IDENTIFICATION OF GLOBAL DIAMOND METALLOGENIC CLUSTERS TO ASSIST EXPLORATION

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Abstract

Of the approximately 6,500 kimberlites known to date, less than 3% are diamondiferous and less than half of those are economically viable. Admittedly, this is a global figure and varies from area to area much depending on geological, logistical, and political circumstances. The number of diamond-bearing kimberlites is an important geobarometer, and an age-frequency profile has been compiled in order to identify diamond metallogenic epochs and provinces. Four primary diamond clusters have been recognised: Siberia (332-370Ma), Kaapvaal South (114-144Ma), Kaapvaal Southwest (84-95Ma), and Slave (52-55Ma). In addition, three secondary clusters are the Kaapvaal Central (506-538Ma), the Man Craton (139-153Ma) and the Kasai Craton (120-130Ma). The Kaapvaal is the only area where kimberlites with diamonds were discovered between 1870 and 1925, except for the Prairie Creek discovery in North America in 1906 and Colossus in Zimbabwe in 1907. Between 1906 and 1940 no major diamondiferous kimberlites were discovered, but many of Africa’s alluvial deposits were found and exploited in that period. Advances in scientific prospecting in the 1940’s rapidly accelerated the discovery rate that peaked in the 1980’s; 39 diamondiferous occurrences were found in the 1980’s, of which 8 became mines and 5 are in feasibility, and nearly 450ha of kimberlite was added to the global resource base. Despite the accelerated exploration expenditure, the last decade (e.g. 2000-2009) has been the leanest since the 1940’s. The most important reason for this decline in exploration success is that any undiscovered deposits are largely buried by younger cover. Understanding complex and geophysical noisy basement geology, as well as decomposition of path-finder minerals are major challenges to further exploration success. Major investments in basic geological expertise and field research will have to be made in order to secure future diamond resources. Integrated geophysical studies, geochemistry diamond forensics, and improved imaging of Earth’s upper mantle are perhaps foremost in this requirement, but the costs of these activities are such that government support will be required if countries are to sustain their diamond mining industry.

1. Introduction

There are now over 6,500 kimberlites and related rocks identified on a global scale (Tanzania 300, Russia 1200, South Africa >850, Botswana 250, North America >800, Australia 450, Angola 600, DRC 60 etc.) (e.g. Heaman et al. 2004, Wilson et al. 2007). Since certain prospective areas have not been fully explored and since technology is continuously improving there are probably many more that have not been found. Of this only just over 3% are diamondiferous and less than 1% have turned into economic mines. Many publications deal with emplacement history emphasising structural control (e.g. Bardet 1974; Friese 1998; Vearncombe and Vearncombe 2002; Jelsma et al. 2004) and/or specific geological time periods of eruptions.
of kimberlites (Heaman et al. 2003; Jelsma et al. 2004, 2009) and/or economic kimberlites (e.g. Kjarsgaard 2007). The feasibility of exploiting kimberlites does not depend only on the quality and concentration of diamonds but perhaps as much on socio-political criteria. Geologically the presence of diamonds relates to the amount of diamond-bearing eclogite and peridotite lithospheric mantle material sampled and to the degree of resorption and mechanical sorting during kimberlite emplacement (Kjarsgaard 2007). In addition, dilution by the host rock (e.g. Koffiefontein, Voorspoed – Karoo; Premier – Gaabro dyke) and thickness of crust and cover sequences over kimberlites (e.g. Jwaneng, Gope, Sytykanskaya and Nyurbinskaya) influences the feasibility of each project.

A global database, based on published information, has been constructed that includes kimberlites and lamproites with grades equal or exceeding 1 cph (carats per one hundred metric tonnes) and where the diamonds are classified as macro-diamonds (>0.5mm).

Here I present an age-frequency model of these mineralised kimberlites and related rocks that includes over 200 diamond-bearing intrusions from all continents. The objective is to identify and analyse frameworks of primary diamond occurrences. Details of the discovery history of the diamond-bearing kimberlites have also been determined and together with better defined regions and periods where and when diamonds were brought to surface. This provides additional insight as to where future exploration should be focussed to improve discovery success. This is critical in view of the growth in demand and decreasing supply of natural diamonds.

2. Age-Frequency distribution model

Age-frequency distributions provide important information on ore deposits in space and time (Kesler and Wilkinson 2006). By defining metallogenic provinces (areas characterised by a particular assemblage of mineral deposits) and metallogenic epochs (geological periods during which notable ore formation took place) on a global scale is it might be possible to identify their origins (Wilkinson and Kesler 2009). With the imminent global shortage of the supply of rough diamonds (Kilalea 2009, Sterck 2009) it is extremely valuable to predict where future ore bodies could be found. Research on features and processes that control the formation of ore deposits in both space and time should also be accelerated if improvements in supply of rough diamonds through exploration are to be realised in the future.

Kesler and Wilkinson (2006, 2007) show that variations in the age-frequency distributions for epithermal copper, porphyry copper and orogenic gold deposits, which form in convergent margins at successively deeper crustal levels, are largely related to the levels of burial and uplift.

Age-frequency patterns for deposits that form at shallow and deep levels in the same geological environment differ due to exhumation. Ore bodies formed at deep levels have an age-frequency patterns characterized by relative few or no young deposits, increasing to a maximum and then a general decline in number of deposits of increasing age (Fig. 1B). Ore bodies emplaced at shallow depths or at surface (e.g. kimberlites and related rocks) are characterized by young deposits with a general decrease in numbers over time (Fig. 1A).
Wilkinson and Kesler (2009) conclude that anomalous epochs and metallogenic provinces for porphyry copper deposits can be defined as those periods and areas where the number and volume of ore is significantly different from the average rate of formation and preservation. They also found that statistically the distribution of these deposits in both space and time is by and large unpredictable, mainly because of the poorly understood complex nature of mineralisation processes under which most ore deposits form (Wilkinson and Kesler 2009). Hence a sound geological knowledge of the ore forming processes is absolutely critical to fill the gaps that still exist if we are to more reliably predict the positions of ore bodies.

Finally improved dating techniques of mineral deposits have greatly improved the estimates of erosion and Kesler and Wilkinson (2007) found that these rates, which ultimately affect the temporal pattern of ore deposits, agree closely with exhumation rates estimated using other methods.

The objective of this paper is to apply the philosophy of Kesler and Wilkinson (2006 and 2007) and Wilkinson and Kesler (2009) to primary diamond deposits and to identify its metallogenic provinces and epochs. Kesler and Wilkinson (2006) have shown that the temporal distribution of ore deposits along converging margins is controlled largely by exhumation. By testing the same philosophy it was hoped that a better understanding of the spatial and chronological relationship of kimberlites and lamproites is achieved. According to Clifford’s rule, mineralised kimberlites are found exclusively on stable ancient cratons (Clifford 1966). Westaway et al. (2003) have shown that thicker lithosphere, lower heat flow and a more brittle lower-crustal layer in Archaean cratons generally reduces vertical crustal motions compared to younger crusts. The exhumation rates on stable ancient shields will therefore be different to that of active converging margins.

The relationship between emplacement ages and kimberlites (Jelsma et al. 2004, Jelsma et al. 2009, Moore et al. 2008) or economic kimberlites (Heaman et al. 2003, Heaman et al. 2004, Kjarsgaard 2007) has been reported on. The former are focussed mainly on southern Africa and the Phanerozoic, and the latter on North America. Economic kimberlites are however artificially constrained since mining costs are directly linked to logistical (accessibility, infrastructure, climate etc.), political and legal requirements driven by environmental, labour and social legislation and these will differ from country to country. At present a mine in Botswana for instance can be mined with a working cost of around 15US$/ton, whilst in Canada this is closer to 40-50US$/ton and in Siberia this is even higher. So using economic kimberlites in an age-frequency model would not provide a consistent model but would be skewed towards the lower operating environments where relatively speaking more mines would be feasible.

The fact that some kimberlites and related rocks are mineralised indicates that they have sampled those parts of the mantle where diamonds are stable with the pressure and temperature conditions conducive for diamond growth and preservation. It also means that those intrusions were able to preserve the diamonds wholly or partially during transport to surface. Geologically the presence of diamonds in kimberlites and related rocks is therefore highly significant. The primary requirement for entry into the database is therefore that the primary host rock is mineralised in the same way that Wilkinson and Kesler (2009) focuses on pregnant fluids in their study of the epithermal gold or porphyry copper deposits.

Kimberlites have been mined with grades varying from 2 to 600 carats per hundred metric tons (cph) which equates to 4ppb to 1.2ppm of diamond respectively. The minimum cut-off grade in this study is for a kimberlite to have a grade of at least 1 carat per 100 tonnes (or 2ppb). Anything less than this would at present even in to most favourable operating environments be regarded as uneconomic. In addition the diamonds used for these grades would have to be present as macro-diamonds or stones above 0.5mm in size.
The database has been set up to reflect the year that each diamond bearing kimberlite/lamproite was discovered, its surface area in hectares (ha), age of intrusion (Ma), average grade (cpht), discoverer, years mined and petrographically to which group it belongs (Group 1, Group 2, Lamproite).

Kimberlites have been grouped into clusters, fields and provinces by Mitchell (1986). According to Kjarsgaard (2007) individual kimberlites in kimberlite clusters are closely grouped together and form over time intervals of approximately 1 to 5 Ma. Kimberlite fields usually form over time intervals of some 10 to 30 Ma, whilst kimberlite provinces may have kimberlites that form over a much wider span of emplacement ages. The assumption has therefore been made that individual kimberlites occurring in the same cluster are of similar age. Information has been obtained from well over 150 scientific publications often linked to individual occurrences, and websites of various exploration and mining companies. Age data on kimberlites has been assembled from published information using a variety of different dating techniques such as Rb/Sr, 40Ar/39Ar and U/Pb.

Weaknesses have been recognised like for instance inaccurate historical data in South Africa, or different evaluation thresholds for kimberlites in Russia. Individual intrusions in clusters have been counted separately where appropriate. Russia is probably not as well represented as for instance South Africa or Canada where many smaller kimberlites have been included in the database. In Russia the cut-off value per tonne to mine kimberlites is much higher than in other parts of the world and hence many diamond bearing bodies are either unknown or have not been evaluated in detail.

4. Introduction of diamonds through time
Diamonds have been part of the earth's history for a long time. Dating of inclusions from diamonds from the Udachnaya pipe in Russia (3.5 Ga, Pearson et al. 1999, Shirey et al. 2002), the Panda pipe in Canada (3.5 Ga, Westerlund et al. 2006), from Wellington in Australia (3.4 Ga, Pearson et al. 1998) and the Finch and Kimberley pipes in South Africa (3.2 Ga, Richardson et al. 1984), have shown that diamonds have been in the mantle since at least 3.5 Ga (Stachel and Harris 2008).

The ages of diamond-bearing kimberlites range from the Archaean meta-kimberlites in Gabon (2850, Henning et al. 2003), through to Proterozoic kimberlites in Australia (1900 Ma Nabberu and Brokman dyke; 1300 Ma Jewill; 800 Ma Maude Creek and Seppelt) (Shee et al. 1999, Wyatt et al. 2003, Jaque and Milligan 2004, Reddycliffe et al. 2003), Botswana (1333 Ma Leralo) (Woodhead et al. 2009), South Africa (1180 Ma Premier Group) (Wilson et al. 2007), Brazil (1150 Ma Salvador) (Watkins 2009) and Canada (1076 Ma Kyle) (Heaman et al. 2004). The 1.76 Ga old Kinozero kimberlite from the Zaonezhskoe kimberlite field of central Karelia in Russia (Ustinov et al. 2009) has been found to be diamond-bearing but only with micro-diamonds (10 – 100 microns) (Kulikova et al. 2008), and it and other bodies like this have therefore been excluded from the database.
Diamond-bearing lamproites of Proterozoic age occur in West Africa (1429Ma Bobi – Ivory Coast) (Bardet 1974), Australia (1175Ma Argyle) (Pidgeon et al. 1989) and India (1075Ma Majhganwa) (Gregory et al. 2006). The youngest kimberlite sources that contain diamonds are Eocene, and occur in Canada (52 Ma Ekati) (Kjarsgaard 2007) and Tanzania (52 MA Mwadui) (Stiefenhofer and Farrow 2004), and the youngest diamond-bearing lamproites are in Australia (22Ma Ellendale) (Jaques 1998) and are Miocene in age.

Further evidence that diamond bearing kimberlites or lamproites have existed in the Archaean comes from rare diamonds that have been recovered from the 2.9-2.84Ga Central Rand Group of the Archaean Witwatersrand (Groves et al. 2005). Diamonds also occur in Proterozoic sediments in Ghana, Brazil, French Guiana, southern Africa and India, and in some areas concentrated enough for exploitation. The Palaeoproterozoic metaconglomerates of the Vila Nova Group in Amapa in northern Brazil (Tompkins 1989) and the contemporaneous Birimian metasediments at Akwatia in Ghana West Africa (Canales 2005) have long been mined. The Akwatia diamond fields have produced over 100 million carats mainly from the Birrim alluvials but more recently from some schist units in the 2.2Ga Birimian Supergroup (Davis et al. 1994, Gueye et al. 2007) that have been interpreted as komatiitic rocks (Canales 2005). This deposit has been correlated with the Danchine volcaniclastic komatiites from French Guiana which is of similar age and setting (Capdevila et al. 1999). The main difference being that the diamonds from Akwatia are peridotitic (Stachel and Harris 1997) whilst in Danchine there is evidence for eclogitic sources (Capdevila et al. 1999). Recently tens of thousands micro-diamonds (smaller than 0.5 mm) and some of macro-diamonds (largest 0.95ct) have been recovered from lamprophyric hosts rocks, dated at 2.6Ga (Wyman et al. 2008), and associated metamorphosed volcaniclastic breccias (Lefebre et al. 2005) at Wawa in the southern Superior Province of Canada. A subduction model has been proposed and several other such deposits, like the California Mother Lode (Wyman et al. 2008), have been excluded not only because they are mainly micro-diamond producers but also because the diamonds are also not mantle derived.

Diamonds have been recovered from the Mesoproterozoic sediments of the Roraima Formation (Tompkins 1989) and the Espanhaõ Range of Minais Gerais where diamonds have been introduced into the basal part of the Sopa Brumadinho Formation at around 1.7Ga (Chaves et al. 2001, Chaves and Neves, 2005). In the 1990’s Minas Gerais produced over 200 000 of carats mainly coming from these Espanhaõ sediments (Karfunkel et al. 1994). Diamonds have been spatially associated with tillites of various ages in Brazil (Jequitai tillites – Upper Proterozoic, Sante-Fé tillites – Cambrian and Itararé Subgroup – Carboniferous) (Tompkins 1989), and South Africa and Zimbabwe (Dwyka Group – Carboniferous) (Moore and Moore 2004, Moore et al. 2009) however no records exist of actual diamond recoveries from these sediments.

Recently diamonds have been discovered and mined out of the basal conglomerates of the Umkondo sediments in eastern Zimbabwe (WGDE 2008). These sediments, generally regarded to be Mesoproterozoic in age, have been intruded by dolerite sills that have been dated at 1105Ma (Wingate 2001) providing at least a minimum age for the sediments. In India, the diamond-bearing Banganapalle conglomerates of the Neoproterozoic Kurnool Group overlie
basement with 980Ma pre-Kurnool dykes which constrain the maximum age for these coarse sediments (Basu 2009).

In summary, some diamonds have long histories starting in the mantle since at least 3.5Ga, being ejected to surface by Archaean, Proterozoic or Phanerzoic kimberlites and lamproites, and having been preserved in Archaean to Quaternary-age sediments. This process has continued throughout the geological history with the last diamond-bearing primary sources extruding in the Miocene. Continued emplacement of primary sources, erosion and burial through time would have recycled many of the diamonds brought to surface.

5. Global diamond metallogenic provinces and epochs

The oldest known kimberlites with diamonds intruded the Ntem Craton in Gabon have been dated as Late Archaean (2850Ma). These have been preserved as hypabyssal facies kimberlite dykes representing root zones that have undergone erosion and metamorphism reaching amphibolite-facies grades (Henning et al. 2003). This is followed by Palaeoproterozoic occurrences on the Yilgarn (Nabberu - 1900Ma) and Pilbara (Brokman dyke - 1900Ma) Cratons in Australia. These have been reduced to small blows and dykes which suggest that significant erosion of Palaeoproterozoic cover of those ancient shields has taken place since 1.9Ga.

The first early Mesoproterozoic diamond-bearing intrusions were found in the Ivory Coast on the Man Craton (Bobi and Toubabouko lamproite dykes - 1429Ma) as erosional remnants that have been mined on a small scale. Other early Mesoproterozoic intrusions occur near Martinsdrift in eastern Botswana (Lerala pipes - 1333Ma) as irregular shaped highly eroded root zones.

The late Mesoproterozoic was marked by emplacement of kimberlites in the Premier cluster (Premier, Schuller and Montrose 1180-1110Ma) on the Kaapvaal Craton, the Salvador pipe (1150Ma) on the São Francisco Craton and the Kyle kimberlites (1076Ma) on the Superior Craton as well as the Argyle (1177Ma), Majhgawan (1075Ma) and Atri (1064Ma) (Masun et al. 2009) lamproites which extruded on the Kimberley and Bundelkhand Cratons respectively.

The Neoproterozoic is characterised by diamond-bearing occurrences in Australia (Aries, Seppelt - 800Ma), Canada (Renard - 640Ma), South America (Guaniamo - 712Ma, Brauna - 630Ma) and USA (George Creek - 600Ma). These are found on the Kimberley, Superior, Guyana, São Francisco and Wyoming Cratons respectively.

So during the Proterozoic diamonds were brought to surface on the Yilgarn, Pilbara and Kimberley Cratons in Australia, the Indian Bundelkhand Craton, the Man and Kaapvaal Cratons in Africa, the Guyana, Amazonia and São Francisco Cratons in South America, and the Wyoming, Superior and Slave Cratons in North America. In other words all major cratons in the world, except the Russian and Chinese cratons, have Proterozoic intrusions with diamonds preserved. Most of those show signs of erosion which corresponds to the model that the older intrusions would have been subjected to longer periods on denudation.
The Palaeozoic period followed with a large clusters of Cambrian kimberlites in northern South Africa and southern Zimbabwe (The Oaks, Venetia, Murowa, Colossus - 500-540Ma) and the Gaheho Kue (542Ma) and the Snap Lake dyke (523Ma) on the Slave Craton, most of which are significantly diamondiferous. The following Ordovician period was restricted to activity in China where small kimberlites with diamonds intruded into the Sino-Korean Craton (Fuxian Pipe 50, Shengli 701-475Ma). This is followed by Devonian pipes on the Wyoming (Kesley Lake, Sloan - 380-390Ma), Karelian (Grib and Arkhangelskaya - 370-373Ma) and Siberia (Udachnaya, Botubinskaya, 23 Party Congress, Zarnitsa, Jubileynaya, Mir - 353-370Ma) Cratons, with some diamondiferous pipes spilling over into the Carboniferous (Sytykanskaya, Aikhal, Nyurbinskaya - 332-349Ma) in Siberia. This period is one of the most important economic diamond epochs in history.

No diamond-bearing intrusions of Permian are known but important kimberlite emplacement took place on the Kaapvaal in the Triassic (Jwaneng - 235Ma, Dokalwayo -203Ma) and lesser so on the Amazonia (Carolina - 230Ma). Jurassic kimberlites are restricted to the Kimberley and Gawler blocks in Australia (Timber Creek - 180Ma, Orroroo - 170Ma), the Man Craton in West Africa (Droujba - 153Ma, Koidu - 146Ma), the Slave (Jerico - 172Ma) and Superior (Victor -175Ma) Cratons in North America and limited activity on the Kaapvaal (Dullstroom - 171Ma, Klipspringer - 148Ma).

Diamondiferous Cretaceous kimberlites are prominent on the Kaapvaal craton represented by both Group 2 (114-144Ma) and Group 1 varieties (84-95Ma), with as many as 22 (e.g. Swartruggens, Voorspoed, Bellsbank, Finch Newlands etc.) and 38 (e.g. Orapa, Letseng, Koffiefontein, Lethlakane, Kimberley pool etc.) being diamondiferous respectively. Most of the South African, Botswana and Lesotho mines fall into the latter Group 1 category. The former category comprises mainly of Group 2 kimberlites with a significant number being dykes. Both groups are two extremely important economic diamond epochs/provinces.

Other Cretaceous diamondiferous pipes are found on the Man Craton (Droujba - 153Ma, Koidu - 146Ma, Tongo - 140Ma, Banakoro - 139Ma), the Kasai Craton in Angola (e.g. Catoca, Chirí, Camafuga, Camathia, Camagico - ~120-125Ma), the São Francisco Craton (Canasta - 120Ma), the Saskatchewan basement in North America (Fort a la Corne kimberlites and Prairie Creek Lamproite - 100-106Ma), and the Kasai kimberlites in the DRC (Tshibwe and Mbuji Maye - 70Ma).

Another important period during which significant diamond-bearing kimberlites were emplaced was during the Eocene on the Slave (14 diamondiferous kimberlites - 50-55Ma) and Tanzanian Cratons (52Ma), many of which are economic mines.

Finally the youngest group of diamondiferous eruptions are the lamproites that occur on the Kimberley Craton in Australia (Ellendale - 22Ma) and these are preserved as craters filled with tuffs and magmatic facies.
6. Age-Frequency model for diamond-bearing kimberlites

The age-frequency curve for diamond-bearing kimberlites was constructed using almost 200 kimberlite intrusions with diamond grades equal and over 1 cph. The grades for most have been proved with appropriate evaluation. In some cases however these were based on small sample sizes or historically information but nevertheless there was sufficient confidence in those results to include these into the database. The data is presented using time intervals or bins of 50 and 100Ma. The 50Ma (Fig. 2) and 100Ma (Fig. 3) bins show distinct peaks in the distribution but overall the trend generally decreases with increasing age.

![Figure 2. Age frequency distribution (normal and log-normal) for global diamondiferous kimberlites in 50Ma bins.](image)

Since the Archaean there have been 4 global metallogenic epochs that appear significant and have more than 10 diamondiferous intrusions each. Firstly, there is the 500-540Ma (Cambrian) period with kimberlites being intruded on the Kaapvaal, Zimbabwe and the Slave Cratons. The second being the 332-373Ma period (Devonian) with the Russian mines on the Karelian and Siberia Cratons, the third which ranks high on the curve is the 114-148Ma (Early Cretaceous) period with peaks on the Kaapvaal, Kasai and Man Cratons, and the final epoch would be the period from 52-95Ma with the main contributors on the Kaapvaal, Slave and Tanzanian Cratons.
By using 10 diamond-bearing kimberlites/lamproites in a province as a minimum (1.0 on a log-normal distribution) falling within the same 50Ma epoch, the intrusions were classified into global metallogenic clusters. Four primary metallogenic clusters were identified: Siberia with (11: 332-370Ma), Kaapvaal South (23: 114-144Ma), Kaapvaal Southwest (39: 84-95Ma) and Slave (14: 52-55Ma) Cratons. These represent the main discovered reservoirs, past and present, of natural diamond - a premier league so to speak. A second tier of global metallogenic clusters have been identified and these are based on between 5 and 9 diamond-bearing intrusions within the same 50Ma period in one province. These are the Kaapvaal Central (6: 506-538Ma), the Man Craton (8: 139-153Ma) and the Kasai (6: 120-130Ma) Cratons.

Neither Argyle nor Jwaneng are part of any of these clusters. Argyle is similar in age to Premier in South Africa and Salvador in Brazil, whilst Jwaneng has a similar age relative in Brazil (Carolina). So although the focus of exploration programs might well be directed towards areas with primary and secondary metallogenic clusters there are anomalies such as Jwaneng and Argyle that fall outside these groups.
Fig. 4. Kimberlite surface areas and intrusions ages of 189 global occurrences

There are generally fewer diamondiferous kimberlites in the older metallogenic provinces and preferentially preservation due to shorter periods of erosion and denudation (northern Canada) and/or burial by younger cover (Siberia, Kasai, central Botswana) might be contributing factors. This would conform to the exhumation model of Kesler and Wilkinson (2006) however intense regional erosion of the Group 1 kimberlites on the southern Kaapvaal Craton (Hanson et al. 2009) does not support this. Also a plot of kimberlite sizes through time indicates that there is only a very weak correlation between size and time and there is little evidence that the pipes are getting smaller with age (Fig. 4). This suggests that erosion and denudation models over stable cratons are very different to that of converging margins.

7. Discovery history

For the first 25 years, from 1870 until 1895, all diamond-bearing kimberlites found are Group 1 kimberlites and these had no or very little surface cover. During that period the Kimberley pool, Koffiefontein, Jagersfontein and Monastry mines had been discovered by prospectors or local farmers. The only Group 2 kimberlite that was discovered in those first 25 years was Newlands in 1882.

Over the following 25 years, from 1896 to 1920, and except for the Premier kimberlites, mainly Group 2 kimberlites were discovered such as Lace, Peiserton, Blaaubosch, Robert Victor, Makganyene, Voorspoed and West End etc. And like the Group 1 discoveries none of those occurrences had any cover to speak of. Interestingly, Peiserton was found some 60 years before Finch, Lace 10 years before neighbouring Voorspoed, and the diamonds around Seta on the Limpopo were found in 1903 whilst Venetia was only discovered in 1980. Between 1920 and 1930 only the weakly diamondiferous Palmietfontein was found.
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Except for the discovery of the Prairie Creek Lamproite in the USA in 1906, in the 60 years following 1870 all diamondiferous kimberlites and related rocks were found in South Africa until the Koidu and Tongo kimberlites and Majhgawan lamproites, in Sierra Leone and India respectively were discovered in 1930.

Although sporadic diamond-bearing intrusions were found in South Africa over the 25 years between 1930 and 1955, the focus shifted to Tanzania (Mwadui 1940), DRC (Mbuji Maye 1946; Tshibwe 1955), Angola (Camafuga 1952, Camatchia 1955), Russia (Zarnitsa 1954) and Lesotho (Kao 1954).

Within 5 years of the first finds in Russia and Lesotho some major discoveries were made in those countries - Mir (1955), Udachnaya (1955), Sytykanskaya (1956), 23rd Party Congress (1959), and Aikhal (1960) in Russia; and Letseng (1957), Liqhobong (1957), Mothae (1961) and Kolo (1961) in Lesotho. The Russian finds in Siberia became most significant in terms of global production.

Although Finch was discovered in 1961, the 60’s belonged to Botswana with the important finds around Orapa (1967) and Letlhakane (1970). Whilst De Beers continued to make important discoveries in Botswana in the 1970’s with Jwaneng (1973), a spring of new finds were made around the world – China (Pipe 50 - 1971), Zimbabwe (River Ranch - 1974), Swaziland (Dokofwayo -1975) and Australia (Ellendale -1976, Argyle - 1979). And although the Russians kept finding new pipes in Siberia, Internationalaya (1969) and Jubileynaya (1975), it were the discoveries of lamproites in Australia (Ellendale -1976; Argyle - 1979) that sparked a keen interest in the presence of diamonds in rocks other than kimberlite.

More discoveries were made in the Limpopo region (Venetia -1980; The Oaks - 1986) but the 80’s saw diamonds being found in new areas, with the discovery of Arkhangelskaya (1980) on the Karelian Craton, Venezuela (Guaniamo - 1982) and the first more interesting discoveries in Canada (Victor and FALC - 1988). The latter continued into the 90’s where the North West Territories of Canada (Slave Craton) proved to be the next important region for new mines (Ekati - 1992, Diavik - 1994, Gahcho Kue - 1995 and Snap Lake - 1997). Discoveries continued to be made on the Karelian Craton in west Russia (Grib - 1996), Siberia (Botubinskaya - 1994, Nyurbinskaya -1998) and Zimbabwe (Murowa - 1997). Over the last ten years the main discoveries made were in Canada (Renard -2001), Brazil (Carolina -2003) and India (Atri - 2004) with the latter being perhaps of most interest.
Figure 5. Number of diamond-bearing kimberlites and related intrusions discovered per decade.

Figure 5 illustrates the number of diamond-bearing intrusions discovered per decade from 1870 when the first diamondiferous kimberlites were found (Jagersfontein, Koffiefontein, Du Toitspan and Bultfontein all in 1870). The decades 1870-1879 (7 discoveries), 1900-1909 (12), 1950-1959 (16), 1970-1979 (29) and 1990-1999 (39) stand out as the most prospective periods. The 1870’s and 1900’s highlight central South Africa, the 1950’s Russia, Lesotho and Angola, the period from 1970 to 1979 Botswana and Australia and the 1990’s Australia, Brazil and particularly Canada. However since the number of discoveries include many small ones with blows and dykes the significance of a large discovery is best highlighted by the cumulative surface area (in ha) of all discoveries during a decade (Fig. 5). And this highlights the 1940-1949 (190ha), 1950-1959 (385ha), 1960-1969 (155ha), 1970-1979 (421ha), 1980-1989 (447ha) and 1990-1999 (125ha) as the most successful decades with each adding cumulatively over 100ha of discoveries to the global diamondiferous pool. It should be noted that the 1980-1989 decade is heavily skewed due to the Fort à la Corne (FALC) finds.

Figure 6. Total hectarage discovered globally during every 10 year period.
Importantly there is a distinct drop in number and size of diamond-bearing intrusions over the last one and two decades respectively. This trend is perhaps best illustrated by the average size of diamond-bearing intrusion discovered per decade declining from 38ha in the 1940’s to roughly 8ha in the period 2000-2009 (Fig. 7).

![Graph showing average hectarage per diamond-bearing kimberlite found per decade.](image)

**Figure 7. The average hectarage per diamond-bearing kimberlite found in each decade.**

Many of the early mines in South Africa were found by prospectors and local farmers walking over areas without much cover (boots on the ground). The first kimberlites to be found by systematic sampling were those in Tanzania (Williamson - 1940) and the DRC (Forminière - 1946). De Beers started with their systematic heavy mineral sampling programs in the mid 1950’s in Tanzania, Zambia, Zimbabwe, South Africa and Botswana and the Russians roughly around the same time in Siberia. The heavy mineral sampling technique – stream, loam or till sampling, was and still is the key to explore prospective ground. Airborne geophysics is utilised to define drill targets in areas highlighted by the initial sampling programs. Ground geophysics, magnetic, gravity and/or electromagnetic, is subsequently applied to provide first pass models of the causative bodies. Lately integrated geophysical techniques can provide 3-D models of the intrusions.

It is very unusual for geophysics to be used as an initial application to find kimberlites. The only kimberlite fields that have been found by geophysics alone are FALC and Buffalo Hills which were found whilst flying airborne surveys in the search for Uranium and Oil/Gas respectively.

### 8. Technologies

The age-frequency profile suggests that new large mines will come from the younger metallogenic groups: Devonian and younger in age. The discovery history has also shown that most of the discoveries up to the mid 1950’s have come from areas with little or no cover. Siberia and Botswana provided the first challenges of finding covered diamond-bearing kimberlites and there is no doubt that future mines will be hidden under sedimentary and/or volcanic cover. This will require significant investment in new technology. Firstly, better targeting using mineral chemistry of satellite minerals (garnet – peridotitic and eclogitic,
ilmenite, chrome-spinel, Clino-pyroxene, olivine) as a guide to define areas of interest, not only with respect of the physical conditions of the underlying mantle, but also whether that mantle contains carbon. Secondly, finger printing of diamonds would vastly improve our ability to link isolated and alluvial diamonds to sources. And thirdly, geophysical techniques require large investments in both research and application if detecting of isolated pipe-like features at depth and under cover will be successful.

8.1 Petrology and Mineral chemistry

When the first kimberlites were discovered in 1870 very little was understood of what these deposits were. Initially these were interpreted as ‘dry diggings’ left behind by ancient rivers. The first scientific paper on a microscopic study of ‘porphyritic peridotite” was by Prof Carvill Lewis (Lewis 1888) who recognized he was dealing with a volcanic breccia. He also suggested that this rock belonged to the family of peridotites but recognized that this was a new rock type and proposed to call it ‘Kimberlite’ from the famous locality where it was first observed. Since then many scientific contributions have vastly improved our understanding of kimberlite intrusions. These include work on kimberlite definition highlighting the complex nature of this rock type (e.g. Skinner and Clement 1979), petrographic and isotopic differences between Group 1, Group 2 and Lamproites (Skinner 1989), Kimberlite lithofacies descriptions (Clement 1982, Field and Scott Smith 1999, Stripp et al. 2006), and models of kimberlite pipe formation (Hawthorne 1975, Sparks et al. 2006, Lorenz and Kurszlaukis 2007).

Mineral chemistry was pioneered by Sobolev (1971) in Russia and by Gurney (1984) in South Africa. This led to a method of prediction whether kimberlites would be diamondiferous. Later with the introduction of the Ni and Cr geothermometry Griffin et al (1989) and Griffin and Ryan (1995) were able to improve significantly on the confidence of this method using trace elements in kimberlitic minerals.

8.2 Airborne geophysics

Although airborne surveys had been going on since the 1940’s it had never been used in the search of kimberlites. In 1968 based on proposals from Ken Biesheuvel and Eddie Kostlin, Anglo/De Beers embarked on the first ever airborne magnetic survey for kimberlites over the just discovered Orapa province. This was subsequently picked up by Falconbridge who used this successfully in the discovery of Gope. In 1986 the same geophysical team from Anglo/De Beers designed and flew the first 4-sensor airborne magnetic gradiometer survey. Presently great strides have been made with the development of the low temperature SQUID gradiometer with much more sensitive magnetic sensors which are able to measure the remnant magnetic field.

Over the last ten years BHPB and De Beers started testing airborne gravity systems in the search for kimberlites. This technology had been applied to the Oil industry for many years in the search for large structures and basins but looking for relatively small kimberlites by airborne gravity proved to be substantially more difficult. BHPB started flying their Falcon system in 2002 and De Beers started testing a very similar system shortly thereafter. However the ‘noise’ or turbulence level by the light aircraft used to carry the gravity meter proved to be too difficult to overcome. For that reason De Beers moved the instrument to a more stable Zeppelin airship. Although the results were very encouraging the logistics (and costs) surrounding this airship
eventually proved to be too challenging and the project was terminated after two years. Success of the Falcon airborne gravity system was limited to the discovery of the Aries Kimberlites pipes (up to 18ha in size) in NW Australia (Thundelarra Exploration, Crabb 2002). However ground gravity remains a powerful technique and will take a more central stage in future exploration programs particular if speed of data acquisition can be increased.

Improvements of the EM systems have also enhanced the chances of finding kimberlites under cover (Power and Belcourt 2004, Lo et al. 2009) and continuous development of this technique will see more use of airborne EM particular outside of Canada. The VTEM system has now been commercially available since 2002. However, ultimately it will be the integration of different geophysical datasets that will lead to the discovery of new mines under significant cover. Governments will have to see how they can get involved in this type of research if they wish to improve on their respective resource base particular in areas with recent sediment and/or volcanic cover.

Conclusions
An age-frequency distribution curves of all globally known diamond-bearing kimberlites and lamproites has identified four primary diamond metallogenic clusters based on the number of diamondiferous intrusions per province. These are Siberia (332-370Ma), Kaapvaal South (114-144Ma), Kaapvaal Southwest (84-95Ma) and Slave (52-55Ma). In addition, a lower tier of three secondary clusters has been identified as, the Kaapvaal Central (506-538Ma), the Man (139-153Ma) and the Kasai (120-130Ma) Cratons. By ranking these different metallogenic clusters Botswana (buried Group 2 and ilmenite - poor Group 1), Kasai and Russia have been identified as the most likely areas to produce a world class diamond mine provided the appropriate technology is applied. The distributions clearly show a decrease of the number of diamondiferous kimberlites/ lamproites with time. This work suggests that this is primarily due to variable depths and episodes of erosion and burial.

The discovery profile of the diamondiferous intrusions indicates that the first mines found from 1870 onwards, had little or no cover and were all found in southern Africa; first the ilmenite-rich Group 1 and later the Group 2 kimberlites. Systematic exploration from the 1940’s onwards increased the number of discoveries significantly until the 1990’s. A major drop off has been experienced in the last decade in the number, and in the last two decades in the sizes of the discoveries. Hence exploration will have to focus on areas with sedimentary and/or volcanic cover to find new major mines. Thus research for features and processes that control the formation of such metallogenic clusters must persist and intensify. New technology to find future diamond mines will have to be geophysically driven and will require large investments to succeed, whereby governments interested in developing their natural resources will have to be involved.

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