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Nature, origin and age of diamonds: a state-of-the-art report

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ABSTRACT. — Over the past fifteen years many scientific papers have been published on the nature and origin of diamonds. Modern analytical techniques show that diamonds' solid inclusions are sometimes as small as 150-200 microns. They have also shown that diamonds invariably derive from peridotitic and eclogitic rocks; kimberlites and lamproites are generally more recent than the diamonds themselves indicating that kimberlites and lamproites are not necessarily and directly linked to the origin of these precious crystals, but constitute instead the means by which diamonds reach the surface of our planet. It has also been shown that diamonds associated with peridotitic rocks are about 3.3 billion years old, whereas those associated with eclogitic rocks vary in age between 1.6 and 1.0 billion years. In light of their considerable age difference we can safely surmise that, as diamonds generally precede their including volcanic rocks, their genetic connections to kimberlites and lamproites are rare; that they have been intermittently generated over long periods of the planet's geological history, and that kimberlites and lamproites are mixed volcanic rocks derived from deeper magmatic sources than previously hypothesized. Although kimberlitic rocks are present in all continents, important diamond-bearing deposits can be located not only in the continental cratonic masses, but also in adjacent regions, particularly in the associated «mobile belts». Even if the kimberlitic and lamproitic rocks belong to intrusive phases of different ages, they can still crop out in the same geological sectors; therefore some diamantiferous diatremes may contain diamonds of different ages. As the majority of kimberlitic and lamproitic rocks belong to relatively recent intrusive phases (the last 200 million years), some significant intrusions reveal ages of about 1.6 billion years (Low Proterozoic) as well as ages preceding 2.6 billion years.

RIASSUNTO. — I numerosi lavori scientifici pubblicati negli ultimi quindici anni hanno contribuito a chiarire molti concetti riguardanti la natura e la genesi dei diamanti. In particolare il notevole contributo di conoscenze maturato in questo periodo è derivato dall'avanzamento degli studi geochimici sulle inclusioni solide – di dimensioni limitatissime, non più grandi di 150-200 micron – resi possibili dalle moderne tecniche e tecnologie analitiche.

I recenti risultati tratti dalle inclusioni hanno dimostrato che questi minerali derivano, senza alcuna eccezione, da rocce peridotitiche e da quelle eclogitiche. Le rocce kimberlitiche e le lamproitiche, a cui di regola sono intimamente associati i diamanti, risultano però generalmente più recenti di questi. Da tale fatto si deduce chiaramente che le kimberliti e le lamproiti non sono necessariamente e

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direttamente legate alla genesi dei preziosi cristalli ma costituiscono piuttosto il mezzo attraverso cui si realizza il trasferimento dei diamanti verso la superficie del nostro pianeta, ove si ritrovano in giacitura alloctona. È stato anche dimostrato che i diamanti associati alle rocce peridotitiche hanno un'età di circa 3,3 miliardi di anni, mentre quelli associati alle rocce eclogitiche ne accusano una variabile tra i 1,6 ed 1,0 miliardi di anni.

Alla luce di questa notevole differenza di età si può affermare che, poichè i diamanti sono generalmente antecedenti alle rocce incassanti (kimberliti e lamproiti), raramente sono legati geneticamente ad esse e che il minerale si è formato in modo intermittente durante lunghi periodi della storia geologica della Terra. Le altre considerazioni emerse inducono a puntualizzare che le kimberliti e le lamproiti sono rocce vulcaniche particolari derivate da sorgenti magmatiche più profonde di quanto fino a pochi anni fa fosse stato ipotizzato, che le kimberliti sono presenti in tutti i continenti, ma che i depositi diamantiferi molto importanti, economicamente e scientificamente, sono localizzati non solo nelle masse cratoniche continentali ma anche nei settori adiacenti, specialmente nelle «cinture mobili» ad esse associate. Le rocce kimberlitiche e lamproitiche, pur connesse a fasi magmatiche di età diversa, possono affiorare negli stessi settori geologici; pertanto alcuni diatremi diamantiferi possono contenere diamanti di età completamente differente. Infine c'è da notare che sebbene la maggior parte delle kimberliti e lamproiti siano correlate a fasi piuttosto recenti (ultimi 200 milioni di anni) alcuni corpi di notevole importanza rivelano età di circa 1,6 miliardi di anni (Basso Proterozoico) e oltre, antecendenti a 2,6 miliardi di anni.

KEY WORDS: *Diamonds origin, solid inclusions, kimberlites, lamproites.*

INTRODUCTION

Recent discoveries of diamonds in the Canadian territories of the North West, the Provinces of Quebéc and Saskatchewan, and other regions of Canada, together with the finding of extensive placer deposits along the banks of the tributaries of the Guarani and Icabaru rivers in Venezuela, have renewed the interest of the mining industry in the genesis of this mineral.

The nature of these precious stones, the means of transport, the mechanism of accumulation, the type of including rock, and the geology commonly associated with their presence, are themes which have always interested scientists: both on account of their economic and industrial importance, and their intrinsic beauty. Only in the last ten years, however, has any considerable progress been made towards an understanding of the geochemical phenomena associated with the genesis of diamonds. New concepts and theories – thanks mainly to the use of highly specialized equipment – have enabled scientists to shed light on many aspects concerning the formation of the carbon crystals.

In the present paper the authors propose to present an up-to-date synthesis of the most advanced theories in the field of the origin of these minerals, basing their discussion on both their own personal experience matured over years of teaching at their respective universities (i.e. La Sapienza in Rome, Italy, and Concordia in Montréal, Canada), and consultation of an extensive bibliography.

Among the works cited, a special mention is due to the authoritative papers by Mitchell and Bergman (1991), Ross *et al.* (1989), Nixon (1987), Mitchell (1986; 1991; 1995), Glover and Harris (1984), Dawson (1980; 1989), and the articles published by Gurney (1989), Meyer (1985) and Slodkevich (1983). Other authors, such as Anderson, O.L.(1979), Brummer (1984), Smith *et al.* (1985), Richardson (1986), and Richardson *et al.* (1984; 1990), as well as the recent papers by Eggler (1989), Wyllie (1989), Kirkley *et al.* (1991a; 1992), have been widely cited in this synthesis in recognition of their notable contribution to the understanding of the subject.

PREVIOUS STUDIES

One of the biggest problems left unresolved to date in the study of the genesis of diamonds consisted of the indisputable genetic association existing between diamonds and their including rocks, kimberlites and lamproites. Two fundamental hypotheses reflected the lack of precise knowledge in this field:

TABLE 1

Age of diamonds and of kimberlitic intrusions containing them (modified after Kirkley et al., 1992)

Location (mine)	Age of Diamonds (My)	Age of Emplacement of Kimberlite pipe (My)	Type of Inclusion	Reference
Kimberly south Africa	~3300	~100	Peridotitic	Richardson *et al.* (1984)
Finsch, south Africa	~3300	~100	Peridotitic	Richardson *et al.* (1984)
Finsch, south Africa	1580	~100	Eclogitic	Richardson *et al.* (1990)
Premier, south Africa	1150	1100-1200	Eclogitic	Richardson (1986)
Orapa, Botswana	990	~100	Eclogitic	Richardson *et al.* (1990)
		Lamproite pipe		
Argyle, Australia	1580	1100-1200	Eclogitic	Richardson (1986)

(a) It was thought that diamonds crystallized in both kimberlitic and lamproitic rocks, and that they were genetically associated to these;

(b) It was presumed that diamonds were generated long before the kimberlitic and lamproitic intrusions, and that they constituted a purely chance presence in the including rocks.

The solution to such a complex problem was made possible only through study of the mineral phases contained in the diamonds themselves. It had long been observed that many diamonds contained solid inclusions (i.e. garnets) of microscopic dimensions (a few hundreds of microns) which could be isolated, and which it was possible to date by radiometric methods. Since these mineral inclusions could be considered co-genetic with the diamonds, it was logical to conclude that it would be possible to determine the age of the diamonds by means of a radiometric dating of the solid inclusions contained in them.

In 1979 Kramers, using the U/Pb method and exploiting the isotopic compositions of some inclusions in diamonds from the Finch, Kimberley and Premier Mines in South Africa, managed to obtain dates between 2.0 and approximately 1.2 billion years. However, it was necessary to await the papers by Richardson et al. (1984) and the utilization of the Rb-Sr and Sm-Nd methods before the first significant datings on the garnet inclusions in diamonds from the Finsch and Kimberley Pipes in South Africa could be obtained. The results obtained, for the first time, provided eloquent proof that the diamonds were considerably older than the including kimberlites and lamproites (Table 1).

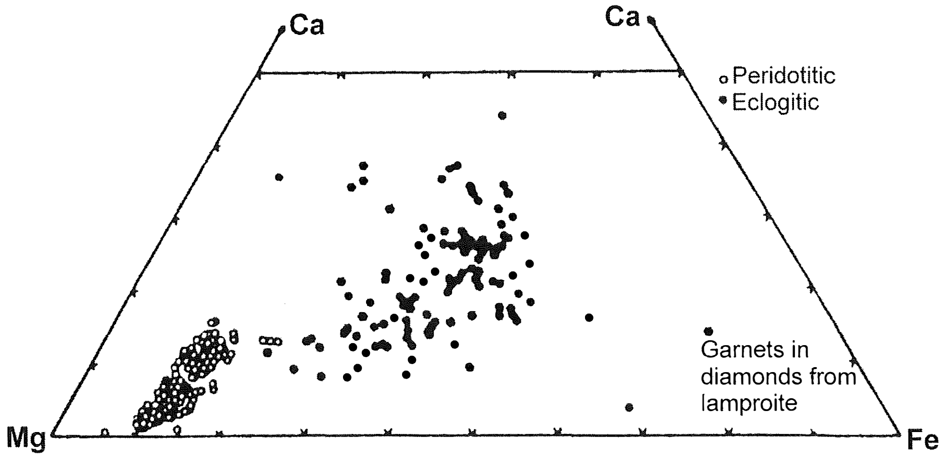

Fig. 1 – Relative abundances between calcium (Ca), magnesium (Mg) and iron (Fe) in garnet inclusions contained in peridotitic and eclogitic diamonds (modified after Meyer, 1987).

The data presented in fig. 1 suggest in fact that:

(a) The diamonds were generated intermittently during the geological history of the planet, particularly between 3.3 and 0.99 billion years ago;

(b) These crystals were accumulated at great depths (i.e. the mantle) prior to being transported to the surface by the kimberlites or lamproites.

Consequently, it is logical to presume that diamonds characterized by very different ages can coexist in the same diamantiferous deposits and in the same including rocks, even if they originate from different sources situated in the mantle of our planet.

THE ORIGIN OF KIMBERLITES AND LAMPROITES

It has been established that diamonds are brought to the surface by the ascent of particular vulcanic rocks – mainly kimberlites and lamproites – during eruptive phases and in important geological ages.

As diamonds seem to come from depths exceeding 150-200 km (see below), it can be assumed that these rocks originated from these depths, and hence that they intersect mantle regions capable of producing the diamonds prior to reaching the earth's crust. From this point of view, then, kimberlites and lamproites appear to constitute volcanic facies derived from much deeper magmatic sources than originally supposed only a few decades ago (Eggler, 1989; Wyllie, 1989).

From a genetic point of view, it can be affirmed that kimberlites and lamproites are «mixed» rocks, as they consist both of xenoliths and xenocrystals derived from the upper part of the mantle, and of magmatic compounds closely linked to the crystallization products of the magmas themselves formed at these depths. The principal mineral components – particularly olivine, clinopyroxene, phlogopite, apatite, perovskite, ilmenite and spinel – are common to both rocks, so that rather similar chemical compositions can be supposed also for their respective original magmatic fluids. However, lamproitic rocks contain a certain number of accessory minerals – leucite, sanidine, wadeite and priderite – which clearly distinguish them from kimberlites. They are also discriminated by their substantial difference in magmatic composition. A comparative table of the paragenetic association of both rocks is given in Table 2.

TABLE 2

Minerals found in kimberlitic and lamproitic rocks (modified after Kirkley et al., 1992).

	Kimberlite	Lamproite
A. Minerals which crystallize directly from kimberlite and lamproite magmas		
Major minerals		
Olivine	X	X
Diopside	X	X
Phlogopite	X	X
Calcite	X	
Serpentine	X	
Monticellite	X	
Leucite		X
Amphibole		X
Enstatite		X
Sanidine		X
Minor minerals		
Apatite	X	X
Perovskite	X	X
Ilmenite	X	X
Spinel	X	X
Priderite		X
Nepheline	X	
Wadeite	X	
B. Xenocryst minerals derived from the upper mantle		
Olivine	X	X
Garnet	X	X
Clinopyroxene	X	X
Orthopyroxene	X	X
Chromite	X	X

Both rocks seem to have originated from the partial melting of very similar but nonetheless distinct peridotitic materials, in environments characterized by pressures with values determined by depths varying from about 150 to 250 km, whereas the formation temperatures are approximately 1100-1500°C. Within this scale of values, kimberlites formed preferably at lower temperatures, while lamproites seemed to favour higher temperatures.

Although generally greenish-grey in colour, lamproites are ultrapotassic while bluish or greyish-brown kimberlites are more or less potassic. The K_2O content of lamproites varies from 6 to 8%; in kimberlites it varies from 0.6 to 2.0%. Lamproites are generally characterized by lower Mg, Fe and Ca contents than kimberlites, but they have higher Si and Fe values. An overall enrichment in trace elements (i.e. Zr, Nb, Sr, Ba and Rb) is also to be noted in lamproites; however, CO_2 content is higher in kimberlites (average 8,6%).

Kimberlites and lamproites are generally found in the form of irregular, cylindrical, cuneiform, horn- or core-like masses; they sometimes appear as dikes and rather flattened lenses, or else shaped like champagne glasses. They frequently consist of a large number of xenoliths. These fragments were pulled from the walls of volcanic pipes during eruption, becoming incorporated in the magmatic fluids as they rose to the surface. From this point of view it can be stated that kimberlites and lamproites are important for an understanding of the deep rocks existing between the continental crust and the upper part of the mantle (Mitchell, 1986; Haggerty, 1986; Meyer, 1985).

Xenoliths are very often characterized by the presence of diamonds. They make it possible to accurately determine the petrological characteristics of the primary rocks which favoured the crystallization of the minerals themselves. Recent studies have shown that the xenolithic fragments containing diamonds are mainly linked to two types of ultramafic rocks: eclogites and peridotites.

It should be remembered that eclogites are rocks consisting basically of a granular, mixture, made up of garnets (i.e. pyrope and almandine) and Na-pyroxenes (i.e. omphacite) and smaller quantities of rutile, kyanite, corundum and cohesite. Eclogitic rocks usually represent crystallization environments characterized by pressures and temperatures coherent with the formation environment of diamonds. They are mainly produced by metamorphism, usually by the transformation of pre-existing basaltic rocks.

Peridotites, on the other hand, comprise a group of rocks known as harzburgites, lherzolites, wehrlites and dunites. The difference between these rocks depends on the chemical composition: i.e. the relative proportions between olivines, orthopyroxenes and clinopyroxenes present in the rocks themselves. In peridotites originating from the mantle the presence of garnets and/or spinels (i.e. chromite) can frequently be observed. The majority of diamonds associated with peridotites appear to originate from harzburgitic rocks, while smaller quantities are found in lherzolitic rocks (Gurney, 1989; Eggler, 1989).

It should be noted that eclogites characterized by the presence of diamonds have been studied in detail in about 100 papers, whereas only a limited number of publications (20) describe peridotitic xenoliths containing diamonds. This is supported by the fact that harzburgitic rocks are typically derived from primary magmas, and most diamonds associated with kimberlitic rocks are derived from these. It could therefore be argued that peridotitic xenoliths undergo highly effective processes of disintegration, perhaps due to reactions between xenoliths and kimberlitic melts or between solid and gaseous phases at the mantle depths (Gurney, 1989).

It should be acknowledged, however, that the xenolithic fragments of eclogite and peridotite found in kimberlites and lamproites do not represent exactly the mineral phases or the chemical-physical conditions typical of the mantle under which these fragments, in theory, should have formed. It has been observed that occasionally, during the ascent to the surface of kimberlites and lamproites, there is a clear phenomenon of fracturing of the xenolithic fragments of eclogite and peridotite containing diamonds. In other cases, substantial modifications can occur during ascent, as a result of chemical reactions between the xenolithic fragments and the magmatic fluids. These modifications depend, of course, on such factors as the duration of contact between xenoliths and magmatic fluids, their chemical compatibility, and the speed of transport. The last factor, in particular, can generate pressure and temperature variations in the ascending magmas, giving rise to important phenomena of digestion and recrystallization.

Studies on the solid inclusions in diamonds make it possible to state that the diamonds present in xenolithic fragments are generally older than the including kimberlitic and lamproitic rocks (Kirkley *et al.*, 1992). It can also be affirmed that the conditions of formation deduced from the studies on these rocks make it feasible to infer with greater precision the physical-chemical conditions of the genetic environment in which the carbon crystals formed.

MINERAL INCLUSIONS IN DIAMONDS

Study of the solid inclusions contained in diamonds was performed with the help of particular techniques which allowed the identification and dating of the minerals contained in the diamonds (Moore and Gurney, 1985; Meyer, 1987; Gurney, 1989). As mentioned previously, the analytical data are interpreted on the basis of the fundamental concept of co-geneticity of the solid phases contained in the diamonds themselves. In order to obtain mineral inclusions (i.e. garnets) in the including minerals (i.e. diamonds), it has of course to be presumed that the solid phase bearing the inclusion must have been generated at the same time and in the same environmental locality as the included phase. If the solid inclusions contained in the diamonds belong to the peridotitic assemblage, it follows that the diamonds themselves formed in peridotitic embedding rocks. This simple rule applies also to diamonds found in eclogitic rocks.

A total of 22 accessory minerals (see Table 2) were found as original solid inclusions in the diamonds examined by Gurney (1989). Only six minerals, however, appear in both the peridotitic and eclogitic assemblages: olivine, orthopyroxene, clinopyroxene, garnet, chromite, and some sulphides such as pyrrhotite. Four additional minerals (i.e. rutile, kyanite, corundum and cohesite) form the lesser constituents typical of the eclogitic inclusions. As a result, these take on an exceptional importance for the interpretation of the data and the differentiation of the primary genetic sources (Mitchell, 1986).

The 11 remaining accessory minerals, which are much rarer, do not offer any statistically significant elements. On the basis of the chemical composition, then, it is possible to classify 98% of diamonds as «peridotitic (i.e. P-type diamonds)» and «eclogitic (i.e. E-type diamonds)» (Kirkley *et al.*, 1992). Garnets are particularly useful, especially if it is considered that the peridotitic garnets contain higher percentages of Mg and lower percentages of Fe and Ca than those associated with the eclogitic rocks (fig. 1). Considering that both types of diamonds (i.e. «P-type» and «E-type») can be found in the same diamantiferous deposit, it follows that the volcanic rocks which constitute the ore deposit must necessarily have sampled rocky masses originating from two different areas of the mantle containing diamonds prior to reaching the surface.

As previously mentioned, the diamantiferous xenoliths originating from eclogitic rocks seem to be much more abundant than those from peridotitic rocks. However, if solely the solid inclusions contained in diamonds are considered, it must be acknowledged that the reverse is true: the «P-type» inclusions are much more frequent than the «E-types». This observation seems to demonstrate an essential fact: as soon as the solid inclusions are included, they are automatically protected from any chemical reactions taking place in the including magmas during the solidification process. Consequently, they are not subject to the disintegrations which appear to modify peridotitic xenoliths during ascent. Hence it should not be illogical to accept the relative abundance of the solid inclusions in diamonds as a basic indicator efficaciously representing their respective percentages, and therefore – analogously – the relative importance of the rock types constituting the source of the material from which the diamonds themselves are generated (Kirkley *et al.*, 1992).

It is well known that the majority of inclusions in diamonds are mono-mineralic; multi-phase solid inclusions are relatively less frequent. The former therefore take on a greater importance, not only from the point of view of their origin from peridotitic or eclogitic rocks, but also from that of the physical and chemical properties characterizing them. They allow accurate estimates to be made concerning the temperatures and pressures existing in the environments in which the effective generation of the solid inclusions takes place, and hence of the diamonds themselves.

THE ORIGIN OF CARBON

Almost all the hypotheses regarding the origin of carbon, which is necessary for the formation of diamonds, have been the subject of numerous scientific debates. Starting from the last century, a whole series of differing conjectures have been put forward by various scientists in numerous publications and at international meetings. In short, these are concerned with the origin of carbon contained in deep sedimentary layers, the origin of the carbon dioxide present in volcanic gases, and the origin of methane gas (Janse, 1984; Mayer, 1985). On the basis of data obtained from recent isotopic evaluations, at present there is a tendency to consider only two different origins of the carbon necessary for the formation of diamonds.

As can be seen in fig. 2, the distribution of isotopic ratios clearly shows that, while the «peridotitic» source is characterized by $\delta^{13}C$ values that vary from –2 to –9 per mill, the «eclogitic» one shows more differentiated $\delta^{13}C$ values, ranging from +3 to –34 per mill (Gurney, 1989). When greatly differing isotopic value distributions are obtained for samples originating from specific localities (i.e. Roberts Victor Mine in South Africa; Deines *et al.*, 1987), it can immediately be seen that the bi-modal distribution of the values found in eclogitic diamonds (i.e. $\delta^{13}C$ from –16 to –5 per mill) is due mainly to two different sources

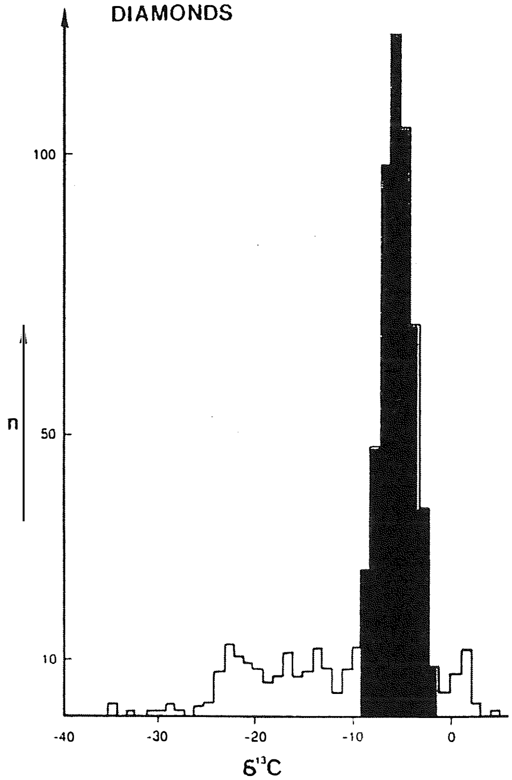

Fig. 2 – Distribution of isotopic ratios of carbon ($\delta^{13}C$) in peridotitic and eclogitic diamonds from different geographical areas. Values for minerals of peridotitic origin are shown in black. Letter «*n*» indicates number of samples examined (modified after Gurney, 1989).

(Kirkley *et al.*, 1991b; Deines *et al.*, 1987). The distribution of $\delta^{13}C$ values for eclogitic diamonds requires a different explanation because it seems to reflect the series of isotopic values obtained from surface carbonate rocks and from organic compounds which favour the generation of hydrocarbon. This similarity, although it seems accidental, is consistent with the genetic model which foresees the carbon present in eclogitic diamonds as being derived directly from crustal material (i.e. ocean-floor basalts with sediments rich in organic matter), provided that this material is transported to the necessary depths (i.e. over 125 km) in subduction zones.

It should also be noted that eclogites have a chemical composition almost identical to that of basaltic rocks. The minerals which make up basalts – mainly feldspar and clinopyroxene – can recrystallize, in environments characterized by high pressures and temperatures, in the form of garnets and omphacites. During a continental collision, the basaltic rocks – which constitute one of the most important rock components of ocean floor – are transported to considerable depths below the continental masses, in areas characterized by high pressures and temperatures. These rocks are gradually transformed into eclogitic rocks. Huge quantities of carbon, in the form of carbonates belonging to oceanic plates under subduction (i.e. calcite or dolomite) or in the form of hydrocarbons (i.e. organic matter), could therefore represent the original source of carbon necessary for the formation of eclogitic diamonds at great depths (Kirkley *et al.*, 1992).

Peridotitic diamonds, on the other hand, appear to possess a more homogeneous source of carbon, perhaps associated with convection zones existing in the upper parts of the mantle. Peridotitic carbon could be primordial (i.e. primary carbon), accumulated in the mantle about 4.5 billion years ago.

OCCURRENCE AND GEOGRAPHIC DISTRIBUTION OF DIAMANTIFEROUS ROCKS

Two fundamental factors characterize the outcrops of kimberlitic and lamproitic rocks: one geographic, and the other geological. The role of these two factors in the emplacement of diamond-bearing rocks was evaluated by Clifford (1970), Janse (1984) and Dawson (1989). Unfortunately a greater emphasis was placed on the genesis of kimberlitic rocks, because knowledge of these is more complete.

It has been demonstrated that kimberlitic rocks are widespread throughout the earth's crust. Approximately 3000 kimberlitic occurrences have been described in South Africa, and about 350 in North America: around sixty of these in the Colorado-Wyoming State Line District. Quite a significant number have been discovered recently in the Prince Albert district and in the region of Fort à la Corne, in Saskatchewan (Lehnert-Thiel *et al.*, 1992), in the Lac de Gras zone, in the N.W.T., and in Quebéc, Canada. Further occurrences are currently being explored in the regions of the Icabaru and Guarani rivers, in Venezuela and in Russia.

If all the kimberlitic occurrences present in the earth's crust are considered, it has to be acknowledged that only about a thousand are characterized by the presence of diamonds, while only sixty or so can be considered economically viable, according to the present market requirements. Moreover, it is calculated that only 12 deposits are currently exploited for diamond production as such. It should be remembered that the core-like masses best known for their production have a circular area which varies from 5 to 30 hectares. In South Africa these deposits contain an average of 20 carats per 100 tons of extracted kimberlitic rock.

The core-like deposits of this rock are grouped in well identified clusters, generally containing a certain number of diamantiferous masses which varies from 6 to 40, as is acknowledged in certain areas of South Africa, Siberia and Tanzania. Recent data show that the five main deposits outcropping in the Kimberley area, South Africa, cover a circular area of about 10 km in diameter, while the main cluster – which contains the most important deposits and all the dikes outcropping in the sector – covers an area of about 40 km in diameter. Janse (1984) suggested that the average distance between various South African and Siberian diamantiferous clusters is around 400 km. This author has also produced some interesting reports on the economically viable and non-viable masses contained in the various kimberlitic clusters, noting values varying from 5 (out of 15) for the productive deposits of Kimberley, from 3 (out of 29) for those of Orapa in Botswana, and 1 (out of 30) for Alakit in Siberia. Many clusters are of course barren, and therefore not economically viable.

Unfortunately, the specialized literature does not provide similar data for those diamantiferous deposits characterized by lamproitic rocks. Even the discovery of the Argyle deposit in Western Australia in 1979 has only partially attracted the experts' attention. Numerous outcrops which were previously mapped as being characterized by lamproitic or similar rocks, such as alnojites, monchiquites and lamprophyres, are currently being reassessed and reclassified. These studies have however led to the discovery of the Prairie Creek deposit (Murfreesboro) in Arkansas, USA. In this case, the rock which was originally recognized as a simple kimberlite has instead proved to be a lamproite with olivine.

The geographical distribution of diamantiferous kimberlites is not accidental, but in fact coincides with the oldest cratonic areas. Furthermore, it has been found that diamond-bearing kimberlites are not found in oceanic environments or along the more recent mountain ranges (Clifford, 1970). It must be remembered that the continental cratonic areas constitute those portions of the earth's crust and of the upper zones of the mantle which have reached a high stability as a result of the complete absence of deformative tectonic processes over considerably long periods of time, particularly in the last 1.5 billion years.

In terms of production, certain cratonic masses seem to be more productive than others. The South African craton of Kaapvaal (Kalahari), in particular, contains 7 of the 11 most productive clusters in the world. Detailed studies regarding the outcropping of kimberlites in the main cratonic masses have revealed that the presence of core-like kimberlitic masses are very common in the most recent sedimentary platforms which almost horizontally overlie the cratonic masses characterized by Archean rocks more than 2.5 billion years old. Indeed, kimberlitic provinces located in the most deeply eroded zones of the continental shields are extremely rare. The most important examples concern the cratonic masses of Western Africa and Tanzania, precisely because these districts are situated in cratonic zones deeply exposed to erosion. This fact has of course led specialists to the hurried generalization that the sectors most favourable to the location of diamond-bearing kimberlites are situated «in the same cratonic masses», considering that the barren zones are apparently located in more remote zones «distant» from these. Such a theory seems in fact to have been contradicted by the discovery of diamantiferous lamproites in Argyle, Australia. This deposit – which today represents the most productive diamond-bearing deposit in the world – is situated in a «mobile belt» integrated with a cratonic mass of about 1.8 billion years old.

This seems to be the demonstration that diamantiferous deposits of great importance can be found not only in the commonly accepted continental cratonic masses, but also in the adjoining regions, particularly in the «mobile belts» sometimes associated with these.

AGE OF INTRUSIVE PHENOMENA AND SPEED OF ASCENT

Kimberlitic rocks have intruded the Earth's crust from the very beginning of the geological history of our planet. This fact is demonstrated by the age of the diamantiferous conglomerates in Witwatersrand, South Africa, which are

TABLE 3

Geological age of some intrusions found in kimberlitic provinces (modified after Dawson, 1989).

Geologic age	Time (My)	Localities
Eocene	50-55	Namibia, Tanzania
Upper Cretaceous	65-80	Southern Cap (south Africa)
Middle Cretaceous	80-100	Kimberley (south Africa)
Lower Cretaceous	115-135	Angloa, west Africa, Siberia
Upper Jurassic	145-160	Eastern north America, Siberia
Devonian	340-360	Colorado-Wyoming, Siberia
Ordovician	440-450	Siberia
Upper Proterozoic	810	Northwest Australia
Middle Proterozoic	1100-1250	Premier (south Africa), India, Mali
Lower Proterozoic	1600	Kuruman (south Africa)

about 2.6 billion years old. The presence of diamonds in these placer deposits points to the existence of kimberlitic (or lamproitic) rocks even older than the age reported. It should be noted that the oldest kimberlitic rocks found so far correspond to the intrusions of about 1.6 billion years old, in the centre of Kuruman, Cape Province, South Africa. These intrusions, situated in the Kaapvaal Craton, are barren. Other kimberlitic rocks belonging to a long intrusive phase of about 1.2 billion years have been found in South Africa in the Premier Mine sector, in the state of Mali, and in India (Table. 3). Further important kimberlitic episodes are listed in Table 3.

Lamproitic intrusions, on the other hand, appear to cover a much shorter geological period, ranging from an age of about 1.2 billion years (in the Argyle Pipe) to one of about 20 million years (Lower Miocene) in the lamproites of Ellendale, Western Australia, situated at approximately 400 kilometers from the Argyle deposit. In the Ellendale group about 50 podiform masses were found, only a few of which are considered to have economic potential. These lamproitic rocks are intruded in platform sediments of the Devonian and Permian ages. Some lamproites in Wyoming, the Antarctic and other localities seem to correspond to much more recent intrusive phases (about 1.0 million years). Very little is known about the diamantiferous deposits discovered recently in the heart of the Canadian shield.

Taking into account also the most recent age datings published within the last fifteen years (Smith *et al.*, 1985), the following conclusions can therefore be reached:

a – Kimberlitic and lamproitic rocks can crop out in the same geological sectors, even if they belong to intrusive phases of different ages;

b – The majority of kimberlitic and lamproitic rocks belong to fairly recent intrusive phases (the last 200 million years). It should be noted, however, that certain intrusions of considerable importance have revealed ages of about 1.6 billion years (Low Proterozoic), and possibly older than 2.6 billion years.

The conclusions reported above do not contradict the fundamental concepts commonly accepted by the specialists. The currently accepted hypothesis is that kimberlitic and lamproitic magmas are the result of the partial melting of peridotitic materials whose compositions are similar and at the same time distinct. These magmas appear to have originated from deep mantle zones varying from 125 km to 400 km of depth. It is acknowledged that the magmas themselves intruded old cratons of the earth's crust, and that the process of intrusion was in fact able to operate from at least 2.6 billion years ago; what has still to be discovered is the mechanism of the intrusion itself.

The fact that carbon crystals reach the surface in an excellent state of conservation, and that they have not been converted into graphite or carbon dioxide or reabsorbed by kimberlitic magmas during the intrusive phase, means that the speed of ascent was without doubt extremely rapid. A slow ascent – or one which entailed frequent slowing down – would most probably lead to the complete destruction of diamond crystals. A classic example of diamonds reconverted to graphite is found in the outcrops of Beni Bouchre, in Morocco (Slodkevich, 1983). In this case, the diamond/graphite transformation has been mainly attributed to the slow cooling of the magmatic masses and the slow pressure reduction.

Although it is generally accepted that kimberlitic magmas reach the earth's surface very rapidly, the exact speed of ascent is not yet known; it is thought to vary between 10 and 30 km/hr (Eggler, 1989). These values appear to be fairly accurate, and it is thus possible to calculate that magmas with diamond crystals could reach the surface in 5 to 15 hours. This time interval would correspond to the minimum time necessary to transport the diamonds to the surface from the zones of production, situated at the depths mentioned at the base of the continental cratonic blocks. It is evident that the speed of ascent could change considerably in the last 3 or 4 km (see below).

In any case, the sole factor indispensable for the mechanism of ascent seems to be the availability of zones of crustal weakness or deep fractures able to extend beyond the base of the cratonic blocks, at depths exceeding 150 km. These fractures are naturally present only in areas which have been geologically very stable for long periods of time. However, the mechanism responsible for the creation of these zones of crustal weakness and their tendency to recur is still unclear: indeed, repeated kimberlitic intrusions can take place over long geological periods in the same geological sectors, and even within the same diamantiferous deposits. Eggler (1989), Dawson (1989) and Mitchell (1986) have proposed some solutions to the problem, suggesting that there migth have been crack propagation (Anderson, 1979) caused by the intrusions themselves during the ascent of magmas, as well as rapid lithospheric deformation mainly due to movement of the crustal plates.

Sampling of the mantle and transport to surface

In a discussion of the sampling of diamonds and their transport from the upper part of the mantle to the earth's crust, the genetic models published in the specialized literature must be taken into account. Particular reference shall be made to those originally proposed by Haggerty (1986), Eggler (1989), Wyllie (1989), and Kirkley *et al.* (1992)

These authors have pointed out that in all cratonic areas the geothermal gradients are relatively low in comparison with the oceanic zones of the planet. For this reason, the isothermal lines tend to show a curvilinear configuration, concave towards the bottom (Kirkley *et al.*, 1992). On the other hand, according to Kirkley *et al.* (1992), when the equilibrium curve between graphite and diamond is compared with a cratonic section, a curve is obtained with a convex tendency towards the top. Hence a debatable hypothesis may suggest that eclogitic diamonds must have been generated at depths exceeding those considered for peridotitic diamonds.

The diagrams proposed by Kirkley *et al.* (1992) may also indicate that the eclogitic rocks originated from oceanic basalts have been transported below the continental masses by subduction processes. This eclogitic material is probably distributed throughout all the peridotitic lithospheric masses, given that an active subduction must have pushed portions of basaltic crust below the continents for millions of years. The most significant zone is that situated between the 900° and 1200° isotherms. This zone is further restricted by the graphite-diamond equilibrium curve (i.e. central zone), which represents an area in which physical-chemical conditions are favourable to the preservation of diamonds. A kimberlitic diatreme, like that denoted as K1, is ideally situated in the thickest part of the craton; it should therefore contain diamonds, provided that the speed of ascent was favourable. Analogously, the kimberlitic diatreme K2 would be rich in diamonds only if the geothermal gradient – found at the base of the cratonic block – did not exceed 1200°C, at a depth of 175-250 km.

On the contrary, the diatreme K3 should be barren, as it is situated in zones marginal to the cratonic mass. An exception to the rule would be represented by the lamproitic deposits of Argyle and Ellendale, situated in zones which are marginal to the cratonic masses, but nevertheless belonging to the mobile belts. In an attempt to explain the presence of diamonds in these deposits, Haggerty (1986) suggested sampling in appropriate zones of the mantle mainly characterized by a complex system of deep fractures, probably interconnected each other (i.e. lamproitic diatreme L1).

Morphological configuration of diatremes

The term «diatreme» is generally attributed to sub-volcanic cuneiform pipes filled with brecciated material and emplaced by violent gaseous explosions. As it has such a general meaning, this term can be attributed to rocky

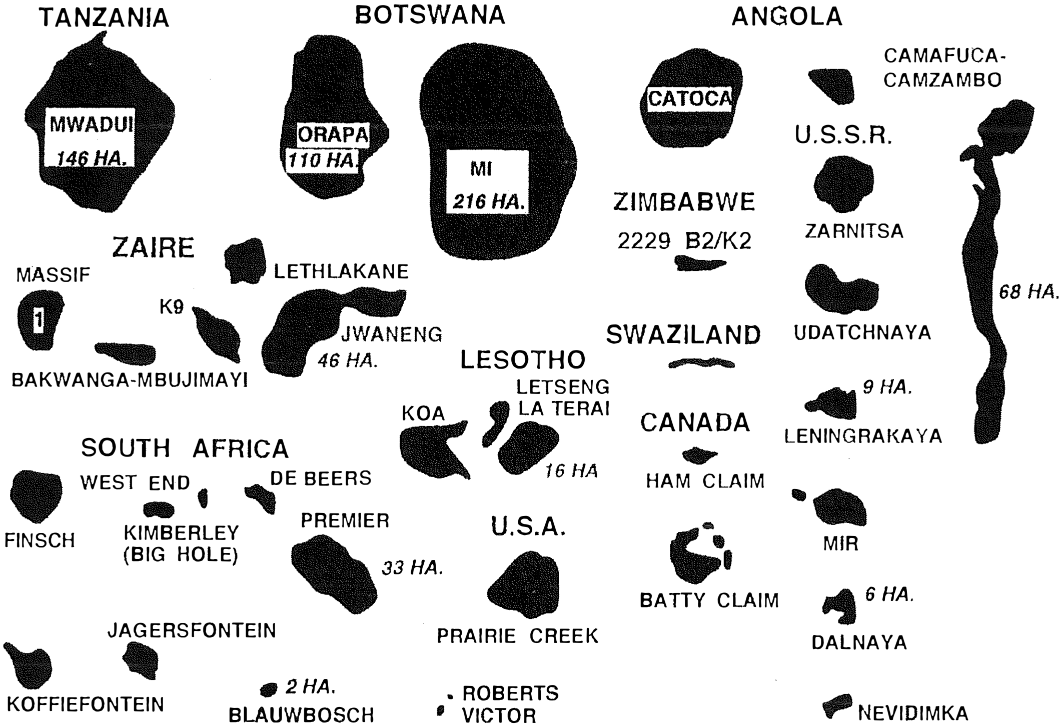

Fig. 3 – Examples of morphological appearances encountered in kimberlitic diatremes (modified after Jennings, 1990).

masses of various types, in different geological situations (i.e. basalt diatreme). However, the set of geological characteristics which make up the diamantiferous diatremes seem to be attributable exclusively to kimberlitic or lamproitic diatremes, both for the incredible depth at which these formations originate, and for the considerable quantity of gas they contain and/or emit.

The main geological characteristics of kimberlitic or lamproitic diatremes (Hawthorne, 1975), although some are possibly common to all types, are as follows:

(a) the specific morphology of the mineralized masses (fig. 3),

(b) the subdivision into three distinct zones (roots, main diatreme and crater) which constitute the main body of the deposit (fig. 4).

The classic representations of diamantiferous diatremes, especially those concerning the kimberlite masses in South Africa, show a fairly regular mass, with core-like or cuneiform morphology, with the acute tip terminating very rapidly towards the bottom. The advent of new mining techniques and the need to increase production in depth have led to the discovery of geological features which are extremely important for an understanding of the mechanism of intrusion in the including rocks. In particular, it has been observed that the central part (the so-called «Principal Diatreme») is characterized by strongly brecciated kimberlitic rocks which do not appear to have metamorphosed the including rocks of the volcanic chimneys or the xenolithic masses contained in the kimberlites.

Lastly, certain surface characteristics appear to be essential in the description of a

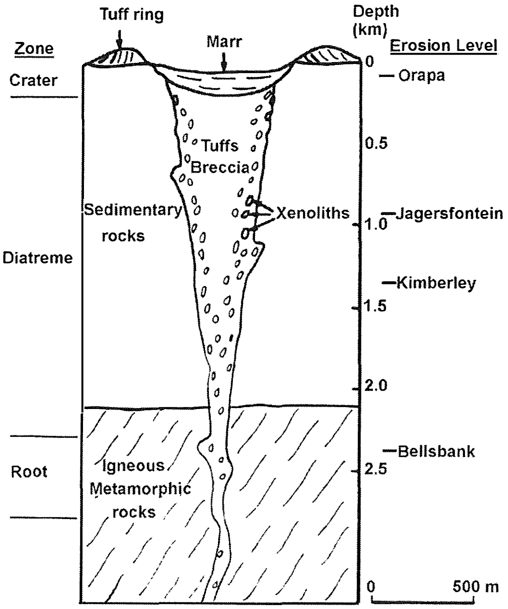

Fig. 4 – Idealized model of kimberlitic core-like diatreme, showing the upper (crater), central (main diatreme), and deepest parts (root zone) (modified after Hawthorne,1975).

diamantiferous diatreme (i.e. the presence of a tuffaceous ring around the edge of the central crater). Very often – as for example in the case of the recent discoveries in Canada and Eifel – the diatremes are covered by small lakes (maars) of glacial origin, concealing the deposit itself. It should be remembered that kimberlitic or lamproitic rocks are rather soft in comparison with the including rocks, and are therefore easily eroded at the surface, especially in periglacial environments. Hawthorne (1975), combining all the characteristics described, was able to develop an ideal model of diamond-bearing diatreme.

The model proposed by Hawthorne, starting from the deepest part of the diamantiferous mass, recognizes above all the «root zone», irregularly cuneiform in shape, which extends vertically for about 500 metres, from 2 to 3 km below the earth's surface (fig. 4). This zone was composed of a kimberlitic magma crystallized in accordance with the typical conditions of an intrusive rock. In this intrusive mass, xenoliths and xenocrystals typically originating from the mantle can be recognized. Deep down the root zone gradually becomes an individual feeder dike which extends in depth, though not always continuously. In some cases, the fractures which usually constitute the preferred zones for ascent of magmatic material may open and then close again immediately after the passage of the magmatic liquid; the feeder dike may be extremely irregular in shape. The root zone and the feeder dike usually contain diamonds. Production in the root zone is usually avoided if the thicknesses are minimal and the volume of rock present is considered insufficient.

The threshold for economic exploitation is at present represented by dikes with a minimum thickness of 60 cm and length of about 20 metres. The main diatreme zone constitutes the central part of the deposit: ideally, and when there is no surface erosion, this area extends from the root zone to approximately 300 metres from the surface. This region often reaches considerable vertical extensions, sometimes as deep as 2 km. By virtue of the remarkable volumes of rock present, the main diatreme zone becomes the deposit itself. This rocky mass is generally characterized by a homogeneous distribution of the diamantiferous grade. The type of rock present is described as a kimberlitic breccia of a «tuffaceous» nature (Kirkley *et al.*, 1992), containing abundant xenoliths originating from the mantle and supracrustal rock fragments from the walls of the pipes crossed by the magmas during ascent (i.e. basalts, gneiss and schists). These blocks appear cemented by the crystalline products present in the kimberlitic matrix. The tuffitic features of the including rock are due to the considerable quantities of gas present in the kimberlitic magma. In particular, when the ascending magma is able to reach levels very close to the surface (i.e. 2 or 3 km in depth), a sudden expansion of the gases (i.e. carbon dioxide and steam) from surface and contained in solution in the magma itself can be observed.

This violent degassing phenomenon can be compared to a sudden subterranean explosion. This results in a typical kimberlitic mass characterized by a high speed of ascent (probably about 100 km per hour) and a highly fluid mixture composed of solidified blocks, magmatic liquids and gases of various nature, which is able to perforate the final 2 or 3 km of the earth's crust. This fluidized mass is further able to crush any crystallized kimberlitic masses present in the typical cuneiform or core-like eruption vent. Finally, the kimberlitic magma – rapidly crystallizing as a result of the lowered temperature and pressure – cannot produce thermic reactions of contact with the including rocks or the xenoliths contained inside them.

Any diamonds present in the eruptive mass are therefore not converted into graphite, since the temperature at this stage is low enough to allow their survival .

The crater zone occupies the highest part of the deposit. It generally extends to about 300 m in depth, and is characterized by a mixture of rock fragments, tuffs, lapilli and pyroclastic material. On the surface this zone takes on circular morphological features as a result of the presence of the tuffaceous ring; in many cases a lake or maar is present. It is to be noted that only a few rare examples of kimberlitic volcanoes are known to exist: in Tanzania, Mali and Botswana. In certain cases kimberlitic volcanoes consist of low-relief craters.

Fig. 4 shows that the distance between the highest part of the crater and the base of the main diatreme is about 2,300 m. Considering the local geomorphological and topographical characteristics and an average speed of erosion equivalent to one metre every 30,000 years, it can be easily foreseen that the majority of known kimberlitic diatremes are eroded as far as the root level in about 70 million years. During this period of time, the diamonds contained in the including rock will be freed and deposited in ore bodies of fluvial gravels or sandy littoral deposits (i.e. placers). It is noteworthy that some mines in South Africa (i.e. Orapa, Jagerfontein, Kimberley and Bellsbank), all cretaceous in age, present greatly differing levels of erosion. Consequently, the Bellsbank mine has very limited economic potential, as almost all of the mineralized part belonging to the crater and main diatreme has already been removed by surface erosion. The Orapa mine, on the other hand, has preserved intact nearly all of the main diatreme to a depth of about 2,000 m, so that production can be guaranteed for at least another hundred years.

THE DISCOVERY OF DIAMONDS IN CANADA

Several exploration attempts have been made in the last thirty years to discover diamonds in Canada. Brummel (1984) has, for instance, reconsidered the question of the presence of diamonds in the glacial moraines of Ontario and in the regions of the Great Lakes in the USA. The author has again examined all the available data on known occurrences of diamonds in Canada, concentrating his attention on the outcroppings in Ile Bizard (Montréal, Quebéc) and those of Somerset Island (N.W.T., Canada). Both these deposits contain microscopical diamonds, but are not economically viable. Since 1988 further kimberlitic deposits have been found near Prince Albert and at Fort à la Corne, Saskatchewan (Lehnert-Thiel *et al.*, 1992). The two most interesting discovery – perhaps the most promising from an economic point of view – are the BHP Koala Camp, owned by Dia Met Minerals (i.e. Lac de Gras, 350 km northeast of Yellowknife, N.W.T.) and the Snap Lake property (same district) owned by Winspeare Resources Ltd. Oif Vancouver. The Koala Camp discovery was made thanks to the prospector Chuck Fipke and John Gurney, and it is probably destined for economic production in the near future, considering that around 30% of diamonds found in surveys have proved to be of gemological value.

This discovery, which is now a producing mine, was made possible mainly as a result of geochemical sampling techniques (fig. 5) which utilize marker minerals such as garnet

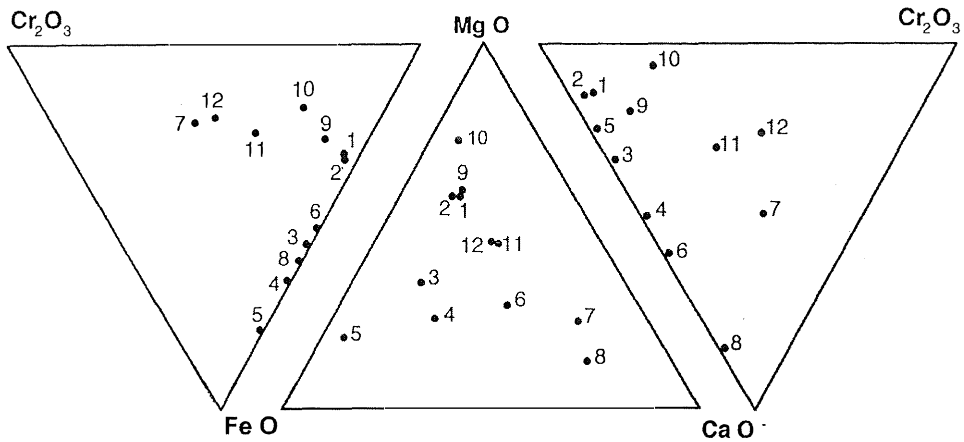

Fig. 5 – Average chemical composition of pyrope-type garnets, based on the classification method proposed by Dawson and Stephens (1975, 1976).

G10, poor in Ca (ca. 4%) and rich in Cr and Mg, and chromite, which is exceptionally rich in Cr, generally exceeding 62.5% (Dawson and Stephens, 1975, 1976; Griffin *et al.*, 1991; Gent, 1992). Another geochemical marker is represented by ilmenite, which – although not always present in the stability field typical of diamonds – seems nevertheless to play an important genetic role. Indeed, it has been observed that, when the iron in ilmenite is highly oxidized, the diamantiferous diatremes are barren (Gurney, 1984, 1989). This fact appears to be directly proportional to the temperature conditions and the quantity of oxygen present in the kimberlitic magma. The oxidization of iron in ilmenite thus appears to be a good criterion for assessing the persistence of diamonds in the kimberlitic magma. Indeed, it seems certain that the fugacity of oxygen in the ascending magma induces «vaporization» of the carbon minerals, transforming them automatically into CO_2 or CO.

Another group of diamantiferous outcroppings has recently come to light in an area situated on the border between Ontario and Quebéc, almost below the southernmost tip of Hudson Bay. This is a significant finding for two reasons: firstly, it would constitute at last a logical explanation for the discovery of diamonds in the glacial moraines of southern Ontario, and secondly, it would indicate for the first time the presence of diamonds in lamproitic rocks in territories of the Canadian shield.

Finally, the most exciting discovery to date, has been made in the Snap Lake area, Camsel Lake district, N.W.T., owned by Winspear Resources Ltd. of Vancouver, B.C. The results of the recently completed drilling program have indicated the extend of a potentially mineable hypoabyssal kimberlite dike system hosted in precambrian granitic material. Notably, substantial amounts of kimberlite carrying abundant macro and micro diamonds, underlie the north shore of Snap Lake (J.A. McDonald, personal communication, 1998).

Considering the gentle dip of the structure, the easy acces to eventual open pit operations, the exceptional grades, beauty and weight of the stones found during bulk sampling, the Snap Lake property seems to shape up as «the true» diamond mine in Canada.

The interest shown by various mining companies is therefore justified: the majority of Canadian territories consist of areas belonging to the immense North American craton which, in certain zones (Superior and Slave provinces), is ideally characterized by very ancient rocks (i.e. Archeozoic), and hence theoretically suited to containing economically viable quantities of diamonds.

CONCLUSIONS

Modern dating techniques applied to the mineral phases found in diamonds have shown that the solid inclusions are generally very old indeed, their ages varying from 3.3 to 1 billion years. Since the diamond inclusions are considered as cogenetic phases with the including carbon crystals, it follows that diamonds too are extremely old and characterized by the ages just mentioned. Moreover, it has been seen that the kimberlitic and lamproitic rocks are generally younger than the diamonds themselves, their ages varying from 0.1 to 1.2 billion years. It has also been demonstrated that kimberlites and lamproites are not the rocks in which the diamonds themselves crystallize, but instead constitute the means of transport which permit the carbon minerals to reach the earth's surface.

Of course the mechanism of sampling from the primary source in the upper part of the mantle is still not altogether clear. As the chemical-physical conditions for the formation and conservation of diamonds exist ideally at depths more than 150 km, it is supposed that they are temporarily stored in highly stable areas of the mantle, situated directly beneath the vast continental cratons. In these areas, the relatively lower temperatures and high pressures would permit the crystallization and conservation of the carbon minerals until the moment of sampling, and consequently their ascent. Recent isotopic studies have also shown that the diamonds originating from peridotitic rocks seem to have been generated in fairly homogeneous zones of the earth's mantle. Instead, the diamonds originating from eclogitic rocks have apparently been generated from crustal plates transported in depth by subduction phenomena related to the drifting of the continental plates.

The studies reviewed in this syntesis therefore confirm the hypothesis that the most interesting areas for the finding of diamond deposits are those of the ancient, stable continental cratons, situated directly above the areas of the mantle which are most favourable for the creation and conservation of diamonds. Kimberlitic and lamproitic rocks, as they are younger than the diamonds themselves, often prove barren. These rocks, however, are mineralized only if they are able, prior to ascent, to intersect those sectors of the mantle where peridotitic or eclogitic rocks, also containing diamonds, originate. The detailed study of inclusions in diamonds is therefore essential for serious, technically advanced prospecting.

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REFERENCES

ANDERSON O.L. (1979) — *The role of fracture dynamics in kimberlite pipe formation*. In: Proc. Second Int. Kimberlite Conf., Boyd and Meyer (eds), Vol.1. *Kimberlites, Diatremes and Diamomds: Their Geology, Petrology and Geochemistry*. Vol. 2. *The Mantle Sample: Inclusions in Kimberlites and Other Volcanics*. Am. Geophys. Union, Washington D.C., Vol. 1, pp. 344-353.

BRUMMER J.J. (1984) — Diamonds in Canada. In: *The Geology of Industrial Minerals in Canada*. Guillel and Martin (eds). Can. Inst. Mining Bull., Spec. Publ. No. 29, 311-320.

CLIFFORD T.N. (1970) — *The structural framework of Africa*. In: African Magnetism and tectonics. Clifford and Gass (eds), 1-26, Oliver and Boyd, Edinburgh.

DAWSON J.B. (1980) — *Kimberlites and their xenoliths*. Spinger-Verlag, Berlin, New York.

DAWSON J.B. (1989) — *Geographic and time distribution of kimberlites and lamproites: Relationships to tectonic processes*. Proc. Fourth Int. Kimberlite Conf., Perth 1986, In: *Kimberlites* *and related rocks*. Ross *et al.* (eds), Vol. 1, 323-342, Geol. Soc. Austral., Spec. Publ. No. 14.

DAWSON J.B. and STEPHENS W.E. (1975) — *Statistical classification of garnets from kimberlite and associated xenoliths*. J. Geol., **83**, 589-607.

DAWSON J.B. and STEPHENS W.E. (1976) — *Statistical classification of garnets from kimberlite and associated xenoliths*. J. Geol., **84**, 495-496.

DEINES P., GURNEY J.J., and HARRIS J.W. (1987) — *Carbon isotopic composition, nitrogen content and inclusion composition of diamonds from the Roberts Victor kimberlite, South Africa: Evidence for $\delta^{13}C$ depletion in the mantle*. Geochim. Cosmochim. Acta, **51**, 1227-1243.

EGGLER D.H. (1989) – *Kimberlites: how do they form?* In: Proc. Fourth Int. Kimberlite Conf., Perth 1986, Kimberlites and related rocks. Ross *et al* (eds). Vol. 1, 489-504., Geol. Soc. Austral. Spec. Publ. No. 14.

GENT M.R. (1992) — *Diamond exploration in Saskatchewan*. Can. Inst. Mining Bull., **84**, 64-71.

GLOVER J.E. and HARRIS P.G. (1984) — *Kimberlite occurrence and origin: A basis for conceptual models in exploration*. Glover and Harris (eds), Geology Department and University Extension, University of Western Australia, Publ. No. 8.

GRIFFIN W.L., RYAN C.G., FISHER N.I., and FRIEDMAN J.H. (1991) — *Trace elements in garnets and chromites: Their use in diamond exploration*. CSIRO, New South Wales Australia reprint No. 8.

GURNEY J.J. (1984) — *A correlation between garnets and diamonds in kimberlite*. In: *Kimberlites occurrences and origin: A basis for conceptual models in exploration*. Gloves and Harris (eds), Geology Department and University Extension, University of Western Australia, Publ. No. 8, pp. 143-166.

GURNEY J.J. (1989) — *Diamonds*. In: Proc. Fourth Int. Kimberlite Conf., Perth 1986, *Kimberlites and related rocks*. Ross *et al.* (eds), Vol. 2, 935-965, Geol. Soc. Austral. Spec. Publ. No. 14.

HAGGERTY S.E. (1986) — *Diamond genesis in a multiply-constrained model*. Nature, **320**, 34-38.

HAWTHORNE J.B. (1975) — *Model of a kimberlite pipe*. Phys. Chem. Earth, **9**, 1-15.

JANSE A.J.A. (1984) — *Kimberlites: were and when*. In: *Kimberlite origin and occurrence: A basis for conceptual models in exploration*. Gloves and Harris (eds), 19-61, Geology Department and University Extension, University of Werstern Australia, Publ. No.8.

JENNINGS C.M.H. (1990) — *Exploration for diamondiferous kimberlites and lamproites: Modern exploration techniques*. Sask. Geol., Soc., Spec. Publ. No. 10, 139-148.

KIRKLEY M.B., GURNEY J.J., and LEVINSON A.A. (1991a) — *Age, origin and emplacement of diamonds*. Gems Gemol., **27**, 2-25.

KIRKLEY M.B., GURNEY J.J. and LEVINSON A.A. (1992) — *Age, origin and emplacement of diamonds: a review of scientific advances in the last decade*. Can. Inst. Mining Bull., **84**, 48-57.

KIRKLEY M.B., GURNEY J.J., OTTER M.L. HILL S.J. and DANIELS L.R. (1991b) — *The application of C isotope measurements to the identification of the sources of C in diamonds: a review*. Appl. Geoch., **6**, 477-494.

KRAMERS J.D. (1979) — *Pb, U, Sr, K and Rb in inclusion-bearing diamonds and mantle-derived xenoliths from southern Africa*. Earth Planet. Sci. Lett., **42**, 58-70.

LEHNERT-THIEL K., LOEWER R., ORR R.G., and ROBERTSHAW P. (1992) — *Diamonds-bearing kimberlites in Saskatchewan, Canada: The Fort à la Corne case history*. Explor. Mining Geol. **1**, 391-403.

MEYER H.O.A. (1985) — *Genesis of diamond. A mantle saga*. Am. Mineral., **70**, 344-355.

MEYER H.O.A. (1987) — *Inclusions in diamonds*. In: *Mantle xenoliths*, Nixon (ed.), 501-522. J. Wiley, New York.

MITCHELL R.H. (1986) — *Kimberlites: Mineralogy, Geochemistry and Petrology*. Plenum Press, New York.

MITCHELL R.H. (1991) — *Kimberlites and Lamproites: Primary sources of diamond*. Geosci. Can., **18**, 1-16.

MITCHELL R.H. (1995) — *Kimberlites, Orangites and related rocks*. Plenum Press, New York and London.

MITCHELL R.H. and BERGMAN S.C. (1991) — *Petrology of lamproites*. Plenum Press, New York.

MOORE R.O. and GURNEY J.J. (1985) — *Pyroxene solid solution in garnets included in diamond*. Nature, **318**, 553-555.

NIXON P.H. ed. (1987) — *Mantle Xenoliths*. J. Wiley, New York.

RICHARDSON S.H. (1986) — *Latter-day origin of diamonds of eclogitic paragenesis*. Nature, **322**, 623-626.

RICHARDSON S.H., EHRLANK A.J., HARRIS J.W., and HART S.R. (1990) — *Eclogitic diamonds of Proterozoic age from Cretaceous kimberlites*. Nature, **346**, 54-56.

RICHARDSON S.H., GURNEY J.J., EHRLANK A.J., and HARRIS J.W. (1984) — *Origin of diamonds in old enriched mantle*. Nature, **310**, 198-202.

ROSS J., JAQUES A.L., FERGUSON J., GREEN D.H., O'REILLY S.Y., DANCHIN R.V., and JANSE A.J.A. (eds) (1989) — Proc. Fourth Int. Kimberlites Conf. *Kimberlites and related rocks*. Vol. 1. *Their* *composition, occurrence, origin and emplacement.* Vol.2. *Their mantle/crust setting, diamonds and diamonds exploration.* Geol. Soc. Austral. Spec. Publ. No. 14.

SLODKEVICH V.V. (1983) — *Graphite paramorphs after diamonds.* Int. Geol. Rev. **25**, 497-514.

SMITH C.B., ALLSOPP H.L., KRAMERS J.D., HUTCHINSON G. and RODDICK J.C. (1985) — *Emplacement ages of Jurassic-Cretaceous South Africa kimberlites by the Rb-Sr method on phlogopite and whole-rock samples.* Trans. Geol. Soc. S. Africa, **88**, 249-266.

WYLLIE P.J. (1989) — *The genesis of kimberlites and some low-SiO_2, high-alkali magmas.* In: *Kimberlites and related rocks.* Ross *et al.* (eds.) Proc. Fourth Int. Kimberlite Conf. Vol. 1, 603-615, Geol. Soc. Austral. Spec. Publ. No. 14.