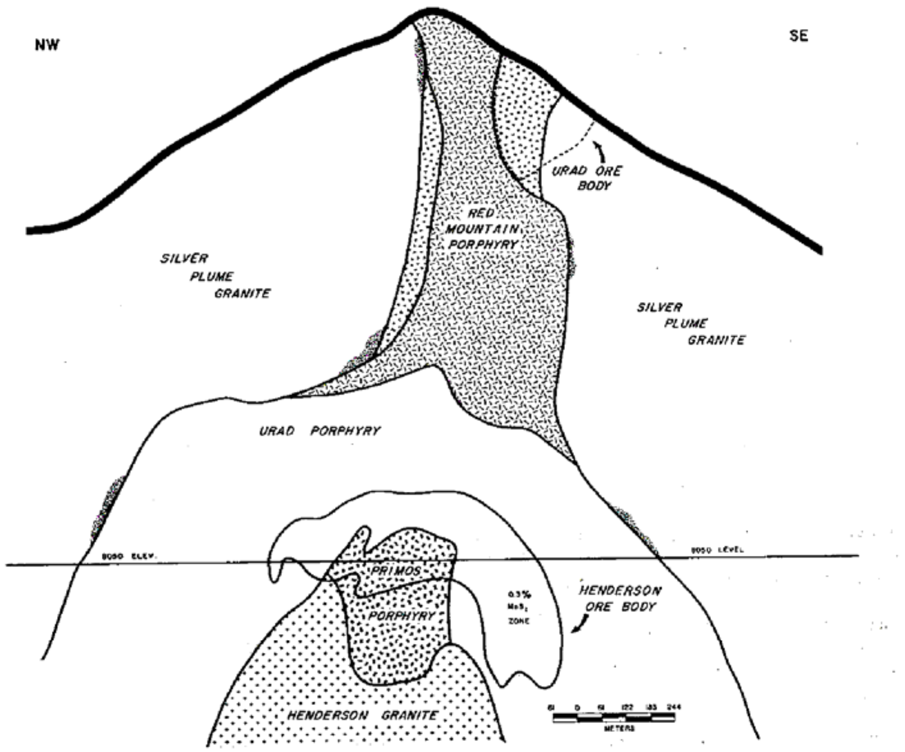


Figure 5. Geologic section of Red Mountain.

Figure 9. Geological section of the Henderson and Urad Porphyry ore-bodies

The Climax Molybdenum Mine has been extracting molybdenum bearing ore from an intensely fractured ore-body via block caving mining methods since 1919. Like the Henderson and Urad deposits the ore deposit at Climax has been emplaced in Precambrian granite. These host Precambrian granitic rocks contain schist inclusions with foliations that can act as planes of weakness for cracks and fractures to propagate along (Bucky, 1945). In areas where the rock mass is already highly fractured and weak such as at Climax, these types of foliations are extremely important. The host rock granite is also cut by several sericitic filled fractures and tertiary dikes, both of which will create even more planes of weakness in the rock mass (Bucky, 1945). Once it is known that the rock is likely to fail along these fractures and foliations it is important to understand the structural geology of the ore-body and host rocks. The fact that the ore-body dips at near vertical angles (90°) could potentially mean that any subsidence extending beyond the edges of the elliptical ore-body would have to have followed fractures in the cap rock, not the orientation of the rock units.

The final molybdenum deposit to use block caving is Questa. Once again the major host rock unit of andesitic and rhyolitic igneous rocks has been intruded by granitic plutons. The Precambrian rock within this region has been highly metamorphosed, which means that just like in previously discussed mines with foliated metamorphic sequences, foliations within this rock are likely to impact the outcome of surface subsidence. The ore deposit is also overlain by andesitic flows and tuffs known as the Latir volcanics (Ross et al., 2002). Fracturing at Questa due to what is believed to be an extensional rift environment, combined with alteration extending outwards from the emplaced metal-bearing plumes, has created a weak rock mass that is unlikely to avoid subsidence.

All of the information provided on the several different types of porphyry deposits illustrates the diverse nature of these deposits, and that geological settings vary greatly from region to region whether they be highly fractured volcanic and volcanoclastic rocks in the Andes of Chile, to thick sequences of sedimentary and volcanic deposits in the southern United States. There is however one factor that all porphyry deposits have in common: the fact that they have all formed within active tectonic margins, whether it be island arc convergent margins in the Phillipines or rift extensional margins in the United States (Climx-molybdenum type deposits). The next step in searching for relationships between ore-body genesis, geology, and subsidence in block caving mines is to look at deposits that have formed via alternative ore-body genesis processes.

4.0 Skarn and Related Porphyry Deposits:

Skarn deposits are typically associated with other types of deposits such as porphyries, where the intrusion of an igneous plutonic rock mass has altered the surrounding host rock. Such is the case in regions like Indonesia where a large skarn system, the Ertsberg East Skarn System, is located in close proximity to the massive Grasberg, Papua deposit. In the following sections the geological characteristics of skarn deposits and their related porphyry deposits will be looked at in more depth to identify the geological characteristics of these deposits that play a major role in surface subsidence.

4.1 Ertsberg East Skarn System:

There are three mine sites located within the Ertsburg East Skarn System (EESS) that employ block cave mining techniques. These three mines: Ertsberg East, Dom (Block A) and DOZ (Deep Ore Zone), are located within the Irian Jaya province of Indonesia. This skarn system (EESS) is very important in terms of block caving mining as it is contains several ore-bodies with large quantities of extractable copper and gold. In terms of geology the system is hosted by Tertiary-age carbonates (early Eocene dolomitic basal units of the New Guinea Limestone) that have been altered to calcium-magnesium silicate skarn (Barber et al, 2001). Both the Ertsberg East and Dom deposits are located along the contact between this limestone unit and an intrusive diorite unit. The hanging wall contact in this deposit is a skarn reaction front that is in sudden contact with barren marble (Barber et al., 2001). Coinciding with this hanging wall contact is a zone of localized faulting and brecciation leading to an extremely weakened rock mass. The footwall alternatively is bounded by the previously mentioned diorite intrusive, a unit that is related to the creation of the overall skarn system.

Figure 10 shows a geological section through the mine area, illustrating the orientation and angle of rock contacts, as well as the depths to which the specific rock units extend. From the cross section one can see that the cave front for the rock units extends into the skarn unit in the SE and into the Marble and Dolomite in the NE. There is also a large crackline extending up from the DOZ ore zone into the marble in the NE, which has the potential to act as a plane of weakness for failure. One last thing that needs mentioning is that the creation of this skarn was accompanied by heavy alteration of the host rock in contact with the intrusion. This means that the dolomitic and marble rock units near the skarn will have been altered and weakened to the point where they are more likely to cave than maybe a typical unaltered dolomite or marble would.

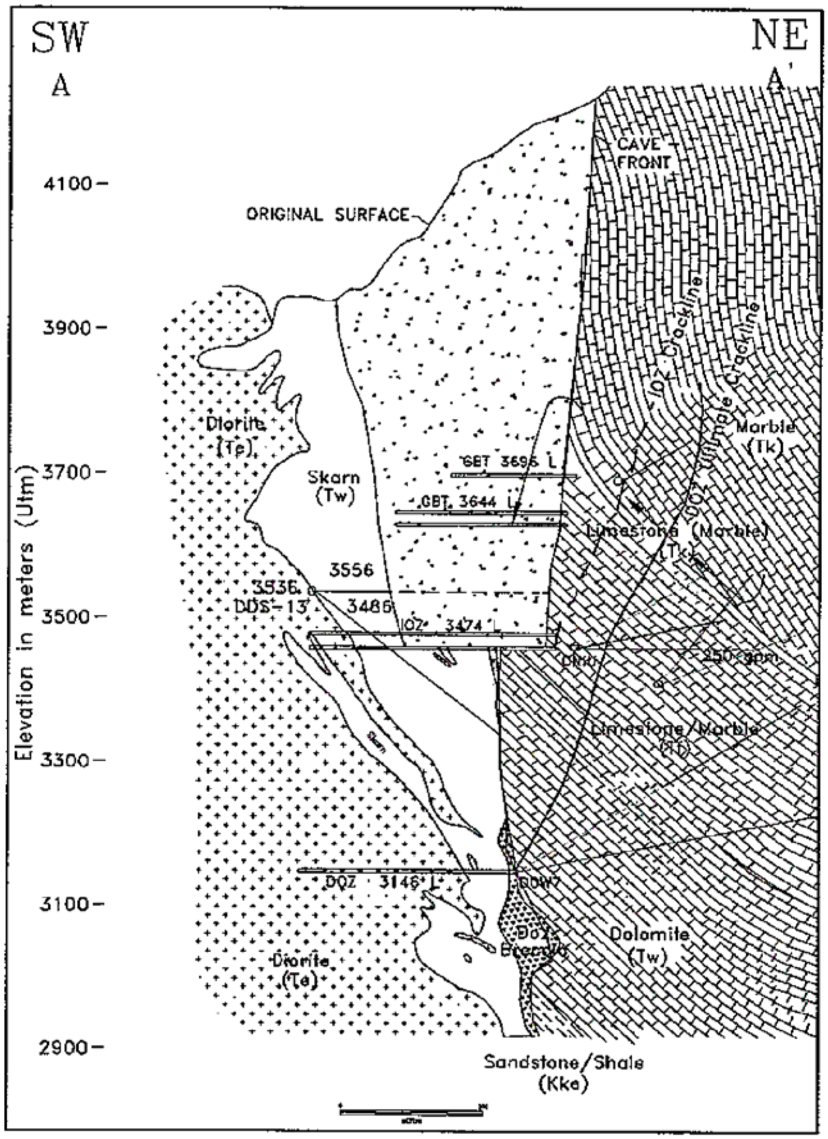


Figure 10. Geological Section through the EESS

The massive Grasberg (Papua) porphyry deposit which is also located within this region formed within the porphyritic intrusion rather than in a skarn created by the intrusion. Therefore the host rocks for this deposit are the same tightly folded carbonates as those that surround the skarn deposits of the EESS. The mineralization at Grasberg occurs from 4200 m elevation to 2700 m elevation as an intensely developed quartz-magnetite dilational stockwork (Pollard et al., 2005). This is where this deposit differs from the skarns in the same region.

From the geology at this mine one can infer that the depth at which ore is mined and the orientation of the carbonate folds will be the major determinants in the type of surface subsidence that results. This is also true for the skarns, though with the skarns the degree to which alteration extends into the host rock from the edge of the skarn will heavily impact the extent of subsidence.

4.2 Mines Gaspe, Quebec:

Another region within the world that mines mineral deposits from a porphyry-skarn system is in Gaspe, Quebec. The Gaspe mine complex was created by the intrusion of several rhyodacite dikes, sills, and plugs into calcareous Lower Devonian sedimentary strata (Allcock, 1982). According to Allcock this calcareous sedimentary strata is also composed of siliceous siltstones and limestones that have been hydrothermally altered and metamorphosed in the near vicinity of the igneous intrusions. The hydrothermally altered calcareous units are where skarn mineralization has occurred, the same as in Ertsberg East. The main difference between the two hydrothermally altered calcareous units at Gaspe and Ertsberg East is that some of the rocks at Gaspe have been metamorphosed. Therefore metamorphic structural features such as foliations will be one more important geological feature that must be taken into consideration at Gaspe. Finally it must be emphasized that the nature of the depositional environment (ie. synclines and anticlines in the Mines Gaspe region with fold limbs that dip at angles up to 30°) is extremely important to the type and extent of subsidence that results from block caving at depth.

4.3 Kamioka Mine, Japan:

Another skarn based ore deposit is the Kamioka lead-zinc mine located in the Hida Gneiss region of Japan. According to both Shimazaki and Kusakabe (1990) and Hashimoto (1990), the ore-body here formed as a contact metasomatic ore deposit. It was accompanied by the skarnization of lime-silicate gneisses due to the intrusion of Cretaceous granite porphyries and quartz porphyries. The Kamioka Zn-Pb deposits consist of clinopyroxene-rich skarns replacing limestone lenses in Hida gneiss rocks. The known igneous rocks in the mining area are Paleozoic metabasite, early Jurassic Funatsu granitic rocks and late Cretaceous porphyritic dikes and stocks. The contact metamorphism that has shaped the host rocks surrounding the ore zone will possess local foliations that can factor into any subsidence that occurs as a result of the block caving. This type of contact metamorphism of limestones adjacent to the ore zone is very similar to that of the Mines Gaspe region. Therefore like at Mines Gaspe the orientation of these foliations, along with the shape and depth of the ore-body, will be the key determinants in the extent of subsidence that occurs around the Kamioka deposit.

A conclusion that can be drawn concerning all of the various skarn deposits is that the ore-bearing skarn rock tends to be much weaker than the surrounding host rocks that have not gone through the same amount of hydrothermal alteration. Therefore the ore-body rock in these mines are likely to play a much more significant role in the amount of subsidence that results from the removal of ore than it may in other deposits like the porphyries, where there is little difference between the rock mass properties of ore and host rocks.

5.0 Kimberlite and Lamproite Deposits:

There are ten mines in the world that use block caving methods to mine ore from kimberlite pipes. All of these kimberlite pipes have been emplaced within Achaean rock of similar age and composition. There are eight mines in southern Africa (Bultfontein, Cullinan, De Beers, Finsch, Kimberley, Koffiefontein, Venetia and Jwaneng) that are Type I Kimberlite Pipes which formed within the Karoo Supergroup Formation. There is also another Type I Kimberlite mine in the Northwest Territories of Canada called Ekati. It is similar in composition to the kimberlite pipes in Southern Africa, with the only main difference being that it is younger and less affected by erosion. The final diamond-bearing mine that employs block caving methods is Argyle, which is located in north-eastern Australia. Argyle is a special case as it is the only economically productive Lamproite (Type II Kimberlite) pipe in the entire world.

Kimberlite pipes are extremely important in terms of block caving and associated subsidence profiles due to the generally weak nature of their highly altered ore rock and great depths to which they extend (up to a few kilometres deep). Kimberlite pipes tend to have a consistent geological make-up in terms of ore rock types, host rock types, shape of the intrusion, and extent of alteration due to ore mineralization. Thus kimberlite deposits should have very similar subsidence profiles as one another. The next step is then to understand the nature of the formation of kimberlite pipes and what this means in terms of overall geology surrounding the deposit, and whether kimberlite pipes should in fact share similar subsidence surface expressions.

5.1 Kimberlite Deposits:

All Kimberlites are composed of volatile-rich potassic ultrabasic rocks that are made up of a macrocryst/megacryst assemblage of ultrabasic rocks (olivine, Cr-poor clinopyroxene, magnesian ilmenite, phlogopite, enstatite and Ti-poor chromite) that are contained within a fine-grained ultrabasic matrix (Field et al., 2008). There are three known processes which can lead to the creation of a kimberlite pipe, with each distinct process being identifiable based on the kimberlite's morphological and petrological characteristics. The three types of kimberlites are Crater Facies Kimberlite, Diatreme Facies Kimberlite and Hypabyssal Facies Kimberlite, with the diatreme facies being the most influential on the geological setting of the deposit area. This is because the kimberlite diatreme dictates the shape of the ore rock zone, whether it be the area at surface level encompassed by this weak rock or the angle of the kimberlite-host rock wall contact.

Crater Facies Kimberlites are composed of pyroclastic (eruptive) or epiclastic (water reworked) rocks near surface. Diatreme Facies Kimberlites meanwhile are composed of volcaniclastic kimberlitic material that encompasses xenoliths plucked from various levels in the earth's crust. Lastly there are Hypabyssal Facies Kimberlites which are igneous rocks that were created by the crystallization of hot, volatile-rich kimberlite magma. The facies types that can be found within each individual pipe are extremely important as they are strong indicators of the geological processes that have shaped the kimberlite pipe and surrounding host rocks. The next step in examining how geology potentially relates to subsidence in kimberlite deposits is to look at the geology of each of the mines that extract diamonds from kimberlite ore.

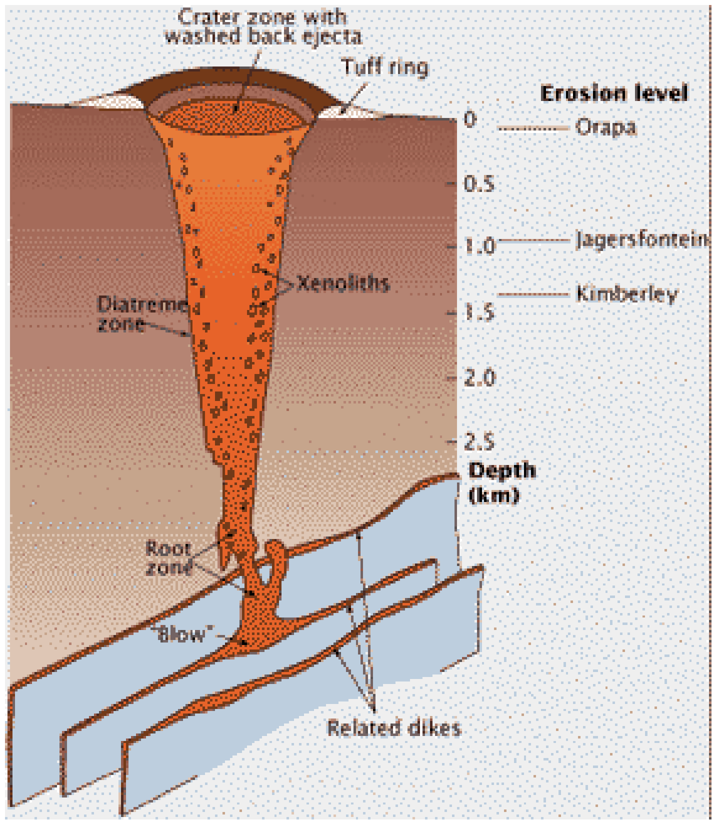
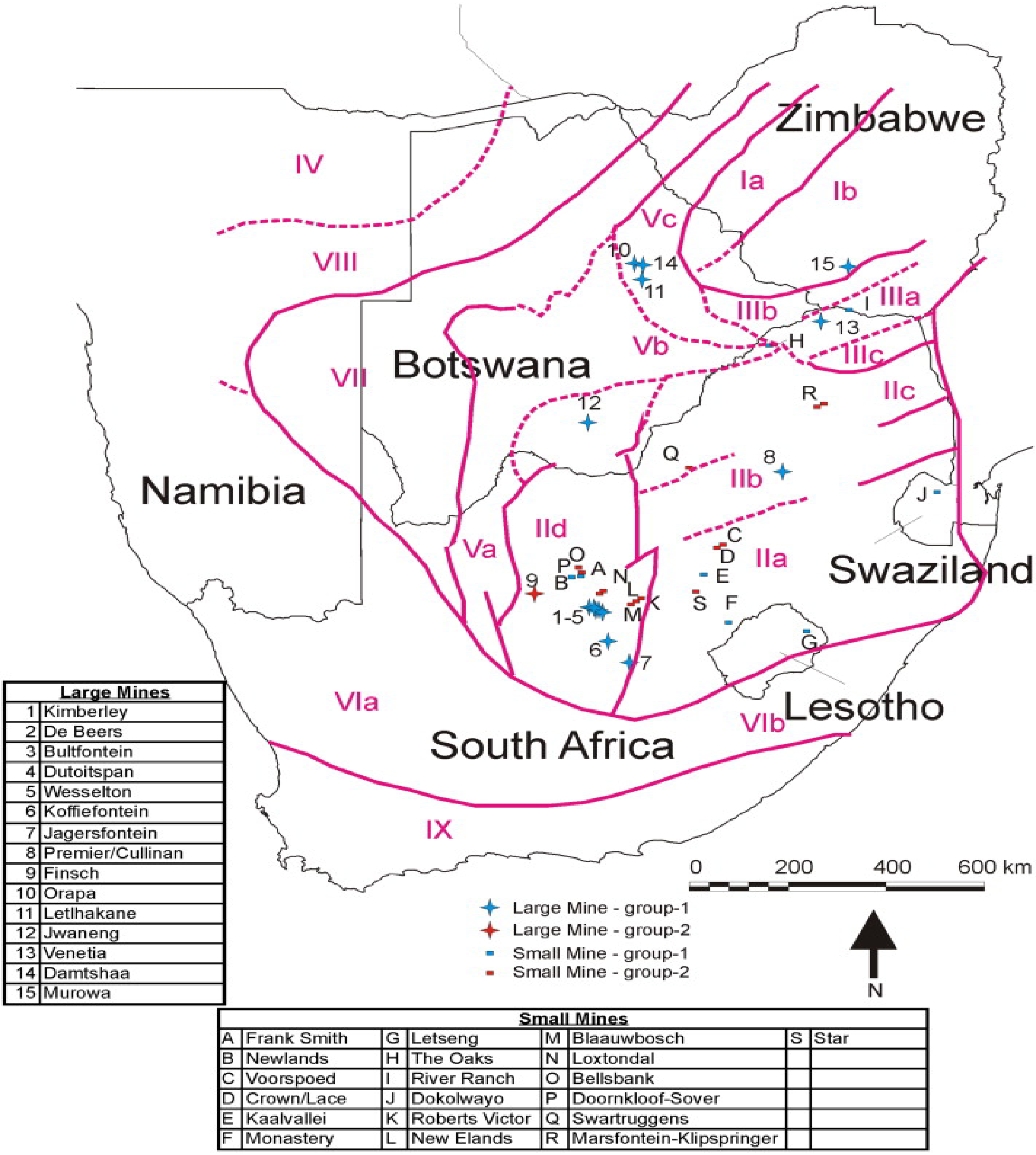


Figure 11. Typical Kimberlite Pipe

5.2 Southern Africa Region Mines:



Large Mines	
1	Kimberley
2	De Beers
3	Bultfontein
4	Dutoitspan
5	Wesselton
6	Koffiefontein
7	Jagersfontein
8	Premier/Cullinan
9	Finsch
10	Orapa
11	Letlhakane
12	Jwaneng
13	Venetia
14	Damtshaa
15	Murowa

Small Mines							
A	Frank Smith	G	Letseng	M	Blaauwbosch	S	Star
B	Newlands	H	The Oaks	N	Loxtondal		
C	Voorspoed	I	River Ranch	O	Bellsbank		
D	Crown/Lace	J	Dokolwayo	P	Doornkloof-Sover		
E	Kaalvallei	K	Roberts Victor	Q	Swartruggens		
F	Monastery	L	New Elands	R	Marsfontein-Klipspringer		

Figure 12. Map showing the location of Southern African Kimberlite Mines

Of the eight mines located within southern Africa, three are located within the well-known Kimberley Mining Region. These three mines are the old

Kimberley mine which was mined out by 1914, De Beers mine which was the first in this region to use block caving techniques, and Bultfontein. Due to the rapid mining at Kimberley and its early closure there were no modern geological investigations carried out on the pipe. There were however some geological descriptions provided by Lewis from 1887 and 1888 (Field et. al, 2008). `Lewis (1888) described the rock as "a volcanic breccia, but not an ash or a tuff". He also noted that a large amount of the surrounding bituminous shale that had been variably baked and altered was enclosed within the kimberlite rock. In fact it was in these outer portions of the pipe with the most abundant shale inclusions that the largest quantities of diamonds occurred (Field et. al, 2008). From these descriptions by Lewis and Field along with the geological cross section in Fig. 13 it is possible to see that the subsidence profile at Kimberley is mainly dictated by the width of the area that used to be filled by the weak brecciated kimberlite. To a lesser extent the upper shale, quartzite, andesite, and conglomerate units of the intruded upper Karoo and Ventersdorp Sequences will also impact the extent of rock failure and subsidence.

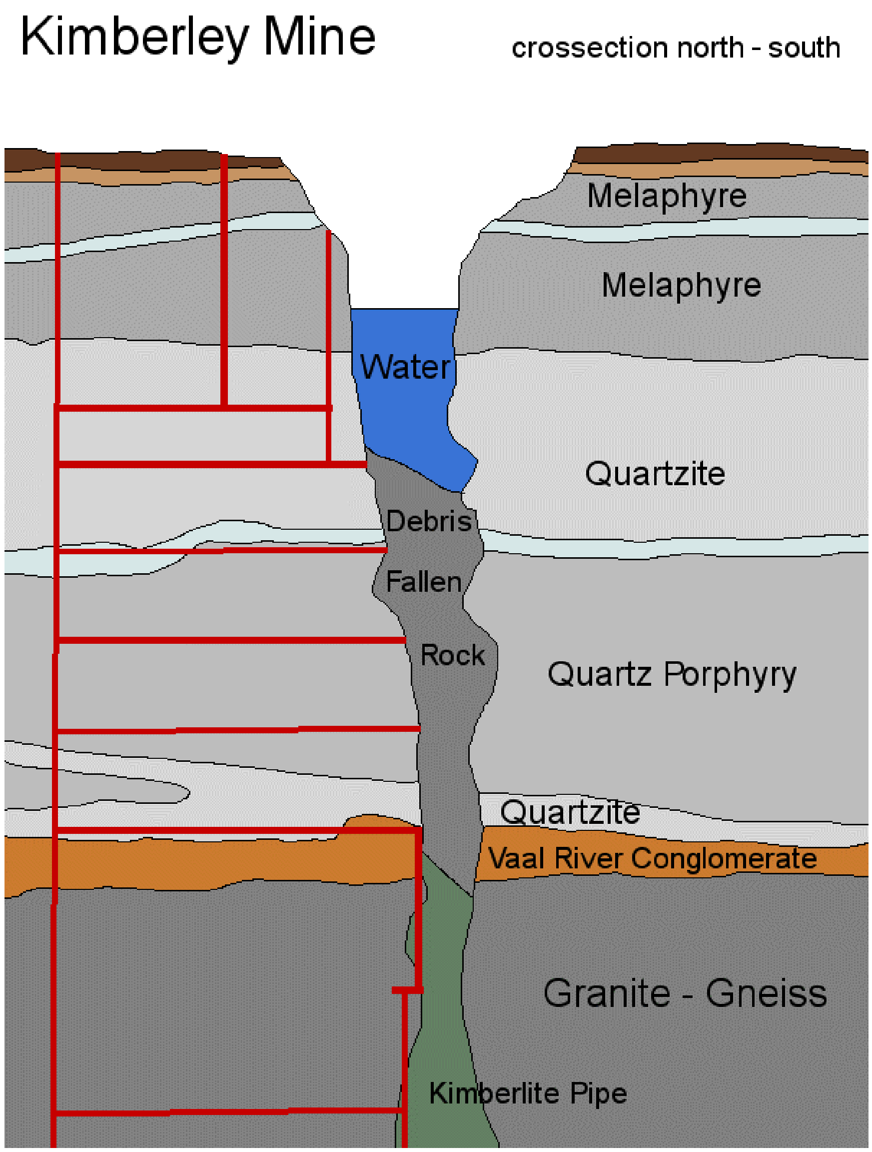


Figure 13. Kimberley Mine Cross Section

The second mine found in this region is the De Beers mine which is composed of kimberlitic rock that is similar to rock found in the Kimberley mine. The rock has been described as a volcanic breccia, which is surrounded by the same sequence of sedimentary and volcanic rocks that surround the mined out Kimberley pipe. Again the surface subsidence at this location is likely to be dictated by the past dimensions of the kimberlite at surface and by the upper few layers of the rock sequence shown in Fig. 14. The third mine within the Kimberley region is Bultfontein, which is made up of three distinct rock types. The first is a diatreme facies Tuffisitic Kimberlite Breccia (much like the De Beers and Kimberley pipes), the second is a kimberlite breccia associated with hypabyssal facies kimberlite, and the third is an enlargement on a dyke (Field et al., 2008). Williams (1932) also described a brecciated column within the pipe that contains abundant fragments of sandstone, shale and dolerite that extends from surface down to the 410 m level (Field et al., 2008). These weak brecciated sandstones and shales will undoubtedly cave back into the mine if they have not already been removed by mining. The deepest level of the mine was 848 m below surface level. This helps to give an indication of the amount of rock overlying the opened cave in addition to the likely stresses and pressures that will be acting on the rock around the opening. Figure 14 below shows how each of the three mines are quite similar to one another, as their shapes, depths, and adjacent host rock sequences (rock type and corresponding thickness) are nearly identical. Thus it is only logical to conclude that all three mines should encounter similar subsidence profiles that would only differ by the surface area that was originally filled by the kimberlite diatreme.

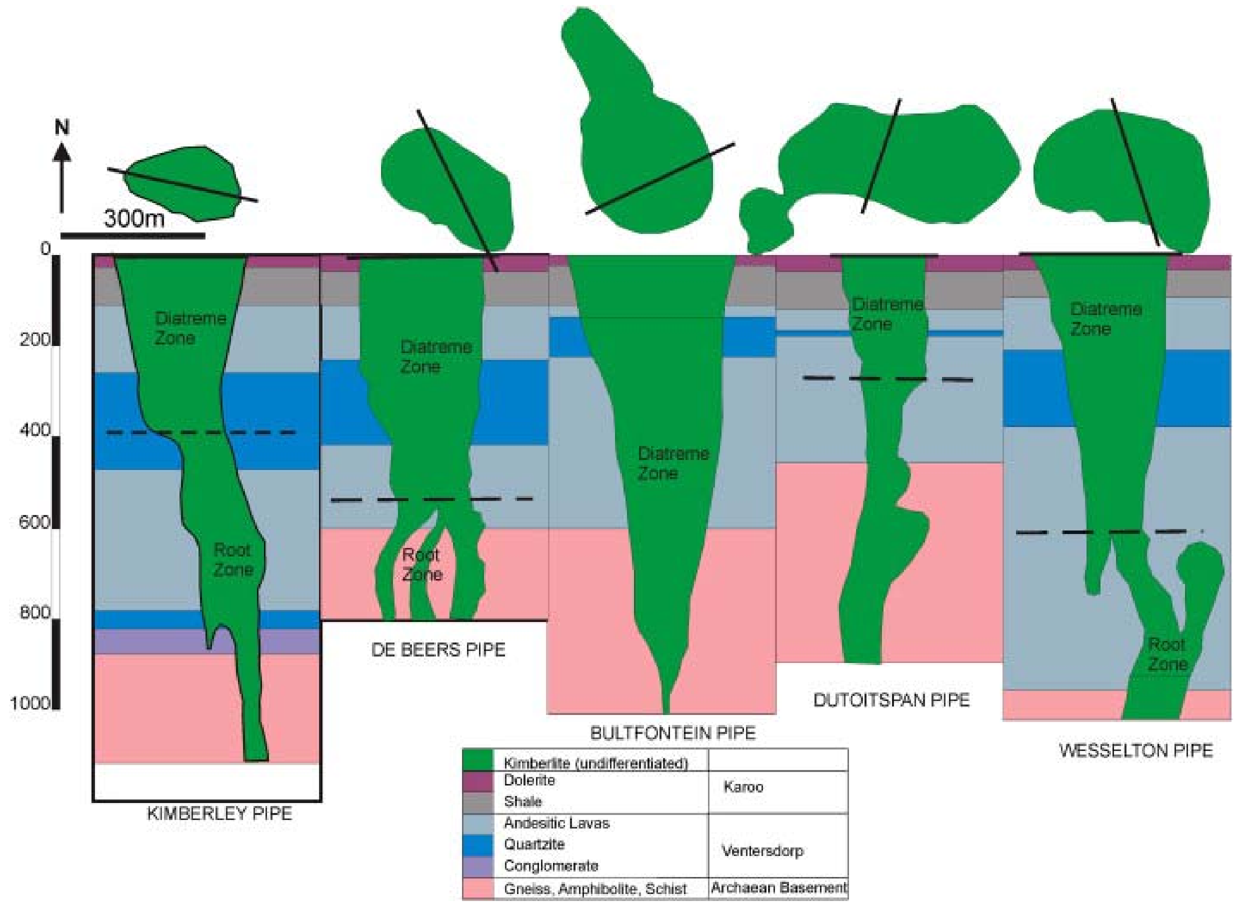


Figure 14. Kimberley Region Kimberlite Pipes

The Koffiefontein pipe, a low-grade, high-value diamond producer, is also found within the Archaean Kaapval craton. It was emplaced approximately 90 Ma ago in basement granite gneiss and overlying Phanerozoic Karoo Supergroup sequence (an accumulation of basinal sediments and basaltic lavas). Red and green mudstones, shales, and sandstone xenoliths within the pipe indicate that the complete Karoo sequence was probably present at the time of emplacement. The pipe also lies on a prominent SE-NW trending structure, believed to be a fissure complex. The diatreme of this pipe, composed of Transitional Kimberlites and Mudstone Breccias, is steep-sided and roughly oval in shape with tapering extremities (Naidoo et al., 2004).

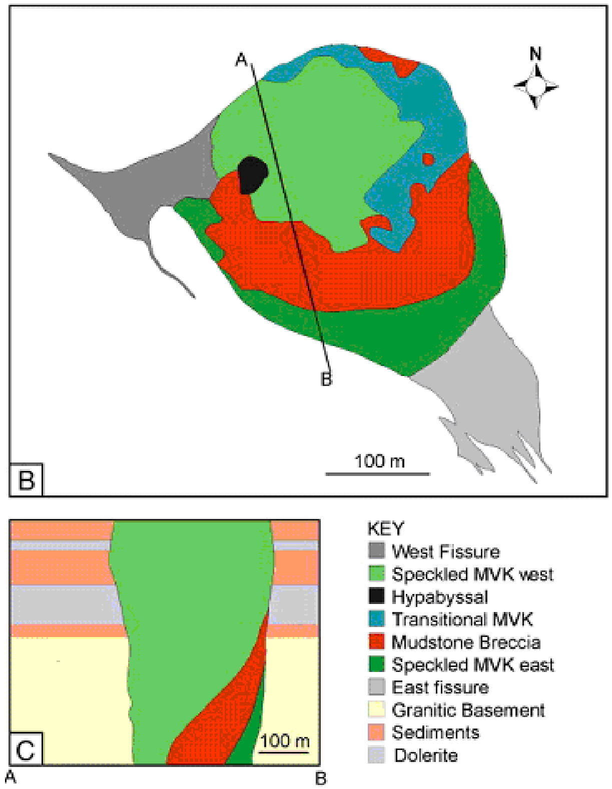


Figure 15. Geological Section of the Koffiefontein Pipe

The phanerozoic sediments which lie above the granitic basement rock will be the rocks that affect the extent of subsidence around the outer edges of the original kimberlite surface once the kimberlite material has been caved. The setup of phanerozoic sedimentary and volcanic host rock on top of granitic basement rock is similar to that of the previously discussed mines from the Kimberley region, and would likely affect the extent of subsidence around the pipe in the same manner as the Kimberley mines.

Premier mine, known as Cullinan mine since 2003, is a classical Kimberlite pipe that has been cut by a 75m thick gabbro sill at a depth of 350m below the surface (Bartlett, 2001). According to Bartlett (2001) the diatreme of this pipe is a complex structure formed by three distinct phases, each producing a different facies of kimberlite. The first phase produced the diatreme that is filled by a brown Tuffisitic Kimberlite Breccia (TKB). The second phase created a grey center of TKB containing Waterberg Quartzite, while the third phase is the intrusion of a black hypabyssal facies kimberlite into the western part of the pipe. The diatreme was then later intruded by carbonatite dykes that break up the kimberlite rock (Field et al., 2008). Fig. 16 and Table 1 below show that once again the ore zone rock is a weak kimberlitic breccia that is surrounded by weak volcanic and sedimentary rocks.

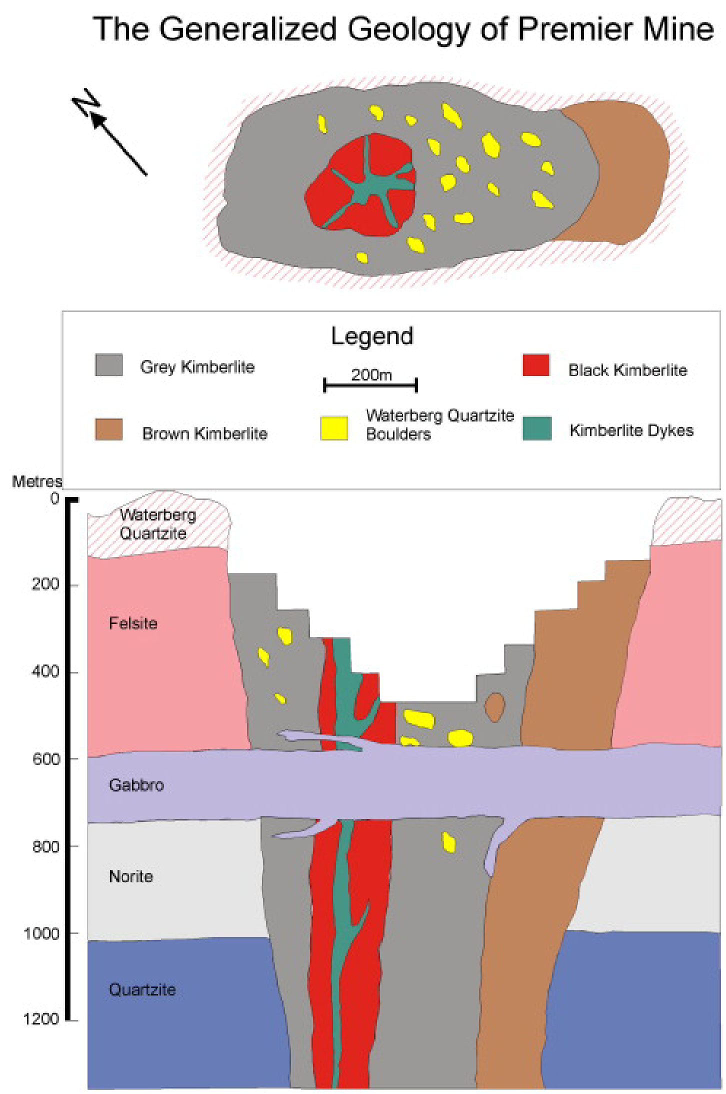


Figure 16. The Generalized Geology of the Premier (Cullinan) Mine

TABLE 52.1 Rock mass properties

Rock type	Tensile strength, MPa	Uniaxial compressive strength, MPa	Young's modulus, GPa	Poisson's ratio	Specific gravity	Rock mass rating
Brown kimberlite	7.9	50-80	16	0.27	2.07	45-55
Grey kimberlite	6.7	60-130	29	0.17	2.67	50-60
Black kimberlite	13.7	73-193	34-65	0.2-0.4	2.8	55-72
Gabbro sill	24.0	160-400	119	0.33	2.81	65
Felsite	16.8	240-300	62	0.29	2.6	72
Norite	16.8	140-220	74	0.25	2.8	45-60
Molasediments	5	60-240	30-167	0.15-0.33	2.5-2.8	40-65

Table 2. Rock Mass Properties for the Premier Mine Rock Units

The next kimberlite mine to be looked at in southern Africa is the Finsch mine, a near-vertical intrusion which consists of dolomite, dolomitic limestone with chert bands, and lenses of almost pure limestone (Preece, 2001). It occurs on an external precursor dyke set striking approximately 50° E of N. Eight different kimberlite types have been identified within the pipe with the most significant intrusion being a diatreme-facies tuffisitic kimberlite breccia. This is the same type of rock which has been found in the ore zones of each of the previously mentioned kimberlite pipes. One difference is that large masses of Drakensburg Basalt, which makes up about 20% of the pipe volume, occur within this kimberlite. Also of note is that the pipe is elliptical and known to extend more than 900 m below the surface with underground caving methods being used at 630 m depth to mine an indicated resource of up to 200 m thick (Field et al., 2008). From the geological section in Fig. 17 one can see that for this particular mine the outside profile extends further from the edges of the pipe due to open pit mining, something that will no doubt impact the subsidence profile of the mine.

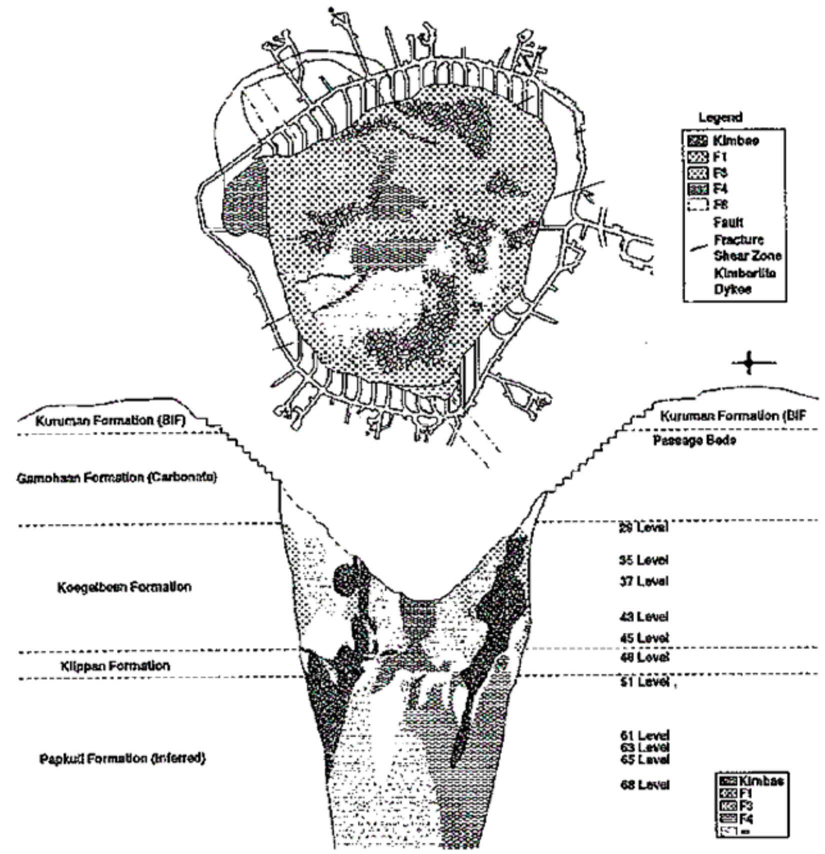


FIGURE 54.2 Typical geological plan and section through Finsch pipe

Figure 17. Geological Section through the Finsch Pipe

The seventh kimberlite pipe to be looked at within this region is Venetia. According to Brown et al. (2008) the Venetia pipe varies somewhat from the other mines in that it was emplaced in stages, the first being an initial explosion followed by alternating phases of accumulation and ejection. It is comprised of layered breccias and pyroclastic rocks of various grain sizes, lithic contents and internal structures. The pipe is made up of two geologically distinct parts, K2 West which is a layered sequence of lithic-rich breccias that dip at 20-45° inwards, while K2 East consists of a steep-sided pipe-like body filled with massive volcaniclastic kimberlite that blasted through the layered breccias. The

K2 West part extends to greater than 900 m depth, which is the part of the ore zone that will be mined using block caving. This means that caving will occur in rock that is tilted at an angle of 20-45 degrees, something that is almost guaranteed to affect the direction in which the mine opening will propagate once it has been cut.

The last mine in this region, Jwaneng, is the only mine within this region to be located within Botswana. This mine consists of three inter-connected pipes that intruded rocks of the Proterozoic Transvaal Sequence including quartzitic shales and dolomites (Field et al., 2008). The pipes at Jwaneng are not typical Type-I pipes as they are actually steep-sided diatremes filled with re-sedimented volcaniclastic kimberlites according to [Field and Scott Smith, 1999] and [Skinner and Marsh, 2004] (Field et al., 2008). The kimberlite in all three pipes is discontinuously bedded meaning that cave-in of kimberlite above the block caving operations may not follow pre-determined bedding planes. Subsidence around this mine much like the others will be dictated by the shape of the actual pipe, with possible bedding planes in the surrounding shales or fractures in the surrounding dolomitic rock playing a minor role in the type of subsidence found at ground level.

5.3 Ekati Diamond Mine:

The Ekati kimberlite pipes formed within the central Slave Structural province in the Northwest Territories of Canada. The kimberlite rocks located within the Koala Noth pipe, the pipe to be exploited by block caving, are mainly volcaniclastic kimberlites, similar to the tuffisitic kimberlite breccias found in the southern African mines. As far as the host rocks are concerned the Ekati pipes have intruded Archean granitoids and metamorphic metagreywackes of the Yellowknife Supergroup (Jakubec et al., 2004). Along the contacts between the kimberlite pipe and these granitoids (granodiorite near the Koala North pipe) the joint intensity of the host rock has been amplified, though this area only extends for about 1-5 metres from the edge of the pipe. Some of the pipes within this region such as the Koala North pipe have been mined by open pit techniques as well, which will affect the area on the surface that is likely to be impacted by subsidence.

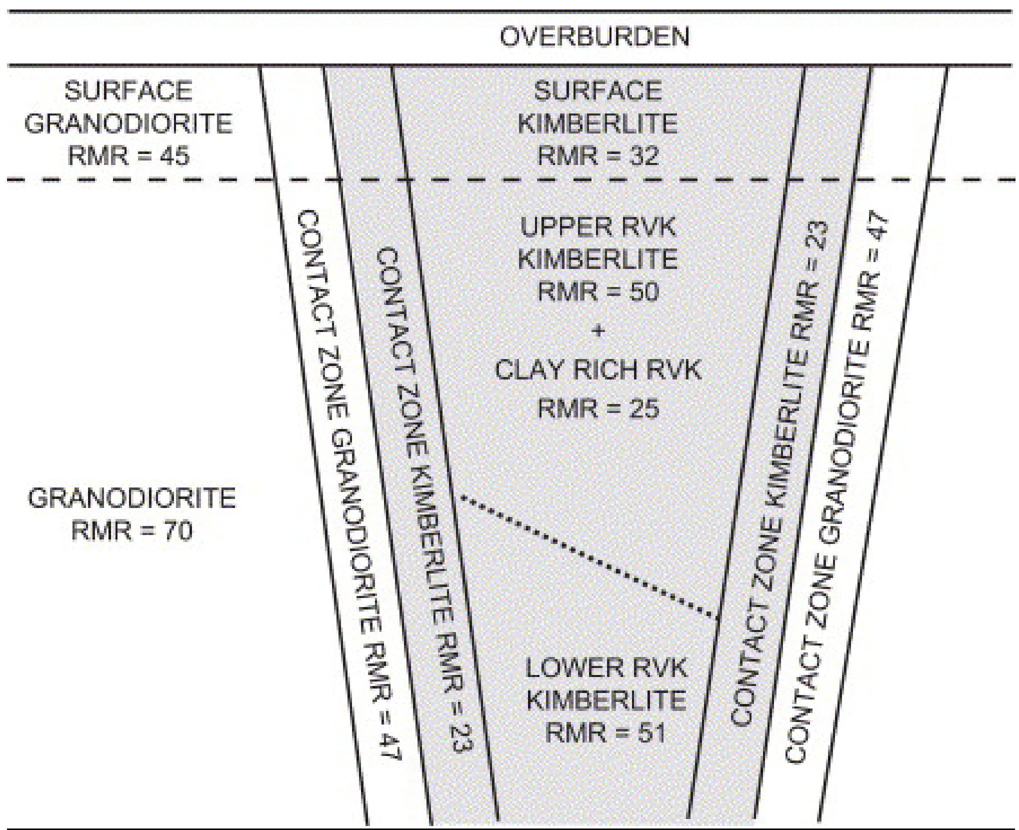


Figure 18. Cross Section through the Koala North Kimberlite Pipe

From the geology of the pipes and surrounding host rocks it becomes evident that subsidence in and around this mine is likely to be most affected by the kimberlitic pipe material along with the highly jointed granodiorites along the pipe-host rock contact. From Figure 18 this is evident in the way that the contact zone granodiorites have much lower rock mass ratings (RMR of 47) than the unaltered subsurface granodiorites (RMR of 70). It is also possible that the metagreywackes could be influenced by caving, though to a lesser extent than the granodiorites and kimberlites.

5.4 Argyle Diamond Mine:

Argyle Diamond Mine is located in the Kimberley region of North-eastern Australia and is the only economically sustainable lamproite pipe currently being mined worldwide.

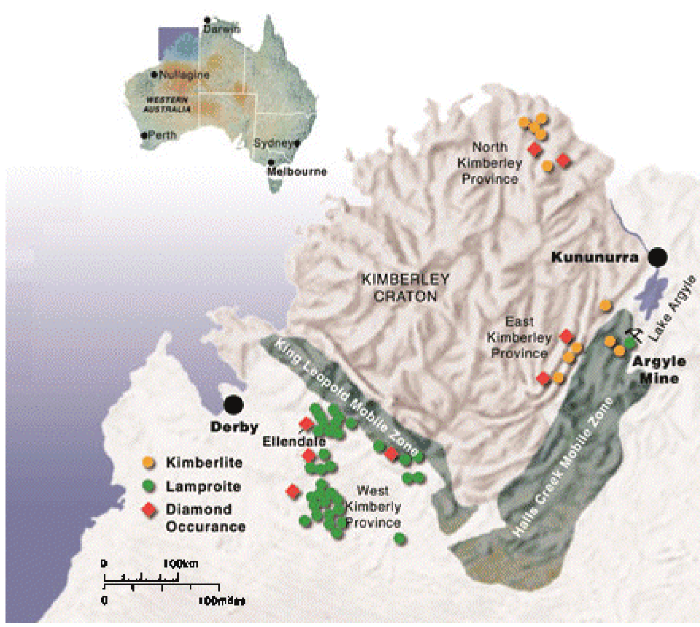


Figure 19. Location of the Argyle Lamproite Pipe

The Kimberley Region consists of nearly flat-lying sedimentary and volcanic rocks deposited between 1.6 and 1.9 Ga. These rocks form the Kimberley Plateau on top of a basement of crystalline igneous and metamorphic rocks more than 2.5 Ga. Diamonds are located within an Olivine Lamproite ore. This Lamproite ore varies a lot compositionally from the other Type I kimberlites, though it is in fact located within similar sedimentary and volcanic sequences to the other kimberlites. Lamproite ores like the one at Argyle have formed by similar processes to that of type I kimberlites, meaning that it will exhibit the similar dimensional features to the kimberlites, with a nearly vertical elliptical pipe that extends to depths of several kilometres below the surface (http://pre mium.infomine.com/minesite/minesite.asp?site=argyle).

6.0 Asbestos Mines:

Block Caving has been used to mine asbestos from ten different mines worldwide. Of the ten mines, seven are located within the Thetford Mines and Asbestos regions of southern Quebec, while the other three are located in southern Africa. In the following sections the geology of the Asbestos mines in both Quebec and southern Africa will be looked at in more detail to determine the important geological features that will factor into the extent of subsidence that occurs due to block caving.

6.1 Southern Quebec Asbestos Mines:

The asbestos sector in Quebec runs along the St. Lawrence River for a distance of 88.5 km. According to Kennedy (1990) this serpentinite belt is a typical ophiolitic complex composed of gabbroic and dioritic rocks with variable amounts of pyroxenite, peridotite, and dunite. The ophiolitic belt has also been described by Kennedy (1990) as a group of partially serpentinized ultrabasic intrusives that were emplaced in the crust along faulted zones of weakness. The complex itself has been extruded into or just under unconsolidated aluminous and siliceous sediments from a eugeosynclinal ocean basin. The chrysotile asbestos fibers of interest in this region occur within a highly serpentinized peridotite unit of the complex.

The Thetford Mines group contains four closely connected deposits that lie in a well-defined zone along the hanging-wall of a prominent fault structure marked by intensive talc-carbonate alteration (Kennedy, 1990). The zone has a length of 1.8 km and width of 457 m with the largest deposits of the King-Bell-Johnson complex extending to depths of 457 m or more. One of the major ore bodies within this region is the King/King-Beaver mine ore-body. This ore-body is a partially serpentinized peridotite with numerous minor fractures, schist zones, shattered shear zones, and large persistent fault planes (Trepanier and Underwood, 1981). As can be seen in figures 20 & 21, something that will impact the subsidence surface expression at this mine is the irregularly shaped nature of the ore-body. The fact that the ore-body has also been mined previously by open pit techniques will factor into the extent of subsidence caused by block caving at depth.

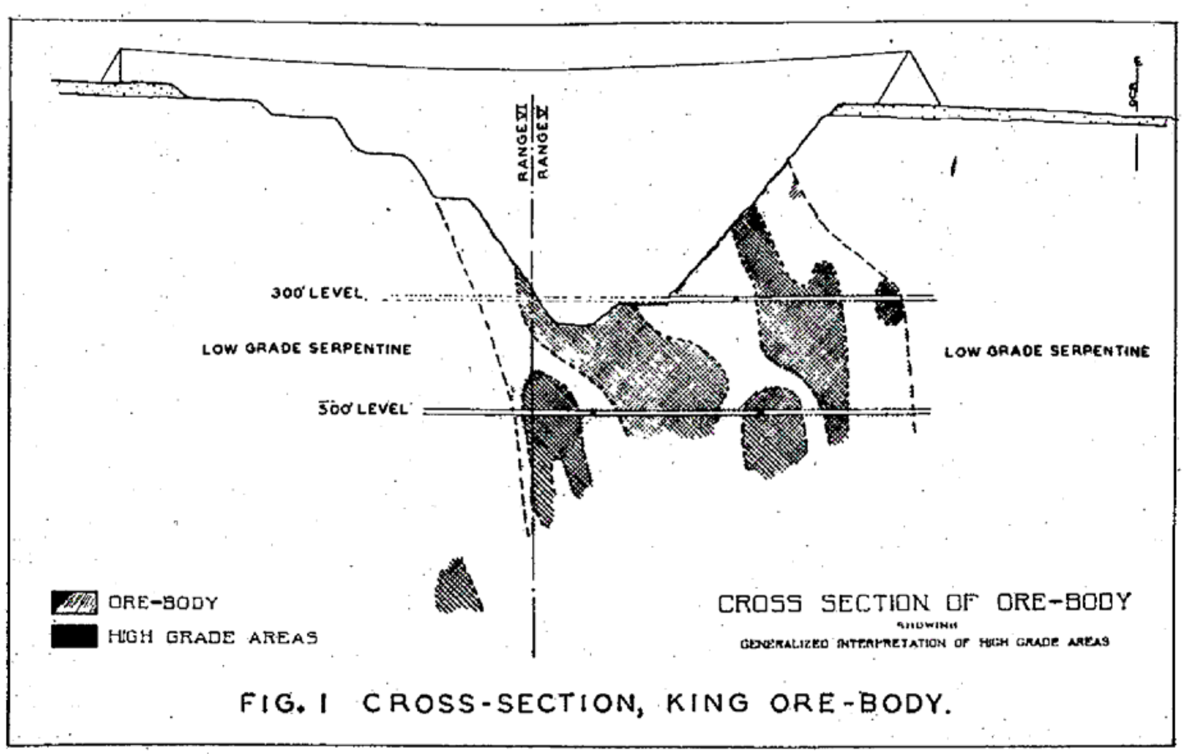


Figure 20. Cross-Section of the King Ore-body

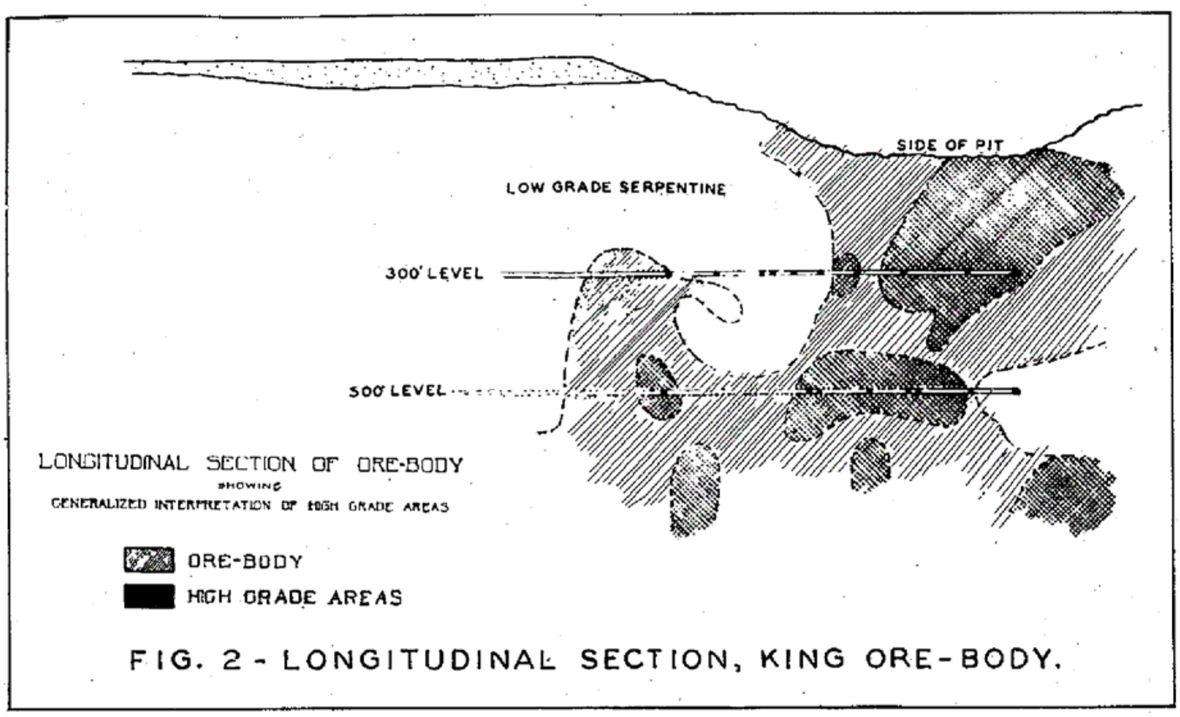


Figure 21. Longitudinal Section of the King Ore-body

The other three mines within this region, Thetford, Johnson, and Bell, have ore-bodies which exhibit similar geological profiles to that of the King-Beaver mine. This would lead one to conclude that the affect their geology will have on the extent of subsidence due to block caving will be similar to that of the King-Beaver mine.

The other two mines within southern Quebec that extract asbestos fibers using block caving mining techniques are located in the Asbestos Ophiolitic region. These mines include the Jeffrey mine, the largest chrysotile asbestos mine outside of the former USSR until its closure in 2002, and the Asbestos Corp Blk 20 mine. Much like the mines in the Thetford region the asbestos fibers in these mines formed within serpentinized peridotite. The Jeffrey mine ore-body is cylindrical in shape and is bounded on both the hanging wall and footwall sides by major faults or zones of shearing that dip south-southeast at about 65-70 degrees (Amabili et al., 2004). Thus any subsidence that occurs at Jeffrey will be controlled by structural features that cut the area, more so than it might in the mines of the Thetford region.

All of these mines extract ore from peridotitic rock which does not vary greatly from the surrounding sedimentary host rocks. Therefore in the asbestos mines of this region subsidence is likely to be dictated by both ore and host rocks, unlike the kimberlite deposits of the previous section. This just means that in the mines of this region equal attention must be paid to the host rock geology, much like in the porphyry deposits where the host rock is likely to play as important of a role on subsidence as the ore rock.

6.2 Southern Africa Asbestos Mines:

There are another three asbestos mines in southern Africa that use block caving to extract asbestos and chrysotile fibers. All three of these mines, just like the asbestos mines in Quebec, are asbestos fiber mines located within a highly serpentinized peridotitic rock unit. One of these three mines is Havelock asbestos, an ore deposit in Swaziland that is located within a succession of the Swartkoppie formation. In the area of the mine, this Swartkoppie formation consists of green and gray schists derived from basaltic to intermediate rocks, banded cherts, siliceous ferruginuous cherts, and a number of serpentinite pods or lenses (Anhaeusser, 1976). Therefore the orientation of the banded chert bedding planes, along with the orientation of the foliations in the green and gray schists surrounding the ore zone must be recognized when studying subsidence. The entire region surrounding the ore deposit has also been intensely folded and faulted (Figure 22). Consequently the orientation of the folds and faults in this region must also be considered when assessing factors leading to subsidence.

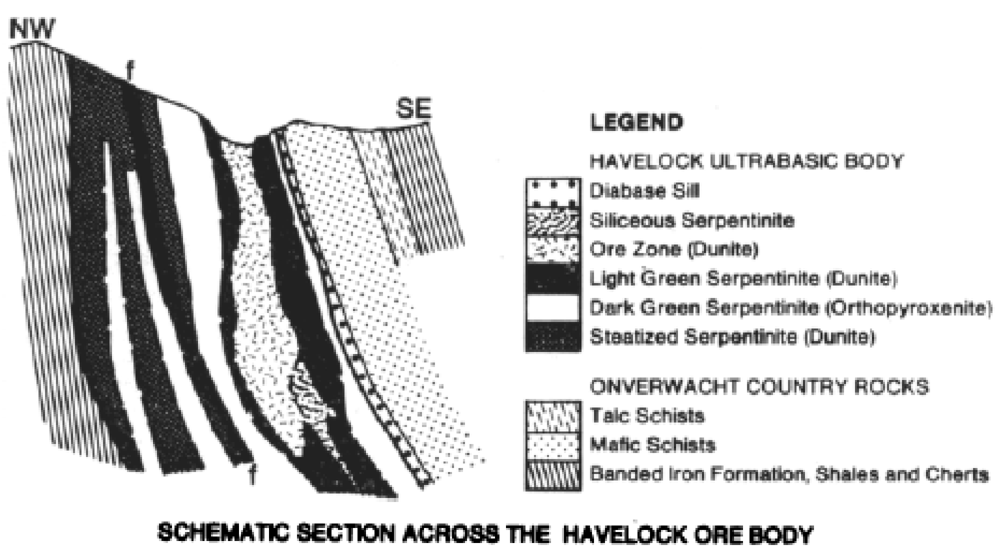


Figure 22. Schematic Section Across the Havelock Ore-body

As previously mentioned all of the asbestos ore deposits in southern Africa, including the King Section of Gaths Mine and the Shabani mine (both in Zimbabwe), are located within a serpentinized peridotitic rock unit. One feature that is specific to the Shabani mine is that the deposit occurs near the base of a lenticular ultrabasic sill (14.5 km long by 2.4 to 5 km wide) that intrudes early Precambrian gneisses (Anhaeusser, 1976). The aforementioned sill is a dunite that is overlain by peridotite, pyroxenite, and gabbro, striking north-west and dipping at an angle of about 40°. There is also heavy talc-carbonate alteration, particularly along the footwall shear zone, that weakens the ore and host rocks. Thus alteration, along with younger diabase dykes cutting the ore zone, has created both a weak ore-body and host rock environment (Anhaeusser, 1976).

All of the information provided within this section demonstrates that each of the asbestos-bearing ore-bodies is composed of a serpentinized peridotite that lies within either sedimentary or metamorphic host rocks that possess similar rock mass characteristics as the ore material. This similarity between ore and host rocks emphasizes the fact that the host rock within these mines will likely impact subsidence just as much as the ore-body rock. Finally it must be stated that the ore rock and host rock environment from one site to the next has been formed by geological processes and features that are specific to that given site, meaning that subsidence will ultimately depend on the site specific geological characteristics of each mine site.

7.0 Iron Ore Deposits:

There are six mines worldwide that use block cave mining methods to mine iron ore. Four of the six mines are located in the United States, while the other two are located in Sweden and China. The largest ore producing mine of the six is Kirunavaara in northern Sweden, which mines iron ore that formed within a fine-grained magnetite. Of the four mines located in the United States, the Cornwall and Grace Mines in Pennsylvania have ore-bodies that are also composed of iron-bearing magnetite. While there are three iron ore deposits that formed in magnetite rock, there are also two mines (Mather and Sunrise) that have economic iron ore deposits that formed within soft earthy red hematites and martites. There is also a Chinese iron mine that extracts ore by block caving, however for the purposes of this paper only the first five mines will be the ones that are studied in more depth.

Kirunavaara mine in northern Sweden is a well known block caving mine that extracts ore from a fine-grained magnetite that contains variable amounts of fine-grained apatite. The 4500 m long ore-body with widths ranging from 2-150 meters has very sharp and distinct hanging wall and footwall contacts. These contacts tend to be brecciated with some impregnated magnetite, with the footwall being composed of a syenite porphyry, while the hanging-wall is a quartz porphyry (Quinteiro et al., 2001). The ore-body itself is tectonically deformed with a lateral dip of 50-70 degrees, which is extremely important to how the ore will cave once the original drawpoints are cut. In addition to the dip of the ore, the mine area rock mass is fractured by three sets of major joints.

Both the Cornwall and Grace ore-bodies are similar to the Kirunavaara deposit, though these deposits happen to have formed within a sedimentary sequence of rocks that have been metamorphosed. The Cornwall deposit consists of massive magnetite that has been emplaced in metamorphosed carbonate rocks, while at the Grace mine magnetite mineralization has replaced a large wedge of impure Cambrian limestone that has been altered to calcium and magnesia silicates by contact metamorphism (Sims, 1968). The properties of these metamorphic rocks are extremely important, as these rocks are the nearest to the ore rock being mined and would be the first to cave into the underground opening. Therefore the manner in which these metamorphic rocks react to caving will impact the manner in which the entire region above the mine will react to caving. At Cornwall mine the ore deposits are covered by an Ordovician Slate and a Blue Conglomerate, both of which will dictate how the entire rock mass above the underground opening will react (Eugster and Chou, 1979). One thing that should also be pointed out is that much like in several porphyry and skarn deposits the magnetites at Cornwall and Grace mineralized within limestone rock units. This could be important as these limestone host rocks may react similarly to caving even if they happen to be host rocks for deposits formed by very different processes.

The other two deposits in this group, Mather and Sunrise, mine iron from soft earthy hematitic rocks. Each hematitic ore deposit has formed within a geological setting that is specific to that mine. The Mather ore deposit has formed within a large east-west synclinorium that plunges to the west, while the Sunrise ore deposit has formed entirely within a schist rock unit. At the Mather mine the ore rock is part of an iron-formation that is over 1300 m thick. According to Bluekamp (1981) this iron-formation at Mather is composed of thin alternating bands of iron oxides and chert that have been intruded by a number of diorite sills, some of which are nearly 122 m thick. The north limb of this banded iron synclinorium dips at about 45° and bottoms out at about 100 m from surface in the central part of the mine. This illustrates the complex nature of the Mather mine and how the geological setting of this mine is controlled by sedimentary rock sequences and their corresponding structural properties (dip, thickness, strength of each sedimentary layer).

8.0 SEDEX, VMS and Stratiform Deposits:

There are a few mines in the Zambian Copperbelt, the Sudbury Igneous Complex, Western British Columbia, Australia, India, and the United States that use block caving techniques to mine ore from sedimentary exhalative, volcanogenic massive sulphide, or stratiform deposits.

The Nchanga and Nkana mines within the Zambian Copperbelt make up some of the world's largest accumulations of sediment hosted stratiform copper deposits. The Nchanga deposit is located within medium strength shales which are up to 12 m thick on average (McGowan et al., 2005). These copper hosting shales are located on top of a strong footwall of granites and arkose. This is quite different from the hanging wall contact rocks which are mainly composed of weak unconsolidated banded sandstones (McGowan et al., 2005). It is evident in this mine that the weak, banded sandstone above the ore shales is the geological unit that is of the most concern when assessing subsidence potential. The gently dipping nature of the layered deposit and overlying sedimentary units will also factor into the potential for subsidence due to block caving. The other Zambian deposit at Nkana is similar to that of Nchanga, with the ore at this locality also being located within a layer of “ore shale”. From the corresponding cross section (Fig. 23) it is possible to see the layered nature of this stratiform deposit, and how the ore shale layer has undergone extensive folding. Overlying the ore shales at this mine are gabbro and quartzite layers, with some areas of quartzite schist overlying the ore where there has been extensive folding.

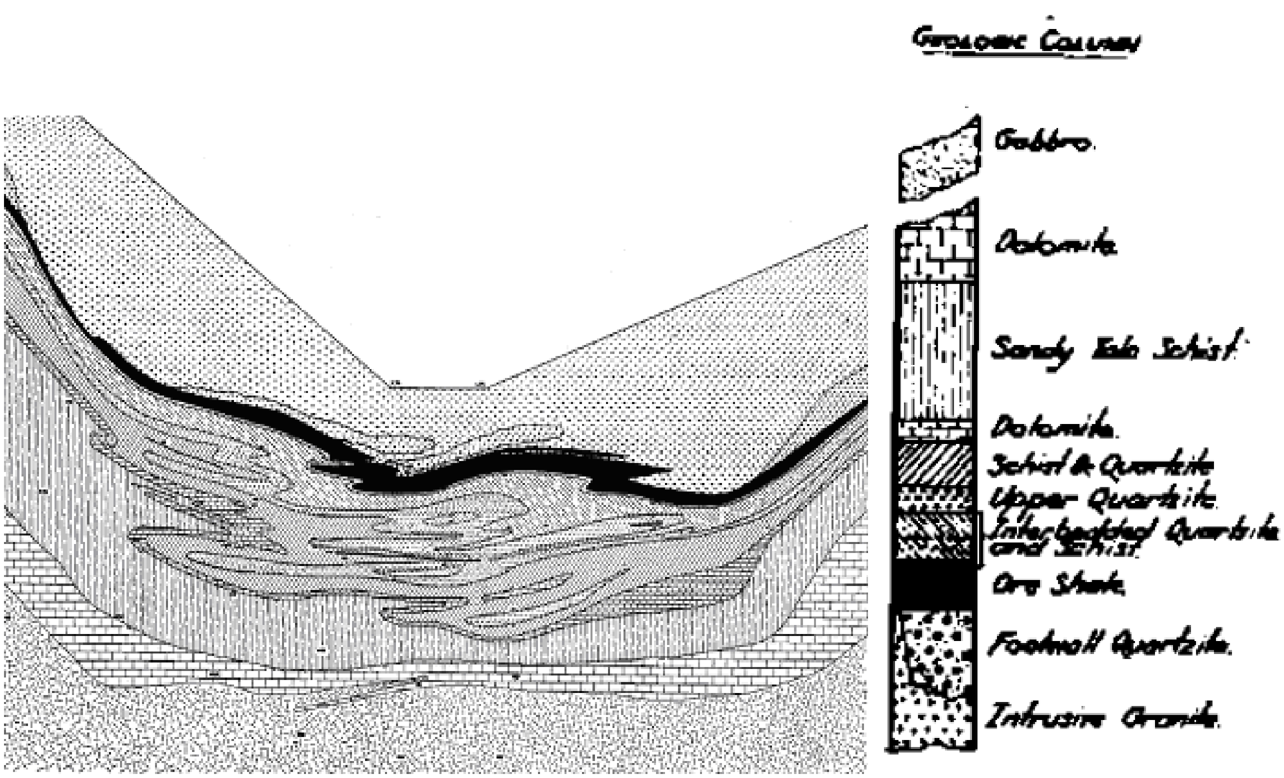


Figure 23. Geological Cross-Section of the Nkana Ore Deposit.

Therefore subsidence at these mines will be dictated by the strength and orientation of the gabbros and quartzites at Nkana, and the weak banded sandstones at Nchanga. This difference in host rock lithologies would lead one to assume that the extent of subsidence at Nchanga would be greater than at Nkana due to the weaker banded sandstones. This is because these weaker bedded sandstones are much more likely to encounter discontinuous subsidence in the form of chimney caving or plug caving that follows the weakly bedded contacts between the sandstone units.

In the Sudbury Igneous Complex there are three mines that have used block caving mining methods to extract ore from modified sedimentary exhalative deposits. These deposits include a Nickel-Copper deposit at Inco's Stobie mine, and Nickel deposits at Errington and Creighton mines. The origin of these mines can be traced back to a large meteoric impact event that led to the mineralization of several ore deposits within the Sudbury region. The Stobie mine focuses on a steeply plunging ore zone (70-75 degrees) that is surrounded by basic metasediments and metavolcanics that range from hard, competent quartzite to a relatively weak and soft metagraywacke (Buksa, 2001). Along with these metasediments the area is said to have been highly brecciated by the Sudbury event, leaving much of the area surrounded by an extensive zone of Sudbury Breccia. The weak and soft metagraywacke along with the Sudbury Breccia will be the rock units that have potential for failure once caving of material has occurred, with the orientations and location of these units being vital to the type of subsidence that occurs at the surface.

The Errington mine is surrounded by similar rocks as at Stobie, with its ore zone being located within a steeply dipping brittle fault zone (Figure 24). The main rock units surrounding the ore zone in this mine are the Mosher Carbonate and a series of mafic volcanics and sedimentary rocks that make up the hanging wall (see fig. 24). Key geological characteristics of this mine region are once again the faulted and fractured nature of the rock units, as subsidence here is likely to be asymmetrical in the direction of the fault and shear zones.

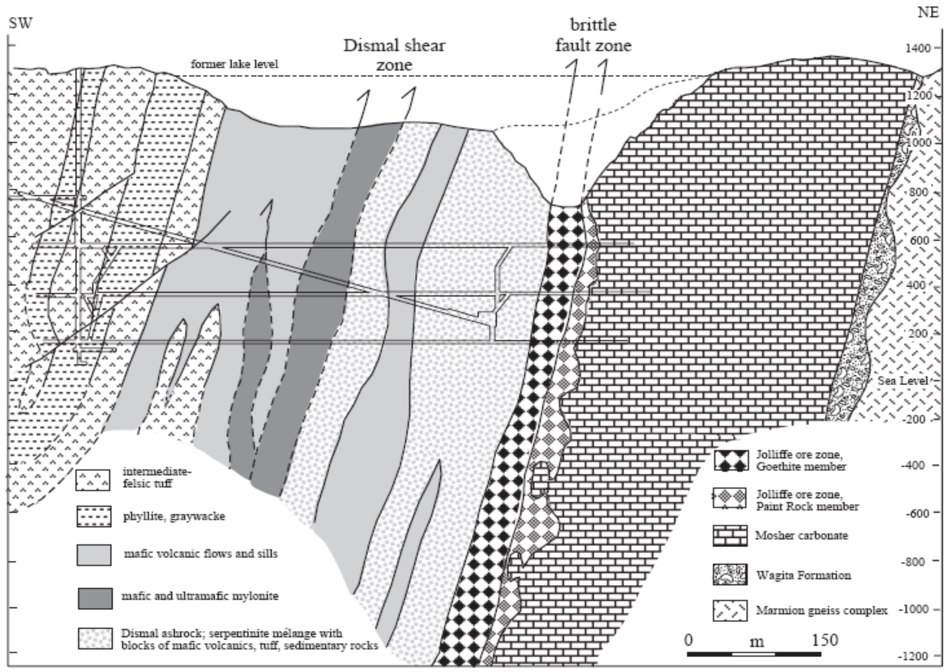


Figure 24. Geological Cross-Section through the Errington Ore Deposit

The third mine within the Sudbury basin is the Creighton mine, which much like the Stobie and Errington mines is located within a sequence of steeply dipping sedimentary and volcanic rocks that have been metamorphosed and brecciated by the Sudbury event. By reviewing the general geology of the Sudbury mines it is possible to see that they are strongly controlled by regional discontinuities like faults and shear zones which have created a steeply plunging region of layered sedimentary and volcanic units. This varies from the stratiform deposits in Zambia that are horizontally bedded and extensively folded. It is also evident that both depositional environments vary significantly from those of the porphyry, asbestos, and iron ore deposits discussed in previous sections, thus only further confirming the idea that the ore-body genesis of each deposit is extremely important in contributing to the geological setting that influences subsidence.

Other sedimentary exhalative (SEDEX) and volcanogenic massive sulphide (VMS) deposits that have been mined by block caving techniques include Mt. Isa Copper in Australia, Granduc in British Columbia, and Bunker Hill in the United States. Mt. Isa Copper is related to a group of SEDEX deposits that occur within brecciated siliceous and dolomitic rock masses of the stratiform Urquhart Shale unit. Mining of copper by block caving currently takes place at the 1100 and 1900 levels in the south part of the property, and at the 3000 and 3500 levels below the lead mine in the north. The stratiform Urquhart Shale layers of this formation are interbedded within lead deposits at an angle of 65° (http://www.mining-technology.com/projects/mount_isa_copper/).

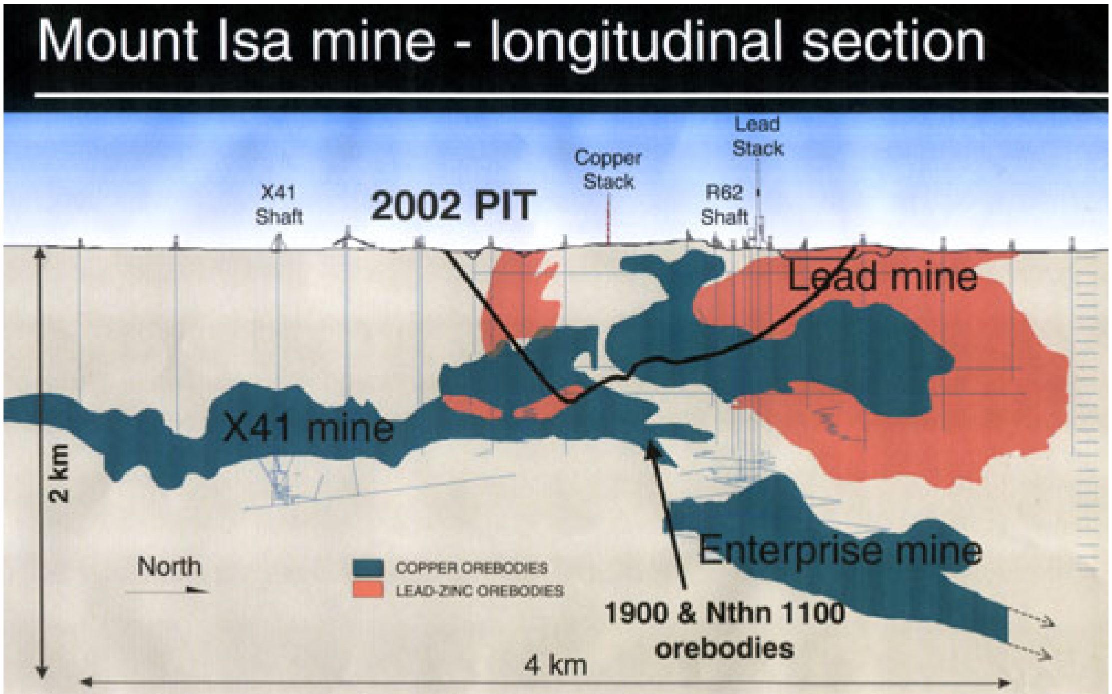


Figure 25. Mount Isa mine- Longitudinal Section

Another similar sediment hosted sulphide deposit is Rajpura-Dariba in India, which has been emplaced within dolomitic marbles, cherts, and schists (Misra, 1999). This mine is likely to encounter subsidence similar to Nkana, as it has been emplaced within stronger rock sequences that contain metamorphic schists. The Granduc mine in British Columbia on the other hand is a VMS deposit that is located within highly deformed volcanic and sedimentary rocks. These units consist steeply plunging metasediments that dip at an angle of 75 degrees (Hancock and Mattson, 1982). According to a survey by Aeroquest Surveys these metasediments consist of repeating layers of argillite, siltstone, mafic tuff, massive sulphide and tourmaline-bearing chert. This sequence of repeating layers of sedimentary and igneous rocks may be unique to this mine, but the alternating layered nature of this deposit is similar to some of the layered iron deposits and stratiform deposits mentioned earlier. Thus it may be possible to make the assumption that this mine may react similarly to the layered iron deposits and stratiform deposits just in terms of structural geology affecting ultimate subsidence.

A final SEDEX deposit is Bunker Hill in the United States, which is now a superfund site after experiencing considerable amounts of acid mine drainage over the years. This deposit consists of silver, lead, and zinc that formed in shear-hosted vein structures within vitreous quartzite, sericitic quartzite, and siltite-argillite rock units (Brennan and Preuss, 2007). This mine site is controlled by several faults which can be traced back to the larger Lewis and Clark Shear zone that has deformed the Coeur D'Alene Mining District in Idaho.

One thing that the several SEDEX, VMS, modified SEDEX, and sediment hosted deposits have in common is that the ore rock is rather similar to the host rock, whether they are layered sedimentary deposits (stratiform deposits, SEDEX deposits), or tilted metamorphic and igneous deposits in the Sudbury Basin. It is also possible to see that though each of these deposits was formed within sedimentary rock sequences by exhalative processes, each mine has very site specific geological features that will factor into the type of subsidence that results from block caving.

9.0 Other Deposits:

There are a few mines that have yet to be reviewed that cannot be placed into any of the previously discussed groups. These mines range from nickel and gold deposits in the Yilgarn craton of Western Australia to a cement mine in the United States that is located within metamorphosed and recrystallized limestones.

The gold deposits in Australia which use block caving are Telfer and Big Bell. Telfer is similar in many ways to some of the SEDEX deposits discussed in the previous section as the gold deposits have formed within a sequence of sedimentary rocks. These ore hosting sedimentary rocks occur at depths ranging from 2500-4500 metres below the surface and are composed of sandstones, mudstones, limestones, and dolostones (http://www.newcrest.com.au/upload/293 3x08x2006100444AM.pdf). The capping rock in this case is a thick quartzite/sandstone unit that is nearly 1500 m thick, something to consider when assessing how geology could potentially impact surface subsidence. The Big Bell deposit on the other hand consists of gold deposits within biotite and altered schist units that are pervasively foliated (Player, 2001). The foliations within the deposit parallel the lithology of the geological environment, while there are 3 major joint sets that cut the ore. The ore-body at Big Bell is lenticular and follows strike for up to a kilometre, with a few cross-cutting pegmatitic dykes. All of these features produce an environment suited for block caving and potential associated subsidence. There are also a few nickel mines within the same region as these Australian gold deposits. These mines include Perseverance and Mt. Keith, both of which have formed within the Yilgarn Craton. The main disseminated ore-body at Perseverance mine occurs within ultramafic rocks in an intensely altered greenstone belt composed mainly of metamorphosed volcanic and sedimentary rocks (Tyler and Werner, 2004). Nickel mineralization is hosted by ultramafic-serpentinite in a lens-shaped ore-body several kilometres long and up to one kilometre wide. The Perseverance ultramafic intrusion, which is emplaced in steeply west-dipping volcanogenic quartzo-feldspathic metasediments and amphibolites also dips steeply westward.

Another large gold deposit that uses block caving to mine ore is a placer deposit in Bolivia known as Cangalli. Cangalli is located in the Tipuani-Mapiri basin with gold minerals having formed within fluvial conglomerate rock. Accoring to Herail et al. (1989) these conglomerate layers are interbedded with silts, laminated clays and thin beds of lignite. The interbedded conglomerates and clays have also been deformed by tectonics leading to the presence of tilted beds, reverse faults, and large bands where the clasts are microfractured and pinched. All of these geological features combined create a very weak rock mass that is likely to encounter large scale subsidence when material is removed at depth by block caving.

Though each of these mines may not fit into one of the other deposit groups, they do tend to share some geological features that are influential to any subsidence or caving that occurs. The only mine that varies considerable from any mines discussed earlier is the Cangalli Placer gold deposit, as it occurs within fluvial sedimentary rocks interbedded with clays and silts.

10.0 Conclusion:

One thing that is constant throughout all block caving operations is that the orebody within the mine area is weak and highly susceptible to caving. There are several explanations as to why the ore, and sometimes surrounding host rocks, are weak with hydrothermal alteration and jointing being the most prevalent. Typically mineralization of the ore rock is accompanied by hydrothermal alteration, whether it be over a large area or only within a few metres of the ore-host rock contact. In some cases alteration also leads to metamorphism of the host rocks. Examples of this type of contact metamorphism, listed in Table 3, have occurred in several skarn deposits where intruded limestone has been metamorphosed.

Metamorphic Deposits	
Mines:	*Host Rock:*
1) Johnson Camp, Lakeshore, San Manuel	Pinal Schists
2) Mines Gaspe Deposit	Metamorphosed siltstones/limestones near intrusives
3) Climax Molybdenum	Schist inclusions within host Precambrian Granites
4) Questa Molybdenum	Highly metamorphosed Precambrian igneous rocks
5) Kamioka Skarn (Japan)	Hida Gneiss rocks
6) Havelock Asbestos	Green and Grey Schists
7) Shabani and Gaths Mines (Zimbabwe)	Dunite Sill intruding Precambrian Gneisses
8) Cornwall Iron Mine	Metamorphosed carbonate rocks
9) Grace Iron Mine	Contact metamorphism of Cambrian Limestone
10) Sunrise Iron Mine	Schist rock unit
11) Crestmore Cement Mine	Recrystallized and metamorphosed limestone
12) Nkana (Zambian Copperbelt)	Some interbedded Schist and Quartzite
13) Stobie Mine (Sudbury)	Metasediments and Metavolcanics
14) Creighton Mine (Sudbury)	Sed. and Volc. rocks metamorphosed by Sudbury event
15) Big Bell Gold Mine (Australia)	Biotite and Altered Schists
16) Mt Keith/Perseverance Nickel Mines (Australia)	Metamorphic Greenstone Belt
17) Rajpura-Dariba (India)	Schists

Table 3. Mines within Metamorphic Host Rock Sequences

This type of metamorphism also occurs within a few porphyry and iron deposits (Cornwall), all due to the intrusion of porphyritic rock masses. The importance of understanding how and where metamorphism can occur in host rocks lies in the characteristics of metamorphic rocks (foliations) that influence the competency of the rock. Other mines that have deposits located within metamorphic rocks include the African asbestos deposits which are surrounded by metamorphosed green and grey schists, or iron deposits like Cornwall and Sunrise that have formed within metamorphosed carbonates in contact with igneous intrusions. The fact that these mines share similar metamorphic host rock sequences does not necessarily mean that subsidence within these mines will be similar, as there are several other geological characteristics of the rock mass reacting differently to block caving. Such characteristics include the dimensions of the ore-body, as porphyritic ore-bodies tend to be irregularly shaped, while skarn, iron, and asbestos ore-bodies in metamorphic rocks tend to follow the lithology of the overall geological region.

Sedimentary rock sequences also possess several characteristics that will impact how the overall host rock environment will react to block caving. Important sedimentary features include the orientation of bedding planes, dip of the sedimentary sequence, thickness of the specific rock units, extent of alteration in the rocks, and the extent of deformation caused by regional folding and faulting. There are several block caving operations that mine ore from sedimentary host environments where such geological characteristics are important. These areas include Arizona and New Mexico where several copper porphyry deposits have intruded sedimentary conglomerates and quartzites. Other areas composed of sedimentary sequences are the Zambian copperbelt, the Mather and Grace iron mines, the Telfer and Cangalli gold deposits, the several skarn deposits that have formed within limestones (EESS, Gaspe, and Kamioka), and to a lesser extent the many kimberlite pipes throughout the globe.

Sedimentary Deposits	
Mines:	*Host Rock:*
1) Bagdad, Inspiration, Miami, Ray, and San Manuel	Sedimentary Host Rock Sequences
2) Cadia East and Ridgeway Porphyries	Ordovician Sediments and Volcanics
3) Bingham Canyon, Emma Nevada, and Resolution	Folded Quartzites, Limestones, and Sandstones
4) Oyu Tolgoi Porphyry	Sequence of Basalts, Tuffs, and Sedimentary rocks
5) Ertsberg East Skarn System Deposits	Limestone/Marble on NE
6) Mines Gaspe Deposits	Hydrothermally altered siltstones and limestones
7) Kamioka Mine	Skarns replacing limestone lenses in Hida Gneiss
8) Zambian Copperbelt Deposits (Nchanga, Nkana)	Weak banded Sandstones (Nchanga), Quartzites (Nkana)
9) Bolivian Placer Gold Deposits (Cangalli, Bolivia)	Fluvial Conglomerate Rock
10) Telfer Gold Deposit	Sandstones, mudstones, limestones, and dolostones
11) Crestmore Cement Mine	Recrystallized and metamorphosed limestone
12) Cornwall and Grace Mines	Limestone (Grace), Slate and Conglomerate (Cornwall)
13) Mather Iron Deposit	Alternating iron oxides and cherts
14) Errington Mine (Sudbury)	Mosher Carbonate to the NE
15) Granduc (BC)	Alternating sedimentary and volcanic rocks
16) Bunker Hill	Quartzites and Siltite-Argillite rock units
17) Mt Isa Copper (Australia)	Urquhart Shale layers
18) Rajpura Dariba (India)	Cherts interbedded with Dolomites and Schists
19) Kimberlite Deposits	Sedimentary rock sequences overlying igneous basement rocks
20) Quebec Asbestos Mines	Peridotites emplaced into or just under unconsolidated aluminous and siliceous sediments
21) El Salvador (Chile)	Andesitic Conglomerates and Sandstones overlain by volcanics

Table 4. Mines within Sedimentary Host Rock Sequences

Though these various deposit types occur within sedimentary rock sequences the manner in which the subsurface material acts under block caving will ultimately come down to the deposit-specific geological composition. The ore-body characteristics that will be unique to each deposit include the dimensions of the ore-body, depth of the ore-body, and orientation of the ore-body. This is where the different ore-body genesis types affect how the overall geological environment will respond to block caving. Examples of this can be seen in the way that deposits like kimberlites are typically cone shaped and extend to great depth, while porphyry deposits are almost always irregularly shaped and found at a depth of only a few hundred metres below surface.

Volcanic rocks are found at all of the block caving mines, and thus it is more their given geological characteristics (rock mass rating, in-situ strength, etc.) that will influence the type of subsidence that results from block caving. The structural geology of each mine region is likely the most important aspect of the geological setting within which the ore deposits are located. This is because structural geological features such as large-scale faulting and folding will impact practically every aspect of the geology of the host and ore rocks, whether it is the individual rock mass properties of each rock unit, or the orientation of the entire subsurface lithology.

Another important factor influencing the extent of subsidence caused by block cave mining is how similar/different the ore-body rock is from the surrounding host rock. This ties back to all of the groupings shown in the above tables (3 & 4), as the difference between the rock mass characteristics of ore rock within sedimentary rock sequences will tend to be greater than it would be between porphyritic ore-bodies that have emplaced either metamorphic or igneous intrusive rocks. The difference between the ore rock and host rock can be extremely important in affecting the outcome of surficial subsidence, as in mines where the ore rock is much weaker than the host rock any subsidence that occurs is likely to occur within the weaker ore rock (ie. Kimberlite pipes in Archean cratonic rock, Palabora carbonatite pipe). However in mines where there is little difference between the ore rock and host rock the extent of surface subsidence is much less predictable, with the possibility that chimney caving or other types of discontinuous subsidence can lead to irregular surface subsidence profiles. This lack of contrast between ore and host rock strength and rock mass characteristics is evident in almost all porphyry deposits, especially in regions such as Chile or the Philippines where the ore-bearing porphyritic intrusive bodies have invaded other intrusive igneous rock sequences. Therefore it is important to not only understand the individual rock types present at each mine site that will impact subsidence, but it is also important to determine whether the ore and host rocks differ considerably from one another in terms of rock mass characteristics and strength, as such a difference has the potential to impact any subsidence that will result from block caving.

Thus, in conclusion there are various geological aspects of the entire mine region around each block caving operation that will impact the extent of subsidence that results from mining material underground. Some of these geological aspects may be common throughout several mines, though in the end each specific block caving operation will encounter subsidence that is unique to its given geological environment.

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