Argyle Diamond Mine – Geology and Mining of the AK1 Pipe, Kimberley region, Northwest Australia

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Abstract. The Argyle Diamond Mine, located in the northeast region of Western Australia, is known not only for its very large quantity of diamonds, which vary from brown to yellow and from near-colourless to colourless, but also for a small number of pink diamonds. Until the exploration in the Kimberley region, diamonds were known only in kimberlites. But the lamproite of the AK1 Pipe, established as the first major diamond mining operation in Australia, is richer in diamond than any known kimberlite. The ore grade is around 3.0 ct per tonne host rock, which is three to ten times higher than the typical grade. After twenty-four years of open pit mining, Argyle plans to pass into underground mining to extend the life of the mine to 2018.

1. Introduction

The Argyle mine is situated in the northeast part of Western Australia, approximately 120 km by road southwest of Kununurra, 540 km southwest of Darwin, and 2200 km northeast of Perth (Fig.1). Located in the headwaters of Smoke Creek in a small valley, which is the southeastern extension of the Ragged Range, alluvial diamond deposits occur along Smoke Creek and Limestone Creek draining the AK1 pipe to the north and northeast to the 35 km remote Lake Argyle. The first diamonds were found in these drains. Since 1895, gold prospectors first found diamonds. In 1979 an exploration team found the large, high-grade primary diamond deposit in an olivine lamproite.

Kimberlite has traditionally been considered to be the only important primary source of diamond (Scott Smith & Skinner 1984). In the early eighties lamproites are known also to be a primary host rock of diamond (Jaques et al. 1984). Kimberlites and lamproites are found as dikes or volcanic pipes less than 1 km² in horizontal area, a result of explosive diatreme volcanism from very deep mantle
derived sources. Diamonds in these rocks are accessory and older. Extremely high temperature and pressure are required, about 1000° C and 3.5 GPa, to form diamond rather than graphite from pure carbon. The approximate range of diamond genesis is 100 – 300 km depth. The diamondiferous layers are probably discontinuous in the upper mantle, because their formation requires the existence of a thick cold crust above (Mitchell et al 1991).

2. Geological Setting

The Kimberley Craton consists of a central core of a thick series of nearly flat-lying sedimentary and volcanic rocks that were deposited between 1.9 and 1.6 billion years ago and are underlain by a basement of crystalline igneous and metamorphic rocks. The Argyle lamproite occur at the northeastern extent of the northeast-trending Early Proterozoic Halls Creek Mobile Zone, near the point where the Mobile Zone is overlain by Lower Paleozoic sedimentary rocks (Mitchell et al. 1991). The Halls Creek Mobile Zone marks the eastern boundary of the Archean Kimberly Craton.
The Argyle lamproite is a 2-km-long, north-northeast trending, elongated, tilted vent (Fig.2). The lamproite intruded 700 million years after the main orogenic activity in the Halls Creek Mobile Zone along several well-established, intersecting faults and has been cut by several north-northwest and east-trending, high-angle faults with minor offset. The Vent is located 5 km west of the Halls Creek Fault, a major north-northeast-trending high-angle fault near the southern margin of the Halls Creek Mobile Zone (Mitchell et al. 1991).

Fig.2. Map and sections of the Argyle AK1 lamproite (Evans et al. 2000).
Lamproites are ultrapotassic magnesium-rich mantle-derived volcanic rocks with low CaO, Al₂O₃, Na₂O and high K₂O. Leucite, glass, K-Richterite, K-feldspar and Cr-spinel are unique to lamproites compared with kimberlites. Olivine, Ti-rich and low Al phlogopite are also components of lamproites. Diamond is not a main component and also not always present, but it is the only component which make lamproites important for economic evaluation.

The most common at Argyle are quartz-rich lapilli ash tuffs and tuffs devoid of quartz. The quartz in the tuffs was derived from disaggregation of sediments as the diatreme was emplaced.

Table 1. Mean major-elements chemical composition of the Argyle lamproite in wt% (after Mitchell et al. 1991).

<table>
<thead>
<tr>
<th></th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>44.0</td>
<td>3.40</td>
<td>5.29</td>
<td>8.02</td>
<td>0.14</td>
<td>19.7</td>
</tr>
<tr>
<td>Na₂O</td>
<td>5.27</td>
<td>0.16</td>
<td>3.92</td>
<td>1.25</td>
<td>4.83</td>
<td>2.69</td>
</tr>
</tbody>
</table>

The most olivine lamproites are post-tectonic and occur close to the margins of cratons such the Argyle one. They form from a small amount of partial melting in metasomatized lithospheric mantle and are generally emplaced in high-level, shallow “maar-type” craters (Pell et al. 1998). The magma ascents rapidly to the surface along areas of weakness, entraining fragments of the mantle and crust en route (Pell et al. 1998). These craters are irregular and asymmetric, often less than 300 meters in depth and with a diameter from a few hundred meters to 1500 meters.

Major Facies Groups

Lamproites can be dividing into four main facies groups: lavas; crater and pyroclastic; hypabyssal; and plutonic (Fig. 3) (Mitchell et al. 1991).

Lava Flow Facies

Many lamproite lavas cooled down during eruption and form glassy-to-porphyritic rocks. More voluminous lava lakes or domes cool slowly enough to form coarser-grained, holocrystalline lithologies. Lamproite lavas are characteristically vesicular and exhibit flow alignment of platy phlogopite phenocrysts as a main feature (Mitchell et al. 1991).
Crater and Pyroclastic Facies

This facies are the most important and texturally variable of all lamproite facies, as the Argyle Pipe is characterized by that, because diamondiferous lamproite vents belong to the crater facies. Pyroclastic or fragmental rocks in such vents have typically the highest diamond grade relative to host rocks and economic significance. The two dominant crater facies rocks of the Argyle vent are quartz-rich polygenetic lamproite ("sandy") tuff and quartz-lacking monogenetic lamproite ("nonsandy") tuff (Mitchell et al. 1991).

Hypabyssal Facies

Hypabyssal facies lamproites are dominantly massive and dense holocrystalline rocks, which may also form sills and dikes. They are formed by the in situ crystallization of intrusive bodies of lamproite magma. Fragmental hypabyssal facies lithologies may occur in the marginal contact zones of more massive intrusive bodies (Mitchel et al. 1991). Hypabyssal facies breccias may form by the incorporation of country rock xenoliths in lamproite magmas.

Plutonic Facies

Plutonic facies lamproites result from the relatively quiescent intrusion and crystallization of large volumes of magma in a near-surface environment (< 2-5 km depth) (Mitchell et al. 1991). Fragmental lithologies are limited to the outer margins of the intrusive body. Plutonic facies lamproites are coarser grained than hypabyssal igneous rocks.

Fig. 3. Schematic diagram (not to scale) illustrating relationships of lava, crater or pyroclastic, hypabyssal and plutonic facies lamproites in several idealized vent complexes. Also illustrated the appearances of lamproite vents after erosion of the maar crater. (after Mitchel et al. 1991)
3. Diamonds

Diamonds don’t occur in lamproites but are xenoliths that represent samples of the mantle occurring near, and overlying, the source rocks of these magmas. Despite their rarity, these samples contribute significantly to the economic and scientific importance of lamproites (Mitchel et al. 1991).

The diamonds in lamproites are considered to be xenocrysts and derived from parts of the lithospheric mantle that lie above the regions of lamproite genesis. The stability field of diamond formation is the harzburgitic peridotite and eclogite mantle region. A possible geologic model proposed by Boxer et al. (1989) make clear that the lamproite magma, which formed the AK1 pipe, rose within a zone of weakness in the crust along the mobile belt into overlying quartz-rich sediments. The interaction of heated magma with groundwater in these permeable sediments resulted in a series of volcanic explosions over an extended period of time (Atkinson et al. 1984).

Diamond is always older than its host rock. Radiometric dating of the lamproite rocks within the Argyle pipe indicates an emplacement age of 1.178 ± 0.047 billion years (Pidgeon et al. 1989). The diamonds themselves are age-dated at approximately 1.58 billion years (Chapman et al. 1996).

Diamonds are classified into two major groups, type I and type II depending on the presence or absence of infrared-detectable nitrogen. Type I diamonds are by far the most common in kimberlites, forming over 95% of the total population. Studies by Harris and Collins (1985) showed that Argyle diamonds are mostly type I stones.

Argyle diamonds are dominantly frosted and etched, irregularly shaped stones while macles or aggregates are subordinate. Dodecahedral or resorbed octahedral-dodecahedral forms are common in all Argyle stones. The dominant colour of all samples is brown with less than 20% yellow and colourless stones. Green and pink stones are rarely present but make the Argyle Diamond Mine as famous as no other diamond mine. The mean size is <0.1 carat (1 carat = 0.2 g) and the largest about 16 carats.

Origin

As mentioned earlier, diamonds derived from the upper mantle from the peridotite and eclogite region. Peridotite is an ultramafic and ultrabasic dense, coarse-grained igneous rock with dominantly olivine and pyroxene. Peridotite is the dominant rock of the upper mantle and of special interest, because they provide samples of the Earth’s mantle roots of continents from depth of about 30 km to 200 km. Adjacent to diamond isotope ratios of osmium and other rare elements are of special interest, because they record processes over three billion years ago and clues to the composition of the Earth’s early mantle.

Eclogite is a coarse-grained mafic metamorphic rock with red to pink garnet (almandine- pyrope) in a green matrix of sodium-rich pyroxene. Eclogite results
from high-pressure metamorphism of typically basalt or gabbro as it plunges into
the mantle in a subduction zone.

Peridotite and Eclogite are formed under high pressures of about 1.2 GPa and
more (45 km depth) at >400-1000°C and usually in excess of 600-650°C. The
most diamonds from eclogite xenoliths have a $^{12}$C/$^{13}$C isotope ratio different from
that typical of diamonds from peridotite xenoliths. The carbon isotopic differences
between harzburgitic and eclogitic diamonds supports the hypothesis that eclogitic
diamonds formed from basalt carried down within subduction zones. This
hypothesis of recycling of crustal carbon back into the mantle by subduction is
supported by the wide spread of oxygen isotope ratios in eclogite xenoliths from
Roberts Victor (Jagoutz et al. 1984).

Carbon isotope measurements of lamproite diamonds show a wide range of
$^{12}$C/$^{13}$C ratios. Hall and Smith (1985) reported $^{813}$C values for diamonds from
Argyle (between -7.5‰ and -11.1‰). An extensive study of about >70 stones by
Jaques et al. (1989) found that stones with eclogitic inclusions from Argyle are
markedly depleted in $^{813}$C (-5‰ to -16‰) and stones with peridotitic inclusions
ranging from -4‰ to -9‰ (mostly from -5‰ to -6‰). Primary inclusions in
Argyle diamonds are dominantly (>76%) of the eclogitic paragenesis. There is no
significant correlation of isotopic composition of the Argyle E-type diamonds
(eclogitic) with color, shape, inclusion composition, equilibration temperature, or
provenance within the pipe (Mitchell et al. 1991).

**Mineral Inclusion Suite**

Mineral inclusions in diamonds have been classified into two major groups;
peridotitic (P-type) and eclogitic (E-type), as said before. Syngenetic inclusions
reported in lamproite diamonds include olivine, Cr-pyrope, Cr-diopside, enstatite,
Cr-spinel, almandine-pyrope, omphacitic clinopyroxene, coesite, rutile, pyrrhotite,
kyanite, ilmenite, and moissanite. Probable epigenetic inclusions include
orthoclase, phlogopite, talc, calcite, quartz, hematite, magnetite, chlorite, anatase,
rutile, kaolinite, and rare priderite.

Jaques et al. (1989) recognized a correlation between diamond crystal
morphology and mineral inclusion type in Argyle stones. Sharp-edged octahedral
stones with etched and frosted surfaces contain only peridotitic inclusions and
resemble diamonds recovered from peridotitic xenoliths at Argyle. In contrast,
rounded, resorbed, dodecahedral stones contain eclogitic inclusions (Mitchell et al.
Diamondiferous or Nondiamondiferous?

It is very difficult to distinguish diamondiferous from nondiamondiferous host rocks. There are no macroscopic features for differentiation. The most favorable conditions in the lithosphere for diamond formation are in regions of low heat flow, i.e. where the geotherm is lower than average. Areas of lower than average heat flow occur in two tectonic regimes; subduction zones and below stable shield areas. Lamproites and other intrusions with very deep magma sources sample material on their way to surface (Fig. 4).

![Fig. 4. The diamond stability window in the mantle lithosphere produced by the downward deflection of continental geotherms. The path of a kimberlite/lamproite magma travelling through this window (red) will sample diamonds and diamond indicators. The other intrusion (blue) will not sample.](image)

It is not possible to determine whether the lamproite or other intrusion sampled material from within the diamond stability window by using the compositions of indicator mineral grains alone. Fig. 4 shows that the red intrusion will have traveled through the diamond window and sampled both diamonds and mantle indicator minerals which record a 900-1200°C temperature range. The blue one will sample mantle indicator minerals with mantle compositions but the recorded temperatures will be much higher, indicating that the magma did not sample material from the diamond stability field. This information about the maximum temperatures can be used to determine whether the magma may traveled through the stability window of diamond or not.

Various minerals including Mg-Cr garnet are used to characterize the diamond potential of an intrusion. The exchange of trace-quantities of Ni from olivine into the garnet structure is temperature dependant. So, the Ni-content of garnet can be used as a single mineral thermometer (Barnes 2004). Garnet has also a high affinity to heavy rare-earth elements (HREE), from europium (Eu) to lutetium (Lu). Garnet which has grown and been in the mantle for long periods should have heavy REE enriched patterns and should show little or no REE zoning. If such minerals will then exhume quickly, they will preserve this REE pattern. This method can used to determine whether the magma ascends quickly or not, which is important for diamondiferous intrusions.
4. Mining

Adjacent to the AK1 Pipe there is an associated alluvial deposit as a result of erosion of the orebody. Diamonds are distributed along the entire length of Smoke Creek which drains the pipe to the north. This alluvial deposit contains a range of diamond qualities and sizes, which vary with the distance from the source and the degree of erosion and is known as the secondary deposit of the Argyle diamond pipe.

Mining of the alluvial and surface deposits began in 1983 and by the end of 1985, more than 17 million carats of diamonds had been produced. The mining of the AK1 pipe began with expectation that the mine would produce 3 million tonnes of ore and as much as 25 million carats of diamonds each year. At the beginning of the year 2000, the remaining proven ore reserves at the Argyle pipe were 61 million tonnes of lamproite ore with an average grade of 2.9 ct/tone.

Drilling and blasting are used to break up the overburden and ore, which is overlain by hills of the Matsu Range. The open pit is 2 km long, 1 km wide and covers an area of almost 300 hectares. To widen the pit, it was necessary to cut back the sides of these hills at a specific angle (for stability). Large excavators then load the material into a truck for transporting either to the processing plant (if it is ore) or to the waste storage area (if it is overburden). Since production commenced in 1983, over 670 million carats of diamond have been produced, with a peak of 42.8 Mcts in 1994 (Fig. 5). The production consists of 5% gem and 70% near gem with the remaining of 25% being industrial diamonds.

The end of the open pit is probably 2008, so the underground option was proposed to complement the possible low grade open pit expansion and to extend the life of the mine as far as 2018.

Between 60 and 80 million tonnes of material is currently extracted from the open pit including between 25 and 30 million carats of diamonds. With the pass into underground mining, diamond output will fall to around 50% of current capacity.
References

Mitchell Roger H., Bergmann Steven C (1991) Petrology of Lamproites
Pohl Walter (1991) Lagerstättenlehre
Shigley James E., Chapman John, Ellison Robyn K. (2001) Discovery and Mining of the Argyle Diamond Deposit, Australia

http://www.mining-technology.com/projects/argyle/