MINING DIAMONDS USING UNDERGROUND METHODS IN THE LARGE KIMBERLITE PIPES

Dr. P. Bartlett

CONSULTANT
- Depth of origin – diamondiferous kimberlites are located in the old cratonic areas of the world and tap the diamond stability field at depths in excess of 120 kilometres.
- Kimberlite “magma” is made up of ultrabasic, often unstable, minerals such as magnesium-rich olivine, serpentine, calcite, pyroxene and phlogopite. The infill of the large pipes is dominated by volcanoclastic and pyroclastic material containing the above minerals often deuteronically altered to a range of secondary minerals. The kimberlite that is mined is usually incompetent and contains clay which exhibits extreme swelling clay properties when the ore comes into contact with water.
- The uniaxial compressive strength of kimberlites typically ranges from 30 to 120 MPa. Mining rock mass ratings can go as low as an MRMR value of 30 over extensive areas of the orebody.

Several hundred kimberlite pipes and dykes are known to exist in South Africa. Very few of the intrusions contain diamonds in economic quantities. Only Premier, Wesselton, De Beers, Kimberley, Kamfersdam, Du Toit’s Pan, Bultfontein, Jaggersfontein, Koffiefontein and Finsch have been considered to be suitable for underground mining methods using low cost massive mining methods. In Botswana the current Jwaneng and Orapa open pits might economically sustain massive underground mining operations. Work is in progress to take the Venetia open pit underground. Individual mines daily production ranges from 1000 tons to 30 000 tons.

3. History of open pit mining

The Kimberley pipes, the first diamond-producing open pits, started operations in the 1870’s. On surface the kimberlite pipes were generally divided into 31 feet by 31 feet claims and miners proceeded to mine using manual labour wielding picks and shovels to increasing depths. Hundreds of individual claims were mined in each pipe. Most mining people are familiar with the endless rope haulages used to take ore from the claims to hundreds of small individual treatment plants. Initially mining in weathered kimberlite - termed “yellow ground” - was easy but, as mining progressed with increasing depth into “blue ground”, drilling, blasting, flooring and crushing was required. Pumping water out of the workings was problematic and costly. Individual claims were consolidated by mining magnates such as Banato and Rhodes. In 1888 De Beers was formed and continued to mine the richer pipes using open pit methods down to depths of some 200 metres. Wesselton, Kimberley, De Beers, Kamfersdam, Du Toit’s Pan, Bultfontein, Jaggersfontein, Koffiefontein, Voorspoed and Lace were all mined in this way.

The large Premier pipe, 32 hectares in area at surface and owned in its entirety by Thomas Cullinan, was similarly mined as an open pit to a final depth of 189 metres.

The pipes were not benched as are most modern open pits. Any and all benching was done within the confines of the orebody resulting in the spectacular “glory holes” at Kimberley, Wesselton, Bultfontein, Du Toit’s Pan, De Beers, Jaggersfontein and Premier.
Finsch, discovered in 1965, was benched and mined to a depth of 423 metres as an open pit. Koffiefontein, originally also a "glory hole" was closed and, after the closure of Jagersfontein, benched-mined as an open pit starting in 1972.

It is interesting to speculate that had these mines been found later and exploited by open pits using modern benching many of them would probably have been mined to depths of 700 metres and more. The Kimberley mines have weak Karoo age sediments near surface but progress at depths of some 200 metres into extremely competent Ventersdorp lava that could sustain pit slope angles in excess of 65 degrees. Premier, currently using underground mining methods, situated in competent felsites and norites and with an area of some 17 hectares at 763 metres below surface, could certainly have been exploited as an open pit to depths of 700 metres and more.

4. History of underground mining

No technical literature is available explaining the reason for the Kimberley mines progressing to underground mining methods such as chambering. It can be speculated that safety issues pertaining to slope instability, pumping and the problems associated with using endless rope haulages to take the ore to surface would have forced first access and then mining underground.

Chambering was eventually replaced as an underground mining method by block caving using scrapers. Jagersfontein was the first mine to convert to block caving in the 1950’s and, following successful implementation here, caving became the method of choice in the Kimberley mines. Block caving was successfully employed as an underground mining method until the mid 1980's. Safety and profitability of the underground mines improved markedly.

As the mines moved deeper and technology improved the mines employed sub-level caving and vertical crater retreat mining methods with varying degrees of success, but returned to block caving using scrapers by the 1990’s.

Mining the Premier pipe as an open pit started in 1902. The pit was closed in 1932 at a depth of 189 metres. In 1947 the mine re-opened as an underground operation using open benching as the mining method. Four block caves using scrapers were introduced in the 1970’s and continued until the 1990’s. The Premier kimberlite pipe is unique in that it is cut a depth of between 480 and 520 metres below surface by a dipping 50 metres thick gabbro sill. Sub-level caving, sub-level open stoping, the Janelid method (analogous to an inclined cave) and block caving were all considered as mining methods. Sub-level open stoping was introduced in a trial mining block but, after failure of the method due to premature caving of the sill, the mine reverted to mechanized block caving in 1989, a method that is still being used.

5. Mechanised block cave mining

Block caving is generally considered the lowest cost underground mining method with mining costs approaching those of open pits once the high capital costs of installing the required mining infrastructure has been spent. The method is capable
of producing extremely high tonnages. Production from block cave mines throughout the world is currently estimated at 390 000 tons per day and is estimated to rise to 920 000 tons valued at US$ 23 million per day within the next 20 years as current caves such as El Teniente and Andina expand and other massive open pit such as Grasberg and Bingham Canyon move underground.

The principles of block caving are simple. Geotechnically it must determined that the orebody will cave, that the fragmentation reporting to drawpoints will not make the mining method uneconomic and that the stability of the mining infrastructure can be maintained throughout the life of the mining block. A slice of ore of sufficient areal extent is removed from the base of the mining block to induce caving. The ore caves and broken rock moves towards underlying drawpoints where it is loaded before moving through the rest of the ore transport system. Figure 1 illustrates the three dimensional geometry of mechanized cave layout. Figure 2 further illustrates the detail of the layout.

The major advantage of block caving is that it allows large ore tonnages to be moved by mechanised equipment at relatively low costs. El Teniente, currently the largest underground mine, produces 120 000 tons of ore per day from underground. Several mines are planning caves that will produce in excess of 200 000 tons per day. Quoted mining costs range from US$2-00 per ton to US$5-50 per ton.

Major disadvantages of block caving are the long time that it takes to gather information, plan and implement the mining systems. Implementation costs are high and must be spent at the start of mining on infrastructure and capital equipment. The history of several recent projects shows that the time it takes to implement a mine from information gathering through concept to full production is between 15 and 20 years. The cost of implementing a block cave to produce 20 000 tons per day is of the order of R11 billion. Costs are detailed in Table 1.

![3-D view of cave geometry](image1.png)

![Cave layout detail](image2.png)

Figure 1. 3-D view of cave geometry

Figure 2. Cave layout detail

Table 1: Costs of Block Caving
Table 1. Typical costs of taking a block cave underground – includes new treatment facility

<table>
<thead>
<tr>
<th>Area</th>
<th>Item Description</th>
<th>Item Total (rands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shaft System and Infrastructure</td>
<td>1,450,000,000</td>
</tr>
<tr>
<td>2</td>
<td>Underground Development</td>
<td>3,600,000,000</td>
</tr>
<tr>
<td>3</td>
<td>Underground Infrastructure and Indirects</td>
<td>1,100,000,000</td>
</tr>
<tr>
<td>4</td>
<td>Ore Processing</td>
<td>1,700,000,000</td>
</tr>
<tr>
<td>5</td>
<td>Surface Services and Infrastructure</td>
<td>460,000,000</td>
</tr>
<tr>
<td>6</td>
<td>Surface Buildings</td>
<td>330,000,000</td>
</tr>
<tr>
<td>9</td>
<td>Project Support Services (INDIRECTS)</td>
<td>2,300,000,000</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>11,000,000,000</strong></td>
</tr>
</tbody>
</table>

Table 1. Typical costs of taking a block cave underground – includes new treatment facility

Constraints on the mining method are:
- *Lack of competent, skilled, experienced people to plan, implement and operate these complex mines.* Historically most mines were operated by people the majority of whom progressed through the mining organization over an extended period of time and had in-depth knowledge of both the orebody and the mining method. Employment patterns are changing even as mines proceed to greater depths and become more difficult to mine.
- *The stresses associated with the caving process.* Block caving mining demands a detailed understanding of stress levels in, around and below the caving excavation.
- *Rock quality and strength of the ore and surrounding rock relative to the stresses.*

![Diagram of Axial Stress](image)

Figure 3. Comparison of Intact Rock and Rock Mass behaviour (after Villaescusa (2004))
Most volcanoclastic and pyroclastic kimberlite is weak rock. Figure 3 illustrates the concept that rock mass strength can be considerably less than rock mass strength. Increasing levels of stress with increasing depth make it increasingly difficult to maintain excavations in weak rock using conventional mechanized caving layouts.

- **Heavy support requirements to maintain the stability of the mining infrastructure over many years of mining in areas subjected to high and varying stress changes, LHD or scraper loading and extensive secondary drilling and blasting.** Increasingly intensive support is required to maintain the stability of excavations. Installing this support is expensive, time consuming and onerous.

- **Continuous secondary drilling and blasting operations to reduce ore to a manageable size before transport by LHD’s**

Automation of cave management provides an opportunity to improve the safety and profitability of caves by ensuring interactive draw, avoiding problems of early waste and water ingress and high stress concentrations. Effective utilization of loading equipment can be markedly improved as a consequence of increased availability.

6. Example 1. The Present: Cullinan Mine BB1E Mining Block

The BB1E mining block was the second mechanized cave planned and implemented at Cullinan Mine. Lessons learned from the first cave - the BA5 mining block - were implemented. An advance undercut mining sequence was used with limited development on the 732 extraction level completed and supported prior to the undercut on the 717 metre level above being advanced with a shallow V-shaped face shape. Figure 4 illustrates the undercut layout and Figure 5 the stresses associated with the advance undercut layout and mining sequence. Initially implementation went smoothly, but problems were encountered as water resulted in decomposition of the kimberlite in places and remnant pillars were left on the undercut level. Draw control was poorly implemented. An attempt to change the mining sequence to a pre-undercut resulted in unexpected stress problems and tunnels on both the undercut and extraction level were crushed. A recovery level was subsequently developed at considerable cost 15 metres lower down on the 747 metre level to access ore that would otherwise have been lost.

The concept of an advanced undercut has now been implemented to extend the BB1E towards the centre of the pipe. Only small vent tunnels are developed on the extraction level prior to the undercut being moved overhead. Once the undercut abutment has passed overhead development of the extraction level is done in the stress shadow using the concept of “technical limits” to ensure that extraction level development is done as rapidly as possible, cutting down on the time to bring drawpoints into production from 130 days to 60 days or less. Damaging stress effects are limited and a rapid production build-up results in improved financial rates of return.
7. Example 2: The Present: Finsch Diamond Mine Block 4 Cave

The Finsch pipe was originally mined as an open pit. The decision to proceed underground was partly motivated by the concern that diesel might no longer be easily available as South Africa was subject to increasingly stringent sanctions at the time. Electricity was nationally produced and cheap. As diesel became more freely available every effort was made to extend the open pit to greater depths and delay the capital expenditure required to take the mine underground. The open pit stopped mining at what was probably an economically sub-optimal depth of 423 metres. A shaft system and decline were developed to take mining operations underground using a blasthole open stoping as the mining method with the first underground ore produced from the 244 metre level.

A decision was made to change the mining method from blasthole open stoping to block caving as a result of inherent risk of dolomite sidewall and internal kimberlite failures.
In order to utilize existing infrastructure the extraction level for the planned cave was at 630 metres below surface resulting in an ore column height of 100 metres to the bottom of the open pit above. In order to maintain production whilst the block cave was being implemented a 20 metre slice was mined from the top of the column reducing the column height to 80 metres.

The Block 4 cave is using an advanced undercut mining sequence with production tunnels and stubs developed and supported on the extraction level prior to the undercut abutment moving overhead.

Development is carefully controlled and support is intense. A comprehensive cave management system is in place and the mine has implemented an automated trucking system to move the block cave ore from the LHD’s to the crusher, a new concept for De Beers.

The mechanized Block 4 cave is working well.

8. Example 3: The Future: Jwaneng Mine

The Jwaneng pipe was discovered in 1972. Open pitting started in 1979 and the pit is currently operating at a depth of some 380 metres. It is probable that the pit will be mined to a depth of 730 metres by 2020. Production thereafter might be from underground.

Figure 7. The Jwaneng Geological model

Both within the De Beers Group and internationally it has been shown that it can take many years to take mining operations underground or take existing underground operations deeper. Debswana has taken heed of this lesson. Exploration to delineate and evaluate the resource to a depth of 1200 metres is in progress. Conceptual work is also in progress to determine the optimum time to proceed underground.
Major considerations are:

- **Accurate delineation and evaluation of the resource at depth.**
  It might be necessary to sink a shaft for exploration purposes expeditiously to gather the required information for underground mine planning as it is proving difficult to drill core holes longer than 500 metres in kimberlite. The cost of delineation and evaluation to a depth of 1200 metres using core and large diameter drilling, geophysics and shaft access could be as high as R700 million and take 5 years to complete.
- **The ability to implement a block cave that will mine high tonnages at a depth of some 1000 metres below surface in weak kimberlite over an extended period of time**
- **The availability of trained, skilled and experienced underground and block caving mining personnel.**

Major geotechnical considerations are (after Brown E.T.)

- Optimum height of the ore column to be caved
- Will the cave propagate upwards through the full block height?
- Minimum thickness of the surface crown pillar required to allow simultaneous surface and underground operations
- For how long may open pit and underground mining be carried on simultaneously?
- The nature and extent of subsidence, its’ timing and its’ effect on surface and underground infrastructure
- Geotechnical hazards and their management
- Caving in deep, relatively massive rock masses could induce seismicity and **rockbursts**
- If caving propagation is arrested and a void is created, sudden failure of the cave back could cause an **air blast**
- Early **failure of the surface crown pillar** could jeopardise continuing open pit and underground operations
- **Surface subsidence** could influence open pit operations and surface and underground infrastructure
- The open pit could act as a catch basin for rainfall, increasing the risk of **water inflows** or **mud rushes** into the underground mine

9. **The future:**

Block caving in weak pyroclastic and volcanoclastic kimberlite at ever increasing depths is proving problematic. Moving to advance undercutting and increasing support specifications is expensive, time consuming and technologically challenging. Other methods of mining at depth in kimberlite are being considered.

9.1. **Superpits that mine to ever increasing depths.**
9.2. **Inclined caves**
9.3. Smaller tunnels are geotechnically more stable but curtail equipment size and productivity. Low profile equipment and even scrapers must be investigated.
9.4. **Roadheaders** represent new technology with the promise of faster development and less tunnel damage during development.
10. Conclusions

10.1. Diamond mining has contributed massively to the development of southern Africa since the 1870's. The Kimberley mines and Jwaneng must be rated as 2 of the most valuable mining areas ever found and exploited.

10.2. The mining history of the major diamond pipes has been dictated as much by world events, national politics, strong personalities and changes in technology as by economics and an assessment of risk.

10.3. Long term, strategic planning has often not been clearly defined.

10.4. As mines move deeper, become hugely capital intensive and geotechnically difficult to mine economics, risk perceptions, technology and skills will become deciding factors.

10.5. Many established mining groups are becoming increasingly risk averse.

10.6. Mining personnel are systematically addressing many of these problems.

11. References

