Prospecting for Diamonds in South Africa
在南非的鑽石勘探

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作者簡介南非的天然鑽石開採歷史，並敘述該地的鑽石勘探所涉及的地質情形、勘探情況、評估、處理和篩選程序。

What drives the urge for prospecting? Essentially man's will to discover and an instinctive drive for "treasure hunting".

Earth is an extraordinary planet filled with marvels of nature including beautiful gemstones for which man has an innate almost insatiable desire. The most priceless of these is diamond, which is not only the hardest natural mineral but has many other extraordinary attributes that offer a variety of uses other than just that of a 'luxury' item of adornment. The known properties of diamond are truly amazing and extend to thermal, optical and quantum, mechanical, electrical, chemical and biological sciences; applications all beneficial to mankind. We are probably at the tip of the iceberg in terms of the discovery and application of its uses – but this is a topic that merits another whole article.

Natural Diamonds

Testing has shown the age of natural diamonds to be >990 Ma.[Million years] (Kirklye, M.B., Gurney, J.J., & Levinson, A.A. (1991) Age, origin and emplacement of diamonds: Scientific advances in the last decade. Gems & Gemology, Spring, 2-25) That's greater than 990 million years old – indeed much older, given that certain diamond pipes such as at the Cullinan mine have emplacements dating from 1.3 to 3 billion years ago. It is extraordinary to think that the natural diamonds that we see in engagement rings, and other jewellery worn by people just walking along the streets each day, carry the information and experiences of billions of years of life on this amazing planet!

Indeed, diamonds are treasures beyond our wildest dreams, and this is why the urge for prospecting for diamonds has always been so great. The first diamonds that were discovered and made famous were from Golconda in India in the 16th Century. The most famous of these was the Tavernier Blue, a Type IIb of 115 carats, which was bought by King Louis XIV of France. Most other Golconda diamonds were Type IIa, of magnificent quality including exceptional diamonds such as the Koh-i-Noor, the Great Mogul, the Wittelsbach, the Regent, the Orlov, the pale pink Daria-i-Noor and the Dresden Green[1].

It was in 1869 that the first diamond, "The Eureka", weighing 21.25 carats, was found in South Africa on the banks of the Orange River. Later in 1871, a diamond of 83.5 carats was discovered at Colesburg Kopje spurring a 'Diamond rush' to the town. And 'rush' is not an exaggeration – as in March 1927, near Lichtenburg in South Africa, 25,000 runners took part in a race, to peg their claims in the largest public diggings mined until that date.

Geology

Diamond forms at depths of 120 km and more below the earth's surface. This is what is termed the 'diamond stability field' as it is at these depths that the high temperature (around 950°C) and pressure (around 4.5 GPa) conditions exist for the formation of diamond crystals. These are then brought to the surface by geothermal activity in the magma, which is forced up and pierces the earth's surface where there are weaknesses in the crust.

Consequently, the surface geology is generally not indicative of where such a volcanic eruption may occur, creating, when it does, a ***Primary Source*** of diamonds. These are named "Kimberlite pipes" after the town of Kimberley, the site of the first recognised occurrence of such an eruption. They contain a host rock formed from the magma transporting the diamonds and other molten magmatic rock to the surface.

Footnote 1: The descriptions containing the word "Noor" mean "Light".

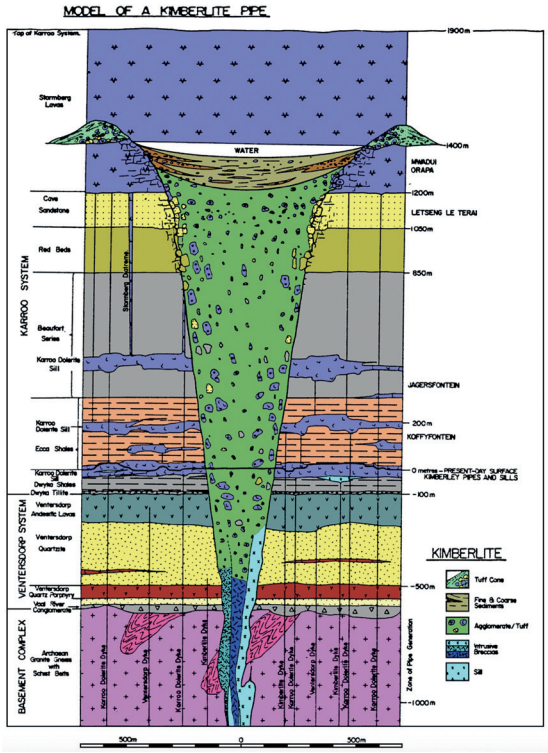

Fig. 1 Hawthorne's 1975 model of a kimberlite pipe. *(Hawthorne, 1975)*
Hawthorne 1975年著作的金伯利岩管模型

Diamonds from ***Secondary Sources*** have been eroded away from the kimberlite pipes by forces of nature, notably water and glaciers, and have generally been washed into ancient river systems. At certain points in South Africa there may have been as much as 1 kilometre of kimberlite pipe eroded from the surface of the primary source and washed into the river systems. So in principle, there are still a lot of alluvial diamonds to be discovered.

A study of the geomorphology of a region is a great help to the prospector in seeking out features of ancient river systems. It is often important to note that the best concentration of diamond in these ancient river systems took place under tropical conditions rather than the more arid climates that now characterise southern Africa and India of today. At various times since the break-up of Gondwana and the Cretaceous Period, there have been radical changes in climate, and those periods of very high rainfall, such as the Eocene and early to middle Miocene, appear to have been times of considerable erosion of kimberlite and the concentration of diamond in contemporary rivers. Partial erosion of these drainages during arid periods, combined with continental uplift, have brought about radical changes to the direction of flow of the early river systems as well as preserving sections of them under desert sands. It is these buried river deposits, these remnants of former drainages, that give cheer and excitement to the avid diamond prospector.

Alluvial Gravels containing diamonds may contain rounded pebbles, worn by ancient rivers or oblong pebbles washed by ancient seashores.

Of further interest is that ancient riverbeds may be found on the tops of hills formed by a process of ***twin lateral*** erosion, where streams on either side of the riverbed erode the riverbanks resulting in the bedrock ending up, over time, on the top of a topographical high point[2].

Discovery – Primary Sources

Primary source discovery differs from secondary given the irregular occurrence of these kimberlite emplacements over the surface of the earth. Hence, in addition to identifying general indicator minerals, the means of detecting kimberlites has been the use of geophysical surveys to detect geomagnetic anomalies, gravitational anomalies and the use of radar.

Payable primary sources, however, seem to be governed by what has been termed the "Clifford Rule" proposed by T.S. Clifford in 1966, which states that payable kimberlites will be found on Archaeon cratons, the oldest land masses on the planet with formation dating back from 2.5Ga to 4.5Ga ago. The general idea is that the thickness of the craton permits the diamond to travel to the surface at temperatures and pressures sufficient to prevent diamonds turning to graphite. There are exceptions to Clifford's rule, notably the Argyle mine in Australia, which is a lamproite and some lamprophyres; the geological origin probably being plate tectonic subduction.

Of the world's kimberlites only around 10% contain diamonds and of those, only about 4% contain diamonds in payable quantities, bearing in mind the costs of extraction. That means that only 0.4% of kimberlites in the world are payable — a very small fraction indeed.

Generally, common to both primary and secondary sources are the indicator minerals which have made the journey with the diamonds from deep

Footnote 2 Note: There is still some debate as to whether the rivers previously flowed North-South or South-North and whether glaciation played a role.

below the earth's surface and these include pyrope garnet, chrome diopside, olivine and picro-ilmenite.

When my great-grandfather discovered the Premier Mine in 1902 on which the magnificent Cullinan Diamond (3,106 metric carats) was discovered in 1905, geomagnetic and gravitational anomaly data were not available to the prospector. It was the "in situ" discovery of a blue white diamond against the fence of the farm called "Elandsfontein", which led him to believe that there could be a pipe there.

Prospecting Rights

Until recently, rights to the land contained both surface and mineral rights. However today, in most countries, the mineral rights are owned by the State and prospectors have to apply for leases over the land they wish to prospect.

Prospecting applications are generally required to include the prospecting programme as well as environmental approvals regarding the use of water, any disruption of land and vegetation and plans for rehabilitation after the prospecting work has been completed. Usually a financial rehabilitation guarantee is required in advance of any license being granted.

Indicator Minerals

To put indicator minerals into context, we have to consider the geological processes that brought them to the surface, which is an extremely complex topic that includes geothermal and magmatic activity.

It is John Gurney and his team of Mineral Services in Cape Town who have conducted the most recent pioneering work in indicator mineralogy. His work, on the use of garnets as an indicator mineral for payable kimberlites, centred on the analysis of the composition of calcium and chromium in garnet and initially discovered that G9 and G10 pyrope garnets are associated with payable perioditic kimberlites. (Fig. 2) Pyrope is the only member of the Garnet family always to display a red colour.

Aside from the composition of garnet established by microprobe, an analysis of the physical appearance of garnet is particularly useful to the prospector to determine distance travelled from the source (i.e. the appearance of percussion marks or abrasion owing to travel). Garnets are softer than diamonds and do not generally travel far without breaking up, so that primary sources can be pinpointed by this method to within 2 km of the source. Soil and stream sediment sampling is used to obtain the indicator minerals for laboratory and visual analysis.

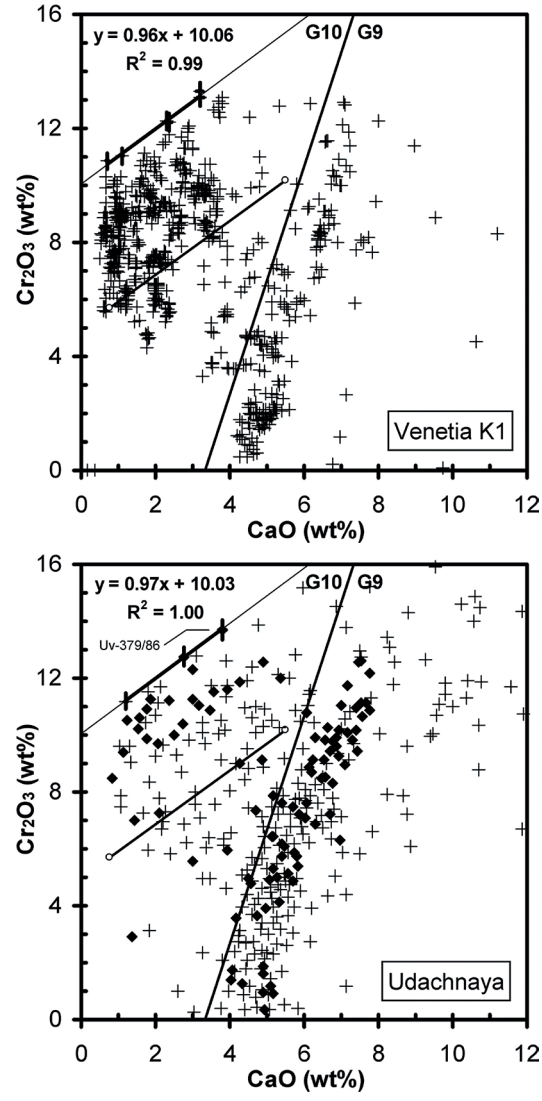

Fig. 2 Calcium Chromium plot of G9 and G10 Garnets at Venetia and Udachnaya. *(Grutter, Latti, Menzies, 2006)*
韋內齊亞和烏達奇內的G9和G10的柘榴石和氧化鉻比例圖

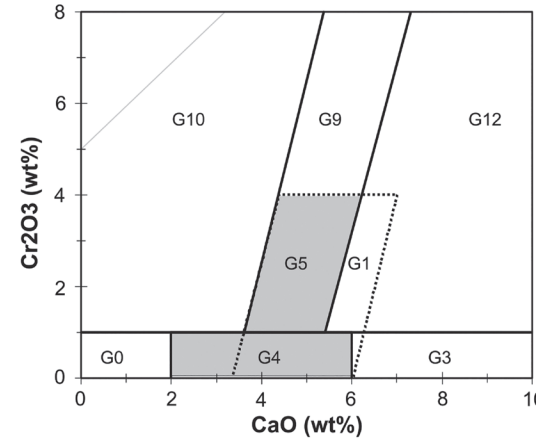

Fig. 3 Graphic analysis of garnet indicator classes. *(Grutter H., et al, 2004)*
柘榴石指示的圖形分析

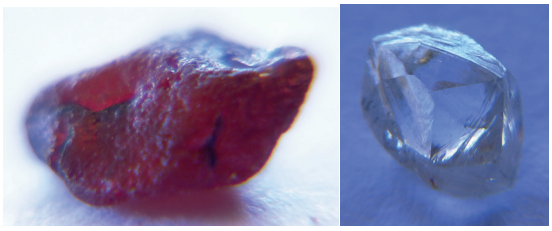

Fig. 4 G9 garnet with 'orange peel' skin associated with payable peridotitic kimberlites and found with the diamond represented here. *Photos: the author*
G9帶有"橘皮狀" 皮殼的柘榴石，其形成與橄欖岩金伯利岩有關，並與該地區的鑽石一起被發現。

Fig. 5 Typical "Rooikoppie alluvial gravels".
Photo: the author, August 2016
典型的"Rooikoppie沖積礫石"

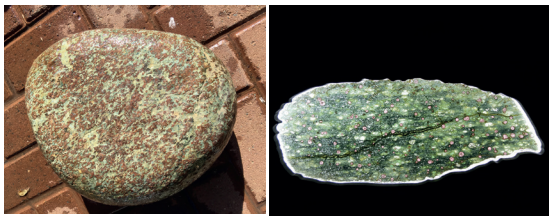

Fig. 6 Eclogyte and thin section of an eclogite, "Messengers from the Mantle" exhibition, 35IGC, 2016.
Photos: the author, August 2016
榴輝岩層及榴輝岩薄片

It has been shown that G9, G10 and G12 garnets are associated with Perioditic emplacements (and are magnesium and chromium rich), and Harzburgite, Lherzolite and Wehrlite 'xenoliths' (rock), respectively. G3 garnets are calcium and iron rich and are associated with Eclogytic emplacements; the more metasomatised eclogytes are thought to be diamond bearing. (University of Cape Town, Geological Department, 2016.)

At depths below 240 km, iron-nickel phases are present and diamonds may contain metal inclusions and majorite, a form of garnet with excess silicon. Much work is currently being done on 'deep carbon' by a group of around 1,000 world-class scientists investigating the origins of carbon in the earth to understand global warming.

A paper in Science Magazine (Smith, Shirey et al, 2016) was a watershed in terms of understanding this subject. In this article they proposed that these 'deep carbon' diamonds be termed "CLIPPIR" diamonds, an acronym for "Cullinan Like, Inclusion Poor, Pure, Irregular shaped and Resorbed" to describe the type and nature of these diamonds which are of very high quality. It is thought that these diamonds come to the surface in eclogitic emplacements, which had their origin in the subduction of tectonic plates containing carbon in basalt and other organic forms. The proposition is that the eclogitic carriers of the deep carbon diamonds, coming from depths of up to 800 km below the earth's surface, produce notably large gem diamonds.

Drilling, Pitting, Trenching

Prospectors will drill in order to determine whether an area contains a diamondiferous resource bearing alluvial gravel or kimberlite. Percussion, reverse-circulation or Auger drills, each of which have their own merits, may be used. Drill spacing and positioning will depend on the geological features; but not so far apart as to miss an ancient paleochanel or oxbow of a river. Drilling is reasonably accurate in the case of a fixed kimberlite body. However, for alluvials, estimations of what is below the surface are notoriously difficult to make with any level of confidence and so opening pits and trenches will reveal considerably more of a potential resource.

Evaluation

Having discovered the location of a prospective deposit, the prospector's next challenge is to process a sufficient quantity of ore in order to establish the average grade of the deposit. The payability (economic viability) of a deposit is determined by the grade multiplied by the price per carat.

♦ Grade

Grade is a measure of the number of carats recovered per measure (usually per 100 tonnes). In alluvial deposits, diamond quality may be high, because poor quality diamonds often do not survive the journey down the river system. If the quality is high, the grade can be as low as 0.5 cpht (carats per hundred tonnes) for the deposit to be payable.

In primary deposits, the grade would normally have to be about 60 cpht and in the higher-grade deposits it can be up around 180 cpht.

♦ Price per carat

A low-grade deposit can be payable if the price per carat is high. Unusually, both the Letseng diamond pipe in Lesotho and the Karowe AK6 pipe in Botswana have particularly low grades, at around 2 cpht. However, both are very profitable mines having a high occurrence of very large diamonds with exceptionally high price per carat values; the value per carat increasing exponentially as the size of the stones increases.

In order to establish both of these parameters, it is necessary to undertake a bulk sample, which would involve processing at least 50,000 to 100,000 tonnes of ore or obtaining at least 5,000 to 10,000 carats of diamonds from an alluvial deposit for assessment. In terms of the requirements for listing a public company, the criteria are so stringent that an alluvial deposit would necessitate sampling at least 10% of the deposit.

Resources & Reserves

Resources need to be defined in order to estimate the size, nature, capacity and cost of a potential mine. The difference between the two terms is that Reserves, which are further classified into Probable or Proven, are more certain than Resources, which are much more of an estimate. Resources are further classified into Inferred, Indicated and Measured as the geological knowledge and confidence increases.

Processing Methods

In order to liberate diamonds from the host rock, the rock must be crushed, scrubbed and screened. Alluvials are less likely to require crushing, unless the gravels are contained in a hard conglomerate rock. Otherwise, scrubbing usually involves passing the ore through a horizontal rotating barrel, which uses the collision of the rocks as a way of breaking them down. The next step would be classifying the size through screening into different size fractions.

Fig. 7 Mark and his colleague Baxter with pan plant in the background. *Photo: Mike de Witt*
作者和他的同事Baxter攝於處理機械前

Kimberlite, unless it has weathered (and kimberlite weathers quickly when exposed to the elements) is pretty hard and requires crushing. Typically in jaw crushers, the width of the jaws needs to be carefully calibrated; not too narrow, which would risk large stones being crushed, and not so wide that smaller diamonds could be lost into the tailings.

Liberation and Separation

Next, the specific gravity of diamond is used to reduce the throughput of the ore by separating the heavy material from the light to reduce processing volume and cost. In this way, the material is reduced to a concentrate. Diamond, with a specific gravity of 3.52 will report to the heavy side and consequently separation methods use the same principle as panning whereby the light material is floated off. The liberated rocks are mixed with water in the pan (In alluvial mining 14' rotary pans are common) and the concentrate containing diamond is tapped off from the bottom of the pan. Another method, largely used in treatment of kimberlite is Dense Media Separation (DMS), which uses ferrosilicon to float off material that is lighter than diamond. This process utilises a cyclone to spin the material, adding centrifugal force in order to achieve this result. In certain deposits that contain a preponderance of metallic rocks, such as banded ironstone, magnetic separation may be involved in a processing plant.

Sorting

Having finally produced a concentrate from the processing plant, other properties of diamond are used for the recovery of diamonds from the concentrate. In the field, while prospecting, old-fashioned methods of sorting by hand are frequently used.

Fig. 8 The author and his colleague, Baxter, sorting concentrate manually. Kimberley prospect, 2008. *Photo: Neil Cullinan*
作者和他的同事Baxter正在人工篩選從機械所結集的鑽石原石料

Fig. 9 Grease table sorting
Photo: the author, August 2016
油脂平台篩選鑽石

Fig. 10 X-ray Sortex Machine (note the locks for security!).
Photo: the author, 2016
X-射線篩選儀器

Many sorting plants use forms of X-ray sorting, detecting the diamonds in the concentrate by their fluorescence. Most diamonds fluoresce to some degree although some, notably Type IIb, which includes highly valuable blue diamonds, don't. Hence, some plants have resorted to the old fashioned 'grease tables' as a secondary sorting procedure. This uses the anhydrous property of diamond that repels water and sticks to grease. This has always been an effective way of sorting concentrate – although is not the most secure as it lends itself to theft. Monitoring grease tables is a full time task!

Recently, however, the use of another form of X-ray has presented itself; XRT or X-ray Transmission, notably in a sorting machine manufactured by 'Tomra' of Norway. Such machines cost as much as US$1m, whereas the Sortex mentioned above costs around US$500,000. However, if this process prevents the loss of just one important and valuable diamond, the price of a more expensive machine will have been justified. XRT uses the principle that X-ray passes through Carbon and not through the other materials in the concentrate. Consequently, diamond can be singled out for selection from the concentrate by the pulse of an air jet. A number of large diamonds have been discovered in the past couple of years by this XRT method, which represents a very exciting development.

Conclusion

Hence, the process of prospecting, in order to verify a definitive resource that contains a payable supply of diamonds, involves cost, risk and many involved processes, utilising the unusual properties of diamond, to make an evaluation of the viability of establishing a mine. However, that has never deterred the avid prospector from following their dreams and going to extraordinary lengths to discover fame and fortune!

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