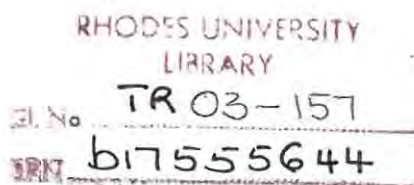


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Presents:

*Geotectonic Controls on Primary Diamond Deposits*  
*-A review of Exploration Criteria-*

Submitted in partial fulfillment of the requirements for the Master of Science  
(Exploration Geology) degree of Rhodes University.

January 2002

# Abstract

The origin of diamonds, their preservation and transport to the surface have been important issues over the last decades after the acknowledgement that diamonds are xenocrysts in the host kimberlites and after the discovery of new transport media such as lamproites. Different types of diamonds -E-type diamonds, P-type diamonds- and different types of hosts -Eclogites, Peridotites- have been distinguished. Each type corresponds to particular formation criteria. Ecogitic Diamonds are mostly related to subduction processes, whereas more uncertainties remain regarding the formation of Peridotitic Diamonds. Komatiite extraction and subduction of graphite-bearing serpentinites have been proposed as the more likely processes involved in their formation. A typical mantle signature for diamonds implies a thick, cool, reduced lithosphere. The keel-shape model is the most popular. Archaean cratons are therefore the most promising exploration target and area selection will expect to follow the Clifford's Rule. However, the evidence of cratonic areas hidden under younger formations through seismic profiles and the discovery of diamond structurally trapped outside their stability field, have increased the potential of diamondiferous areas. Preservation of diamonds inside the lithosphere requires that the mantle-root remains insulated against excessive reheating and tectonic reworking. Mantle-root friendly and mantle-root destructive structures are distinguished. Small-size cratons are usually the most promising exploration targets.

Transport of diamonds to the surface is dependant on the same criteria of preservation. Only kimberlites and lamproites have been recognized as efficient transport media. Their ascent to the surface is conditioned by a multitude of parameters, amongst them the nature of the magma, the speed of ascent, the presence of pre-existing structures in the crust and the availability of ground water in the near-surface environment. The origin of kimberlite magma probably lies near the transition zone. Mixtures of depleted asthenospheric sources and metasomatically enriched and possibly subducted materials are likely to be at the origin of the different kimberlite magmas. Kimberlite magmatism correlates generally in time with global tectonic events, triggered by either plume activity or by subduction processes, depending of the tectonic school of thought. Kimberlite alignments have been interpreted as hotspot tracks, and kimberlite magmas as volatile-rich melts issued from the remaining plume tail. The plume head produces flood-basalts in an adjacent "thinspot" of the lithosphere, generally on the edges of the cratons. Kimberlite and lamproite ascent to the surface are unconditionally influenced by regional structures. Rift structures, ring structures, transform faults, suture zones and deep-seated faults have been mentioned as controlling or accompanying features of kimberlite magmatism. Near-surface emplacement constraints are better understood and the ultimate shape of the intrusion(s) depends on the nature of the country rocks, the availability of ground water and the near-surface faulting pattern. The recent discovery of "fissure" kimberlites is one of the more important breakthroughs of the last decade.

With a better understanding of the processes involved in diamond formation, preservation and of kimberlite emplacement, major diamond discoveries have recently increased on all the continents. Successful diamond exploration requires today an integration of all geophysical, petrologic, geochemical and structural information available. The particular study of the northwestern Australian lamproite and kimberlite fields, the Brazilian kimberlites, the eastern-North American kimberlite fields, the Lac de Gras kimberlite field, the South African rich-kimberlite provinces, and the Yakutian kimberlite fields provide concrete examples of the geotectonic controls on primary diamond deposits. Area selection criteria based on the previous models and examples, are expected to yield to many more discoveries in the coming years.

# Acknowledgements

This dissertation would have never been achieved without the encouragements and supports of a number of people.

I would like first to give a special thank to Prof. J. Moore and Dr. R. Sheets who have made this year of master for me an unforgettable year and who have allowed me another year to finish this dissertation.

With great thanks to Dr. L. Ameglio without who I would never have come to South Africa and who initiated the subject of this dissertation. Thanks again for your comments, brilliant ideas, and corrections.

Thanks to M. Skinner and J. Gurney for your comments.

Special thanks to C. Williams for a special year, for your support along this master and for your time spent to correct my English pronunciation and spelling.

Thanks to the Gemcom team for your support and understanding to help me finish this dissertation in time despite the huge amount of work here in Johannesburg.

To finish, I would like to say a great thank to all my family and friends in France and in South Africa who support me along this master. Thank you Maman and Pierre for your love and understanding during this time take on yours in France, where I wrote the bulk of this dissertation.

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# Introduction

Prior to the discovery of the first kimberlites, diamond exploration was historically conducted by prospectors, and restricted to alluvial deposits. These deposits were until recently, the major supply for world's diamond production and it is still the major production of several countries, such as Sierra Leone, Brazil, India. The primary source for these deposits still remain largely undiscovered. The use of alluvial diamonds and other indicator minerals as tracers, led to the discovery of the principal primary source rock called kimberlite. Until recently, diamond exploration was therefore restricted to the search of kimberlites and understanding of their location and emplacement. Worldwide exploration has been conducted with the knowledge that economically viable primary diamond deposits occur on cratons of Archaean age (Clifford, 1966).

However, significant modern discoveries have represented important exploration breakthroughs in terms of new geographic areas, inside and outside cratons, and recognition of new types of primary host rocks, e.g. lamproïtes. Thus, the last decade saw an explosion of the world diamond production and producers all over the world, while in the last century major producers were confined to those where alluvial deposits and follow-up kimberlite pipes were exploited.

In the need to explore new terrains at low exploration costs, improving area selection becomes a major priority. Area selection is integral and fundamental to any exploration program. The knowledge concerning the genesis of the resource is used to select regions in which to apply local exploration techniques or to supplement information gained from traditional exploration techniques.

Understanding of the controls governing kimberlites and lamproïtes location and emplacement has been and is still the fact of an ongoing debate and advanced little. Much has improved the knowledge of the formation of diamonds. The major breakthrough of the last decade was the recognition that diamonds are xenocrysts and that igneous host rocks are simply a transport medium from the upper-mantle source to the surface. Thus, the geotectonic environment of diamond formation could form a complete distinct problem from the geotectonic controls of kimberlites or lamproïtes emplacement.

The present dissertation will attempt to present a geotectonically based diamond-exploration overview. Prediction of areas under which diamonds have formed and were preserved, as well as prediction of areas where economically viable kimberlites and related rocks could have intruded and been preserved, will therefore constitute the bulk of this report.

In order to understand fully the choice of a particular favourable environment, elements of past and more recent theories, related to mantle processes and plate tectonic, will also be presented and discussed.

As most of the following ideas are still debated, this report does not aim to give a definitive area selection model, but it will review the most advanced models, which are illustrated by chosen examples all around the world. We thus hope to shed light on present diamond discoveries and future diamond exploration strategies.

# 1. Generalities

## 1.1. Types of diamondiferous occurrences

Diamond is pure C, and as carbon is the fourth most abundant element in the solar system, diamond is quite common in the universe. Some diamonds are presolar, other diamonds formed with the solar system, and diamonds from our planet could be considered as a window to the geodynamic evolution of Earth's deep interior (Haggerty, 1999).

Economic primary diamond deposits on earth, exception of alluvial deposits, are found in mantle-derived igneous rocks, the principal hosts being kimberlites and lamproites. There are however a number of other diamond-bearing rock types including peridotite and eclogite mantle-derived xenoliths found in kimberlites, high-pressure metamorphic rocks and meteorites. These occurrences, while principally uneconomic, are fundamental in the understanding of diamonds origin. A brief presentation of the diamond host rocks is presented below.

**Kimberlites**, as stated by Helmstaedt (1993), are volatile-rich, potassic, ultrabasic rocks. A complete description of their composition and textures can be found either in Dawson (1980), Mitchell (1986), or Smith (1983). Kimberlites are usually divided into two groups (Smith, 1983): (i) Group I or olivine-rich monticellite-serpentine-calcite kimberlites; (ii) Group II or micaceous kimberlites. These groups are derived from sources that are either depleted (Group I), or enriched (Group II) in light rare earths elements with respect to a bulk earth reference composition. While Group I kimberlites occur worldwide, Group II kimberlites are so far known only from southern Africa, where they form a slightly older province. Occurrences of kimberlites are not restricted to Precambrian cratons, however diamondiferous kimberlites are mostly confined to cratons with few exceptions found in mobile belts.

**Lamproites** have been reviewed recently by Mitchell (1991). Like kimberlites, they are hybrid rocks, consisting of mixtures of magmatic crystallisation products with upper mantle xenoliths and xenocrysts. Lamproites are peralkaline, ultrapotassic, and are closer to Group II kimberlites. Their chemical, textural, mineralogy and emplacement characteristics are very close to kimberlites, and in many instances, lamproites have been first confused with kimberlites (Prairie Creek, USA; Bobi, Ivory Coast). Many of them are still under investigation. Lamproites, like kimberlites, occur as pipes, dikes and sills, but lamproites have a champagne-glass shape rather than cones. They are usually lower grade than kimberlites. Lamproite ages range from late Proterozoic to recent (20 Ma).

**Other diamond-bearing rocks** are reviewed notably by Nixon (1995). Apparently other mantle-derived igneous rocks with sufficiently deep origins and uplifted rapidly to the surface by tectonic processes, such as alpine peridotites, could also be diamondiferous. The discovery of graphite pseudomorphs after diamond octahedral in alpine ultramafics at Beni Bousera, Morocco, gives the proof that not only kimberlites or lamproites can collect diamonds. Diamonds and coesite have also been found in metasedimentary and metabasic rocks of metamorphic belts, indicating that crustal rocks have travelled a tectonic two-way street from the surface into the diamond stability field and back. It seems to be the case for diamonds found in the metamorphosed layered ultramafic complex near Kaya (Burkina Faso). Diamonds have also been recorded in other host rocks, like in harzburgites from the Koryak Mountains (Russia) or in eclogites from the Dabie Mountains (Eastern China).

## 1.2. Kimberlites, clusters and diamond content

A particular terminology to group kimberlite bodies has been used in South Africa. Skinner *et al.* (1992) defined: (i) kimberlite *provinces*, as geographically coherent trends of occurrences emplaced in a spanning time less than 100 Ma and possibly extending across tectonic boundaries; (ii) kimberlite *fields* as geographically coherent trends of occurrences locally restricted to specific tectonic domains; (iii) kimberlite *clusters* as similar groups of occurrences exhibiting distinct preferred linear orientation; (iiii) kimberlite *complexes*, as close association of more than one phase of intrusion.

Diameter of clusters is generally on order of 40 km, and distance between clusters or fields is around 400 km (Janse, 1984). However, certain kimberlites of different clusters and completely distinct composition occur within less than 50 km of each other in South Africa and Gurney (1989) stated that distances between clusters show no single pattern. The individual surface extent of kimberlites is generally very small, rarely exceeding 1 km.

The number of pipes and dykes in one cluster varies considerably from 1 to 120. With few exceptions, generally few pipes are economic in the same cluster (table 1).

Most kimberlite fields and lamproites are barren and of approximately 4000 known occurrences in the world, probably 500 to 1000 are diamondiferous and less than 60 have been mined profitably (Jennings, 1995).

Botswana	3/31 1/12	Orapa etc. Jwaneng
Canada	7 + ?/80 +	N.W.T. Lac De Gras
C.I.S.	3/11 4/120 1 or more ?/50	Mir etc. Aikhal, Sytykan, Jubilee, Udachnaya, Daldyn, Alakit Field Arkhangelsk
China	1/11	
India	1/4 +	
Lesotho	1/30?	
South Africa	5/68 1/9 1/16 1/14 1/17 1/6	Kimberley, Group 1 Cluster Jagersfontein Koffiefontein Premier Veneta Finsch
Tanzania	1/35	Mwadui
Zaire	1/40?	Mbuji-Maji

Table 1: Ratio of potential economic or producing pipes to total in same clusters (after Jennings, 1995).

Repartition of diamonds in kimberlites inside a cluster is not yet completely understood. Discrepancies in diamond grades in different clusters inside a same kimberlite field and even in different adjacent pipes inside a same cluster remain largely unexplained. Janse (1984) stated that large diameter pipes usually have a higher diamond content than smaller ones in the same cluster, and that these biggest pipes tend to be more centrally located in the cluster. However, recent discoveries tend to disprove the former statement (table 2).

The quality of diamonds does not also seem to be related to the size of the pipes or their diamond content. Generally diamonds coming from lamproites seem to be of poorer quality than kimberlite diamonds. The understanding of such features did not advanced much. Some answers will be proposed in the following sections.

Pipe	Area (ha)	Grade (ct/100 t)	Average US\$/ct	Average US\$/t
Aikhal	3.0	120	100	120
Argyle	46.0	549	9	49.4
Arkhangel	118	75	80	60
Bultfontein	9.7	40	75	30
Camatue	9.3	12	200	24
Catoca	66.0	46	60	27.6
Dia Met Panda *, Canada	3.1	118	127	150
Dia Met Koala *, Canada	3?	75	110	82
Dia Met Misere *, Canada	2.5?	330	43	142
Dalnaya	5.4	50	85	42.5
De Beers	4.8	90	75	67.5
Dokolwayo	2.8	40?	50?	20
Dutoitspan	10.8	20	75	15
Finsch	18.0	75	40	30
International	1.7	400	120	480
Jagersfontein	10.0	7	200	14
Jwaneng	45	147	110	161.7
Kimberley	3.6	100	200	200
Koffiefontein	10.3	7.4	150	10.5
Letlhakane	11.6	33.8	150	50.7
Letseng	16.0	3.5	400	14
Mbuji-Maji	18.6	600	10	60
Mwadui	146	6	150	9
Orapa	110	63	50	34
Premier	32.2	50.6	35	17.7
23 Party Congress	1.5	600	120	720
Udatchnaya	20.0	100	100	100
Venetia	12.7	137.5	100	137.5
Wesselton	8.7	27	100	27
Yubileynaya	40	100	100	100
Zarnitsa	21.5	15	120	18

Table 2: Area, grade, and values for economic kimberlites (from Jennings, 1995).

### 1.3. The Clifford's Rule

In 1966, Clifford published a paper in which he observed that economically diamondiferous kimberlites occur only in areas underlain by basement older than 1500 My, which he thought represented Archaean cratonic terrain.

This statement had a considerable impact on diamond exploration. Prior to this realisation, exploration was carried out in a random fashion in areas of known alluvial diamond deposits, by systematic sampling of kimberlite indicator minerals. Now the last recent discoveries were in areas where no alluvial diamonds deposits were known.

Various authors including Gurney (1989), Atkinson (1989) have stressed that diamondiferous kimberlites are restricted to cratons, characterised by thick crust and low geothermal gradients. The cratonic association of diamonds will be explained in details later.

However, certain confusion exists around the term "craton". It can be used in a time-stratigraphic sense and then it is synonymous with Archaean basement, or it can be used in a tectonic-structural sense. In that case, cratons represent rigid, coherent blocks of Archaean cores surrounded by Proterozoic mobile belts. In 1984, Janse proposed a different classification of cratonic blocks:

- Archon designed Archaean craton of minimum age 2400 m.y.
- Proton designed cratons of early to middle Proterozoic age, older than 1600 m.y.
- Tecton designed cratons of late Proterozoic age deformed by younger events.

In that sense, Janse (1984) stated that economic diamondiferous kimberlite pipes and dykes are restricted to Archons.

The discovery of economic primary diamond deposits in Western Australia (Cf. Atkinson *et al.*, 1984) in a mobile belt adjacent to older cratonic block however, contradict this rule. Argyle mine in Western Australia and Prairie Creek mine in Canada occur on Protons. However these deposits are not kimberlites, but diamondiferous lamproite pipes.

Janse (1991) stated that diamondiferous kimberlites are restricted to Archons, while diamondiferous lamproïtes occur preferentially in Protons.

Archons and Protons have thus economic potential, while no economically viable primary diamond deposits have yet been found on Tectons.

Recent discoveries of diamondiferous kimberlites in mobile belts has led to the assumption that kimberlites can be emplaced in an older basement prior to its involvement in orogenic movement (e.g. Cross, British Columbia) (Helmstaedt, 1993). Alternatively, parts of the Proterozoic terranes could have been over-thrusted onto an Archaean craton.

Proterozoic orogenic belts should therefore be also considered as potential diamond exploration targets, for diamondiferous lamproïtes and for diamondiferous kimberlites. Clifford's rule is thus not any more valid, as diamondiferous kimberlites have been found in mobile belts.

## 1.4. Primary diamondiferous occurrences around the world

An actualised world map of the diamondiferous primary deposits is presented in figure 1. It is striking to note that kimberlites are widespread around the earth, while a few decades ago, South Africa was still considered to be the only kimberlite diamond producer. The worldwide distribution of lamproites is less well known than that of kimberlites, because of the only recent interest for lamproites as diamond source rocks. The three major lamproite provinces are the Kimberley area in northwestern Australia, Leucite Hills in the Wyoming and Murcia-Almeria in southeastern Spain, but only Argyle (Australia), Kapamba (Zaire), Majhgawan (India), Prairie Creek (USA) and Bobi (Ivory Coast) are known diamondiferous lamproites (Hemstaedt, 1993).

Significant major recent discoveries of primary diamond deposits have greatly expanded the global supply of natural stones. Diamonds are now produced from 22 countries all over the world, the most important producers being Botswana, then C.I.S. (Russia) and South Africa (table 3). According to Jennings (1995), world production for 1993 was estimated to be 104 million carats, compared to 15.5 million carats in 1950. 2001 world production is estimated at 120 million carats.

The major discoveries of the last decades include Orapa and Jwaneng (Botswana, 1967, 1975), Argyle (Australia, 1979), Udachnaya and Yubileinaya (C.I.S, 1984), Ekati (Canada, 1991). However if the world production increased dramatically, the world output by value did not, 80% of the world natural diamond production by weight being of industrial quality, for which Argyle is a major contributor (Cf. Atkinson, 1989).

Country	Mines	Tonnes ('000)	Carats ('000)	US\$/ct	US\$ ('000)						
						D.R. Congo					
						Mbuyi-Maji	9,000	15	135,000		
						Small operators + artisans	7,500	60	450,000		
						<b>Total D.R.Congo</b>	<b>16,500</b>	<b>36</b>	<b>585,000</b>		
South Africa	Venetia	3,686	4,498	90	404,820						
	Premier	2,846	1,782	80	142,560						
	Kofffontein	2,199	151	250	37,750	Central African Rep.	Small operators+artisans	450	160	72,000	
	Kimberley	3,508	569	110	62,590	Ghana	Small operators+artisans	500	27	13,500	
	Namaqualand	6,141	810	185	149,850	Tanzania	Williamson	2,958	317	45,985	
	Finsch	4,204	1,925	75	144,375	Ivory Coast	Artisans	150	145	21,750	
	Marsfontein	531	436	115	50,140	Liberia	Artisans	170	160	27,200	
	The Coks	212	118	200	23,200	Sierra Leone	Artisans	250	250	87,500	
	Baken	725	46	418	19,228	Guinea	Small operators+artisans	450	230	103,500	
	Others		250	300	75,000	Lesotho	Small operators+artisans	20	250	5,000	
	<b>Total South Africa</b>	<b>24,062</b>	<b>10,583</b>	<b>106</b>	<b>1,109,513</b>	Brazil	Small operators+artisans	650	45	29,250	
Botswana	Orapa	14,882	12,172	50	608,800	Venezuela	Small operators+artisans	350	130	45,500	
	Lethakane	3,511	959	200	191,800	Guyana	Small operators+artisans	20	85	1,700	
	Jwaneng	9,237	11,520	115	1,324,900	China	Small operators	180	103	16,480	
	<b>Total Botswana</b>	<b>27,430</b>	<b>24,661</b>	<b>88</b>	<b>2,125,200</b>		<b>Total lesser producers</b>	<b>3,587</b>	<b>121</b>	<b>469,247</b>	
Namibia	De Beers Marne	2,500	576	220	126,720	Australia	Argyle	11,500	26,000	338,000	
	Namco	250	200	160	32,000		Merini	800	200	22,500	
	Namdeb contractors	1,800	91	350	31,850		<b>Total Australia</b>	<b>12,300</b>	<b>26,200</b>	<b>360,500</b>	
	Namdeb onshore	23,457	653	350	228,550	Canada	Ekati	2,500	2,529	173	453,555
	<b>Total Namibia</b>	<b>28,007</b>	<b>1,520</b>	<b>276</b>	<b>419,120</b>	Russia	Udachnaya	9,000	12,500	90	1,000,000
Angola	Caioca	2,000	1,500	70	105,000		Jubilee	9,000	5,300	55	225,000
	Luzamba	165	106	327	24,562		Others	3,500	3,000	90	270,000
	Small operators + artisans		2,400	250	600,000		<b>Total Russia</b>	<b>21,500</b>	<b>20,500</b>	<b>75</b>	<b>1,595,000</b>
	<b>Total Angola</b>	<b>4,006</b>	<b>186</b>	<b>186</b>	<b>729,662</b>		<b>World total</b>	<b>110,176</b>	<b>71</b>	<b>7,356,395</b>	

Table 3: World production of diamonds for the year 2000 (Cf. [www.terraconsult.be](http://www.terraconsult.be)).

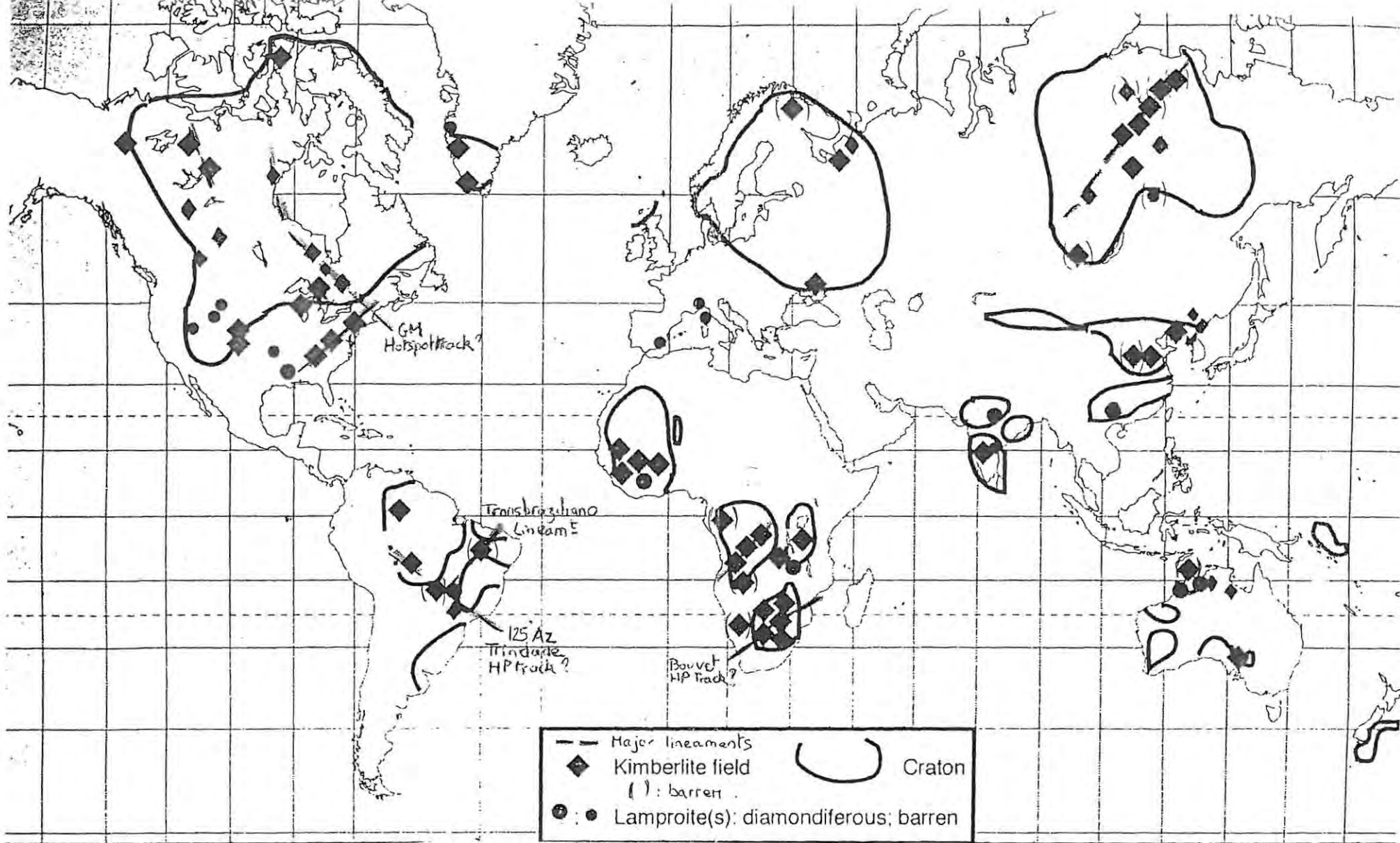


Figure 1: Diamond primary deposits, actualised world map.

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 Geotectonic Controls on Primary Diamond Deposits

It is evident that, in the same way that not all kimberlites are diamondiferous, not all Archons contain kimberlites. Future discoveries may change this situation. But worldwide observation shows that the biggest diamond deposits occur on Archons, which have the thickest platform cover and which have been uplifted the most (Janse, 1991). Very few kimberlite pipes are known in the exposed cores of the cratons, probably because they have been extensively eroded, like in the West African craton. This point will be elucidated later in section 3.8.

## 2. Geotectonic controls on diamonds formation and preservation.

### 2.1. Mantle signature for diamonds

It has been estimated from geothermobarometry on the silicate phases that the diamonds were formed at pressures corresponding to depths of 150 to 200 km and temperatures generally not exceeding 1200°C. A few unusual high-pressures corresponding to depths greater than 300 km, have been recorded for majoritic garnet inclusions in diamonds from the Monastery Kimberlite in South Africa. Diamond stability is controlled additionally by oxidation state and carbon speciation. Only strongly reduced environment stabilises carbon as CH<sub>4</sub> (figure 2). Sulfur and N<sub>2</sub> intervene as catalysts in carbon reduction, thus explaining the abundance of sulphide inclusions (Fe-rich and Ni-rich sulfide minerals) in diamonds (Cf. Haggerty, 1986).

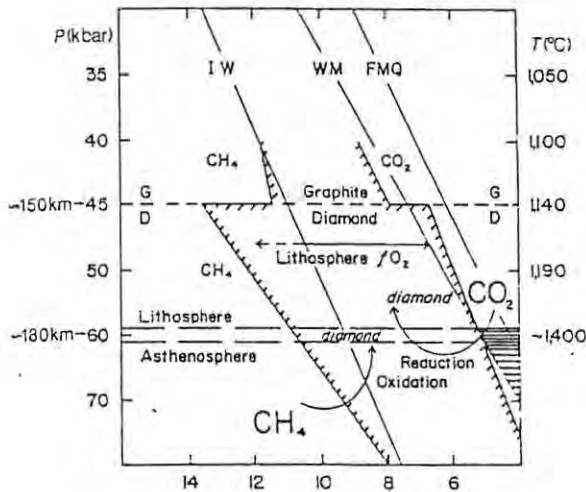


Figure 2: Diamond stability field (for details see Haggerty, 1986).

These constraints are coherent with a crystallisation of diamonds in a reduced lithosphere. Lithospheric conditions for diamond genesis and preservation imply a thick (>150 km) and by association cool (surface heat flow less than 40-45 mW.m<sup>-2</sup>) lithosphere in which the downward deflection of isotherms caused a corresponding upward expansion of the diamond stability field (Helmstaedt, 1993). A keel-shape model for the lithosphere under stable cratons is therefore favoured (figure 3).

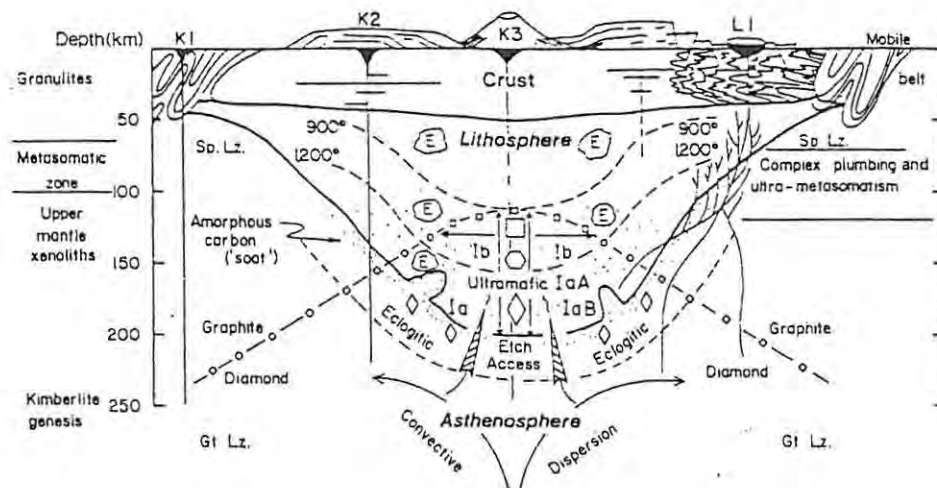


Figure 3: Schematic cross section of a subcontinental, subcratonic lithospheric keel showing the diamond-graphite inversion curve (from Haggerty, 1986). Sp. Lz.: Spinel Lherzolite, Gt. Lz.: Garnet Lherzolite, E: Eclogite.

In the case of South Africa, the petrologic signature of the diamondiferous mantle root under the Kaapvaal Craton and the Kalahari Craton in relation to mineral assemblages associated with diamonds, have been reviewed by Gurney (1990). Boyd and Gurney (1986) proposed a simple model for the mantle-root beneath the Kaapvaal Craton, summarised in figure 4. The lithosphere-asthenosphere boundary under the craton is thought to be approximately of 170 to 190 km, against 140 km beneath the adjacent mobile belts.

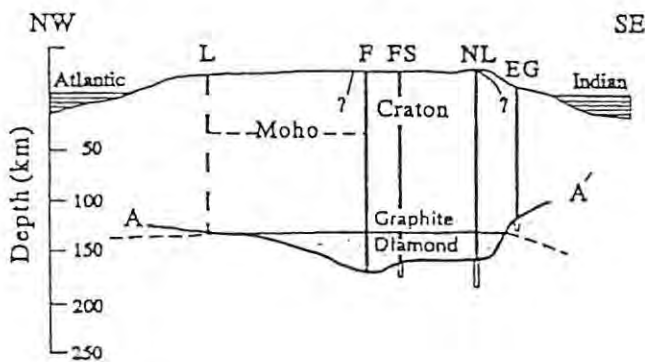


Figure 4: Mantle-root beneath the Kaapvaal Craton (from Boyd and Gurney, 1986). Only on-craton kimberlites (Northern Lesotho, Frank Smith and Finsh) have xenoliths derived from the diamond stability field. The line A-A' is interpreted as the base of the lithosphere.

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Geotectonic Controls on Primary Diamond Deposits

This model is supported by seismic and geothermal data, showing that plates in old cratons are of greater thickness and are underlain by layer of anomalous mantle material (Cf. Helmstaedt and Gurney, 1995). Since the end of the 80s, seismic tomography realized under the Canadian Shield, has showed that the diamondiferous mantle-roots are of relatively fast shear waves, coherent with cooler lithospheric temperatures relative to adjacent hotter asthenosphere.

The petrological model of mantle-roots is consistent with the heat-flow model. It seems that only ancient terrains have sufficiently large, low heat flow areas, reflected in thick, cool lithosphere favourable for diamond formation and preservation. A number of hypotheses have been reviewed by Morgan (1995) to explain these features. It appears that younger terrains are characterized by heterogeneity in their crustal radiogenic heat production, reflected in the lateral heterogeneities in their lithospheric thickness, which prevent the formation of extensive thick cool lithospheric roots, contrary to Archaean terrains.

To summarize, the petrological and geophysical models of diamondiferous mantle-roots are in accordance with an origin of diamonds in Archaean cratons. For exploration purpose, these observations are of great interest in explaining why younger stable terrains are barren. Applications of geophysical methods to detect potential diamondiferous mantle-roots are already a success in diamond exploration. For example the limited high shear-wave velocity under the southern Slave Province in Canada suggested the high diamond potential of this area and permits the discovery of an economic diamondiferous province (Morgan, 1995). Studies of the particular geophysical signature of the mantle-roots under the diamond-rich southern African and Siberian Cratons will certainly permit an improved exploration model for the other cratons in the world.

However, Morgan (1995) points out two major problems remaining in using geophysical tools and models to characterize diamondiferous mantle-roots. The first one is the poor depth resolution of the techniques. Only seismic data could give good 3-D imagery at depth (> 200 km), while other techniques based on potential field values, such as heat flow, gravity and magnetics commonly yielded to different interpretations. Thus uncertainties in geotherm extrapolation and physical properties at depth result in a lack of precision in the determination of potential diamondiferous mantle-roots. For example, a lithospheric thickness of 180 km will be considered less favourable for diamonds than a lithosphere of 200 km. But there is no precise value of lithospheric thickness or other physical properties at which the transition diamond-barren/diamond-fertile could be traced. Morgan (1995) suggests that the margin of error inherent to these uncertainties should be small enough to provide useful constraints on diamond occurrences. The successful application of geophysical techniques presented above in the case of the Slave Craton, shows clearly that in general this error is negligible and that physical properties of the lithosphere could be nowadays determined with a certain degree of confidence, using notably seismic refraction, seismic tomography, and magnetotelluric studies. Internal structures of the mantle-roots are also today accessible, with seismic reflection studies.

The second problem in using physical models for Archaean terrains is the geological time. Is the modern lithospheric structure probed by these techniques applicable to the lithosphere at the time of diamond formation? Some terrains may have possessed conditions favourable for diamond genesis and been reactivated later. In this case, potential diamondiferous provinces could be situated outside the Archaean terrains previously defined by the Clifford's rule. According to Morgan (1995), the USA Wyoming province falls into this category. Morgan proposes thus to use the elevation history of a region to infer its thermal and lithospheric thickness history. However it will be unreasonable to look at the lithospheric conditions since Archaean times. Preservation of diamonds requires the same reduced cool environment and transport of diamonds to the surface by the kimberlitic event is likely to occur prior to the reactivation episode. Lithospheric conditions at the time of kimberlite emplacement are thus the most useful.

## 2.2. Age of diamonds

The most important conceptual change affecting our understanding of the diamond formation since the last 25 years concerns the genetic relationship between diamond and kimberlite, with a gradual conversion from the phenocryst to the xenocryst school. The phenocryst school believes that diamonds originally formed at depth from the crystallisation of kimberlite magma and thus are phenocrysts -genetically related to the magma. On the other hand, the xenocryst school thinks that diamonds were formed prior to the intrusion of kimberlite and collected by this transport medium en route to the surface. Although the concept that kimberlites may be not the true parent rock of diamonds was proposed early in the 1900s with the discovery of diamond-bearing eclogite xenolith, it is only at the Third International Kimberlite Conference in 1981, that it was recognized. First proofs that diamonds are much older than the kimberlite that brought them to the surface came from U-Pb studies by Kramers (1979) on sulfide inclusions in Finsch. These suggestions were confirmed by Richardson et al. (1984) who established an age of 3300 Ma for diamonds from the Mesozoic kimberlites of Finsch and Kimberley. All the recent data confirm that diamonds were formed during Archaean to Proterozoic times.

Diamonds are thus very old, formed continually, intermittently throughout most of earth's history (3300 Ma to 990 Ma) while sampling by kimberlites or lamproites occurred much latter between 1600 and 20 Ma, except for Premier Mine, where eclogitic diamonds would have apparently the same age than the kimberlite (1150 Ma, data from Richardson et al., 1993). The following diagram represents the age ranges of diamond host-rocks compare to the age ranges of the diamond deposits on surface (figure 5).

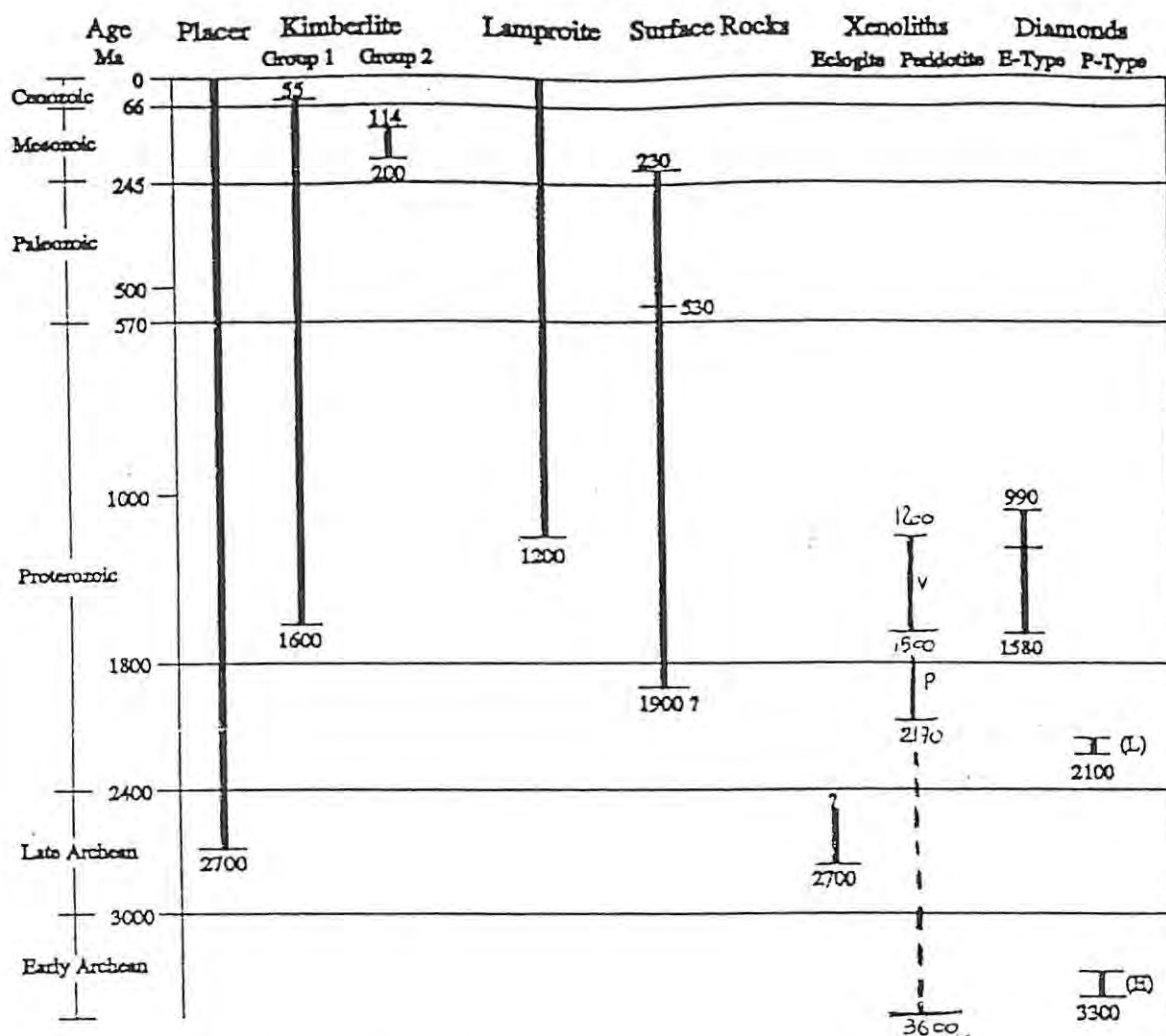


Figure 5: Age ranges of diamondiferous deposits compared to ages of mineral inclusions in E-type and P-type diamonds. H=Harzburgitic, L=Lherzolic assemblage (from Helmstaedt, 1993). Peridotite xenoliths ages are from Carlson et al., 1999 (v:venitia, p: premier).

Diamonds cannot be dated directly, but the ages of mineral inclusions in diamonds can be determined with the decay systematics of radiogenic isotopes: Sm-Nd for garnet, Ar-Ar in Ca pyroxene inclusion, Re-Os and U-Pb in sulfide inclusions (Haggerty, 1999).

Concerning diamond dating, lots of discussions remain in which technique gives the best age precision. Navon (1999) recently reviewed the different methods of diamond dating. In the case of isotopic dating of diamond inclusions, it should be reminded that meaningful ages representing the formation of diamonds will be obtain only if:

- All the diamonds analysed are part of a the same discrete event of diamond formation,
- This event reset the isotopic system in the inclusions,
- The analysed inclusions remained a close system since diamond formation.

It appears in the study of Navon (1999) that U-Pb, Nd-Sm, Re-Os isotopic dating are not always reliable and must be used carefully. Rb-Sr system may be the most sensitive method for dating diamond formation, but inclusions and also fluids at the diamond-inclusion interface must be analysed. New method, based on the kinetics of nitrogen aggregation gives temporal information on the diamond itself rather than on its inclusions and starts to be used as thermometers in old diamonds.

Recent dating of diamonds is thus more and more accurate but uncertainties still remain concerning age precision.

### 2.3. Diamond host-rocks

Studies of mineral inclusion in diamonds and of mineral assemblages in diamond-bearing xenoliths reveal that diamonds are associated with two major rock-types in the lithosphere: (i) eclogites (yielding E-type diamonds with eclogitic inclusions); (ii) garnet peridotites (yielding P-type diamonds with peridotitic inclusions).

It will be important to remind here that inclusions document the host-rock mineralogy at the time of diamond formation, while xenoliths are direct samples of diamond host-rocks prior to the kimberlitic eruption. Temporally and compositional differences between xenoliths and inclusions are thus expected.

Eclogite is a dense coarse-grained ultramafic rock consisting of garnet and clinopyroxene. Eclogite is indicative of high-pressure environment, consistent with that in which diamonds form. Typically, eclogites occur in deep crustal metamorphic regions below continents. Eclogite is enriched in crustal elements and is geochemically more primitive than the mantle keel, which implies later injection of eclogite into the keel. Since the original discovery of diamond-bearing eclogite xenoliths in South Africa by Bonney in 1899, many thousands of them have been recovered from about a dozen mines. The diamond grade of some diamondiferous eclogite xenoliths is very high, exceeding that of the host kimberlites by several orders of magnitude (Helmstaedt, 1993). Gurney (1989) presented also evidence that the average stone size increases with the proportion of eclogitic diamonds. It could be questioned in the case where E-type diamonds predominate, if the bulk of the diamond production may not have been derived from the disaggregation of the diamondiferous eclogite xenoliths.

Peridotite is a coarse-grained ultramafic rock consisting roughly of olivine with or without pyroxenes, garnet and spinel. Peridotite is thought to be the most common and abundant rock type in the earth's mantle and is strongly depleted in crustal elements by contrast to the eclogites. Most peridotitic diamonds are of garnet-bearing harzburgite type, with minor lherzholite type. Peridotitic diamonds form the most abundant diamond source rocks. Diamond grades in the peridotite xenoliths are higher than in the host kimberlites, but lower than those in the eclogite xenoliths.

In general there is no apparent correlation between the relative abundance of eclogite xenoliths and E-type diamonds, neither between peridotite xenoliths and P-type diamonds. If diamonds with peridotitic mineral inclusions (P-type diamonds) are far more common than those with eclogitic inclusions (E-type diamonds), diamondiferous peridotite xenoliths are however very rare compare to diamondiferous eclogite xenoliths. One of the reasons advocated for this disparity could be a preferential disaggregation of peridotite xenoliths during transport in the kimberlite. Eclogites, though rare in the upper mantle and concentrated in local pockets, have therefore a better chance to survive.

Best grades are thus expected in deposits where eclogite xenoliths predominate. As eclogites are concentrated in small local pockets in the mantle, disparities in diamond grades between adjacent pipes is not unlikely.

The Argyle lamproites in Australia is a good example where E-type diamonds predominate but not eclogitic xenoliths. However if the deposit is quite high grade, the quality of diamond is very poor.

In summary, a unique correlation between observed diamond grade in kimberlites, diamond quality, diamond inclusion types and estimated upper-mantle composition has not yet emerged (Helmstaedt, 1993).

The relative proportion of P-type and E-type diamonds suggests a chemically highly depleted, peridotitic mantle source with lenses of eclogitized mafic rocks (Gurney, 1989). The fact that these two types of inclusions are unrelated one with each other has been clearly demonstrated by the discovery of P-type and E-type diamonds from a single pipe at Finsch with drastically different ages. P-type and E-type diamonds are thus unrelated in time and may have formed by different processes. In general inclusion ages indicate that peridotitic diamonds are Archaean in age, while eclogitic diamonds are Proterozoic in age.

These evidences suggest that peridotitic diamonds have resided in highly depleted harzburgitic mantle-root since the Archaean, while eclogitic diamonds reflect episodic mantle events during the Proterozoic.

## 2.4. Origins of diamonds

Once the identity of the two main diamond-bearing assemblages is known, it remains to identify the processes responsible for their formation and verify if such processes are coherent with the geophysical model of diamondiferous mantle-root presented earlier (section 2.1).

### 2.4.1. E-type Diamonds and eclogite Xenoliths

The genesis of eclogitic diamonds was still enigmatic and highly controversial in the 1980s. The long prevailing view that they were igneous resulting from crystallisation of basaltic magmas in the upper mantle has been challenged progressively by the view that they may represent subducted and metamorphosed basalts and gabbros (Helmstaedt, 1993). The main ideas concerning eclogitic diamond genesis are presented beneath.

Helmstaedt and Schulze (1989) interpreted eclogites xenoliths in kimberlites as subducted metamorphic fragments. They gave petrologic evidences that probable protolith of eclogites are likely to be subducted metabasites. They also noticed that the relatively high-pressure, low temperature gradient required for diamond genesis is more likely to be achieved by rapid tectonic burial of relatively cool rocks during shallow-angle subduction (figure 6). That would lead to the formation of a cool sub-continental lithosphere.

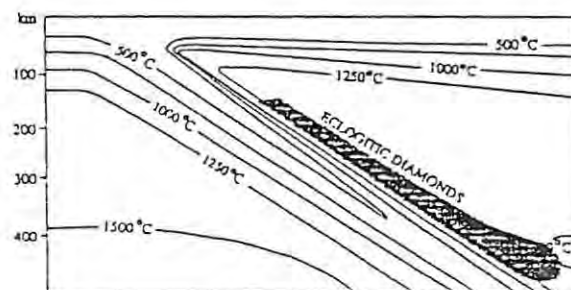


Figure 6: Thermal model of subducted oceanic slab, showing downward deflection of isotherms to bring eclogitized oceanic crust into the diamond stability field (from Helmstaedt and Gurney, 1995).

Alternatively, Ringwood et al. (1992) proposed that subducted oceanic crust could be remelted to produce basaltic melts. These melts could be entrapped near the transition zone and crystallized as eclogite. This hypothesis would thus reconcile magmatic features with a recycled component.

In parallels, eclogitic diamonds are generally believed to come from the base of the lithosphere, like peridotitic diamonds.

Haggerty (1986) suggested that eclogitic diamonds growth from low-pressure sulfur-rich melts of basaltic composition under metamorphic conditions. These melts are either trapped in the lithosphere or underplated onto the lower crust of the early Archaean.

Now, the subduction model is widely accepted, supported by geochemical and isotopic evidences for a contribution of recycled crustal material in eclogitic diamonds.

Proofs are provided first by carbon isotopic studies and determination of carbon sources. In general, the wide range of  $\delta^{13}\text{C}$  values for eclogitic diamonds, between +3 and -34, is hardly compatible with a homogeneous deep mantle source for the carbon, in contrast to  $\delta^{13}\text{C}$  values for peridotitic diamonds (figure 7). This wide isotopic dispersion of carbon in eclogitic diamonds implies diversity in carbon sources. The low  $\delta^{13}\text{C}$  values correspond to a subducted source of carbon that do not fully homogenised on its way to the diamond stability field. Carbon may have derived either from carbonate minerals produced during hydrothermal alteration of the crust, or from biogenic carbon contained in subducted sediments. Subducted altered oceanic crust is also enriched in  $\text{CO}_2$ . Release of  $\text{CO}_2$ -rich fluids into the lithosphere could possibly be responsible for the high diamond grade of mantle eclogites.

However, the eclogitic diamond population, for which  $\delta^{13}\text{C}$  values are around -5, was possibly formed from a similar carbon mantle source than the peridotitic diamonds (Navon, 1999).

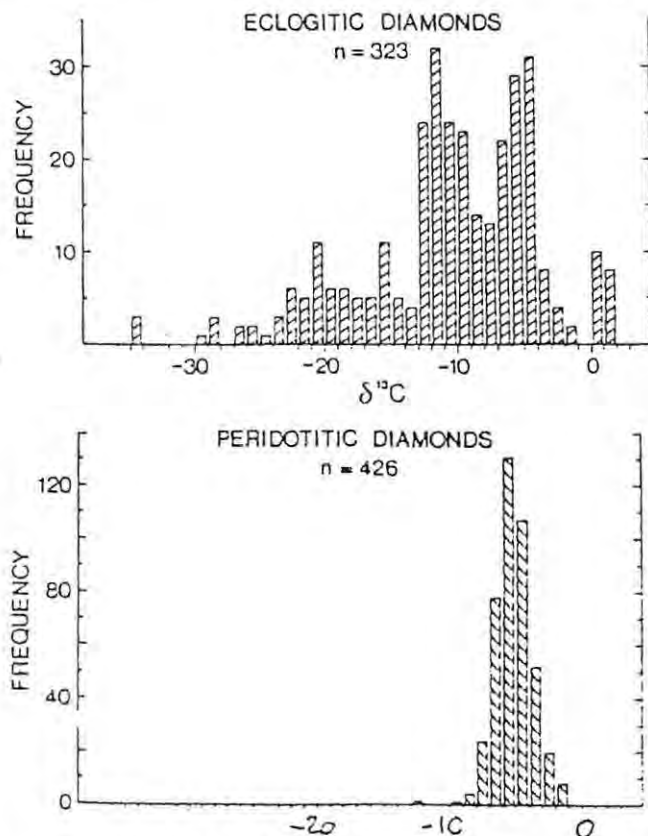


Figure 7: Distribution of  $\delta^{13}\text{C}$  values for E-type diamonds compared to P-type diamonds (from Gurney, 1990).

Oxygen isotopic ratios in eclogitic diamonds favoured also the subduction hypothesis. The wide range of  $\delta^{18}\text{O}$  values, differ from the mantle value, and therefore strongly imply the involvement of surface processes, which increase oxygen isotopic values. Hydrothermal alteration of sea floor basalt prior to subduction is generally evocated. Jacob et al. (1994), in a petrologic and isotopic study of diamondiferous eclogites from Siberia, provide evidences that these eclogites are remnants of an Archaean oceanic crust of a composition range between komatiite and oceanic basalt. This oceanic crust experienced low-temperature seawater alteration, responsible for the increase of oxygen isotopic values, followed by subduction.

The strongest argument against the subduction model comes from the contrast between the negative  $\delta^{15}\text{N}$  of most eclogitic diamonds and the positive values of crustal nitrogen, pointed by Navon (1999). However, the source regions for N in cratonic diamonds are uncertain because primary heterogeneity in the mantle is unknown, and because of possible isotopic fractionation of N and C at high-pressures. More studies in this domain are thus needed, to make any conclusions.

Further, studies of sulphur and lead isotopes in sulfide mineral inclusions from South African kimberlites have also provided evidence for the involvement of recycled sediments in diamond formation (Elridge et al., 1992).

The discovery of young eclogitic diamonds in the Dabie Shan ultrahigh pressure crustal metamorphic rocks in eastern China argues in favour of the subduction model. Shutong et al. (1992) showed that these metamorphic rocks record a subduction of continental material to a depth of more than 100 km and its subsequent rapid uplift to the surface.

To resume petrological and isotopic studies favoured a subduction origin of eclogitic diamonds. The fact that Archaean isotopic signatures have also been identified for eclogitic diamonds, like those coming from the Robert Victor Pipe in South Africa or from the Udachnaya Mine in Yakutia (Jacob et al., 1994), removed arguments against plate tectonics during the Archaean. It was commonly thought before that plate tectonic could not be considered to be a viable mechanism during Archaean times (Cf. Vlaar, 1997). It has then been recognized progressively that mafic volcanic sequences of greenstone belts could have originated in proto-oceanic or marginal basin setting, as Archaean analogues of Phanerozoic ophiolites. Now, plate tectonic is largely recognized to occur during the Archaean with the recent seismic reflection profiles realized under the Canadian Shield, which provide visual proof for tectonic underplating during Archaean times (e.g. Calvert et al., 1995). The type of subduction favoured during Archaean times is likely to be shallow and low-angle subduction with fast rates of spreading.

#### **2.4.2. P-type Diamonds and peridotite Xenoliths**

The chemically depleted and highly refractory nature of the peridotitic diamond assemblage have been interpreted either as residue after melt extraction from normal mantle peridotite or komatiites or more voluminous basalts (Gurney, 1990, Richardson et al., 1993) or as products of tectonic underplating by imbricated slabs of subducted oceanic lithosphere (Helmstaedt and Schulze, 1989; Kesson and Ringwood, 1989; Helmstaedt and Harrap, 1999).

While much disagreement remains regarding the origin of this rock type, hypotheses involving in situ depletion of mantle peridotites by komatiite melt extraction continue to dominate (Richardson et al., 1993). The Archaean age and depleted nature of the peridotitic diamonds is coherent with such hypothesis. Boyd and Gurney (1986) indicated first a possible connection between low-Ca garnet diamondiferous harzburgites and Archaean komatiites.

Richardson et al. (1993) establish a temporal, spatial and compositional link between komatiitic magmatism and subsequent harzburgitic diamond formation in the Archaean in South Africa based notably on isotopic studies. Carbon isotopic studies of P-type diamonds particularly inferred this hypothesis. The peridotitic diamonds, with few exceptions, are characterized by narrow  $\delta^{13}\text{C}$  range of -2 to -9, which is very close to the mantle values. The carbon source is thus believed to derive from an homogeneous convecting zone within the upper mantle. This mantle carbon may have come from the primitive mantle sometimes 4500 Ma ago, and remained in place until diamond crystallized within the peridotite, or it may also be homogenized, recycled carbon from subducted crustal material.

However Herzberg (1993) reviewed recently the komatiite residue hypothesis and concluded that the relative high  $\text{SiO}_2$  content of many of the xenoliths from the kimberlites of the Kaapvaal craton is incompatible with the low  $\text{SiO}_2$  of most komatiites. Peridotitic xenoliths may rather have formed by extensive melting of normal mantle peridotite, either in a gigantic plume or from a high  $\text{SiO}_2$  terrestrial magma ocean. Furthermore, experimental studies seem to support the komatiite-residue hypothesis only for the Cr-poor population of low-Ca garnets (Helmstaedt and Gurney, 1995).

Strong evidence against the komatiite extraction hypothesis comes also from the absence of apparent komatiites in the diamondiferous Archaean Slave Province. It is however possible that the komatiites did not erupted there. If we refer to the recent discovery of microdiamonds in volcanoclastic komatiite in French Guiana (Capdevilla et al., 1999), a link between diamond formation and komatiitic magmatism is still to explore.

However, the wide acceptance of a subduction model for most of the eclogitic mantle sample, and the recognition of extensive subduction processes during the Archaean, led slowly to similar suggestions of subduction origin for peridotitic diamonds. It is surprising that E-type and P-type diamonds have often been treated as separate problems in the literature, while they can occur in the same pipe. A model of subduction of depleted ultrabasic rocks should be also considered as a potential source for highly depleted harzburgitic xenoliths.

Helmstaedt and Schulze (1989) proposed a subduction origin for both eclogitic and peridotitic diamonds, based on a petrologic study of the xenoliths. They gave also possible protoliths for all the inclusion types, including a subducted graphite-bearing serpentinites for the origin of P-type diamonds (table 4).

<i>Inclusion type</i>	<i>Possible protolith</i>
Eclogites	Subducted metabasites (possibly modified by melting) (Walker 1979; Ater <i>et al</i> 1984; MacGregor 1985). Subducted metabasites and metasomatized garnet clinopyroxenites (Helmstaedt & Schulze 1979, in press)
Grosopydites	Subducted metarodinites (Helmstaedt & Carmichael 1978). Subducted meta-anorthosites (Jagoutz <i>et al</i> 1985)
Peraluminous garnet-kyanite rocks	Metapelites (modified by melting) (Hall 1985; Helmstaedt & Hall 1985)
Alkremites	Subducted Al-rich metasedimentary rocks (Exley <i>et al</i> 1983). Blackwall alteration around metaserpentinites
Low-Ca garnet harzburgites, dunites, peridotite suite diamond inclusion minerals, diamonds.	Subducted graphite-bearing serpentinites (Schulze 1986)
Green garnets (related to wehrlites)	Subducted uvarovite-rich portions in serpentinites (Schulze 1988)

Table 4: Kimberlite inclusions for which subduction origin has been proposed (from Helmstaedt and Schulze, 1989).

In a study of slab-mantle interactions, Kesson and Ringwood (1989) proposed also a model of formation of peridotitic diamonds during shallow-angle subduction. They provide a wide range of evidences, which suggest that a significant proportion of the protoliths of peridotitic diamonds formed by the dehydration and metamorphism of subducted body of graphite-bearing metaserpentinite (see also Schulze, 1986). During serpentinisation of normal peridotites, Ca is lost or redistributed by hydrothermal alteration processes, which thus explains the low Ca nature of garnets in P-type diamonds.

Subduction is thought to have occurred sub-horizontally for considerable distances at depths of 130-200 km beneath the cratons. However, the subducted slab descends with a steeper dip than in the model proposed by Helmstaedt and Schulze (1989).

In the model of Ringwood et al. (1992) hydrous melts provided by the dehydration of serpentinites during subduction, migrated away from Wadati-Benioff zones, hybridising large volumes of adjacent depleted peridotites, and thereby producing potential source regions of alkaline magma when subjected to partial melting (figure 8). Peridotitic diamonds may crystallize during the final stages of this process.

In this model, both eclogitic and peridotitic diamonds originated thus from a combination of subduction and partial melting processes.

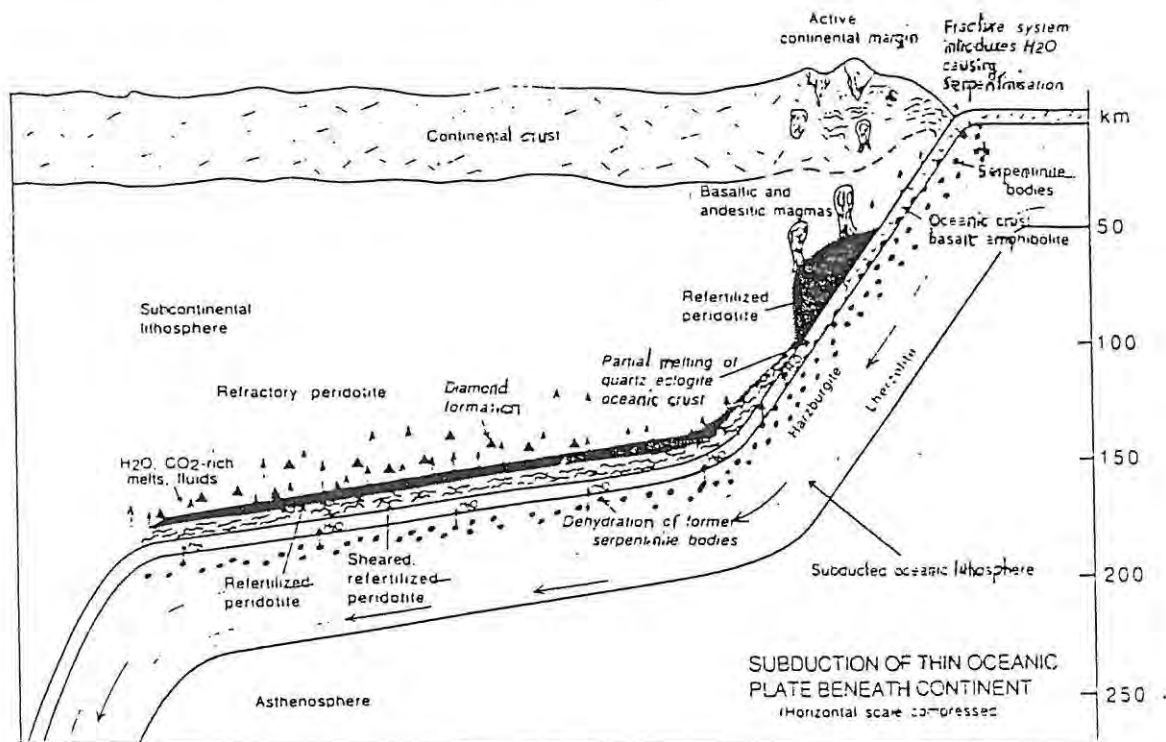


Figure 8: Model showing partial melting of the eclogitic crust of the subducted lithosphere at depths below ~150 km being initiated by water released from bodies of former serpentinite. These melts may precipitate diamond in eclogitic lithologies. Slab-derived melts also migrate into overlying refractory peridotite, undergoing extensive hybridization and crystallisation. Peridotitic diamonds may be precipitated in the final stages of this process (from Kesson and Ringwood, 1989).

If we considered that at least a part of diamond formation under Archaean Craton is related to subduction of Archaean oceanic lithosphere, it must be speculated that the thick, cool lithosphere favourable for diamond formation and preservation formed where continental crust was repeatedly underplated (Helmstaedt and Harrap, 1999). It remains however to be able to relate ages of diamonds with particular events of subduction.

## 2.5. Preservation/Destruction of diamondiferous mantle roots

Once the conditions for diamond formation have been determined, it remains to preserve diamonds until the transport by kimberlites or lamproites. The first criterion is the oxidation state of the lithosphere keel. Clearly, redox conditions must permit diamond to survive in the lithosphere for an extensive period, and not to be converted to CO<sub>2</sub> or CH<sub>4</sub>.

Typical mantle-roots favourable for diamond formation and thus preservation, have been described sooner, and can be now detected by various geophysical techniques (Morgan, 1995). It remains however to determine if these roots existed at the time of kimberlite emplacement. If a craton with identified mantle-root contains kimberlites postdating the formation of this mantle-root, these kimberlites would be potentially diamondiferous. However, if a craton does not have the geophysical properties of mantle-roots and contain kimberlites, these kimberlites will be diamondiferous only if they were emplaced prior to the destruction of a potential earlier mantle-root. The mantle-root signature of sub-cratonic lithosphere at the time of kimberlite eruption could be eventually determined by the composition of diamond indicator minerals in kimberlites (Helmstaedt and Gurney, 1995). It is also possible to identify earlier mantle-roots by a study of the geodynamic history of the craton prior to kimberlites eruption, and identify the mechanisms responsible for preservation or destruction of these mantle-roots. Seismic data could give precious information concerning the evolution of the cratons.

Preservation of diamonds in a refractive, relatively cool and low-density mantle-root implies that this root remains insulated against reheating and excessive tectonic reworking, and stay attached to the craton during subsequent plate motions (Helmstaedt and Gurney, 1995). Metasomatic events, thermal erosion and tectonic displacements are thus the main factors of destruction of a mantle-root. Some structures have been identified as such destructive, like plumes, rifts and collision zones. On the opposite, thrust belts and horizontal dike swarms could be considered as "mantle-root-friendly" structures.

It has also been suggested that a smaller-size craton would be more preserved than a larger one. Effectively, a large craton would be destroyed progressively by mantle heat rising beneath the mantle-root, whereas heat flows would escape more easily around the edges of a small craton (Cf. Helmstaedt and Gurney, 1991). The long survival of the southern African mantle root could thus partially result from its relatively small size.

The discovery of diamonds in different host-rocks like in metamorphic sequences, leads to reconsider the mechanisms of diamond storage in the lithosphere. It has been envisaged that diamonds may become structurally trapped outside their stability field by fault movements in the subcontinental lithosphere. They may also be preserved outside their stability field in an Archaean lithosphere that has isostatically rebounded after the erosion of an obducted Proterozoic orogen (Helmstaedt and Harrap, 1999). The potential storage of diamonds outside their stability fields, favoured by the structural complexity of the lithosphere, could possibly explain the variations in diamond populations within individual and adjacent kimberlite pipes.

Careful studies of orogenic and magmatic processes, which have affected the cratons, should thus lead to a better delineation of potential target areas.

### 3. Geotectonic controls on kimberlites and related rocks

We saw that the diamond source rocks (garnet harzburgites and lherzolites, eclogites), are confined to the roots of Archaean cratons. However, even if they represent potential giant deposits, they are not directly accessible. A transport medium through the surface is needed. If some of the micro-diamonds could possibly have formed inside the kimberlite melt, it is however certain that macro-diamonds formed before, were collected randomly, and partially resorbed during the transport by oxidation (Mitchell, 1991). Collect and transport of diamonds by kimberlites or lamproites lead thus to a significant dilution of diamond grade and deterioration of diamond quality.

Determination of the economic potential of diamondiferous kimberlites and related rocks depends on their ability to satisfy the following requirements (Helmstaedt and Gurney, 1995):

- The host rock must originate in or below the diamond-source region,
- The host rock must ascend fast enough and in a non-oxidising environment to preserve diamonds,
- The near-surface conditions must allow the host-rock to reach the surface and to form sufficiently large bodies,
- The geological environment must favour the preservation of pipes.

For exploration purposes, understanding the temporal and spatial distributions of diamondiferous primary deposits is primordial.

Geotectonic controls on kimberlites have been at the middle of debates for years, and no consensus has yet been found. Numerous hypotheses have been proposed, but none of them seems to satisfy the diversity of kimberlites and lamproites emplacements. Kimberlites have been related to:

- Regional domal uplifts above upwelling convection currents (Dawson, 1970),
- Diapiric upwelling in the upper mantle (Willy, 1988),
- Deep-reaching fractures and fault zones (Bailey, 1993; Friese, 1998),
- Transform faults (Marsh, 1973; Williams and Williams, 1977),
- Rifting of continents (White et al., 1995; Kaminsky et al., 1995),
- Mantle hotspots (Crough, 1980; Le Roex, 1986; Haggerty, 1994),
- Flat-dipping subduction zones (Sharp, 1974; Helmstaedt and Schulze, 1989, McCandless, 1999).

This diversity of geotectonic processes reflect the failure to integrate all aspects of kimberlite magmatism in a coherent model, e.g. depth of formation, magma origin, transport routes to the surface, near-surface emplacement controls, composition and isotopic signatures of the kimberlite rock-forming assemblages.

It is noticeable that some of the processes summarized above concerned indifferently sublithospheric processes and geotectonic environment of the upper lithosphere. It should also be noticed that some of these processes, even if related spatially to kimberlite magmatism, are not always related temporally to it. Different mechanisms can play different roles in kimberlite magmatism at different times. Moreover, the diversity of kimberlites and lamproites compositions and locations imply that different processes are involved in their formation.

We will thus try to cover here all the aspects of the kimberlites magmatism from the base of the lithosphere to the surface that could explain their distribution. As few studies have been published yet on lamproites, we will emphasize on kimberlite geotectonic controls.

### 3.1. Age database

Kimberlites and lamproites have intruded the Earth for a very long period as stated by ages ranging from 1600 Ma to 20 Ma (table 5). The occurrence of diamonds in the 2600 Ma old conglomerate in the Witwatersrand basin, is a proof that a still older primary diamond deposit could have existed. Most known kimberlites are younger than 600 Ma but deposits hidden by depositional cover or removed by erosion may obscure this distribution. About seven major diamondiferous eruptive events have been identified by Haggerty (1997). A first population of kimberlites at 1.1-1.25 Ga (Africa, Brazil, Australia, Siberia, India, Greenland), a second around 440 Ma (China, Canada, Zimbabwe), a third at 370 and 410 Ma (Siberia, USA), a fourth at 250-320 Ma (Siberia, USA), another is around 200 Ma (Botswana, Canada, Swaziland, Tanzania), the mid-Cretaceous spike at 80-120 Ma is prominent throughout Africa and finally the most recent since the Eocene (Canada, Tanzania). However such divisions vary a lot from one source to another.

Although information concerning lamproites is scarce, they are known to cover a range from 1200 Ma ago (Argyle, north-western Australia) to about 20 Ma ago (Ellendale, north-western Australia). It is noticeable that two pipes separated by only 400 km emplaced about 1200 Ma apart.

Age determinations of a large number of pipes show thus that kimberlites and lamproites could occur at the same place at different geological times. The Siberian Platform has five distinct periods of kimberlite intrusion, the Kaapvaal craton five, and the West African Craton, five.

Time	Ma	Kimberlite volcanism	Lamproite
Quaternary		Igwisi, Tanzania	Gaussberg; Leucite Hills; (SW Uganda); (Sulawesi)
Miocene	5-25		SE Spain; Algeria; Tunisia; Ellendale <sup>a</sup> , W Australia; Francis, Utah; (Moroto, Uganda) Smoky Butte, Montana; (Copeton, NSW)
Oligocene	26-38		
Eocene	45-53	Tanzania	
Eocene-Paleocene	50-64	Namibia; Tanzania; NWT, Canada	Yellow Water Butte, Montana
U. Cretaceous	65-79	SW Cape; Namibia; Mbuji-Mayi, Zaire	
M. Cretaceous	80-114	Kimberley; Kundelungu, Zaire; Lesotho; Orapa; Brazil; Sask. Canada; Huangjiacun, China; Sierra Leone-Guinea-Mali	Hills Pond, Kansas; Prairie Creek <sup>a</sup> , Arkansas; Coromandel <sup>a</sup> , Brazil
L. Cretaceous	115-144	S. Africa Gp II; Angola; Kuoika, Siberia; Liberia	Murun, Irkutia
U. Jurassic	145-174	New York; Swartruggens, S. Africa; Pri-Lena, L. Olenek, Yakutia; SE Lesotho; E. Griqualand; SE Australia	Swartruggens, S. Africa; (Wandagee, Western Australia)
L. Jurassic	175-204	Pennsylvania; Jwaneng; E. Griqualand; Dokolwayo, Swaziland	
Triassic	205-239	Kimberlites, W, Greenland	Kapamba <sup>a</sup> , Zambia
Permian	240-290	Kentucky; Cross, Canada	
Pennsylvanian	305		(Bulljah Pool, Western Australia)
Devonian	340-409	Alakit-Daldyn, Maio Botuobinsk, Yakutia; Colorado-Wyoming Somerset Island, Canada	
Silurian-Ordovician	410-499	Muna, Yakutia; Shandong and Liaoning, China; Arkhangelsk, Russian Platform	Mt. Bayliss, Antarctica
Cambrian	500-600	Zimbabwe; Venetia, S. Africa; West Greenland	
U. Proterozoic	800-1250	North Western Australia; India; Premier, S. Africa; Bubiki, Tanzania	Holsteinsborg, W, Greenland; Majhgawan <sup>a</sup> , India; Argyle <sup>a</sup> , W Aust; (Ngualla, Tanzania)
M. Proterozoic	1200-1500	Gabon; Liberia	Bob <sup>a</sup> , Ivory Coast; Chelima, India
L. Proterozoic	1600-1800	Kuruman, S. Africa; Venezuela	Disko Bugt, W, Greenland
L. Proterozoic	ca. 2000	(Burkina Faso)	

Table 5: Times of intrusion of kimberlite and lamproite provinces (after Nixon, 1995).  
<sup>a</sup> Diamondiferous

### 3.2. Global tectonic

Numerous authors (e.g. Dawson, 1989, Haggerty, 1994 and 1999) suggest a certain periodicity in the kimberlite eruptions, and correlate that with global tectonic events.

Haggerty (1999) related kimberlite magmatism with periods of superchron behaviour of the Earth's geomagnetic field, which are correlated with plume activity (figure 9). In a continental scale, kimberlites are following periods of rifting and extensive flood-basalts magmatism, as a result of plume activity, which correspond to major tectonic events, like the break-up of Gondwanaland.

Kimberlite activity has also been related on a global scale to periods of relatively slow motion of the continental plates (England and Houseman, 1984). The rate of plate motion could be related closely to the style of convection in the upper mantle, at least beneath the continents. Generation of partial melt in the mantle and formation of mantle plumes are favoured by slow-moving plates. It should be noted here that this model contradicts the fact that Group I Kimberlites erupt in South Africa at a time of particularly rapid motion of the African plate.

While the two precedent models both relate kimberlite magmatism with global tectonic events, they are fundamentally opposed. One considers that lower mantle processes-plume activity- are the cause of lithospheric extension and further magmatism, while the other one considers that plume activity is the consequence of upper mantle processes-plate tectonic.

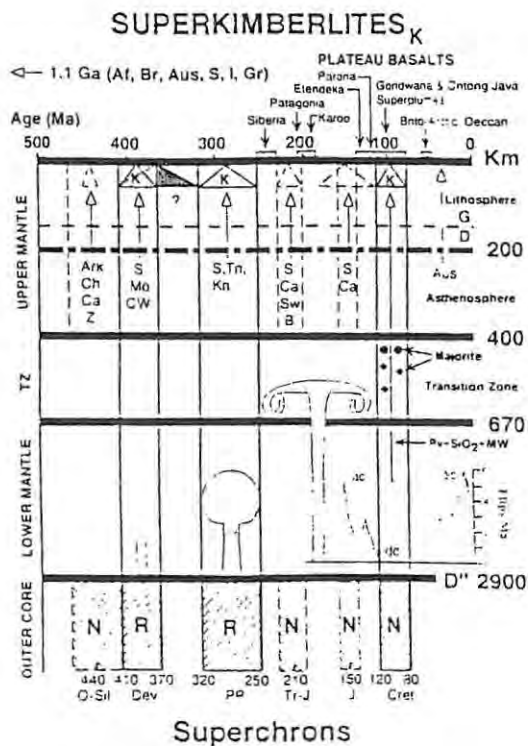


Figure 9: Kimberlite intrusion times linked to periods of superchron behaviour of the Earth's geomagnetic field (from Haggerty, 1994). The abscissa represents time (Ma) showing long N (Normal) and R (Reverse) periods of geomagnetic behavior.

Concerning global tectonics, two schools are thus often distinguished. The first believes that plate tectonic is a self-generating mechanism, and is rheologically decoupled from the mantle (Anderson et al., 1992; Anderson, 1994; Vlaar, 1997). Using tomography evidences, Anderson et al. (1992) conclude that convection in the mantle is triggered by subduction processes, creating instabilities in the surface boundary layer. Upwelling and melting are thus caused by plate processes and not by thermal instabilities. Basalts, usually linked to deep plume activity, form in low-velocity regions of an inhomogeneous upper mantle, contaminated by subduction (possibly near the transition zone?). Magmatism correlates thus in time, with major plate reorganizations and in space, with lithospheric discontinuities. In a same way, extensional plate boundaries and hotspots are related to plate tectonic and occur at pre-existing sutures, rather than at random places, determined by plume activity.

The second school believes that there is a general correlation between core activity, plumes and plate tectonic. Plumes are generally assumed to be responsible for the rifting of plates. For example, it has been proposed that the variation of the hotspot regime in the early Mesozoic, coincides with the break-up of Gondwanaland and with the beginning of opening of new oceans (Zonenshain et al., 1991). Hot-field tectonic, which is related to deep tectonic, is thought to govern the global geodynamics of the Earth and thus also triggers the plate tectonic.

These general considerations discussed above will help us to understand the following debate (section 3.3.2) concerning the controls on kimberlite formation and emplacement.

### **3.3. Origin of the kimberlite magmatism**

#### **3.3.1. Potential sources of kimberlite magma**

Accepting the idea that diamonds are xenoliths in the transport medium, the source material for kimberlites and lamproites do not need to be diamondiferous, but need to be situated beneath the diamond stability field. The minimum depth for diamondiferous kimberlites is estimated at 150 km, and should not be over 400 km (Dawson, 1989).

Kimberlites are conventionally thought to have been formed by small degrees of partial melting from a garnet lherzolite source in the upper mantle.

Studies based on isotopic and petrologic studies on kimberlites xenoliths show that Group I (basaltic) kimberlites have characteristics similar to many ocean island basalts (OIBs) and are derived from a relatively primitive asthenospheric source, while Group II (micaceous) kimberlites are likely to derived from metasomatically enriched parts of the sub-continental lithosphere (Helmstaedt, 1993) (figure 10). However, the asthenospheric source fails to explain the depleted and refractory nature of major element chemistry of the kimberlites.

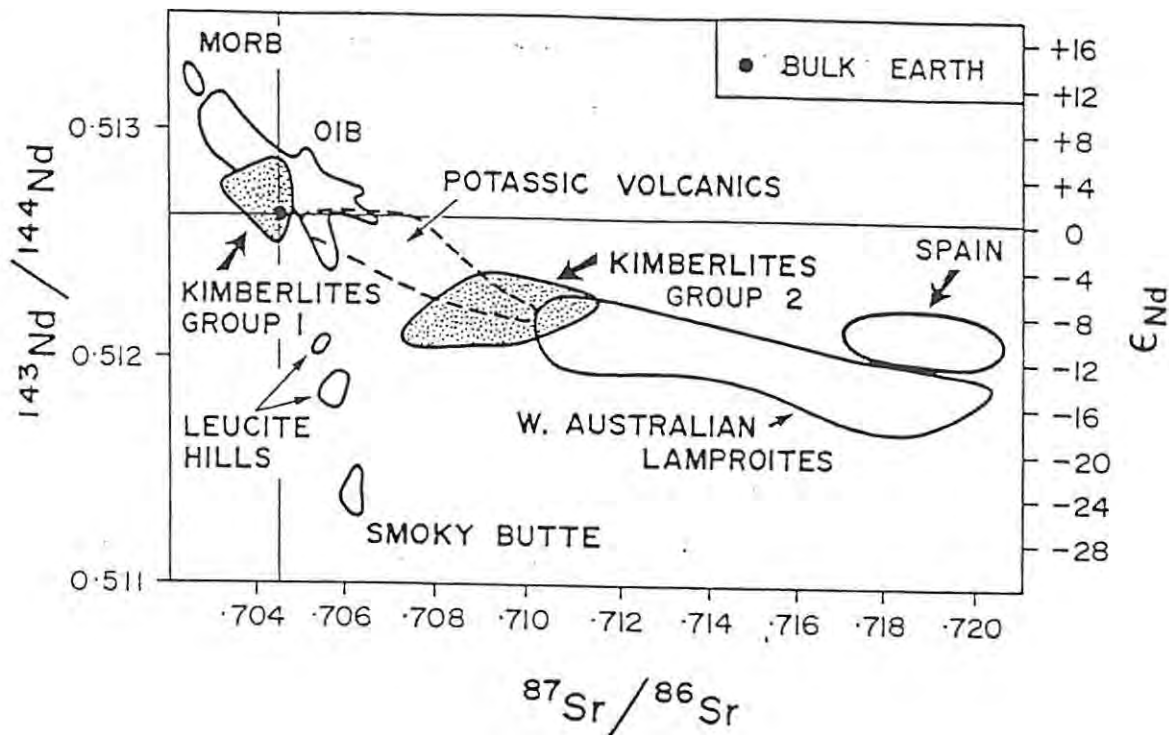


Figure 10: Isotopic compositions of kimberlites and lamproites. Rocks with isotopic compositions close to those of bulk earth and within the upper left quadrant of the diagram are conventionally interpreted as being derived from asthenospheric sources. Rocks with isotopic compositions, which plot in the lower right quadrant are believed to be derived from ancient enriched lithospheric sources (from Mitchell, 1991).

The discovery of majoritic garnet inclusions in diamonds from the Monastery kimberlite, implies depths of 400-670 km, near the transition zone. Two explanations are possible. Kimberlites could originate from much deeper depths than previously thought, or diamonds could convect upwards by rising plumes or convection currents before being collected. Discovery of ultradeep xenoliths from African kimberlites suggests an origin near the transition zone (350-400 km) (Macdougall and Haggerty, 1999).

The hypothesis that kimberlites of Group I could have been derived from source regions in the transition zone, has been proposed by Ringwood et al. (1992) based on melting experiments conducted on Group I kimberlites. The ultimate source of these kimberlites, as well as the OIBs magmas, would lie in the transition zone, in a boundary layer refertilized by partial melts derived from garnet-rich lithologies trapped in the 650km discontinuity (figure 11). The association of refractory, depleted lithologies and fertile garnetite in the transition zone could be explained by the subduction of oceanic lithosphere. The kimberlite source is produced by re-fertilization of the depleted harzburgitic component of this boundary layer. This layer is possibly regularly reheated by convection currents from the lower mantle, which disperse laterally at the contact with the garnetite layer. Heat derived from these currents causes the elevation of the layer and partial melting overhead.

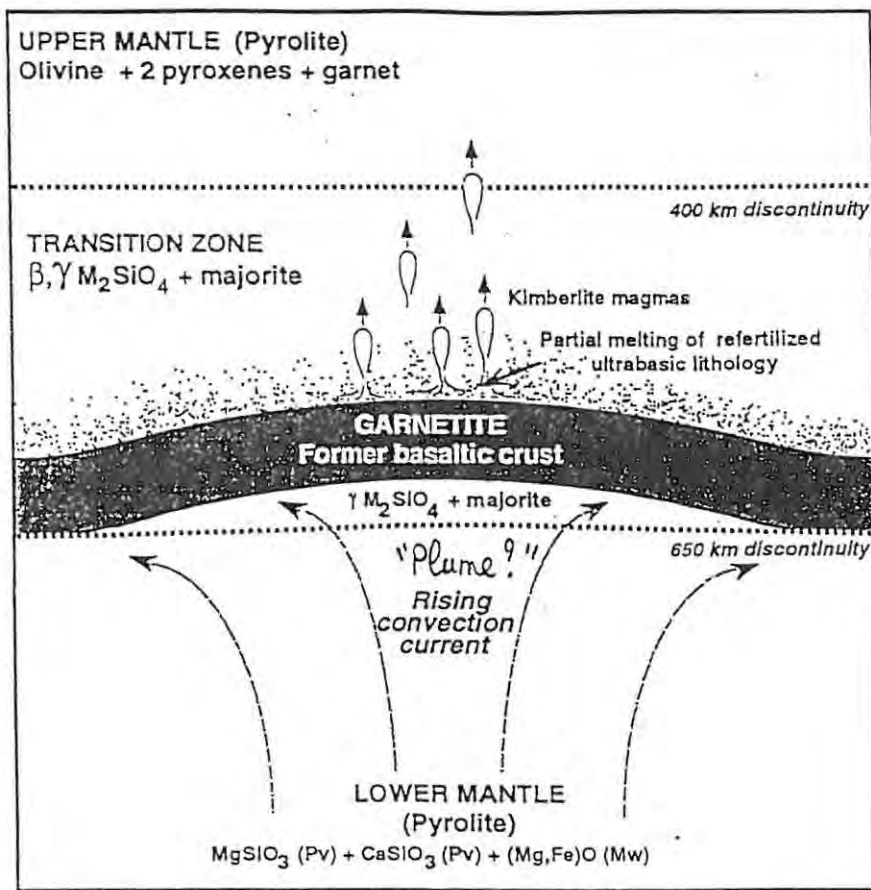


Figure 11: A rising convection current from the lower mantle causes dynamic uplift of the garnetite layer, forming a dome-like structure on the 650 km discontinuity. Elevated temperatures arising from the convection current cause small degrees of partial melting of the refertilized, former harzburgites boundary layer, thereby producing kimberlites (from Ringwood et al., 1992).

In parallel, Group II Kimberlites would thus derived from subducted pelagic sediments and terrigenous material associated with the garnetite layer.

One of the questions arising for such a model is the origin of the rising convection currents. In the case of OIBs magmas, they are identified as a plume, which caused diapirism into the upper mantle. Plume material is thus believed to be the ultimate source for the OIBs magma (Ringwood et al., 1992). As observed by Haggerty (1999), there is a lack of sustained thermal energy in the Transition Zone to produce large clusters of kimberlites. It should be therefore questioned if small rising convection currents are sufficient to trigger such volume of partial melting, and if finally kimberlite magmatism is not trigger too by relatively fixed hotspots, deep in the mantle (Macdougall and Haggerty, 1999).

Recent isotopic and geochemical studies of South African and Russian kimberlites confirm also that kimberlite magmas seem to be mixtures from both asthenospheric and lithospheric sources. Mahotkin et al. (2000) consider that kimberlites were assembled from both liquid and solid contributions from various depths, during magma upwelling. The precursor melts to Group I kimberlites, called protokimberlites, are identified as being mica-poor alkaline picrites, formed from precursor melts in the convective mantle (in a similar way than OIBs magmas).

These two hypotheses of kimberlite magma formation thus recognize the contribution of both lithospheric and asthenospheric sources, acquired either in the mixed transition zone, or during the magma upwelling. They also recognized the necessity of a driven force responsible for the rising convection currents. Mahotkin et al. (2000) consider that the advective heat transfer from the convecting mantle to the sub-lithosphere results of a plume activity, whereas Ringwood et al. (1992) considered a plume activity for OIBs magma but not necessarily for kimberlites for which magma genesis could also be triggered by adjunction of subducted material into the garnetite layer.

### **3.3.2. Geotectonic controls on the kimberlite magmatism**

#### **-The Hotspot Theory-**

Kimberlite eruptive events were related to hotspot activity since the early 80s, due to obvious spatial-temporal trends of kimberlites that could correlate with plate motion.

Crough and al. (1980) were the first to use hotspots tracks to explain kimberlites distribution. They found that a majority of dated kimberlites have the locations and ages predicted by the plate/hotspot motion. Their studies was confined to the South America, Africa zone, within the last 150 Ma. It is considered that inter-hotspot motion is less than 5 mm/yr over the last 100 Ma (Duncan, 1981).

Hotspot track reconstitutions have been largely covered in the literature, especially the Atlantic zone (see Duncan, 1981; Morgan, 1983; Hartnady and Le Roex, 1985; O'Connor and Duncan, 1990). Plate reconstructions notably suggest that several active South Atlantic hotspots were initiated and passed beneath southern Africa in the last 200 Ma.

The relation between kimberlites and hotspot tracks derived also from geochemistry and isotopic studies of South Atlantic basalts compared to kimberlites. It has been shown notably that kimberlites from Group I and Group II in South Africa have similar isotopic and trace element signatures to those seen in South Atlantic hotspots (Le Roex, 1986). The differences between the Group I and Group II kimberlites would thus lie in geochemically different types of plume in the convecting mantle.

Since then lots of kimberlite trends have been interpreted as hotspots tracks. Amongst them, kimberlites in West Africa (Hastings and Sharp, 1979) related with the St Paul's Rocks on the Mid-Atlantic Ridge, Group II kimberlites in South Africa with the Tristan plume (Hatton, 1998), Group I kimberlites with the Bouvet hotspot and Group II kimberlites with the Shona hotspot in South Africa (Le Roex, 1986), Angolan kimberlites with the Tristan plume (Gibson et al., 1998), Bresilian kimberlites with the Martin Vas hotspot (Gibson et al., 1995), Siberian kimberlites with the Azore hotspot (Natapov and Griffin, 1998), East-European (Arkhangelsk region) kimberlites with the "Kola" mantle plume (Mahotkin et al., 2000), North American kimberlites with the Great Meteor hotspot (Heaman and Kjarsgaard, 2000).

These assumptions are comforted by linear distributions of kimberlites on the continents. Throughout the world, kimberlites occur in linear belts of up to 1500 to 2000 km, crossing across major tectonic boundaries (Skinner and Hatton, 1997). The kimberlites within these belts have intrusion ages that could be approximately correlated with plate movement.

Lots of uncertainties remain concerning the hotspots tracks. They are notably linked to possible inaccurate relative plate motion history. The fact that hotspots are fixed with respect to one another over significant periods of time is still beyond discussions. Recently Baksi (1999) showed that detectable movement between hotspots of  $>20$  mm/yr for the past 100 Ma is favoured. Using the analysis of the Geosat satellite altimetry data, Norton (1997) demonstrates recently that the fixed hotspot assumption is completely invalid and cannot be used to measure plate motions. The possibility of undiscovered hotspots, the failure of certain predicted hotspots to match with the bathymetric anomalies (e.g. Bouvet hotspot, Hartnady and Le Roex, 1985), the unavailability of seamount lava samples to study correctly their geochemistry, the lack of crystallisation ages, are all factors of errors in predicting hotspot tracks.

All these uncertainties, while insignificant for Cenozoic times, are large by the mid-Mesozoic, and it seems very difficult to reconstitute hotspots tracks on the continents. In the southern Atlantic Ocean, the Bouvet, Shona and Tristan hotspots have had different trail interpretations, particularly on their paths in southern Africa (Cf. figure 12). Baksi (1999) reviews all these interpretations and concludes that ages and locations of hotspot tracks in the Atlantic and Indian Oceans are incorrect, speculative, and cannot be used to derive plate motions.

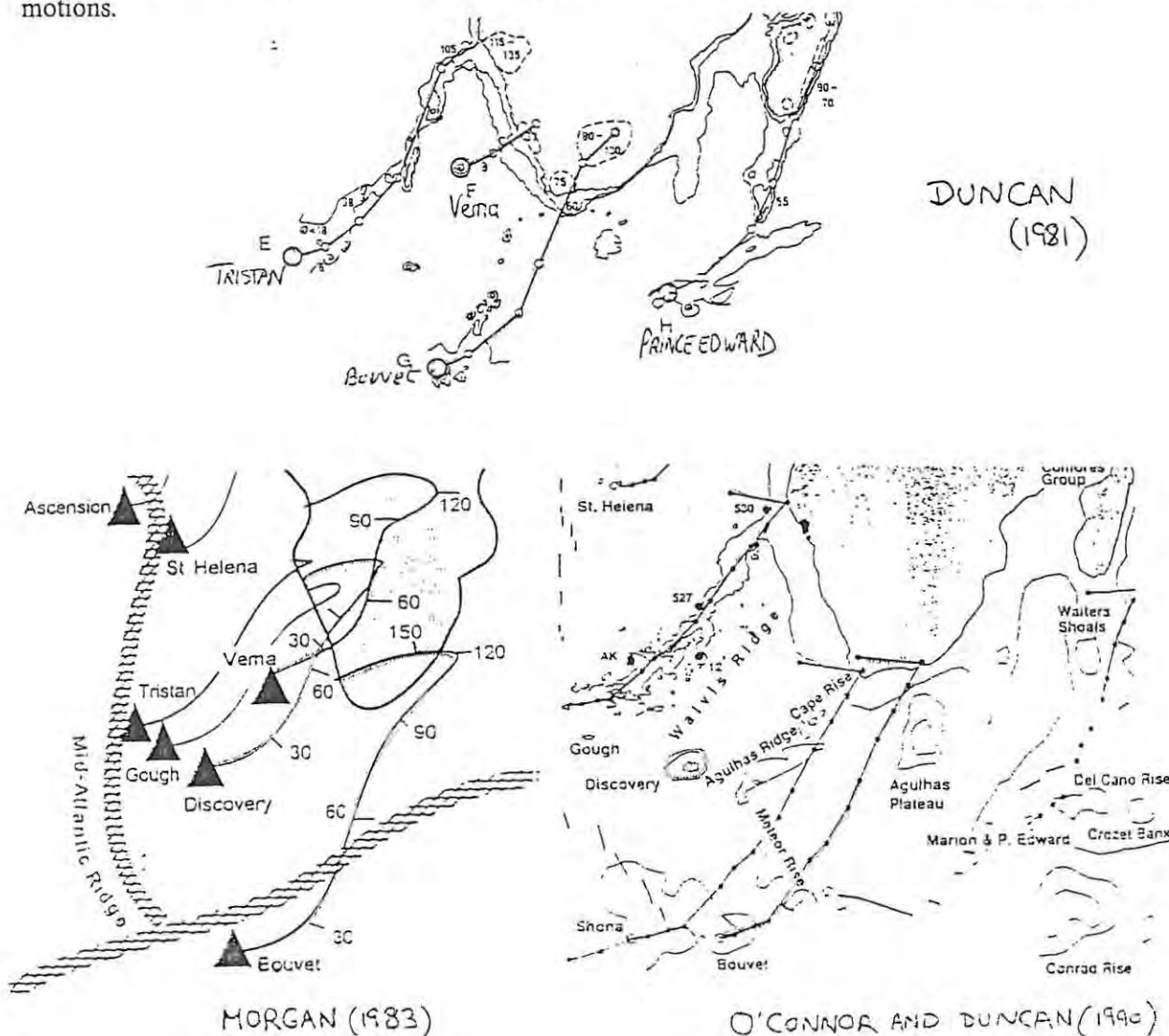


Figure 12: Hotspot positions in southern Africa according to Duncan, 1981; Morgan, 1983; O'Connor and Duncan, 1990 (from the top to the bottom).

In the matter to relate hotspot tracks with kimberlite volcanism, these uncertainties are coupled with the errors linked to the lack of accurate dates for kimberlite magmatism.

If correlation exists between hotspot and kimberlite magmatism, Egger (1989) pointed out judiciously that it is restricted to the lowest mantle with activity of deep plumes. It is unlikely that convection or diapirism occur within the cool, rigid Archaean lithosphere of relatively low density.

Generation of plumes is thought to occur as far as the core-mantle boundary (650 km depth). The initiation of mantle plumes is characterized by large flood basalt eruptions on surface (Deccan, Karoo, Parana...), which represents the plume "head" (Richards et al., 1989). These eruptions are generally preceded by thermal doming events and followed by rifting. It is believed that plumes may weaken the lithosphere, and favour later rifting along zones of weaknesses. Tholeiitic magmas erupted where the cratonic lithosphere is thinner due to subsequent rifting, whereas kimberlites and associated rocks are end-member products, produced directly above the hotspot (See also Mahotkin et al., 2000). In this model, hotspots are thought to represent the continuing magmatism associated with the remaining plume conduit or "tail". The magmatism associated with hotspot tracks is thus much less important in volume than the initial large flood basalts.

A general assumption was to consider that plume heads were located exactly beneath the flood-basalt eruption. It seems however that the large, mushroom-shaped plumes spread out laterally in the uppermost asthenosphere and thus do not intrude automatically at the vertical of the plume. Thompson and Gibson (1991) reviewed the idea that while the region overlying the head of the plume is dynamically uplifted, basaltic magmas erupt at a site of previous local tectonic lithospheric thinning, called 'thinspot', up to hundreds of km away (figure 13). This hypothesis will thus explain the uncertainties linked to the hotspots positions in relation to the large flood-basalts (e.g. Tristan de La Cunha and Parana flood-basalts). This hypothesis is coherent with recent seismic velocity maps studies, which show that the shape of low-velocity anomaly beneath ridge axis suggests the existence of a channel that transports material from the hotspot to the nearby ridge (Zhang and Tanimoto, 1992). It is thus suggested that plumes may not be vertically straight and the head of a plume could be dragged on a particular direction.

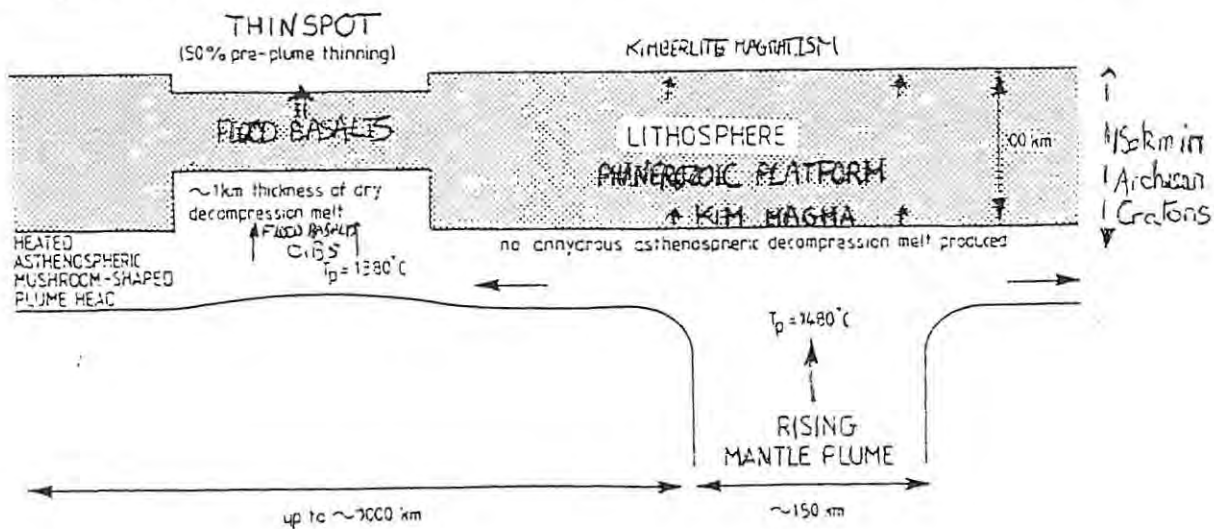


Figure 13: Schematic diagram of mantle plume behaviour beneath a lithospheric plate of uneven thickness (modified after Thompson and Gibson, 1991).

A mantle plume impacting beneath a stable continental craton could thus have no surface igneous expression. Only very small-fraction melts produced by heat transfer could affect potentially the overlying thick cratonic area. These melts would thus be enriched in volatiles, notably in K, and form typically lamproites, minettes or kimberlites (Gibson et al., 1998).

This idea has notably being proposed by Wyllie (1988) for kimberlite genesis in South Africa. The melts enriched in volatile components, rise until they encounter the asthenosphere/lithosphere boundary. Kimberlites generate either within the lithosphere above the plume (Group II?) or from lateral magma chambers as the plume diverged (Group I?). This model review by Gurney (1990) is thus compatible with the one of Mahotkin et al. (2000), and with a mixed origin for kimberlites.

The contribution of subducted material in the Group II Kimberlite magmatism proposed by Ringwood et al. (1992) could also match with the hotspot hypothesis. The geochemistry of South Atlantic hotspots shows two distinct signatures, one from the upwelling of primordial material across the asthenosphere-mesosphere boundary, one from a layer of recycled material (subducted oceanic lithosphere).

The hypothesis of Wyllie is coherent with a recent study of the Gibeon kimberlites in Namibia (Davies et al., 2001). Kimberlite volcanism occurs there about 5 to 10 Ma after the passage of the Discovery plume beneath the Gibeon region. The current plume-related ocean-island basalts and the Namibian kimberlites have also different Sr-Nb-Pb isotopic signature. It has been thus suggested that the plume is not the direct source of kimberlite, but is probably the ultimate responsible for magma production. The model of Davies et al. (2001) implies that fluid-rich melts emanating from the plume, migrate along the asthenosphere/lithosphere boundary, concentrate into the thermally perturbed asthenosphere and cause ultimately kimberlite genesis (figure 14). This model is thus coherent with the asthenospheric origin of kimberlites, and the model of Ringwood et al. (1992), with an ultimate source of kimberlitic magma probably near the transition zone.

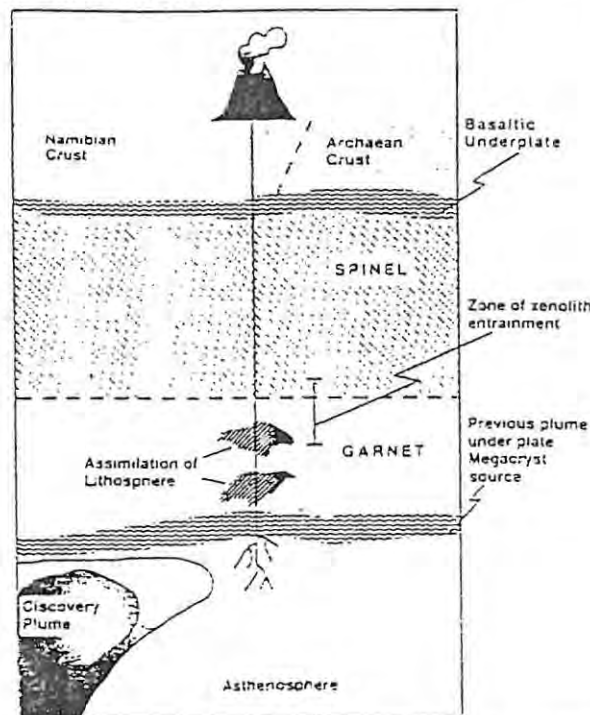


Figure 14: Schematic model to explain the Gibeon kimberlite-megacryst association. Fluids from the plume migrate along the base of the asthenosphere/lithosphere boundary and are concentrated into the thermally perturbed asthenosphere causing ultimately kimberlite genesis (after Davies et al., 2001).

If we resume the previous ideas, it thus seems that deep plumes spread out laterally at the contact with the asthenosphere/lithosphere boundary. Flood-basalts occur where the lithosphere is thinner, generally on the edges of the craton. Small volumes of volatile-rich melts emanating from the plume, concentrate above the plume head at the base of the lithosphere or migrate along the transition zone, and induce kimberlite magmatism. Plumes are thus the ultimate mechanism responsible of kimberlite magmatism.

Haggerty (1994, 1997) proposed in another approach, that peaks of kimberlite activity are linked temporally to periods of normal and reverse superchron and subchron behaviour of the geomagnetic field (Cf. figure 14). Disruption of the "D" layer enhanced core convection and the stabilisation of a constant non-reversing magnetic dipole field, rising plumes and subsequent volcanism. The time lag between the polarity switching and kimberlite eruptions at the surface is of the order of 25-50 Ma, consistent with the travel times modelled for the plumes from the D" layer (core-mantle boundary) to the subcontinental lithosphere. The synchronicity of eruptive diamondiferous volcanism and particular core activity depends thus on the existence of plumes. This model implies thus that kimberlites originated deep in the mantle, and this view is compatible with a kimberlite genesis in the transition zone proposed by Ringwood and all (1992).

A common critic to the hotspot theory is the magnitude of hotspot magmatism. Kimberlites are generally very limited magmatism, much less in volume than the activity associated with the oceanic hotspots. If we compare for example, the Hawaiian hotspot magmatism with the volume of southern African kimberlites, the former represent less than 1% of the hotspot output (Cf. McCandless, 1999). However, if we consider the previous hotspot theory valid, kimberlites formed only from small-volume volatile-rich melts emanating from the plume and does not constitute the bulk of the magma of the plume. It should also be noticed that a major part of the kimberlite pipes could have been eroded.

For the same reasons it could be explained that not all hotspots generate kimberlite magmatism. If we accept precedent models of formation of kimberlites, it implies that if plume activity possibly triggers kimberlite eruption, kimberlitic magma originates from particular melt-composition, and is rather found underneath thick continental areas.

Another aspect pointed out by numerous authors, concerns the distribution of kimberlites. Geographic distribution of plume generated large igneous provinces shows a distinct negative correlation with diamondiferous kimberlites worldwide, at least during the Mesozoic (Coffin and Eldholm, 1994). Continental flood-basalts, such as the Karroo igneous province, are generally located near the edges of cratons, whereas the diamondiferous kimberlites are located within the craton, far from the inferred plume centre. However, if we consider valid the precedent assumptions, the position of the inferred plume may be wrong and could possibly be situated at the vertical beneath the kimberlite fields within the craton.

It remains that the activity of scattered mantle plumes is not matching very well with a kimberlite activity plate-wide, and repeated in the same places. Geographic linearity of kimberlite activity has been also questioned. Kimberlites appear often to have been emplaced in small groups at the centre of cratons, and small-scale linear features could be rather controlled by surface fracture geometry.

The main criticising of the hotspot theory came from Helmstaedt and Gurney (1995). We saw previously that diamond preservation needs certain lithospheric conditions (cool reduced lithospheric keels). This implies that diamondiferous kimberlites are essentially mantle-root friendly features. It seems thus unlikely that diamondiferous kimberlites are related to mantle-root destructive hotspots or plumes that thermally erode the mantle-roots.

However if we consider that the plumes diverge at the asthenosphere/lithosphere boundary under the craton, the overlying sub-continental diamond-bearing lithosphere should be preserved. The metasomatic enrichment of the lithospheric mantle and kimberlites formation caused by relatively small fraction melts rising from the asthenosphere (Gibson et al., 1995) would thus advect negligible heat and leave the thermal structure of the overlying lithosphere undisturbed.

If the hotspot theory could thus be considered as viable, it remains however to demonstrate that plume activity and hotspot tracks correlate with the temporal-spatial patterns of kimberlites. This point is still unclear, because of the great inaccuracy of plate reconstitution and hotspot tracks, notably for ages >120 Ma.

### **-The Subduction Theory-**

It has been showed previously that diamond formation may be related to subduction processes. The formation of diamondiferous kimberlites is thus likely to be triggered by the same processes.

Sharp (1974) has been the first to propose that kimberlites may be related to subduction process. Taking the South African example, he believes that kimberlites were emplaced at the deeper end of an underriding plate, providing material source rocks for the formation of diamonds. The proofs for subduction of an oceanic plate under the continent prior to the break-up of Gondwanaland came much later with the recognition of shallow-subduction models for southern Africa (Helmstaedt and Gurney, 1984; Helmstaedt and Schulze, 1989). Volatiles released from the subducted slab generate the widespread metasomatism of the surrounding mantle under southern Africa. Karroo flood-basalts formed first at the proximity of the subduction zone, while kimberlites formed later at much greater depth.

The subduction theory has found new adepts recently with seismic imaging, which revealed that subducted oceanic lithosphere could be preserved over thousands of kilometres beneath continental lithosphere and with experimental studies, which suggest that fluids can be carried deep into the mantle in dense hydrous silicates.

Similar models of subduction have thus been proposed for the Sino-Korean Platform diamondiferous kimberlites (Jianshan et al., 1992), the East European platform (Skorospelkin, 1992) and the Colorado Plateau (Helmstaedt and Schulze, 1989). The model for subducted oceanic material beneath the Colorado Plateau is notably supported by the presence of hydrate mantle material in the K-rich minette intrusives.

The model of deep shallow-angle subduction has been reviewed recently by McCandless (1999). Subduction is thought to trigger kimberlite magmatism at the deep end of the subducted slab and, as the subducted plate heats up from its deepest end, kimberlite magmatism migrates along a trend perpendicular to the subduction plan (figure 15).

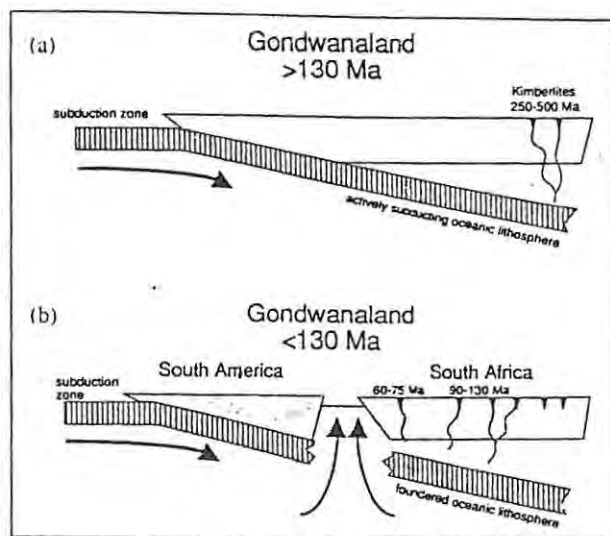
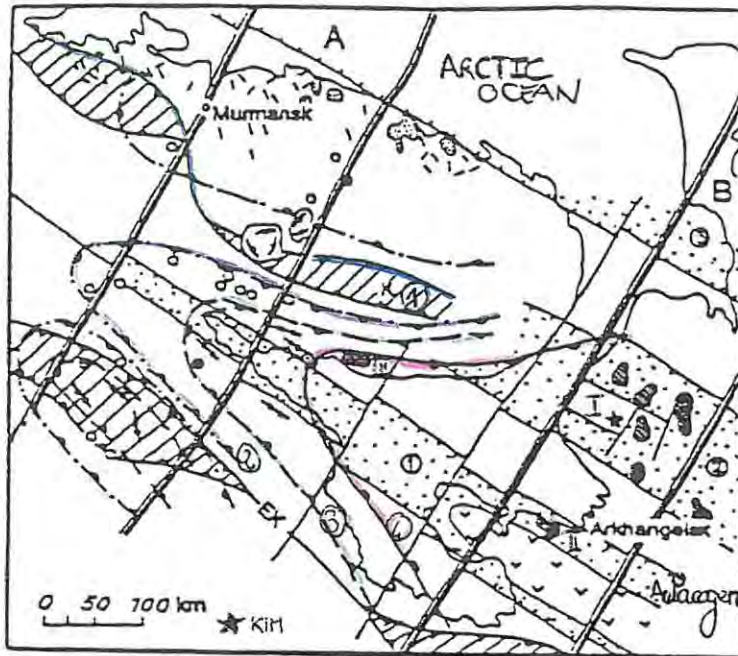


Figure 15: Model of subduction of oceanic lithosphere beneath southern Africa (from McCandless, 1999).

This slow propagation of a hot forepart in front of the subducted oceanic plate accounts thus for a particular magmatic zoning. This both lateral and time zones have been described by Skorospelkin (1992) in the case of the Arkhangelsk kimberlite province, where a succession away from the subducted plan of alkaline-ultrabasic rocks to more alkaline rocks then finally to olivine melilites, porphyrites and kimberlites is observed (figure 16). He believes also that subduction results in large tectonomagmatic activation. Activation zones are often situated by early-formed permeable lineaments represented by rifting structures and associated trap formations. It should be noted that the zones of activation are not always parallel to the earlier rifting structures (aulacogens) (Cf. fig. 16). Deep subduction of these basalt formations favours their regeneration, the deep-seated portions of the lithosphere is excited, leading to mantle upwelling (local arch doming) and ultimately kimberlite production.



**Figure 16:** Lateral magmatic zoning in the case of the Arkhangelsk diamondiferous kimberlite area (after Skorospelkin, 1992). 1: riftogenic volcanic-plutonic belts of Karelides; 2: zone of ultrabasic alkaline massifs of the central type (600-400 Ma); 3: zone of alkaline-ultrabasic, alkaline and carbonatite dikes and explosion pipes (400-380 Ma); 4: zones of pipes and dikes of olivine melilites, picritic porphyrites and kimberlites (380-350 Ma).

The subduction theory could thus also explain the linear trends of kimberlites, observed worldwide. The imperfections of certain of these trends are explained by the heterogeneities in the subducted oceanic lithosphere and the overriding continental lithosphere. That also explains the different compositions of kimberlite magmatism.

### 3.4. Conditions of ascent to the surface

Preservation of diamonds implies that the oxidation state of the transporting melt remains low enough to avoid the diamond resorption. Diamonds in lamproites are, for example, characteristically strongly resorbed, suggesting that the lamproite water-rich magmas are more oxidising than the carbon dioxide-rich kimberlites.

Our knowledge concerning the rate of magma ascent is still very speculative. The rate of ascent is constrained by the fact that diamonds must be preserved during their ascent to the surface rather than reverting to graphite, and that kimberlites also transport large xenoliths of high-density ultramafic rocks. Both of these observations require a fast ascent to the surface.

A case of slow ascent would lead to the conversion of diamonds to graphite, like it has been observed in alpine ultramafics at Beni Bouchera, Morocco, where they discover graphite pseudomorphs after diamond octahedral (Nixon, 1995).

Egler (1986) established ascent velocity of 10 to 30 km per hour. This rate can be even higher close to the surface, for reasons that will be explained later.

It has been demonstrated that ascent velocities, as low as 1 km per hour, require ascent of kimberlites via fractures as opposed to diapirs (Eggler, 1989). The role of fracture dynamics in providing the pathway for kimberlites and magma in general at the base of the lithosphere is still beyond discussions. Anderson (1979) established that fracture nucleates and propagates only if a tensile stress exists parallel to the surface or if there's an abundant supply of low-viscosity liquid. A volatile phase at the tip of the crack would probably allow the fracture to grow faster until the ascending magma can find pre-existing fractures in the crust. In order to preserve diamonds in non-oxidising conditions, this process is of particular importance. The emplacement history of the Jericho Kimberlite Pipes, Canada (Cookenboo, 1999), is a good illustration of fracture propagation by positive buoyancy and further use of pre-existing structures.

The crack propagation by magmatic fracturing theory (Anderson, 1979) is opposed to models favouring pre-existing deep fractures that extend from below the base of the craton, through solid rock, for a distance in the vicinity of 150 km. Based on the location and periodicity of alkaline/carbonatite/kimberlite magmatism, Bailey (1993) favoured a focussing of magmatic fluids into preferred deep release zones. These zones are typically old zones of lithosphere weakness, like deep-seated basement faults, which re-opened with the magma pressure. However, it is unlikely that these faults control the near-surface emplacement of the kimberlite pipes, in parts due to the ductile component of the lithosphere around 20 km deep.

These models are directly opposed to Dawson (1970) theory. He pointed out that if a diamondiferous kimberlitic magma comes into contact with deep-faults or fractures, the gases from the magma would escape, thereby lowering the pressure during the ascent, and promoting the resorption of the diamonds. Lateral dispersion of the high-pressure gases should thus be avoided. Recent experimental studies show in a parallel way that magma are not preferentially channelled along faults in mid- to shallow-crustal levels (Schmidt and Paterson, 2000).

The strongest argumentation in favour of shallow structures controlling kimberlite emplacement comes certainly from the alignment of kimberlite pipes within clusters (see examples in chapter 3.5). However, it has been observed that certain small magnitude alignments of pipes do not correspond beneath to any particular structures (personal communication). It is thus possible that magma flux in mid-crustal levels have their own preferential orientations possibly controlled by the nature of the magma, its viscosity, its speed release and the elasticity of the medium. In that case kimberlite pipes lineaments are probably more controlled by their own magma characteristics than by their general environment. This possibly leads to different distribution patterns between Group I and Group II kimberlites and also between kimberlites and lamproites.

### 3.5. Regional structural controls on kimberlites and lamproites emplacement

#### 3.5.1. Rift-related

Rift-related models of emplacement are mostly supported by Russian geologists (Kaminsky et al., 1995; White et al., 1995). These authors base their models on the observations of preferential distribution of kimberlites and lamproites at the proximity of rift systems, like in Western Australia, on the East European Craton (White et al., 1995), on the Siberian Craton (Milshtein et al., 1998), or on the northern East-Chinese province (Stolbov et al., 1992) (figure 17).

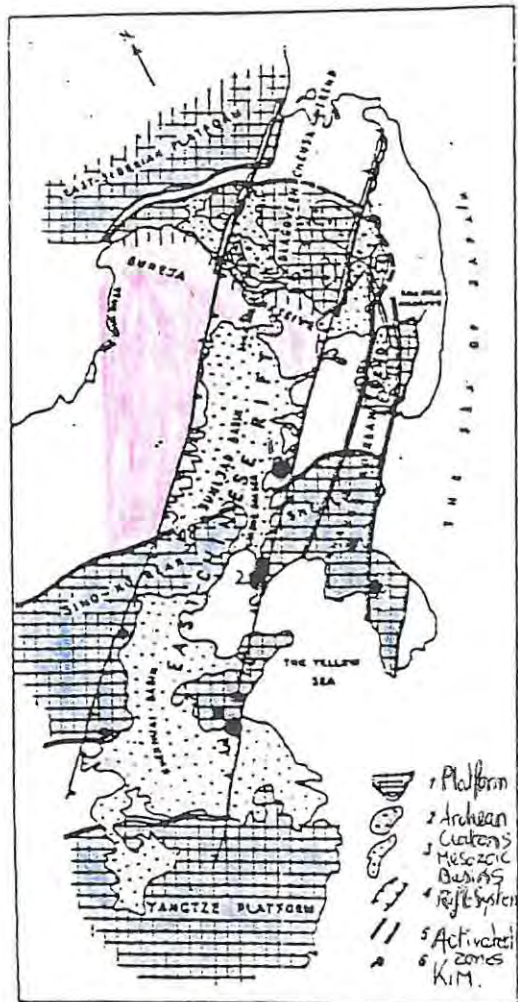


Figure 17: Correlation between the kimberlite fields in northeastern China and Korea and the East-Chinese Rift (after Stolbov et al, 1992) (1: Tieling, 2; Fuxian, 3: Mengyin).

They generally believed that kimberlites and related rocks preferentially occur in graben-type settings especially the linear grabens above deep-seated mobile zones (White et al., 1995).

The lamproite pipes of the Ellendale Province of NW Australia, and the kimberlites of the East European Platform occur on the shoulders of linear grabens. These grabens are associated to aulacogens structures, as expressions of older mobile belts or zones, which were later, reactivated under extension to form linear grabens. The emplacement of diamondiferous intrusives is thus directly related to periods of crustal extension and spreading (Kushev et al., 1992) and link to a phase of reactivation (strike-slip movements) postdating rifting activity (see also Skorospelkin, 1992). The local setting of kimberlites or lamproites within the above major structures is favoured by an intersection with an orthogonal structure, and locally dilational tension gashes and R-shears seem to play a prominent role in the pipes orientation.

Concerning diamond content of kimberlites and associated rocks emplaced in mobile belt setting, it seems to be rather very small (Kushev et al., 1992). Russian geologists have notably established that economically exploitable kimberlites and lamproites are situated almost exclusively within the adjoining uplifts areas on the marginal parts of the rift system (Kaminsky et al., 1995; Milshtein et al., 1999). The axial parts of the rifts only carry weakly diamondiferous rocks.

Helmstaedt and Gurney (1995) also noticed that kimberlites associated with rift structures have generally a weak mantle-root signature, and thus do not carry economic quantity of diamonds.

The rift-related theory is not supported by the majority of the geology community (Cf. Mitchell, 1991; Helmstaedt and Gurney, 1995). The distribution of diamondiferous occurrences around the world shows rather that kimberlite trends (provinces) are crossing tectonic boundaries, and do not follow particularly graben structures.

That is true for South Africa, where a relation of Group II kimberlite with the Ventersdorp Graben (White et al., 1995) is improbable. In a similar way, kimberlite trend from the Siberian Craton transects all the geological lineaments including doleritic dyke swarms and aulacogenes, which are considered to be ancient rift systems (figure 18).

Worldwide distribution of kimberlites and lamproites shows thus no obvious systematic correlation between such magmatism and rift structures. This does not exclude possible temporal and geographic relations linked to periods of regional extension.

It is for example suggested that plume activity could trigger both kimberlite magmatism and rifting, without any particular link between the two processes. Their association is thus more fortuitous.

Natapov and Griffin (1998) proposed that the extension of the lithosphere, caused by hotspot activity, resulted in the formation of a low-angle detachment fault (Wernicke detachment zone, cf. figure 19). Kimberlites occur as an early stage, directly link to the hotspot activity, on one side of the future rift. This particular setting confirms the general distribution of kimberlites on the shoulder of the grabens. In that case, kimberlite activity thus predates the rifting and not postdates it, as suggested earlier by White et al. (1995).

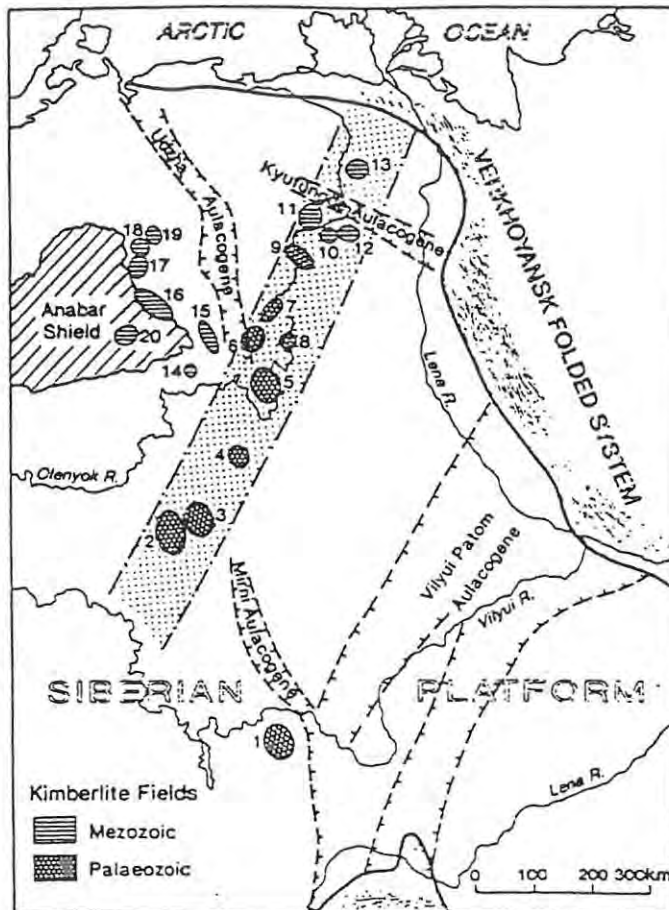


Figure 18: Geographic distribution of Kimberlite fields on the Siberian Craton compared to earlier rift structures (from Kaminsky et al., 1995).

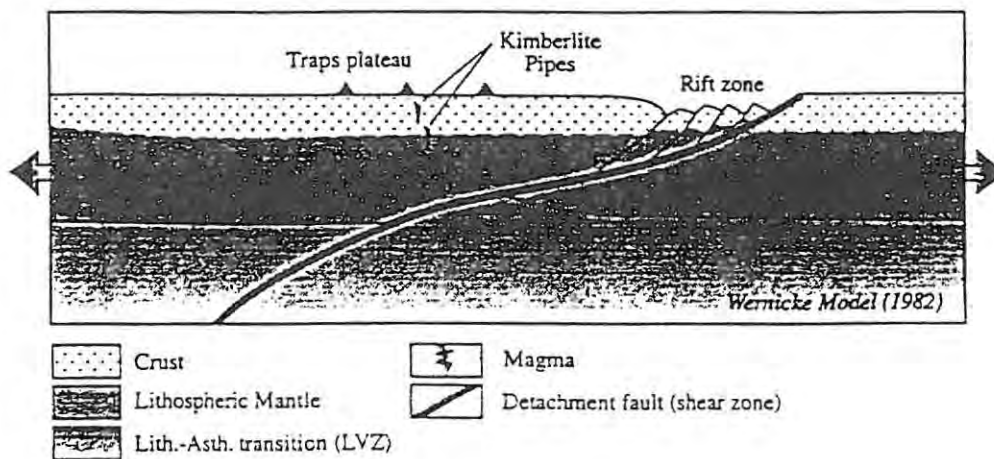


Figure 19: Detachment model for the linkage between Rift and Kimberlite province (adapted from Natapov and Griffin, 1998).

If a genetic connection between rifting activity and kimberlite magmatism is thus not obvious, it is however clear that kimberlite locations correlate with regional linear structures, which could also be old reactivated rifting structures.

Detection of regional geophysical trends and physical lineaments associated with particular structures to locate local targets for exploration of diamondiferous pipes, has been used intensively, notably by Russian geologists. However trends may be used carefully. A recent statistical study of spatial distribution of kimberlites in Nigeria and South Africa revealed that kimberlites are not distributed isotropically (Zhang and Lutz, 1989). However, the trends observed are not apparently related to prominent known geologic structures. Thus it has been deduced that kimberlite trends could be imposed by structures at depth, which have no obvious surface expression.

### 3.5.2. Ring structures

Kimberlite emplacement has also been related to ring structures notably in Russia. Geological models for kimberlite and lamproite exploration made by Russian geologists imply the existence of crust-mantle irregularities from 30 to 90 km in diameter (Kaminsky et al., 1995). These irregularities are characterized by zones of dome-shaped uplift or block-shaped uplift. Kimberlites and lamproites are generally situated at the intersection of this zone with transverse structures, which are deep-seated faults. Locally, a secondary fault system is arranged in a radial pattern of fractures centred on the uplift (figure 20). The surface expression of these patterns is thus characterized by large concentric-radial structures of up to 100 km in diameter.

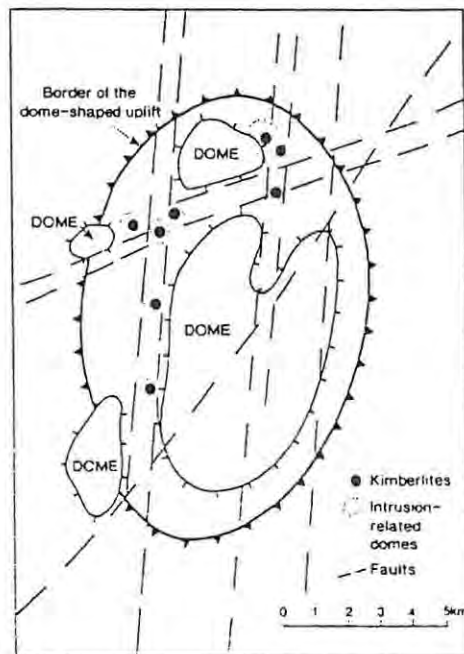


Figure 20: Example of ring structures in the Little Botuobiya kimberlite field, Yakutia. Dome-shaped uplift includes all the known pipes, which are controlled by zones of contiguous faults (after Kaminsky et al., 1995).

Kimberlite fields are thus frequently located by Russian geologists in these zones of radial and concentric fault systems, which overly high-density rock masses identified by seismic surveys, near the crust-mantle boundary.

It is interesting to note that similar arch doming or arch-style uplift have also been identified in the Canadian Shield (Cf. Card, 1999). Movements on the arch structures would triggered minor magmatism and controlled the emplacement of kimberlites and related intrusions. In a similar way than in Yakuta, kimberlites in the Lac de Gras province are located along deep-seated faults namely northwest and northeast trending faults used by the Malley and MacKay dyke swarms (Cf. Wilkinson et al., 2001) and more interestingly at their intersection with arcuate features, represented by the Lac de Gras Dykes.

The geodynamic interpretations of such features differ from the authors. It has been interpreted as the result of plume activity, which trigger the formation of dome-shaped uplifts and juxtaposed linear rift structures (Moralev and Glukhovsky, 2000). The nature of the Lac de Gras swarms, suggesting minor uplift and radial stress, has also been associated with an intraplate plume activity (Cf. Wilkinson et al., 2001).

Areas of local mantle-crust arch doming have also been associated with mantle upwelling, as a direct consequence of subduction process (Skorospelkin, 1992), like proposed by Anderson et al. (1992).

### 3.5.3. Deep-seated basement faults

Emplacement of kimberlites and related rocks is often related to reactivation of deep fractures, faults and shear zones in the continental crust that traverse deep into the lithosphere.

This mode of emplacement has been formulated in numerous kimberlite provinces in the world (East European Platform, Smirnov, 1992; West Africa, Haggerty, 1992; Angola, De Boorder, 1982; Western Australia, White and Smith, 1992; Eureka, South Australia, Morris, 1999).

The major problem is that deep reaching fractures and other deep-seated features are not always obvious on surface that makes their interpretation difficult. Extrapolation of kimberlite trends across large areas where there are no surface signs of inferred lineaments, even at some depths, is thus a delicate exercise and should be used with precaution (De Boorder, 1982).

A common hypothesis has been to consider the deep-seated basement mobile zones or fracture corridors as landward extension of transform faults (White et al., 1995).

Kimberlites lineaments along small circles in southern Africa, West Africa and South Australia have been notably interpreted as continental extensions of oceanic transform faults as soon as the 70s (Marsh, 1973; Williams and Williams, 1977). It is thought that the transform faults would reactivate old continental structures. However until recently, these deep structures were not identified. Furthermore the lineaments of kimberlites along small circles in these areas are still poorly constrained (figure 21). Even if the timing and the orientation of the main diamondiferous intrusions in Sierra Leone and Guinea could be related to a dynamic drifting stage responsible for the reactivation of pre-existing crustal fracture systems (Haggerty, 1992), future discoveries, notably in West Africa may better constraint these interpretations based only on few kimberlite pipes.

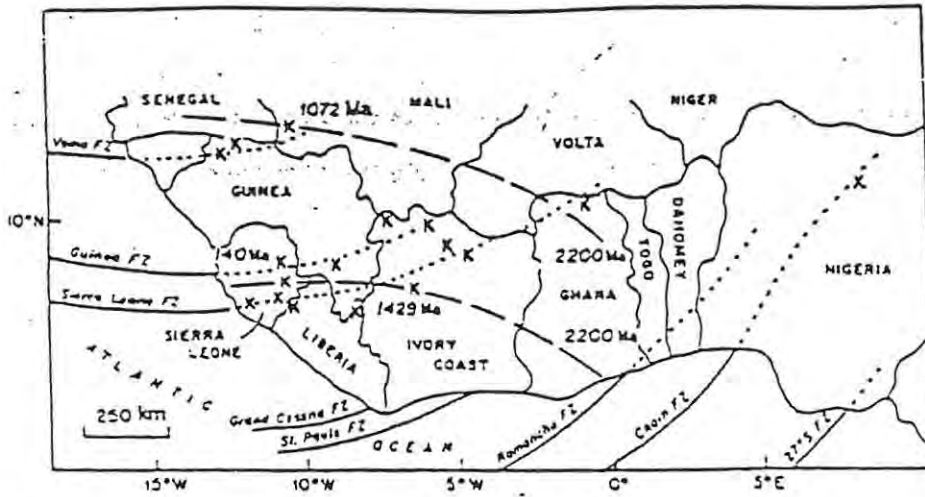


Figure 21: Oceanic fracture zones and their continental extensions in a model to account for the distribution of Kimberlites (from Haggerty, 1992).

Kimberlite trends (province and cluster sizes) have also been associated to deep structures unrelated to transform faults, characterized on surface by elongated zones of faults and magmatic lineaments (Cf. Woodzick and McCallum, 1984). Kimberlites in Angola follow for example a characterized long (>1600km) NE-trending belt of structural weakness and high magmatic permeability from the barren field of Lava in the southwest of Angola to the highly diamondiferous kimberlite fields of Calonda in the northeast extending to the Congo geosyncline (figure 22) (Reis, 1972).

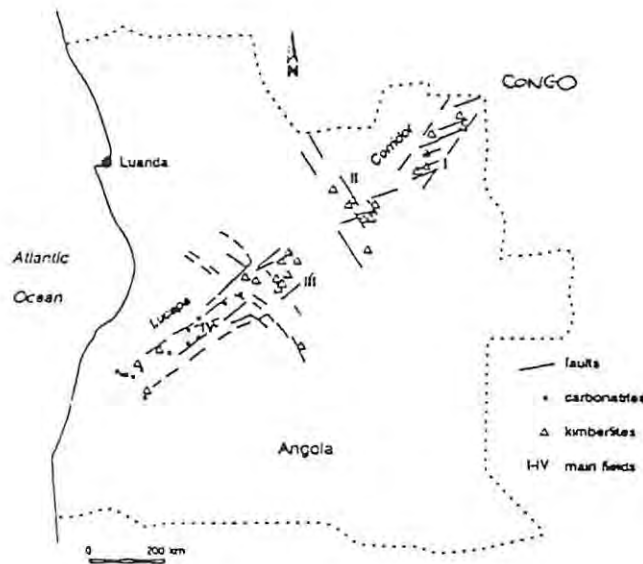


Figure 22: Kimberlites associated with the Lucapa Corridor in Angola. The main diamond provinces are marked I-IV (adapted from Reis, 1972).

With the development of seismic reflection techniques, deep structures are today more easily identifiable, and their discovery lead to a reconsideration of the theories linked to the transform faults. Research regarding neotectonic activity in South Africa for example, has revealed recently that there is a striking match between the tectonic fabric of the southeast Atlantic and southwest Indian oceans and the tectonic fabric of the African Subcontinent.

Friese (1998b) identified several major, possibly trans-lithospheric Archaean terrane boundaries (suture zones) within the craton and demonstrated their repeated control as tectonic-relay structures over magmatism and kimberlite activity in the Kaapvaal Craton since the late Archaean (Cf. figure 49). Deep crustal seismic studies have now documented the presence of these trans-lithospheric faults, which represent pre-existing lines of lithospheric weakness.

The second major difficulty is to determine if these structures, active during kimberlite intrusion, are linked to the origin of kimberlite magmas, or if they are merely zones of weakness, served as passive pathways of the kimberlites to the surface.

In the precedent examples, Haggerty (1992) considered the deep structures as preferential but passive pathways of kimberlite and lamproite magmas through the surface. The motor of melt generation is given by plume activity, which trigger extension.

On the other side, Friese (1998) believed that reactivation of deep-seated fracture zones act as a primary control on kimberlites formation and emplacement. He stated that deep-seated faults are formed or experience reactivation in an extensional setting due to a plate tectonic disturbance. This causes ultimately the decompression melting in the upper mantle and the further ascent of the magmas to the surface. This view agrees with the theory of Bailey (1993) for who the crucial factor in magma genesis is the focussing of fluid release from the deep mantle, whenever old lesions are re-opened through the lithosphere. This hypothesis however contradicts the experimental results of Schmidt and Paterson (2000), which stated that magma ascent is not favoured by any type of structures.

Deep-seated faults have also been considered as primary conduit for kimberlites in the case of the East-European Platform (Smirnov, 1993). Kimberlites and associated rocks would be directly injected into the Earth's crust through newly formed deep-seated faults, extending and breaking the platform structure during extension and splitting of cratonic structures. The formation of these kimberlite-controlling faults would coincide in time with the initial stages of large geotectonic cycles, what Haggerty (1994) called tectono-magnetic cycles.

### **3.6. Note concerning geotectonic controls on lamproites**

Most of the previous mechanisms have been intensively studied in the case of kimberlite magmatism. However, no exploration model explaining temporal and regional distribution of lamproites has yet evolved. We will review here quickly the main ideas concerning lamproites formation and emplacement, but it should be kept in mind that these models will certainly evolved with future discoveries of new lamproite fields.

Contrary to kimberlites, lamproites have not yet been found within cratons, but are generally confined to their margins, or to cratonized accreted mobile belts in regions of thick crust (>40-55 km) and thick lithosphere (>150-250 km) (Mitchell, 1991).

Generally lamproite fields do not overlap kimberlite fields, geographically and tectonically.

The particular tectonic setting of lamproites is illustrated in Western Australia, where the Argyle (1150 Ma) and Ellendale (20 Ma) lamproites are found in the Proterozoic mobile belts surrounding the Archaean Kimberley craton, which itself contain only kimberlites (Cf. West Australia Case Study).

Concerning their formation, the debate still remains. Subducted materials would be excellent candidates for the lithospheric sources of lamproites (Mitchell, 1991). The fact that lamproites carry usually small, highly modified and poor-quality diamonds is associated with long residence times in the metasomatic regions of the lithosphere. A complex plumbing system has been proposed by Haggerty (1986) (Cf. figure 3).

Mitchell (1991) noticed that lamproites are not associated with zones of active rifting, but their relation with regional structures, along continent-scale lineaments or at the intersections of major fault systems (e.g. Ellendale, Prairie Creek), is consistent. Generally regional structural controls, reviewed previously, are also applicable to lamproites.

However, much uncertainty remains with the discoveries of new lamproite fields. The setting of the Kapamba lamproites of the Lungwa Valley in eastern Zambia is in this sense interesting (Scott Smith et al., 1989). Although the lamproites follow a particularly strong NW-SE trend with more diamonds recovered to the northwest, no major faults, neither the close Luangwa graben, show a similar trend. The association with the East African rifting is however not excluded, although the lamproites are dated at 220 Ma and the plume-related melting and magmatism throughout east Africa is 45 Ma old (Ebinger and Sleep, 1998). The tectonic setting of these lamproites remains thus obscure.

### **3.7. Near-surface emplacement controls**

Near-surface emplacements of kimberlites and related rocks have been reviewed by many authors, among them Clement et al. (1989), Lorenz (1975), Field and Scott Smith (1999). In this part, we will describe only briefly the main mechanisms involved in their formation. In an exploration point of view, we will attach more importance to the controls of the surface geology on the morphology of the pipes and their diamond content.

#### **3.7.1. Different types of pipes**

Three different types of kimberlite pipes have already been identified and are resumed by Scott Smith (1999) (Cf. figure 23):

- The classical carrot-shaped pipe, which is a deep (up to 2 km), steep-sided pipe, consisting of a root, diatreme and crater zone. Each of these zones has a different shape and a different infill. This type of pipe has been described first for kimberlites in South Africa (Cf. Hawthorne, 1975).
- The shallow pipes (<500m), which comprise only a crater, zone and are infilled exclusively with volcanoclastic kimberlites. This pipe shape has been defined for kimberlites from the Canadian Prairies.
- The small (<600-700m deep) steep-sided pipes filled predominantly with resedimented material. This type of pipe corresponds to the Lac de Gras, Canada, kimberlites.

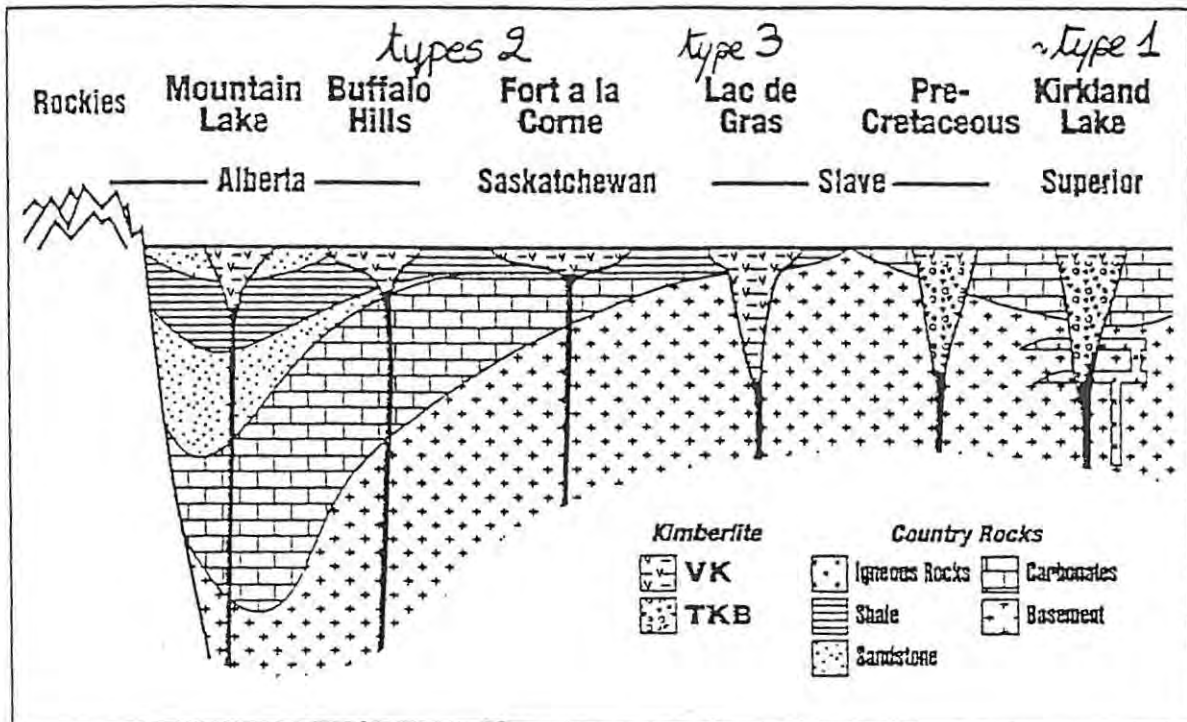


Figure 23: Pipe shapes, pipe infill and geological setting for kimberlites reconstructed for the time of emplacement. VK=volcaniclastic kimberlite; TKB=tuffitic kimberlite breccia. Type 1, 2, 3 are shown. (From Field and Scott Smith, 1999).

The fact that different types of pipes are recognized in different environments implies the control of the near-surface geology on kimberlite emplacement. Different types of magmas and different mechanisms of formation should also be considered.

### 3.7.2. Models of formation

Over the last three decades, two main emplacement mechanisms have been proposed for kimberlites: by either magmatic (Clement, 1982) or phreatomagmatic processes (Lorenz, 1975).

#### -The magmatic model-

The model of Clement (figure 24) involves the development of embryonic pipes that migrate upwards slowly by complex hydraulic fracturing, magmatic stoping and brecciation. About 500m below the surface, explosive breakthrough occurs when the volatile pressure exceeds the confining pressure. One large explosion is responsible for the formation of the diatreme zone by second boiling process (Cf. Skinner, 2000, Rice, 1999). A crater is then excavated. This model explains the presence of several distinct intrusive phases observed in most of the kimberlites, derived from distinct magma batches injected in the embryonic pipe.

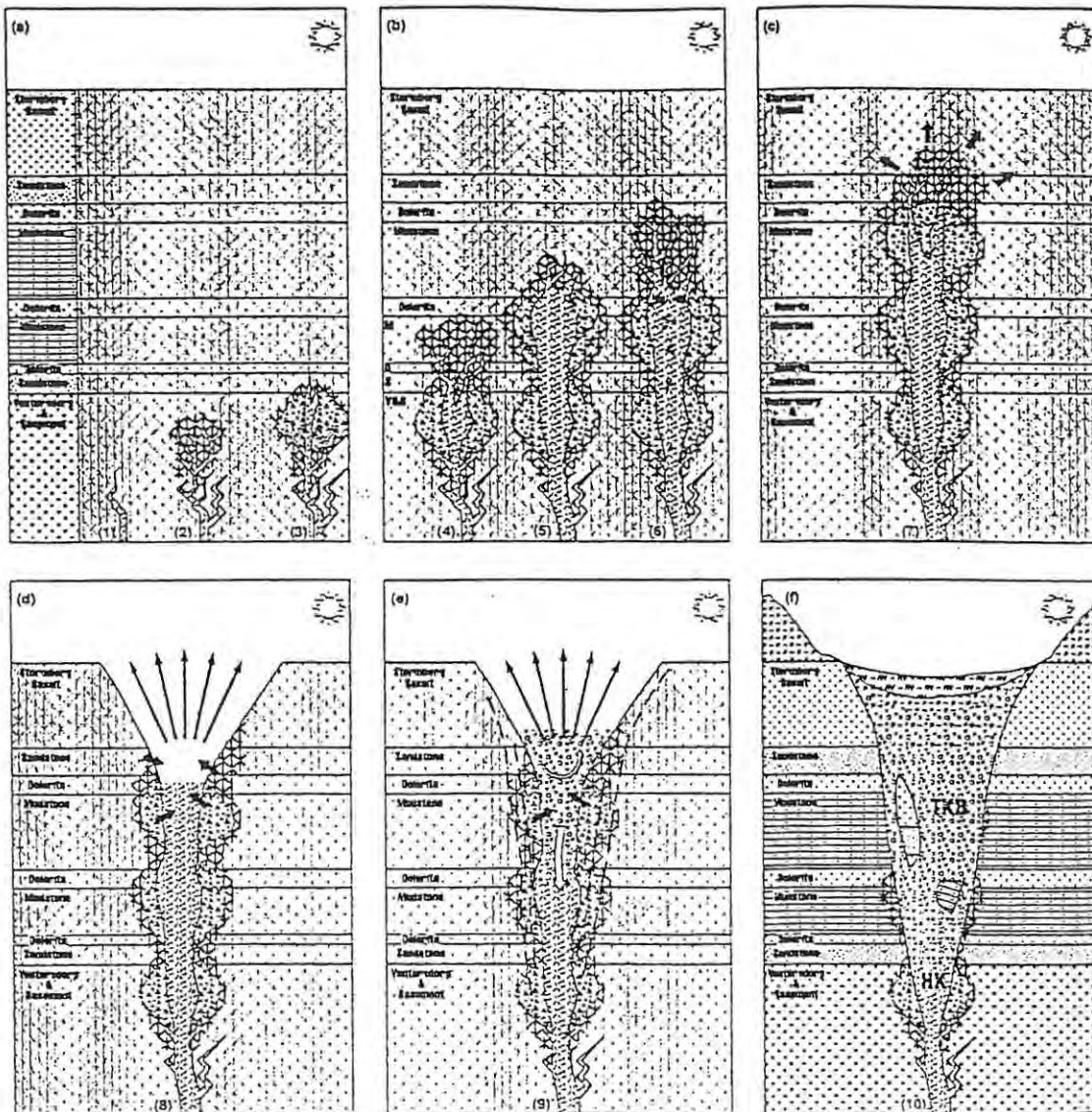
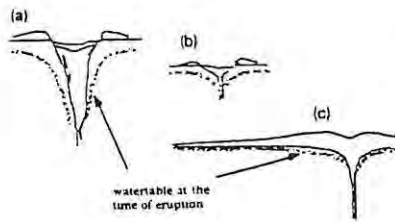


Figure 24: Schematic emplacement model for southern Africa kimberlites (after Clement, 1982).

### -The phreatomagmatic model-

In contrast to the upper model, Lorenz (1975) proposed that diatreme formation occurs when the rising kimberlite magma encounters groundwater, possibly in hydraulically active zones in faults or other zones of structural weakness. Water vapour explosions-phreatomagmatism eruption- of the fragmented magma and the wallrocks cause the crater excavation. Pipes are thus explosion craters, similar to maars.

The depth of groundwater at the time of the eruption and its availability are thus important factors that determine the shape and volume of the deposits. Therefore, Lorenz (1975) believes that this model would explain all types of pipes (table 6).



Superstructure	Maar	Maar	Tuff-ring/apron
Form of volcano (see Fig. 2)	a	b	c
Form of underlying diatreme/feeder	carrot-shaped, > 1-3 km depth	shallow, champagne glass-shaped, < 1 km	small diameter feeder
Ratio of volumes: ejected volcaniclastics to diatreme breccias	~ 1	~ 1	> 1
Floor of crater ediments	below surrounding level of country rocks	below surrounding level of country rocks	above surrounding level of country rocks
Percentage of magmatic component in the tepira	usually less than in tuff-ring	usually less than in tuff-ring	90-100%
Palaeo-aquifer	extensive, shallow to deep, may overlie dry basement	limited recharge, shallow	good recharge, includes a shallow water environment
Water table cone of depression during (final) eruption	steep	shallow	shallow
Fault features	concentric collapsed/stoped country rock	subsidence, but ring faults may be absent	absent to extensive; caldera developed if large volumes expelled from the magma chamber
Volume of potential diamond deposits	large, concentrated in the diatreme	smaller, concentrated in the diatreme	significant volume in the tuff-ring/apron
Significant post eruptive diamond concentration	within crater	within crater	reworked deposits within the apron
Examples	Classical kimberlites e.g., Orapa; Mwadui; ? Angola; Argyle lamproite	Ellendale, Praine Creek lamproites, Mbuji Mayi, Zaure; Singida, Tanzania; Saskatchewan kimberlites	some Saskatchewan ejectamenta

Table 6: Different shapes of kimberlite and lamproite pipes in relation to groundwater levels and availability (from Nixon, 1995).

However if phreatomagmatism is important in crater excavation, it seems unlikely to occur below 700m, and cannot account for diatreme formation (Skinner, 2000). Thus this model cannot account for the formation of the type 1 and 3 of kimberlites.

#### -Modified phreatomagmatic model-

Mitchell (1986) proposed recently an interesting model, which implies magmatic processes for the formation of the root and the lower diatreme, but which involves more phreatomagmatic processes towards the surface. Repeated hydrovolcanic explosions occur subsequently to the breakthrough of the embryonic pipe (figure 25).

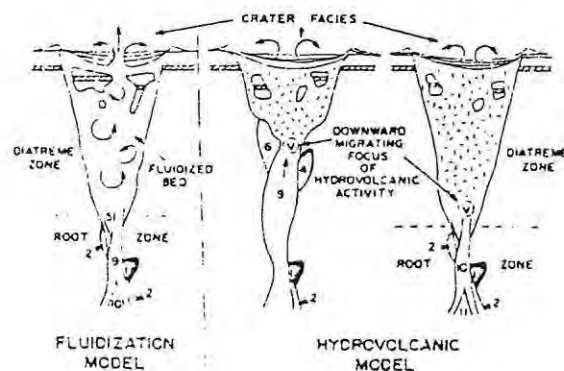


Figure 25: Embryonic pipe development and extrusion as suggested by Clement (1982) followed either by fluidization (Clement, 1982), or downward moving hydrovolcanic explosions (Mitchell, 1986) to deepen the diatreme (adapted from Helmstaedt, 1993).

### 3.7.3. Factors controlling the intrusions shapes

From the above observations, it is clear that a single model of formation could not account for the diversity of pipes and that external factors are as much important. The size, shape and diamond content of kimberlite pipes may depend on many factors, including the upper lithology, the presence of stress and fracturing in the upper crust, the availability of groundwater, the supply of magma, and the nature of magma.

#### **Influence of local structures**

Structural controls on the magma ascent, reviewed in the last paragraph are much more under debate. However it is more commonly accepted that local structures in the upper crust, when they are present, control the final emplacement of the kimberlites and lamproites. The intersections of major fractures are often a favourable site of emplacement and are commonly observed on surface. Indeed, with increasing near-surface structural studies, many pipes have shown successive emplacements along what is usually called a fissure.

The Merlin field in north-western Australia is typically a fissure system (Lee et al., 1997). Drilling revealed that the Palomides and Sacromore pipes join at depth of 120m and it seems that the intrusions are all situated along the same fissure system.

In a similar way, the Doornkloof fissure system in South Africa (Loxton Mine) consists of several parallel kimberlite fissures promising a large increase of the reserves and the life of mine. These fissures do not all occur at surface and it is thus possible that the fissure system is opening up at depth. Not far away the Bellsbank Mine shows one of the best examples of "en-echelon" emplacement in the world. The kimberlite intrusion followed a pre-existing joint system and the kimberlite fissures present vertical and horizontal displacements from 2m up to 150m!

These discoveries offer thus great perspectives, as hidden kimberlite lenses not outcropping at surface are concern.

#### **Influence of the lithology**

The correlations between the type of kimberlite pipe and the nature of the country rocks into which they were emplaced, have been studied in details by Field and Scott Smith, 1998 and are resumed below:

- The first type of kimberlite pipe, carrot-shaped, correlates usually with emplacement through competent country rocks, which form an impermeable barrier to the magma ascent. It is the case in southern Africa, where Cretaceous kimberlites emplaced in the Phanerozoic Karoo sedimentary sequence, which was capped by thick basalt lava flows and intruded by numerous dolerite sills. Such kimberlite pipes are characterized by steep-sided diatremes infilled with tuffisitic kimberlite breccia. A similar shape of pipe and infill is recognized for Kirkland Lake kimberlites in Ontario. These kimberlites emplaced in relatively competent country rocks (carbonates). Igneous rocks have also been reported in the rock sequence.
- The second type of kimberlite pipe, with a shallow champagne-glass-shape, correlates with emplacement into poorly consolidated sediments. It is the case for the kimberlites of the Canadian Prairies (Fort a la Come, Mountain Lake, Buffalo Hills), which were emplaced during the Cretaceous into varying thickness of poorly, consolidated sediments. These pipes are typically infilled with volcanoclastic kimberlite.

- The third type of kimberlite pipe, with a small steep-side shape, correlates with emplacement into a competent Archaean basement covered with a veneer of poorly consolidated Cretaceous and early Tertiary shales. It is the case for kimberlites from the Slave Craton (Lac de Gras). Most of these pipes are infilled with volcanoclastic kimberlite. A same morphology of pipe, and same infill is recognized for the Jwaneng kimberlite pipe in Southern Africa. The emplacement of Jwaneng kimberlite into Proterozoic rocks covered by unconsolidated Karoo sediments is similar in terms of competence with the emplacement of Lac de Gras kimberlites.

These correlations suggest therefore strongly that the near-surface geological setting is a major factor in determining the shape and infill of kimberlite pipes. It is also likely that surface conditions have influenced the mode of emplacement.

The type 1 kimberlite pipe, characteristic of southern Africa kimberlites, seems to be best explained by the magmatic model of Clement (1982).

The type 2 kimberlite pipe, characteristic of Canadian Prairies kimberlites, represents explosion craters excavated into the in-situ country rock sediments. They are thus likely to be formed by crater excavation and crater infilling (Field and Scott Smith, 1999). Such pipes could have possibly formed by phreatomagmatic processes. The position of the aquifer, and thus the availability of groundwater at the time of the emplacement, plays a major role on the pipe's shapes. Deeper explosive events associated with a deeper aquifer will form steeper side pipes.

The type 3 kimberlite pipe, characteristic of Lac de Gras kimberlites, formed by two distinct processes, pipe excavation and subsequent pipe infilling. A different emplacement mechanism should occur in that case and is described in details by Graham et al. (1999). Although the shape of the pipe is similar to those of South Africa kimberlites, they do not contain diatreme-facies. A possibility is that they could have formed by less powerful eruptions in a process similar to type 1 kimberlite pipes.

Another hypothesis involves phreatomagmatic explosions. When the kimberlite magmas reached the Cretaceous shales, these may have been wet mud. Thus, the breakthrough would have been probably easier than in the case of southern Africa kimberlites. Phreatomagmatic explosions could have thus occurred at the magma-wet sediments interaction, but cannot account for the formation of the vent at depth > 700m (Skinner, 2000).

An alternative mode of emplacement, which implies operation of both magmatic disruption and phreatomagmatic processes, could be therefore proposed, similar to the one presented above (Mitchell, 1986). Further work is needed to constraint the model of formation of such pipes.

To conclude, at least three types of kimberlite pipes are recognized based on South African and Canadian examples. It is thus possible that different types of pipes occur in other regions. The kimberlites in the Siberian and East-European Cratons could possibly offer different schemes. For example, the kimberlites of the Arkhangelsk province (Cf. Sinitsyn et al., 1992) are basically vertical pipes filled with kimberlite eruptive breccia intruded in sandstones overlying the crystalline basement. Crater facies are rather rare. The geological environment presents thus similarities in terms of hardness with this of the Lac de Gras kimberlites. However, the major difference is the type of infill, volcanoclastic for the type 3 kimberlites, brecciated for the Russian kimberlites. The morphology of the pipes is also a bit different, being steeper for the Russian pipes.

Therefore, a complete model, integrating all sorts of pipes, still needs to be formulated.

Concerning lamproites, they occur principally as extrusive, subvolcanic and hypabyssal rocks. They do not have any diatremes and root zones, and their vents are shallow and wide. It is thus possible that phreatomagmatism play a role in their formation. The flared champagne-glass structure of the Ellendale lamproite pipes (Western Australia) could be interpreted as an early depression of groundwater with the resultant cessation of explosive activity. On the opposite, Argyle pipe intruded through a thick aquifer, which permitted phreatomagmatic activity at greater depths, over a long period, and developed a carrot-shape (Nixon, 1995).

#### 3.7.4. Near-surface factors controlling diamonds grade

In general, the distribution of diamonds with respect to location of their host kimberlites in the craton shows no obvious pattern. It has been suggested that kimberlites situated at the centre of cratons would carry more diamonds than those towards the periphery (Kushev et al., 1992), but this feature has not been recognized yet worldwide.

The near-surface emplacement geology could however affect the diamond content. It has been shown for example that the fracture pattern in the upper crust has a major incidence on the emplacement of kimberlites. White et al. (1995) observed that diamondiferous pipes occur preferentially in the basement or in the shelf of the grabens, while less economic pipes occur in the deep parts of the grabens, where the accumulation of sediments is thickest (figure 26). This feature is explained by the fact that deep transfer faults in the basement become flower structures in the basin sediments. The multiplicity of faults, as conduits for the magma, causes thus a dispersion of the intrusives in the basin, and a dilution in diamond grade.

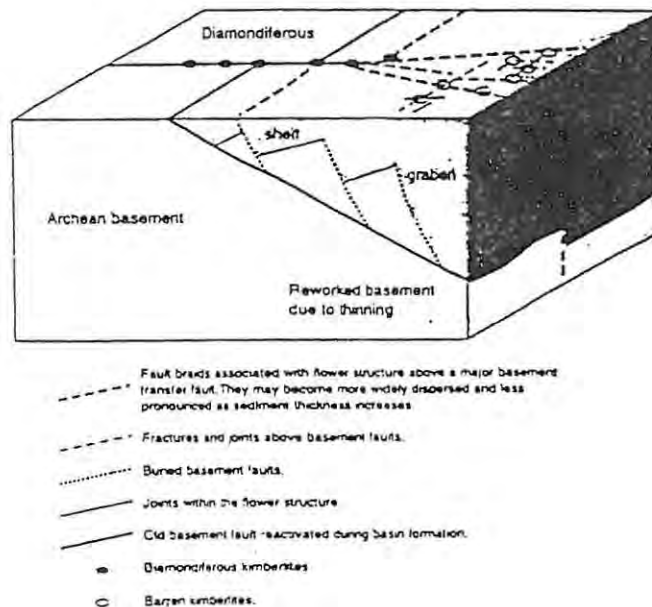


Figure 26: Cartoon illustrating the possible relationships between basement faults, basin structures and kimberlites in a graben. As the depth of sediment infill increases, the basement faults or shears become less distinct and more dispersed and consequently the kimberlite clusters also become wider and more dispersed (from White et al., 1995).

In the same way, we can explain the low grade of most of the lamproites. The formation of "swept conduits" as the eruption progresses decreases the probability of entraining xenoliths and thus diamonds (Mitchell, 1991). It is believed that the initial batches of magma contain the highest diamond load, while later batches are significantly depleted.

The same source depletion effect could be applied to the general trend that higher diamond contents are associated with larger diatreme dimensions and with single phase of intrusion. It should however not be forgotten that some of the highest diamond concentrations have been found in the Helam dikes at Swartuggens, which are less than a metre wide (Gurney, 1990).

In this case, the highly productive part of the diamondiferous pipes and diatremes is located at the top of the magmatic column, while below, at a depth from 1 000 to 1500 metres, subvolcanic pipes and dikes are believed to be less productive (Kushev et al., 1992).

These observations are however subject to debate, as all the data available about diamond grade and quality are not always released by the companies due to obvious economic constraints.

### 3.8. Pipes preservation

For exploration purpose, the geomorphological environment in which kimberlites and lamproites are emplaced and its evolution through time play a major role in the degree of preservation of the pipes (Gold, 1984) (figure 27).

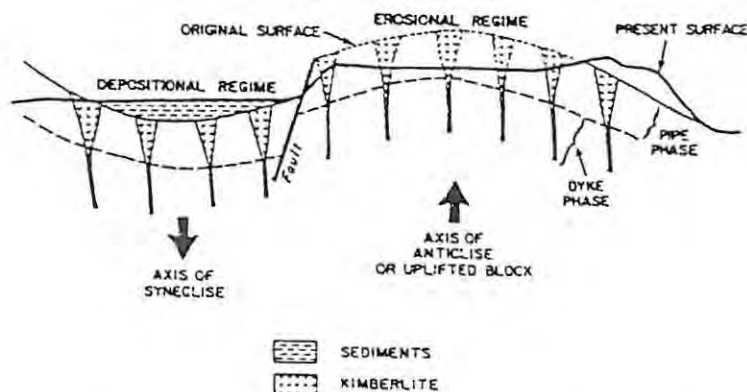


Figure 27: Erosional and depositional regimes in relationship to exposure and preservation of kimberlite (Atkinson, 1989).

Uplifted areas and old decaped shields like the West African Craton are subject to erosion, which remove the upper levels of the pipes, if not all of it. Assuming an erosion rate of 1 m every 30 000 years (Earth actual average), it could be predicted that a typical kimberlite diatreme would be completely eroded away in 69 Ma (Kirkley et al., 1991). The Bellsbank mine in South Africa, has for example a limited economic potential because the entire diatreme and crater zones has been eroded away, whereas Orapa mine have a potential economic potential to a depth of about 2000m.

The distribution pattern of diamondiferous or barren kimberlites depends thus strongly on the erosion levels of the exposed magmatic centres. As seen above, if the pipes are eroded down to stringers or thin dikes, they are generally of relatively low commercial value due to their low diamond content, and their relative limited size.

Conversely, subsidence with subsequent burial of the pipes by younger sediments may inhibit exploration by conventional techniques (Atkinson, 1989). Use of geophysics tools to detect buried target could be there useful, but the depth of the cover could limit their applications (e.g. under the Kalahari sands).

Kimberlite provinces could also suffered of several subsequent tectono-thermal rejuvenation events. The diamond-bearing Liaodung kimberlite field in the northern part of the East-Chinese province undergone for example multiple episodes of post-kimberlites Paleozoic granite intrusions (Stolbov et al., 1992). Tectonic and magmatic activity superimposed on an Archaean craton after kimberlite intrusion is thus possible and does not affect automatically their diamond content. This type of setting make however exploration difficult. As it is known that thermal disturbances are mantle-root destructive events (Helmstaedt and Gurney, 1995), zones of repeated magmatic and tectonic activity are rather avoided in an exploration strategy.

## 4. Cases study.

### 4.1. Exploration strategies

#### -Traditional methods-

Traditional methods of prospecting for diamondiferous primary deposits, typically kimberlite pipes, are based on the identification of alluvial diamonds and indicator minerals from stream gravel, loam or drill spoil samples (Cf. Carlson, 1994). Heavy concentrate studies based on the detection of low-Ca high-Cr (G10) garnets and high-Cr spinels, reveal potential diamondiferous sources. This method has been widely used in southern Africa and in Yakutia, and led to the discovery of numerous diamondiferous pipes. However the indicator minerals signature is not always strong and is lacking in different diamondiferous provinces, like in the Slave Craton in Canada. Moreover, the presence of some indicator minerals could lead to wrong interpretations. For example, most barren kimberlites and lamproites from the Kimberley region in Western Australia contain G10 garnets. Another example, on Precambrian shields, the heavy minerals concentrate is often overloaded with the heavy-fraction minerals of the Precambrian basement, and the method is reduced in efficiency.

As an alternative or as an adjunct, geophysical surveys notably magnetics, electrical methods and resistivity sounding, proved their efficiency on the ground in locating pipes and dykes. Airborne magnetic surveys on a large scale were widely used since the 1970s. They offer a rapid and cheap reconnaissance, and have been successful in the discoveries of several pipes in Siberia and Western Australia. However, geophysical tools are not always useful in particular in areas with a thick cover, e.g. the Kalahari desert, or the ices of the Northwest Territories of Canada. The magnetic response could also being masked by the physical properties of the terrain. Many kimberlites give also no electromagnetic or magnetic signatures. Geophysical exploration methods have been reviewed by Jennings (1995) and Atkinson (1989).

### -New strategies-

In terms to reduce the area to be prospected, and to eventually detect hidden targets, for which geophysical surveys and heavy-mineral studies have failed, structural analysis of the basement of potential diamondiferous provinces offers an interesting challenge. Favourable areas for diamond exploration could thus be predicted by identifying the geotectonic environment and the surface distribution of the pipes in different provinces. The petrography and chemistry studies of diamondiferous primary deposits in relation to particular lithospheric mechanisms imply in their formation and ascent to the surface, could also give fundamental keys to their understanding and their location on surface.

The results of this type of analysis depend strongly on the number of occurrences studied and will improve with further discoveries. Such philosophy led notably to the formulation of the empirical Clifford's rule (1966), which permitted numerous discoveries all around the world in Archaean cratons. Additionally, geophysical and remote control methods have been used efficiently to detect Archaean cratons beneath platform sedimentary covers. In China, Canada and Brazil, exploration without such tectonic analyses would have been inefficient.

The recent view that subduction occurred also during the Archaean led to another type of prospecting. Seismic profiles realized under cratonic terrains permit to detect horizontal plate interactions (Calvert et al., 1995). The most spectacular seismic reflection profile to date is the Snorcle transect of the Lithoprobe project which provide images of deep-crustal and upper-mantle structures under the Canadian Shield (Cf. figure 43).

With such techniques, it will thus be now possible to detect potentially diamondiferous hidden Archaean cratonic terrain beneath younger formation. New potentially diamondiferous provinces, in areas previously considered as barren, because of their position off-craton, will be delineated. It is notably the case for the Wyoming kimberlite province, where diamondiferous kimberlite fields have an off-craton position but contain diamonds with a strong G10 garnet signature (Cf. Helmstaedt and Gurney, 1995). This indicates that diamond-bearing source rocks of Archaean age existed under the juvenile Proterozoic terranes of Colorado Front Ranges during the Paleozoic (figure 28).

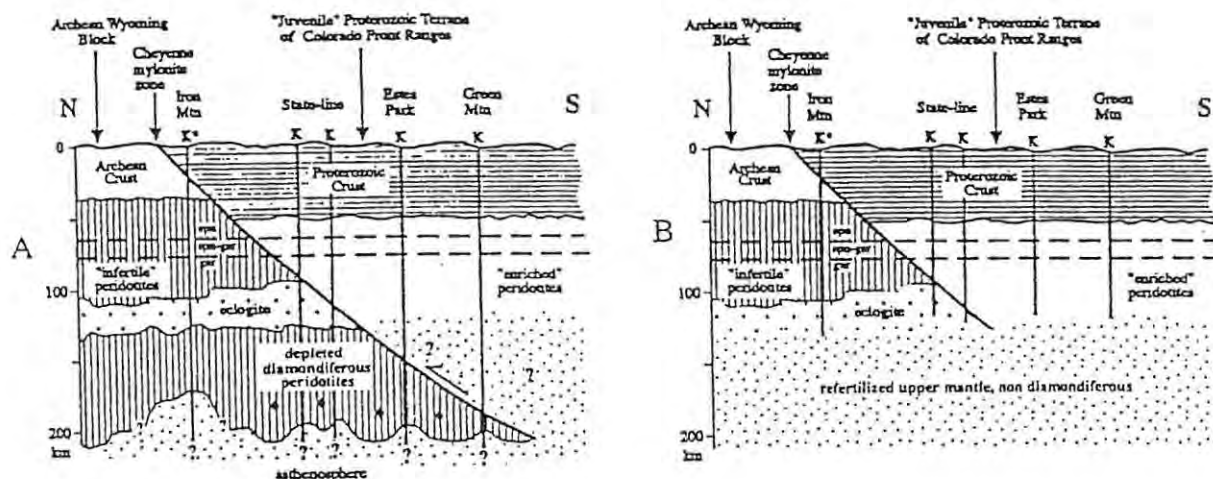


Figure 28: (A) Hypothetical cross-section across thrust boundary between Archean Wyoming Block and juvenile Proterozoic terrane of the Colorado Front Ranges. K represents kimberlites that penetrated diamondiferous root of Wyoming Block extending under Proterozoic. (B) During the Tertiary, when earlier mantle root was destroyed (after Helmstaedt and Gurney, 1995).

In the other hand, partisans of the hotspot theory could determine an exploration strategy based on the reconnaissance of hotspot tracks. The follow-up of these tracks would thus permit the delineation of potentially diamondiferous trends.

In a smaller scale, numerous pipes belonging to a same cluster have shown preferential distribution along fissure systems. This observation offers thus particularly exciting challenges for exploration, retrieving hidden parallel fissures with aerial photographs, satellite image analysis, ground-geophysical surveys and underground exploration.

#### 4.2. Western Australia

North-Western Australia holds the biggest lamproite and kimberlite fields of the country. But most of Australia's economic diamond resources are found in the Kimberley region. The very large, low gem quality content Argyle deposit accounts for about 90% of Australian's diamond production.

The western part of Australia consists of cratonic blocks separated by younger intercratonic mobile zones. The diamondiferous Ellendale Lamproite field and Argyle Lamproite pipe, discovered in the late 70s, occur within two major mobile zones, the King Leopold and the Halls Creek mobile zones respectively, part of the early Proterozoic North Australian Craton and border the Kimberley Block (figure 29).

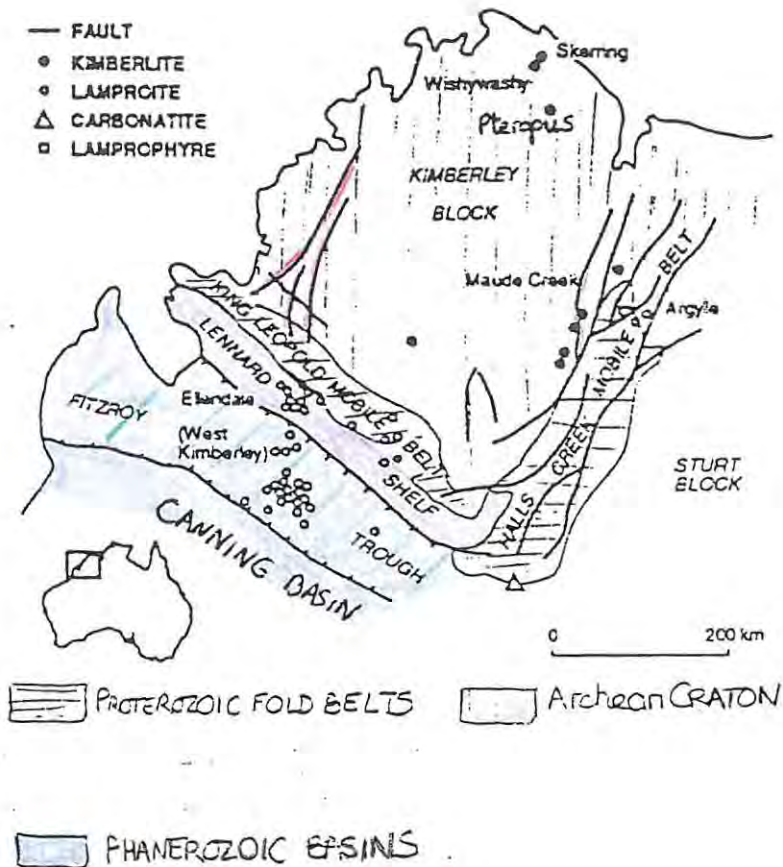


Figure 29: Tectonic framework of the Kimberley area, NW Australia (after Deakin and White, 1991).

The tectonic history of the mobile zones is today still controversial. Both of the mobile zones were active during the last major cratonizing event, the Barramundi Orogeny at 1880-1850 Ma. This event was preceded by significant crustal underplating of basaltic magmas around 2200 Ma. Since that time, both mobile zones have undergone subsidiary tectonic activity, characterized by vertical movements in the King Leopold Mobile Zone and transcurrent movements in the Halls Creek Mobile Zone (White and Smith, 1992).

Geochemical studies of the lamproites suggest the presence of an older Archaean basement (refractory, depleted mantle) and lithosphere (>2000 Ma) underlying the Kimberley block and surrounding mobile zones.

Despite of their situation in mobile belts, the diamondiferous lamproites have therefore an ancient cratonic setting.

The structural setting of the Ellendale lamproite field is illustrated by the following map and deep seismic reflection profile (figure 30 and 31). A major zone of shearing occurs within the King Leopold Mobile Zone, penetrating deep into the mantle. The surface expression of this thrust is the Oscar Fault, which acted as a zone of weakness during Indian Ocean opening in the Late Cretaceous-Early Jurassic (White and Smith, 1992). The Ellendale field is situated on the shelf of the major Fitzroy Graben, formed adjacent to the shear during Paleozoic extension.

Although the Ellendale lamproite field situated also at the proximity of the Oscar Fault Zone is the most diamondiferous field, other lamproites fields are spread over a N-S direction parallel to a major transfer fault system, occurring through the Kimberley Block (Cf. figure 29).

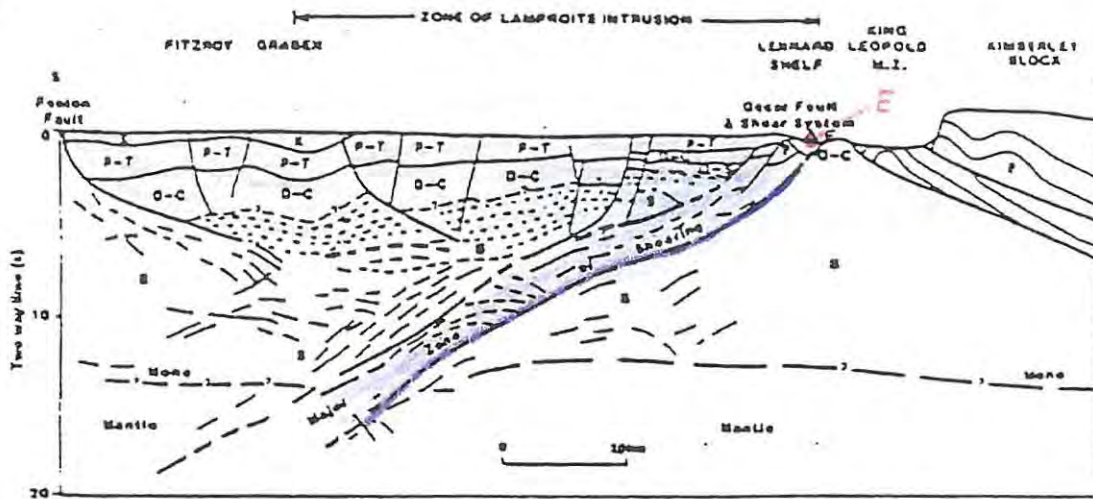


Figure 30: Schematic cross section across the Fitzroy Graben to the Kimberley Block. E: Ellendale field, P: Proterozoic, P-T: Permian-Triassic, D-C: Devonian-Carboniferous, K: Cretaceous, O-S: Ordovician-Silurian, B: Granites and metamorphic rocks (after White and Smith, 1992).

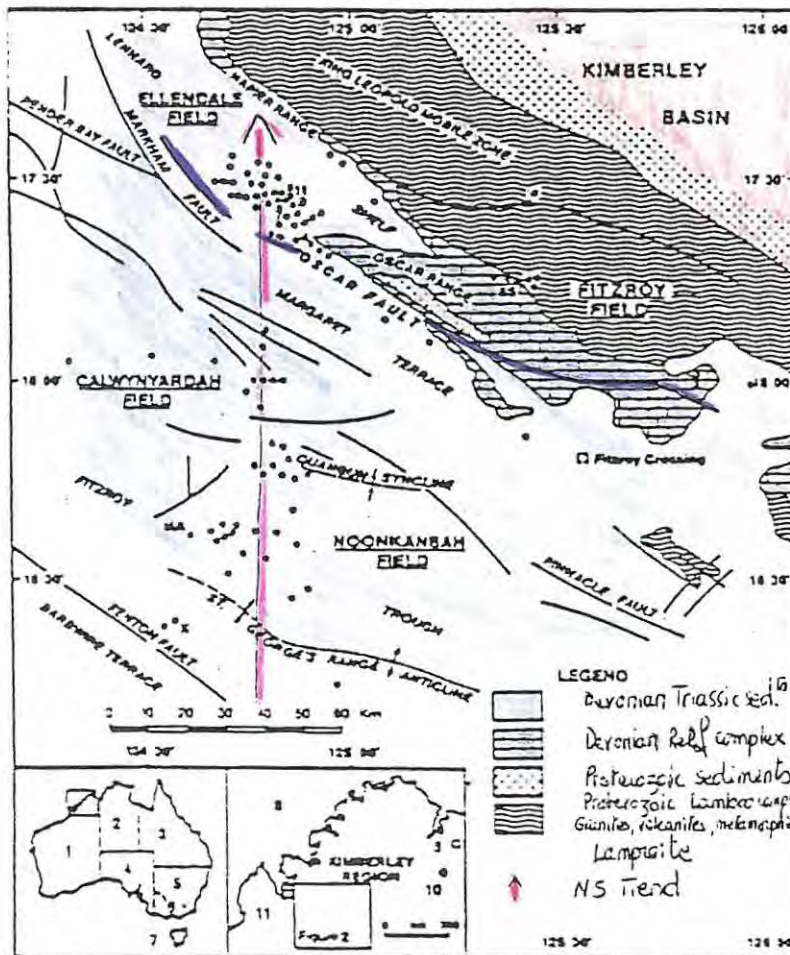


Figure 31: Distribution of lamproites in the West Kimberley Province (after White and Smith, 1992).

Analyses of diamonds from the Ellendale pipes revealed that 50% of their inclusions are eclogitic. A strong depletion in  $^{13}\text{C}$  suggests a formation by recycling of carbonaceous crustal sediments subducted in association with oceanic basalts (White and Smith, 1992). This explanation agrees with the previous proposed models of formation of E-type diamonds. Following this idea, the origin of diamonds in the Ellendale field is probably related to subduction processes occurring possibly in the Late Proterozoic.

Concerning the geotectonic controls on the emplacement of these lamproites, different interpretations could be proposed.

The close association of the intrusions with the WNW Oscar Fault System, with northerly faults in the Kimberley Block and Triassic east-west en echelon faults and folds within the Fitzroy Trough (Pidgeon et al., 1989), suggests a regional structural control on lamproite emplacement.

As some of these faults can be considered to play a second order control on the near-surface emplacement of the intrusions, the deep-seated Oscar Fault and associated shear structure can have possibly play a major role on the emplacement of the Ellendale lamproite field. White and Smith (1992) believed that lamproites were emplaced within and adjacent this shear structure during Tertiary transfer movements. We saw previously that generation of lamproite melts by decompression melting in the upper mantle caused by reactivation of deep-seated structures (Bailey, 1993) is generally applied to extensional setting. Despite White and Smith (1992) suggested that lamproites intruded during extension in the off-shore Browse Basin, it seems unlikely that minor transcurrent movements triggered lamproite magmatism. Furthermore, the Miocene-age lamproite intrusions cannot really be related in time to anterior Phanerozoic rifting episode (Pidgeon et al., 1989).

It is therefore suggested that the emplacement of Ellendale lamproites has no direct time relationship with the major structural events in the Kimberley region. However, it is possible that emplacement occurred along these ancient zones of weakness, as passive pathway.

An alternative hypothesis could thus be advanced. It has been recognized a difference in age between the northernmost intrusions of the Ellendale area, dated at 20-22 Ma, and those further south in the Noonkanbah area, which were dated at 18-20 Ma (Pidgeon et al., 1989). This northerly trend corresponds to major fault structures within the Kimberley Block and is also pronounced by north-south gravity lineaments. The emplacement of lamproites through the Fitzroy Through could thus be interpreted as a passage of a hotspot. The fact that lamproites are not following further south could be interpreted as a dispersion factor in the thick sedimentary cover of the Fitzroy graben and the Canning Basin in a similar way as explained by White et al. (1995) for Russian kimberlites (Cf. paragraph near-surface emplacement controls). This hypothesis would need to be further studied.

Lack of diamondiferous lamproites in the northern part could be explained by the destruction of diamondiferous mantle-roots, or by the resorption of diamonds in an oxidising environment, related to the activity of the shear system and multiple faulting described previously (Cf. figure 30). However, further north the Kimberley Block holds diamond-bearing kimberlites as Aries kimberlite pipe, just north of the King Leopold Mobile Belt. The Ellendale field, situated at the proximity of the Kimberley Block, could expect a less disturbed mantle-root. If a complex plumbing system (Cf. Haggerty, 1986) is considered for the emplacement of lamproites, the Ellendale lamproites could thus have originated under the stable cratonic area and used at the proximity of the surface, the Oscar Fault as an easier pathway. The complexity of the emplacement path could explain the poor quality of the diamonds recovered, as well as for the Argyle Pipe.

The structural setting of the Argyle Lamproite is quite similar to these of Ellendale Lamproites. The Argyle pipe, situated in the Hall Creek Mobile Zone, is surrounded by shear zones and faults (figure 32).

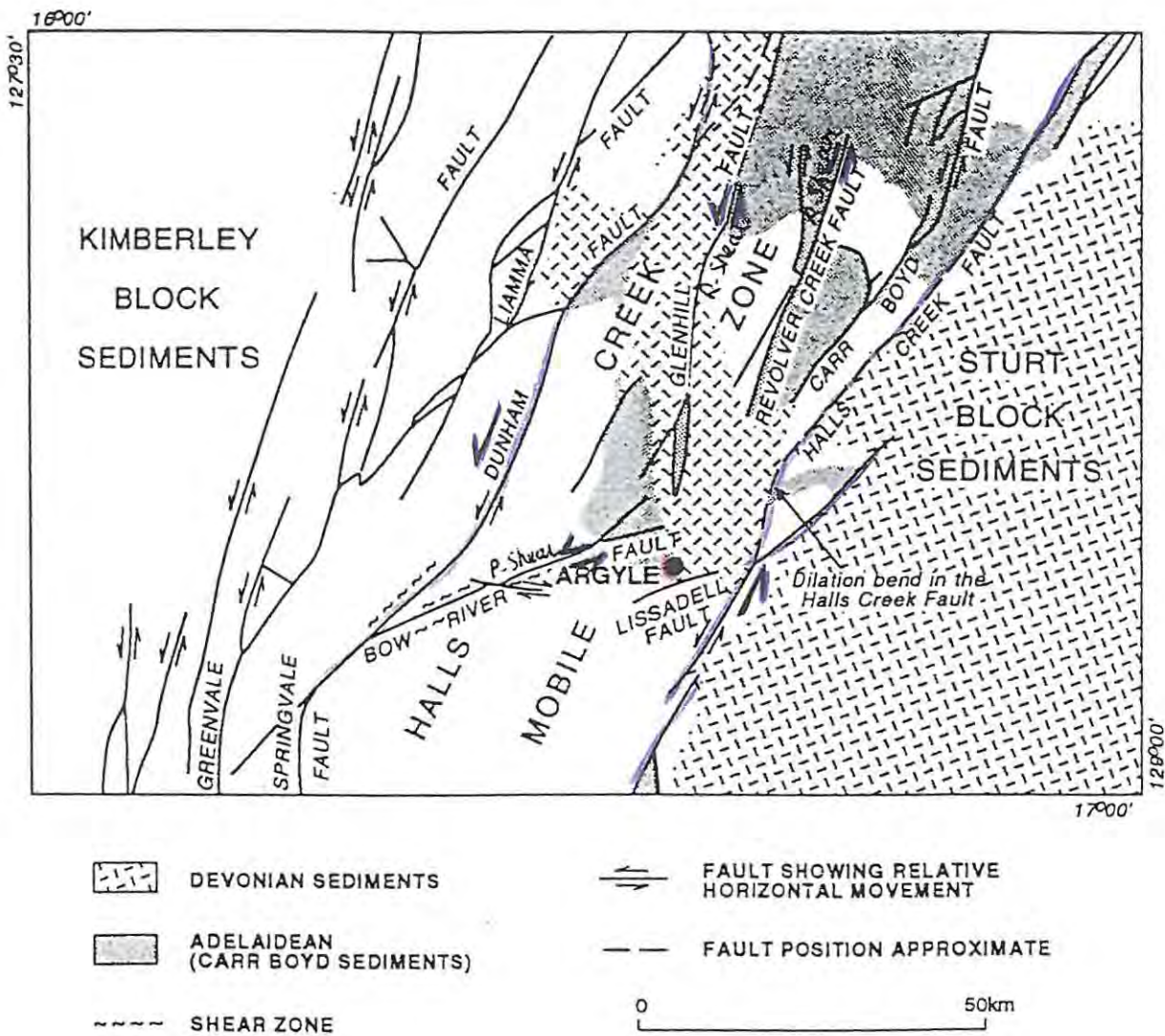


Figure 32: Fault and Shear zone structures in the Halls Creek Mobile Zone in the vicinity of the Argyle pipe (after Deakin and White, 1991).

The orientation of this array of faults conforms to a Reidel pattern (Deakin and White, 1991). These faults interactions create an area of localised extension in the Argyle area, in which the late Proterozoic Carr Boyd sediments were deposited and preserved. The Argyle pipe was emplaced at  $1178 \pm 47$  Ma (Pidgeon et al., 1989) during the Carr Boyd sedimentation and this environment may have favoured the preservation of the pipe along such a long time.

Surrounding second order faults have obviously had a control on the near-surface emplacement of the Argyle pipe.

On a larger scale, the Halls Creek Mobile Zone may be a deep-mantle structure similar to the King Leopold Mobile Zone. During the rifting of the Bonaparte Basin, situated north of the Kimberley Block, the Halls Creek Mobile Zone may have acted as a major intra-continental transfer fault (White and Smith, 1992). Major shears are thus believed to reflect extension during the early-mid Proterozoic Kimberley Basin development. It was during this Proterozoic extension that the Argyle lamproite was emplaced, as well as kimberlites dated at 800 Ma in the northern Kimberley.

Geophysical and thermal signatures of the Argyle area indicate the presence of high heat flow, associated with mantle upwelling, during the early Proterozoic. This activity results notably in WNW trending dike swarms and could have possibly influenced the geometry of faulting in the area (White and Smith, 1992). A similar passage of an older hotspot in this area is not excluded, although the hypothesis is not easily demonstrable (inaccurate plate motions in Proterozoic times, lack of other lamproite intrusions).

It is obviously harder to reconstitute the geotectonic controls on the Argyle lamproite formation and emplacement than on the younger Ellendales lamproites. Similar Proterozoic-aged lamproites may have occurred in northwestern Australia and subsequently disappeared by erosion.

The main certainty is that Argyle pipe was emplaced in the Halls Creek Mobile Zone during transcurrent movements in a localized area of extension (White and Smith, 1992). Formation of lamproite melts by decompression melting in the upper mantle in an extensional setting (Bailey, 1993; Friese, 1998) is thus here also possible.

To conclude for this case study, it seems that major deep-seated fractures in the two mobile zones surrounding the Kimberley Block, played a role if not primary, secondary in the lamproite emplacements.

Presence of diamonds in a mobile belt setting is explained by the fact that the early Proterozoic mobile zones bordering the Kimberley Craton have been stable for approximately 1800 Ma.

Diamonds are however of less quality, more resorbed, in the Ellendale pipes than in Argyle. The diamondiferous mantle-root may thus have been partially affected by destructive events. These events could possibly be plume activity, or processes related to the Phanerozoic rifting along the southwestern margin of the Kimberley block (Cf. Helmstaedt and Gurney, 1991).

Lots of questions concerning the location of diamondiferous primary deposits in the northwestern Australia remain thus open. One of these is the intriguing lack of diamonds of the kimberlites Pteropus and Skerring (800 Ma), intruded in the Kimberley craton (Cf. figure 29), above a probable similar diamondiferous mantle-root than the one responsible for the diamond content of Ellendale and Argyle pipes.

However more interesting prospects are opening up in the North Australia Craton, holding promising kimberlite pipes, like the Timber Creek kimberlite field (Precambrian age) or the Merlin kimberlite fissure field (300 000ct in 2000) in the Batten Region of the north-eastern part of the Northern Territory (Lee et al., 1997). Little information about these pipes does not permit however a full study of their emplacement history and of their possible connections with the geotectonic history of the craton.

### 4.3. Brazil

Brazil is situated within the South American Platform, which was consolidated during Pan African (700–450 Ma) times. Two major cratons are recognized, the Amazonico Craton, the largest to the west, and the Sao Francisco Craton, which is believed to be the western portion of the Congo Craton (Tompkins, 1992).

Brazil is a major producer of diamonds. However, no producing primary diamond source has yet been found, despite fourteen kimberlites/lamproites provinces have already been recognized. Diamonds are known to occur in the sedimentary covers from the lower Proterozoic to the Quaternary. Glaciation events (tillites), with the capacity to transport diamonds intact for long distances, are considered to be a probable source of diamonds. Kimberlites and lamproites discovered on the Amazonico craton and Parana Basin are mostly barren and of cretaceous ages. Thus it has been postulated that a Precambrian diamondiferous event (kimberlite or lamproite) occurred in Brazil (Tompkins and Gonzaga, 1989). These kimberlites have been probably eroded away.

Known kimberlites are all Mesozoic in age, ranging from 65 to 120 Ma from the northwest to the southwest. They occur either along basin boundaries or on the craton (figure 33).

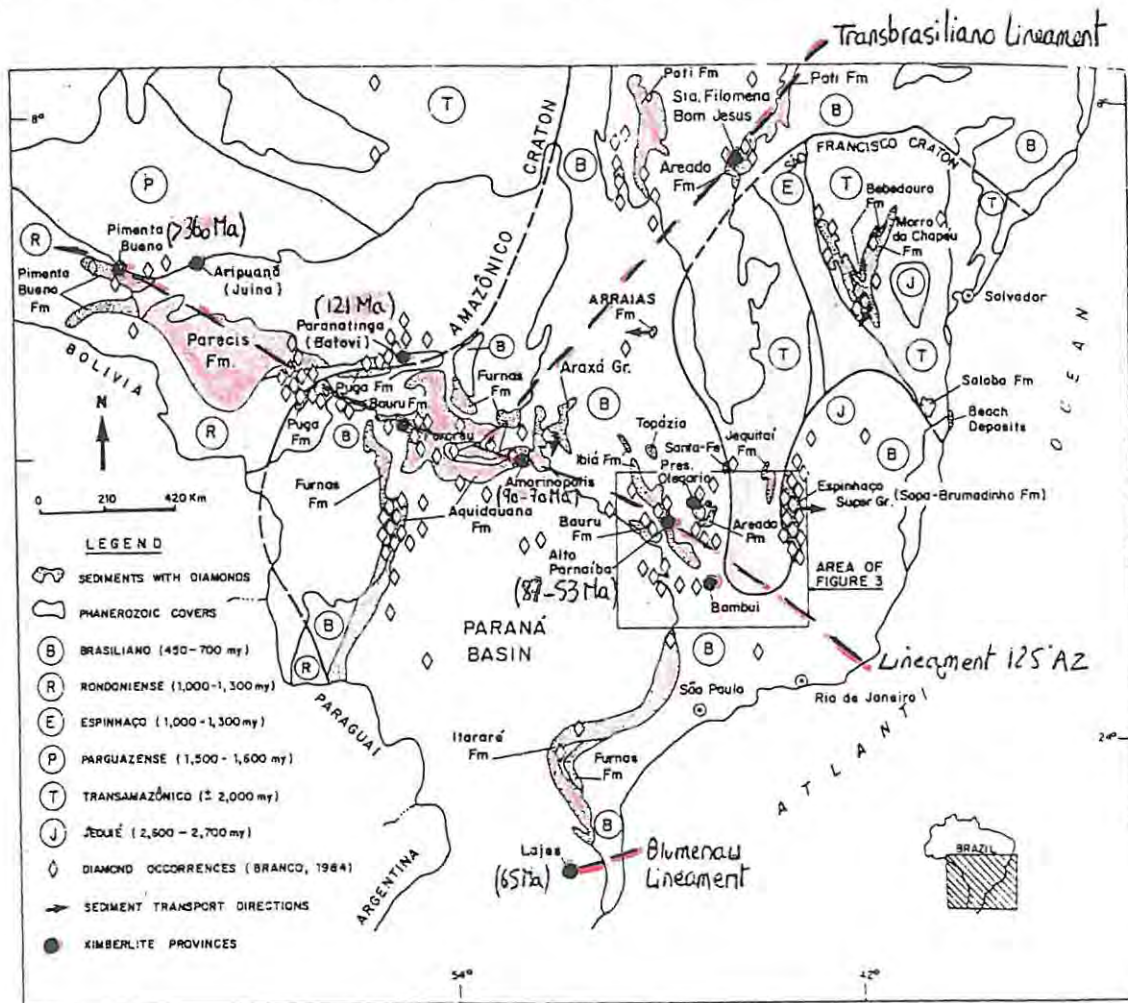


Figure 33: Location of kimberlite provinces in southern Brazil. Cratonic areas and Lineaments are shown. (map modified after Tompkins and Gonzaga, 1989).

Camille Hannon

Geotectonic Controls on Primary Diamond Deposits

Two large continental scale lineaments defined by aeromagnetism and aerial photography, are recognized in Brazil: a NW-SE lineament (or lineament 125°Az), and the Transbraziliano lineament, in a NE-SW direction (Tompkins, 1992). A minor lineament (Blumenau lineament) is believed to occur in the south and like the Transbraziliano lineament is thought to have a continuation into the African continent. These lineaments (Cf. figure 33), which were reactivated during the opening of the South Atlantic, are believed to control kimberlite emplacement in Brazil (Tompkins, 1992). The relations of Bom Jesus kimberlite province in the north with the Transbraziliano lineament and of Lajes kimberlite province in the south with the Blumenau lineament are still inconsistent.

However the lineament 125°Az is to be considered with much more importance. Datation of kimberlites along this lineament suggests that the age of volcanic activity decreases from the northwest to the southwest (Cf. figure 33). This lineament, first interpreted, as a continental extension of oceanic fractures in the South Atlantic, has been later considered as the passage of a hotspot now centred east of Trindade Island in the Atlantic (Crough et al., 1980). It is quite remarkable how the predicted path of this hotspot, called now Martin Vas, matches the ages of the kimberlites along the lineament (figure 34) even if the 120 Ma age of a kimberlite from Paranatinga seems anomalously old (Gibson et al., 1995). The hotspot migration coincide with the south Atlantic rifting and it is possible that the rising magma from the plume utilized pre-existing and reactivated zones of crustal weakness with possible extensions to oceanic fracture zones.

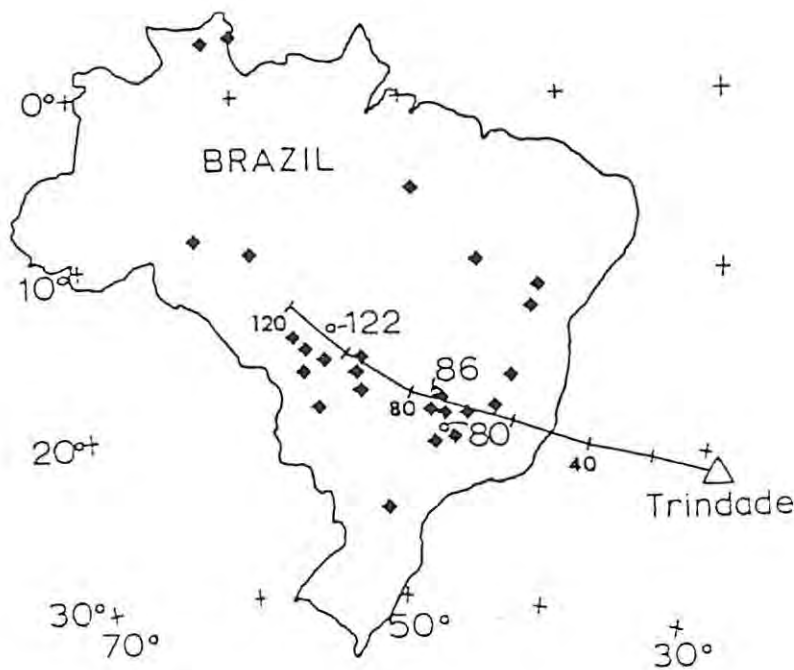


Figure 34: Locations of dated kimberlites (o) and major alluvial diamond deposits (♦) in Brazil compared to the predicted track of Trindade hotspot (after Crough et al., 1980).

In a local scale, major faulting and arcing seem to control the distribution of the kimberlites (Svisero et al., 1984, Tompkins and Gonzaga, 1989).

Concerning the diamond content of the kimberlites, only two provinces, situated on the Amazonico Craton, Paranatinga (Batovi) and Aripuana (Juina) contain diamondiferous kimberlites, but those are uneconomic. These two provinces were not affected by the Brasiliano event (450-700 Ma).

The high diamondiferous western Minas Gerais province is today of particular interest (figure 35). Although situated well off the Sao Francisco Craton, the province lies within the limits of the ancient Paramirim Craton (Tompkins, 1991). This area has been affected by the Late Proterozoic Brasiliano orogeny, caused by the collision of the Sao Francisco craton and the Amazonia cratonic nuclei during the amalgamation of the Gondwana (Gibson et al., 1995). Proterozoic rocks were thrust as slices eastward over the Sao Francisco craton, forming the so-called Brasilia Belt. This thrusting may explain the crustal thickening along the western margins of the Paramirim Craton. It is of interest to note that this hypothetical thrust front would parallel the kimberlite/lamproite intrusions in this area.

It is striking to note that all the kimberlites, which intruded in an area affected by the Brasiliano event, are barren (Cf. Table 1 in Tompkins and Gonzaga, 1989). It is thus believed that the Brasiliano event is unfavourable for primary diamond sources. It can be suggested that this event, like other major tectonic phase, has destroyed the diamondiferous mantle root by probably excessive reheating.

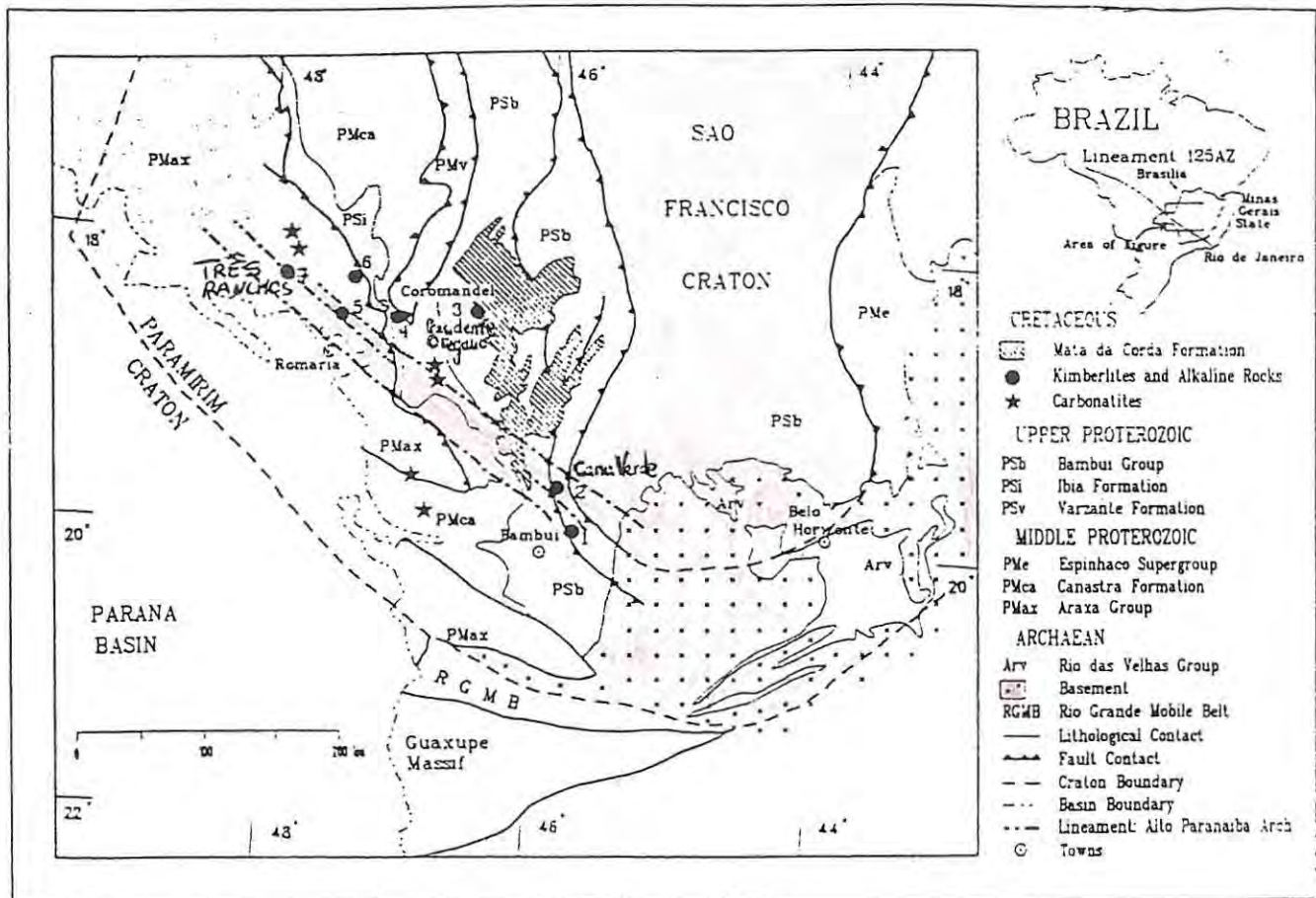


Figure 35: Distribution of kimberlites in the western Minas Gerais province (after Tompkins, 1991).

The primary source of diamonds in this province is thus still unknown. However, analyses of garnets (low Ca, high Cr) from the western Minas Gerais province indicate the presence of a potential diamondiferous mantle-root (Tompkins, 1991).

Two intrusions recently discovered, are reported to contain diamonds, the Cana Verde pipe situated at the southwestern edge of the Sao Francisco Craton and the Tres Ranchos kimberlite situated at the northwest of the province. The Cana Verde intrusion occurs in an area less affected by the Brasiliano event along the border of the Sao Francisco craton. This setting is compatible with a lamproite nature of the intrusion. Xenolith studies from the Tres Ranchos intrusion suggest a very deep source for the parental magma (~150 km), situated in the subcontinental lithospheric mantle (Gibson et al., 1995).

In a recent study, Gibson et al. (1995) linked the intrusions of kimberlites and lamproites of the Alto Paranaíba Province to the activity of the Trindade Mantle plume as suggested previously by Crough et al. (1980). Major extension of the Parana Basin during the Jurassic-Cretaceous period, increased rates of uplift, development of the Alto Paranaíba Arch and simultaneous magmatism in the Alto Paranaíba Igneous Province are the fact of the Trindade starting-plume head. The location of magmatism on the border of the craton is possibly controlled by the lithospheric thickness (Cf. figure 36).

The Alto Paranaíba Province is thus a good exploration target for diamondiferous kimberlites and lamproites, especially in the Brasilia belt near the craton margin and along the Alto Paranaíba Arch. However, a true economic diamondiferous deposit is still to be found and seems unlikely to occur in the Brasilia belt, where the diamondiferous mantle-root may have been at least partially altered. It should be questioned why no diamondiferous deposits occur in the Sao Francisco Craton, which is a relatively small craton comparable to the highly diamondiferous Kaapvaal Craton. A lack of pre-existing zones of weakness, acting as passive pathways for kimberlite magma through the surface, in the rigid Sao Francisco Craton is maybe an explanation.

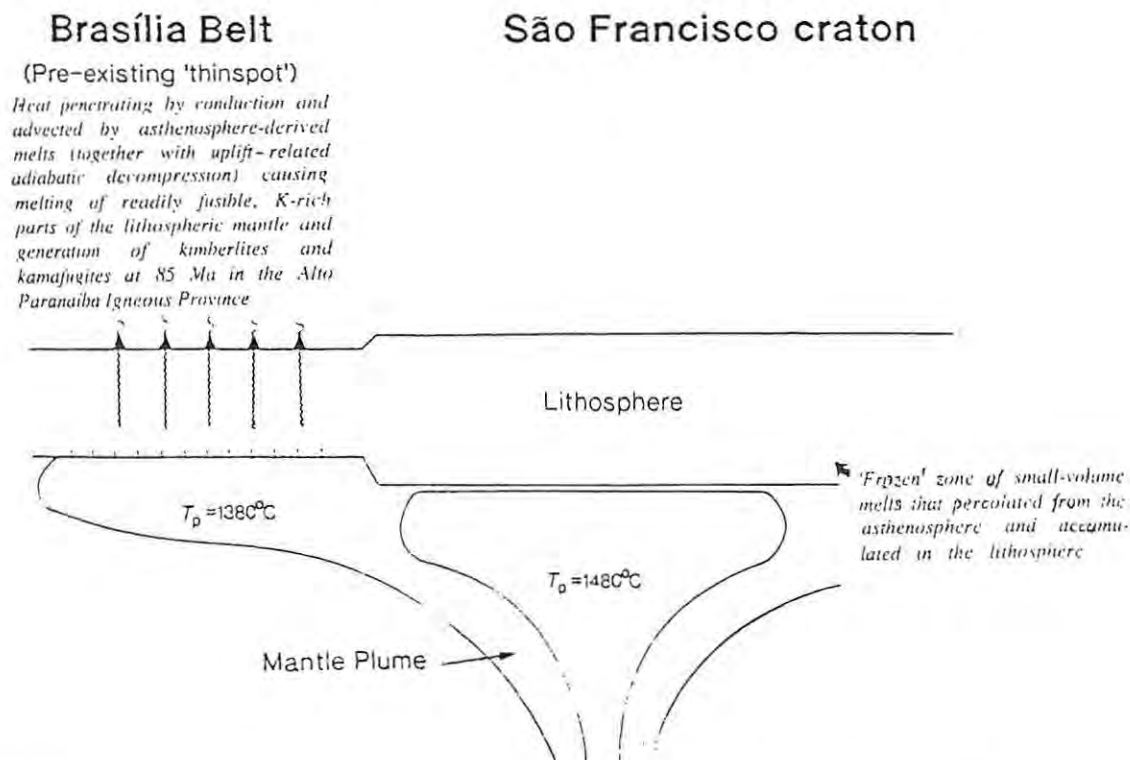


Figure 36: Impact of the Trindade mantle plume beneath the Sao Francisco Craton (cartoon after Gibson et al., 1995).

#### 4.4. Eastern North America

The majority of North American kimberlite fields are located within Archaean cratons such as the Lac de Gras field in the Slave Craton, and the Kirkland Lake field in the Superior Craton (Cf. figure 1). Few kimberlite fields have an off-craton position, like the State Line and Fort a la Corne fields, but it has been shown that the Proterozoic terranes where they intrude, are in fact underlain by Archaean crust at the time of kimberlite magmatism (Cf. Helmstaedt and Gurney, 1995; figure 28).

We will concentrate this case study on the eastern North America kimberlite fields. A number of models have been proposed here also to explain the repartition of kimberlites, including rifting (Taylor, 1984), subduction-related linked to the development of the Appalachian mountains (Sharp, 1974), reactivation of deep-seated basement faults (Parrish and Lavin, 1982) and passage of a mantle plume (Morgan, 1983; Heaman and Kjarsgaard, 2000). Once again, it should be reminded that these theories are not exclusive from one another. Some processes could explain the formation of kimberlite magmas, while other explain the emplacement controls.

The overall distribution of kimberlite fields in the eastern North America is shown in the following figure (figure 42). Recent age determinations (Heaman and Kjarsgaard, 2000) constraint the models of formation. Two major trends are distinguished. The first one is extending in a SW-NE direction from the Elliot County kimberlite in Kentucky to the Syracuse kimberlite (Finger Lakes field) in the New York state. Kimberlites are younger from Carboniferous in the south to Cretaceous to the north. The second kimberlite trend is extending in a southeast direction from Ranking Inlet kimberlites (214-192 Ma) to Finger Lakes kimberlites (148-146 Ma) (Cf. figure 37).

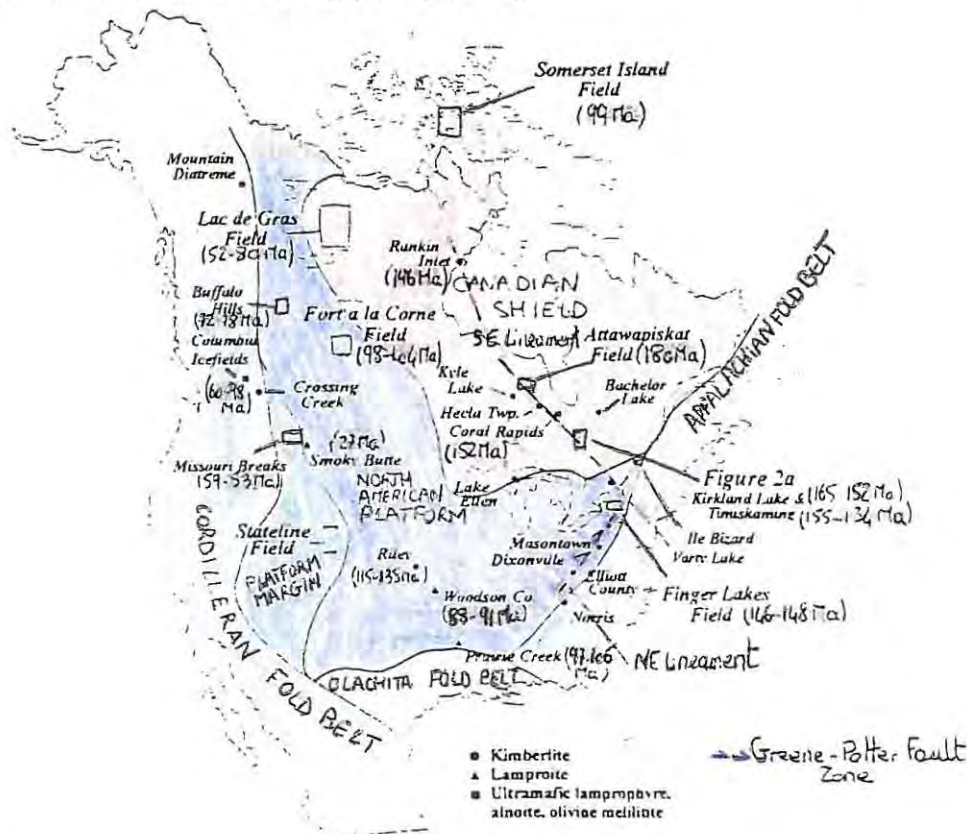


Figure 37: Location of kimberlites in North America (modified after Heaman and Kjarsgaard, 2000).

Within the same clusters, kimberlites were emplaced in relatively short periods of time from less than 2 to 20 Ma apart.

One of the first hypotheses to explain the Mesozoic kimberlite magmatism was to link it to subduction-related processes (Sharp, 1973). However, if plate collision and subduction under the eastern North America craton was the dominant tectonic mode in early to mid-Palaeozoic, it was not the case anymore during Mesozoic times, dominated by mantle upwelling and extension.

The most popular model for the emplacement of the Mesozoic kimberlites of the NW-SE trend is a hotspot track model. This model, controversial in Yakutia with the lack of known hotspot track, and in Brazil with the lack of consistent kimberlite emplacement ages, is however particularly viable in the case of North America with recent accurate emplacement ages and hotspot tracks.

Mantle plumes, active during the opening of the North Atlantic Ocean, have been recognized and hotspot track reconstituted in the North American continent notably by Crough et al. (1980), Morgan (1983) and O'Connor and Duncan (1990). There is a striking match between the relative plate motion reconstitution of North America, the Great Meteor hotspot track and the kimberlite magmatism (figure 38). Even the reduction of plate velocity during the interval 180-140 Ma explained the larger range in kimberlite emplacement ages within individual fields (165-152 Ma) in the Kirkland Lake area (Heaman and Kjarsgaard, 2000). This narrow belt-like succession of kimberlite magmatism is best explained by the model of mantle plume tail of Richards et al. (1989).

Thus the progressive south-eastward younging of kimberlite magmatism throughout much of eastern North America is considered to be caused by small mantle melting occurring along the continental extension of the Mesozoic Great Meteor mantle plume hotspot track initiated during the opening of the North Atlantic Ocean at about 200 Ma (Heaman and Kjarsgaard, 2000).

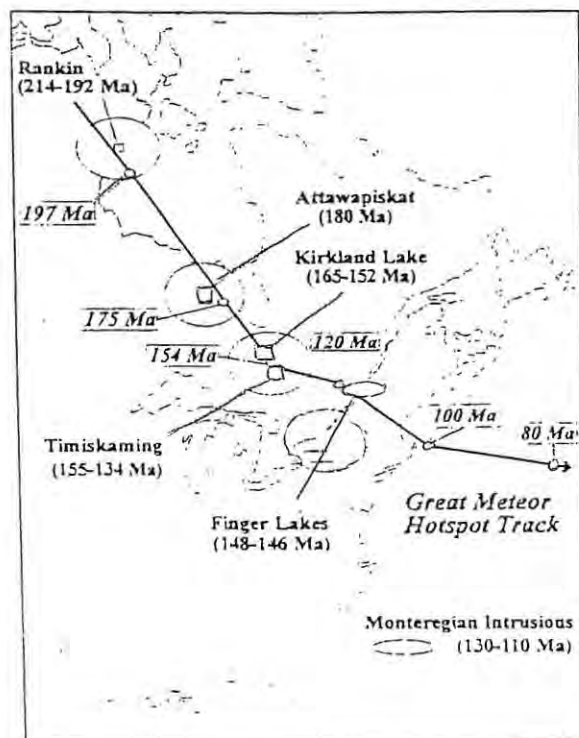
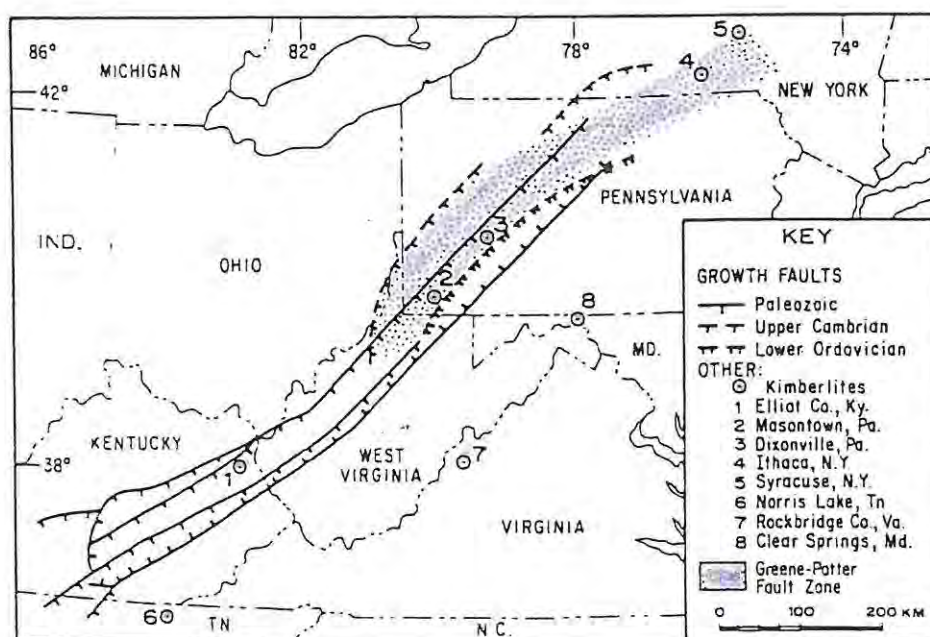


Figure 38: Proposed continental portion of the Mesozoic Great Meteor hotspot track constrained by the progressive younging of eastern North America kimberlite emplacement (after Heaman and Kjarsgaard, 2000).

The biggest objection to this hotspot theory is the recognition of kimberlite magmatism, which cannot be related geographically with any hotspot track. This is the case of the kimberlite alignment from the Kentucky to New York State. Available radiometric ages suggest also a decrease in age from the Permian Elliot County kimberlites to the Jurassic-Cretaceous Finger Lake fields (Parrish and Lavin, 1982). However more recent available age determination indicate a much younger age for Elliot County kimberlite at about 88 Ma (Heaman and Kjarsgaard, 2000).

Taylor (1984) noted that this kimberlite trend parallels the opening of the proto Mid-Atlantic rift progressively from north to south. He believes thus that kimberlite emplacement are linked to reactivation of Palaeozoic basement faults by tensional forces during the northward opening of the North Atlantic Ocean. In a rifting-related model, the major zones of weakness preceding the formation of the corresponding oceanic transform faults, are roughly perpendicular to the rift. In eastern North America, the kimberlite trend is parallel to the Mid-Atlantic rift. Parrish and Lavin (1982) observed that kimberlites in Pennsylvania are located at the intersection of basement fault parallel to the continental edge and cross-structural fracture zones (figure 39). The Cambrian-Ordovician Greene-Potter fault zone is thus likely to have been reactivated under extensional stress conditions and favours the kimberlite magmatism.



**Figure 39:** Relation of kimberlite intrusions in eastern United States to structure-parallel faults and Greene-Potter fault zone (from Parrish and Lavin, 1982).

It is apparent that kimberlite fields from eastern North America are linked to somewhat major deep crustal structures, like also the Rankin Inlet kimberlites with the Pyke fault, the Attawapiskat kimberlite field with the Winisk River structural zone ... (Cf. Heaman and Kjarsgaard, 2000). It is however still to demonstrate if these deep-seated faults have a secondary final control on kimberlite emplacement or are implied directly in kimberlite magmatism.

As eastern North American kimberlite magmatism correlates approximately in time with the Mid-Mesozoic rifting of the mid-Atlantic Ocean, it is possible that the older deep-seated fractures, when experienced reactivation in an extensional setting, causes the decompressional melting in the upper mantle and the further ascent of the kimberlite magma to the surface (Cf. Friese, 1998 and Bailey, 1983). The kimberlite magmatism would thus be directly linked to rift-related faulting during the opening of the North Atlantic Ocean and not to any hotspot activity.

Taylor (1984) gives a different interpretation to the relation between kimberlite magmatism and rifting process. A doming of the lithosphere/asthenosphere boundary is expected under the proto Mid-Atlantic rift. This thermal upwelling, responsible for rifting, would be directly connected with kimberlite formation along this boundary.

As mantle upwelling, lithospheric thinning, regional uplift and ultimately rifting are associated with mantle plume activity, this view could thus join the hotspot theory.

If we compare the distribution of kimberlites in eastern North America with those of the Yakutia province, there is a striking match in the geometry of this distribution. The main NE kimberlite trend in the Siberian platform, believed to be a hotspot track, could be related to the North American kimberlite trend along the path of the Great Meteor hotspot (Cf. section 4.7). The branching system of the Anabar kimberlites, parallel the Udzha aulacogene and emplaced along a reactivated deep-fault system, could be related to the NE trend of North American kimberlites, parallel the Mid-Atlantic rift system and also emplaced in a reactivated deep-fault system (Greene-Potter fault) (Cf. figure 37).

From this point of view, it is possible to link all the phases of kimberlite magmatism in eastern North America with the activity of a mantle plume, centred initially beneath the mid-Atlantic rift system, producing a NW linear trend of kimberlite magmatism with the plume "tail" during successive plate motion, and eventually injected also kimberlite magma along the deep-seated fault system parallel to the continental edge.

Alternatively, the kimberlite magmatism along this last NE axe is produced directly by decompressional melting in the extensional environment.

## 4.5. Canada

### *Kimberlites Emplacement*

Diamond exploration has exploded in Canada since the last decade. Discoveries of kimberlite fields are prominent, notably in the Slave Craton and in the Buffalo Hills region of north central Alberta. Most of the kimberlite pipes have been discovered by a combination of heavy mineral till sampling and detailed airborne magnetic survey.

Although age determination and complete description of these kimberlites are already available, no real model of emplacement of these kimberlites has yet been proposed.

If we look to the overall age repartition of kimberlite magmatism in the Slave Province, unlikely the other kimberlite provinces in the world, no obvious age pattern is noticed (figure 40). Kimberlite pipes in the central Slave craton yield ages from approximately 47 Ma to 84 Ma, whereas pipes in the outside parts of the craton yield a 172 Ma age for the Jericho pipes, chemically classified as Group I kimberlites, in the north and 539 Ma age for the AK5035 pipe, chemically classified as Group II kimberlites in the south (Carlson, et al., 1999).

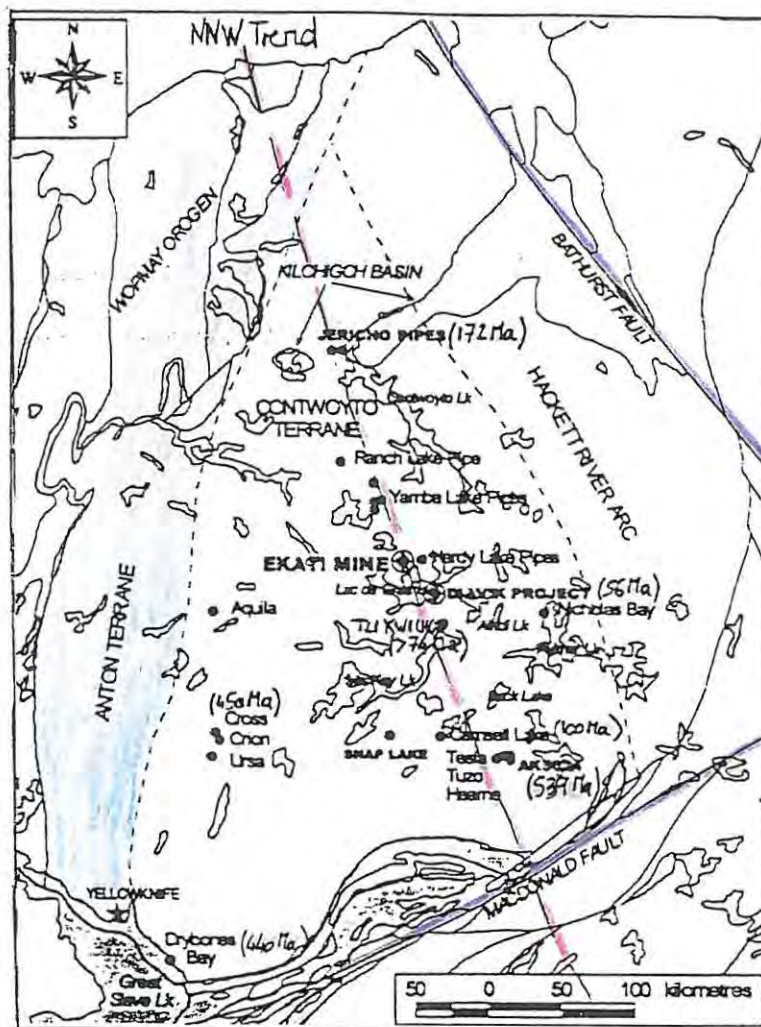


Figure 40: Location of advanced projects and kimberlite occurrences in Northwest Territories, Canada (adapted from Carlson et al., 1999).

The Lac de Gras field occupies the centre of the central Slave Province, with 175 pipes already discovered and more than 50 pipes are diamondiferous. Inside a cluster, kimberlites yield similar ages (figure 41). The Lac de Gras kimberlites are broadly co-eval pipes dated at 47.5 Ma (Davis and Kjarsgaard, 1997), but kimberlite magmatism possibly occurs over as long as 6 Ma in this area (Graham et al., 1999). However, not obvious age patterns have been reported from the recent studies.

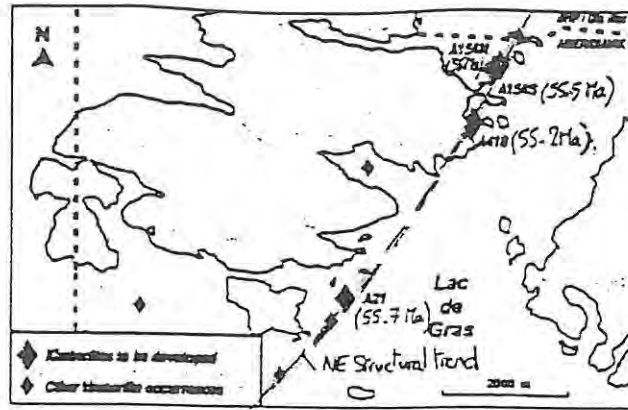


Figure 41: Plan map of the Diavik pipes (after Carlson et al., 1999) Ages Rb-Sr from Graham et al. (1999).

These age disparities and the absence of recorded hotspot activity in the Slave Craton since the Palaeozoic do not favour plume models for the emplacement of the Slave province kimberlites.

The biggest plume-related event, described later on, is linked to the emplacement of the Mackenzie dyke swarms in the mid-Proterozoic. While a direct link with this plume activity and the Cretaceous/Tertiary kimberlite activity is really unlikely, it is possible that kimberlites intruding from greater depth may encounter these dyke when ascending, and may follow the same fracture sets as the dykes during their final ascent (Helmstaedt and Gurney, 1995).

The overall distribution of kimberlites in the Slave Craton follows an approximate NNW trend (Cf. figure 40), which corresponds to the main direction of the Mackenzie dyke swarms. However, weights of evidence calculations for diabase dyke swarms made by Wilkinson et al. (2001) in the Lac de Gras area show no apparent spatial association between these young dyke swarms and known kimberlite bodies.

On the other side, three Paleoproterozoic dyke swarms (Malley, MacKay and Lac de Gras) both individually and combined as a single population show moderate to strong spatial association with known kimberlites (Wilkinson et al., 2001) (figure 42). It is thus strongly suggested that kimberlite magmatism used pre-existing, deep-seated structures. The alkalic nature of the Lac de Gras swarm suggests also possible minor uplift associated with an intraplate plume beneath the Kilohigok basin (Wilkinson et al., 2001). But once more it would be difficult to link directly the late kimberlite magmatism with this plume.

Distribution of kimberlites inside a cluster shows also some apparent structural trend. A northeast trending structural feature associated with elevated heat flow and subtle crustal uplift characterizes the Buffalo Hills kimberlites province (Cf. figure 12 from Carlson et al., 1999), a 70° lineament, possibly a Proterozoic structure, characterizes the distribution of the Jericho pipes of the Slave Craton (Cookenboo, 1999), and a northeast trend characterizes the distribution of kimberlites in the Diavik area, part of the Lac de Gras field (Cf. figure 41).

These trends again appear to correlate with deep structural features. The emplacement of kimberlites possibly occurs along reactivated deep-seated Proterozoic age fault systems. Cookenboo (1999) and Card (1999) favours an ascent of kimberlite magmas through ancient existing fault structures reactivated by plate motion events. Both compressional and extensional events connected with Proterozoic and Phanerozoic orogens and ocean basins, contributed to create northwest and northeast trending basement uplifts. The location and the timing of kimberlites, alkalic rock-carbonatites and related intrusions in the Canadian Shield are believed to be related to these arch-structures (Card, 1999). The Malley and MacKay swarms used also the same pre-existing structures in the crust.

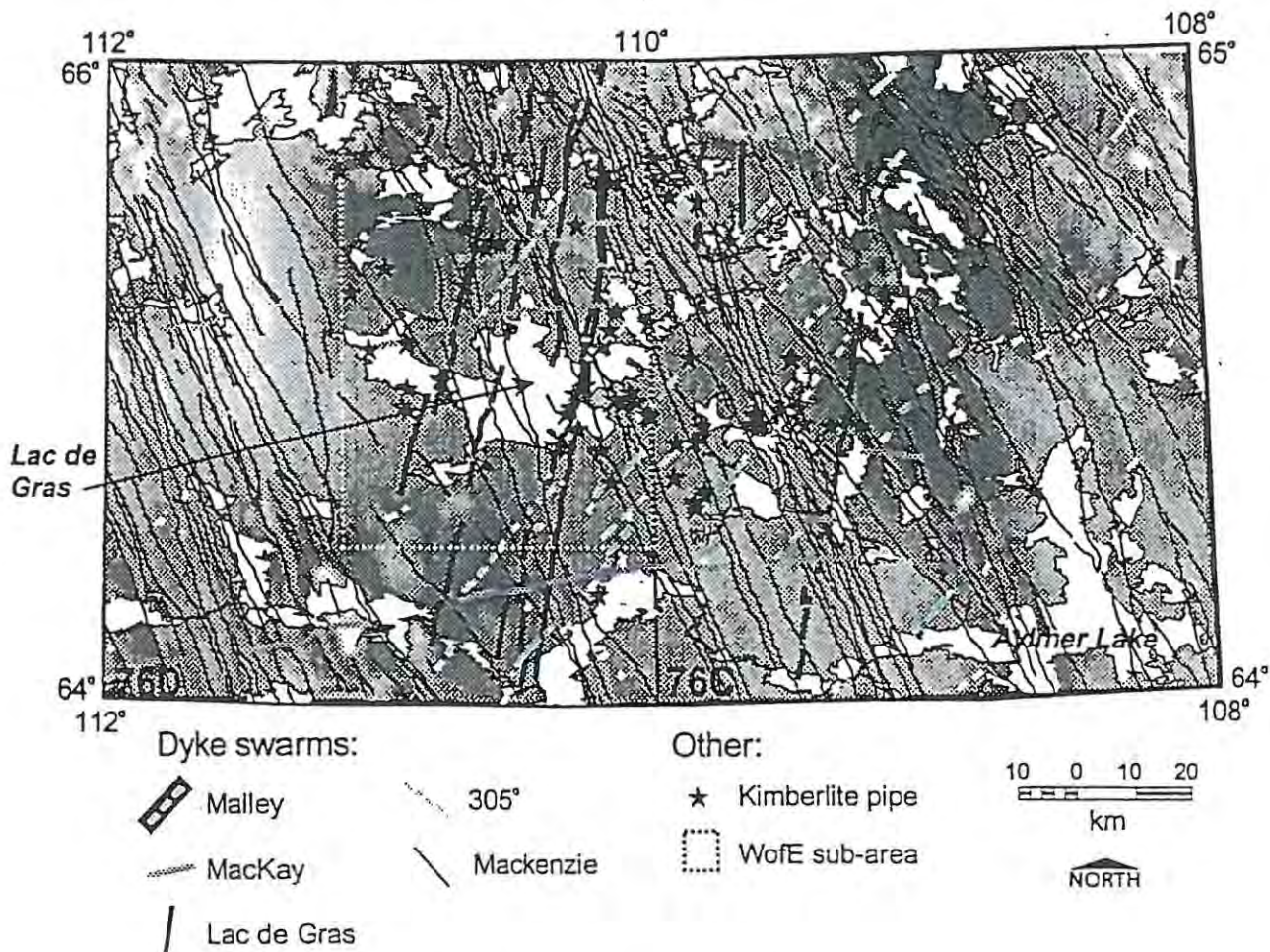


Figure 42: Distribution of kimberlite and dyke swarms in the central Slave Province (from Wilkinson et al., 2001).

In the case of the middle Jurassic Jericho pipes, kimberlite emplacement is almost contemporaneous to subduction and docking onto the northwest margin of North America. Interestingly the angle of docking along the western margin impacted to the east-northeast at about 70° by 170 Ma (time of Jericho pipes emplacement) and shifted to the north-northeast by 45 Ma to 75 Ma (time of Lac de Gras pipes emplacement) (Cookenboo, 1999). These two directions correspond to the trends of the Jericho pipes cluster and of the Diavik pipes cluster. It seems thus that subduction-related events on the western margin of North America triggered the re-opening of parallel fault structures, in which kimberlite magma intruded.

It has been proposed therefore that a deep shallow-angle subduction model favour the generation of kimberlite magmatism, which emplaced successively in either pre-existing structures or newly, formed fractures parallel to maximum stress. This case differs from the others presented previously, by the fact that kimberlites in the Slave Province would thus have been emplaced in a compressional tectonic environment. Emplacement models characteristic of extensional setting would be thus not applicable here (Friese, 1998; Natapov and Griffin, 1998; White et al., 1995).

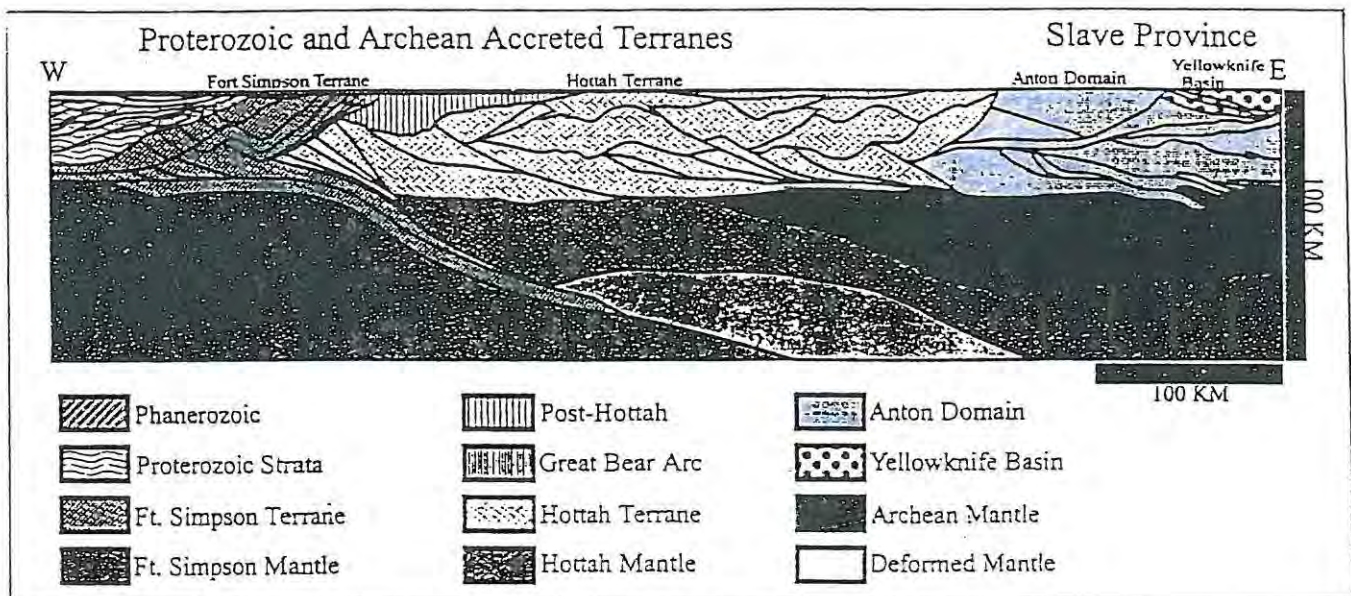
### *Diamondiferous mantle-root*

Diamond presence under the Slave Craton has been the fact of numerous studies these last years, and a model of diamondiferous mantle-root progressively emerges.

Geologically, the Slave craton is composed of granites, gneiss and schists and is divided into three main Archaean domains: ancient crustal Anton domain to the west, younger juvenile Hackett River Arc domain to the east and central accretionary Contwoyto domain (Carlson, et al., 1999).

The understanding of the structure of the lithosphere underlying the Slave craton has improved a lot by the Lithoprobe seismic program. The spectacular seismic profile Lithoprobe Snorcle Corridor 1, crossing the western part of the southern Slave Province and the Proterozoic terranes between the Slave Province and the eastern margin of the Northern Cordillera, offers a detailed view of the diamondiferous lithospheric root (figure 43).

The profile shows clear evidence for eastward-dipping tectonic underplating of Archaean lithosphere under the Slave Province during the Proterozoic (Helmstaedt and Harrap, 1999). It is thus suggested that Archaean diamondiferous segments of the lithosphere may be underlain by Proterozoic terranes.



**Figure 43:** Simplified interpretation of seismic reflection profile along SNORCLE corridor 1, from the Archaean Slave Province, in the east, to immediately east of the Cordilleran front, in the west. This section illustrates the lateral and vertical complexity in the lower crust and upper mantle beneath a typical Archaean Craton and its lateral Proterozoic additions (after Helmstaedt and Harrap, 1999).

This profile shows that a simple horizontal layer-cake stratigraphy of the uppermost mantle is not always the rule. Distinct tectonic slices are imbricated under the diamond-bearing Slave province, and the strong variations in diamond quality and quantity between adjacent pipes reflect the complex nature of the underlying mantle (Helmstaedt and Harrap, 1999). The poor quality of the highly deformed diamonds recovered in the Slave province could also be possibly a consequence of the complex tectonic history of the terranes.

The mantle sampled by the Drybones kimberlite pipes in the south of the craton suggests also Proterozoic subduction from the west whereas the Proterozoic mantle beneath the Jericho pipes in the north of the craton would have been modified during a rifting event (Griffin et al., 1999).

Geophysical data accompanied by geochemical studies allow also a detailed mapping beneath the central part of the Slave Craton. According to Griffin et al. (1999), the Lac de Gras area shows a unique two-layered lithospheric mantle: an ultra-depleted olivine-rich upper layer and a less depleted eclogite-bearing lower layer separated by a sharp boundary at 140-150 km depth. This two-layer structure is nonexistent in the north (Jericho pipes) and in the southwest margin of the craton.

The Lac de Gras diamond suite includes many eclogitic diamonds (50 % of the population) with very low  $\delta^{13}\text{C}$ . The source rock of the eclogitic diamonds is thus likely to be recycled crustal material, representing a layer that we will consider to be subducted oceanic crust. This ultradepleted layer formed thus in what we can call a convergent-margin setting during the 2.75-2.6 Ga accretion of the eastern part of the Slave Craton to the existing continental nucleus of the western part (Griffin et al., 1999). However Griffin et al. (1999) consider this layer to be shallow whereas the Snorcle seismic profile would suggest it to be deeper.

The second part of the diamond population includes ultradeep perovskite assemblage, which is only stable at depth around 670 km. Griffin et al. (1999) consider that this diamond population resides in a deeper layer, which would represent plume-related mantle lithosphere. Plume or diapir would have risen to shallow depth and incorporated both depleted mantle and subducted material (figure 44).

Alternatively, we can consider this diamond population to be trapped Archaean diamonds in the uppermost part of the lithosphere as suggested by Helmstaedt and Harrap (1999) and the Snorcle seismic profile.

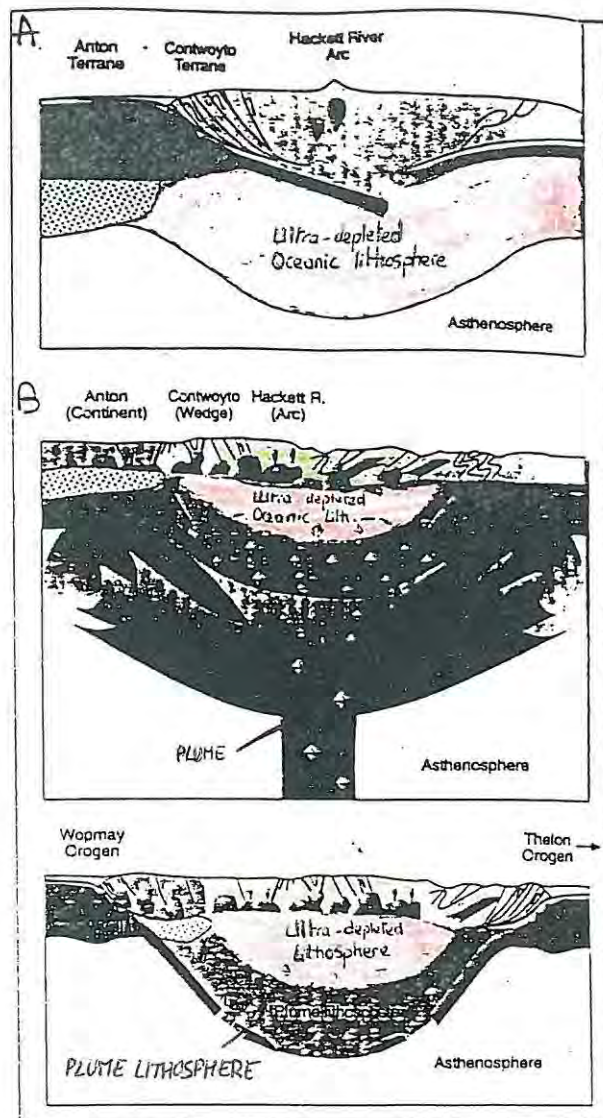


Figure 44: Tectonic evolution of the lithospheric mantle beneath the central part of the Slave Craton (after Griffin et al., 1999). A: Emplacement of Eclogites near the base of the lithosphere during Proterozoic subduction. B: Impact of the plume head beneath the Craton and transportation of diamonds.

The only plume-related events recognized in the northwestern Canadian Shield are the Mackenzie igneous events of the Middle Proterozoic (Le Cheminant and Heaman, 1989). It is believed that plume-generated hotspot (Mackenzie hotspot) caused a large domal uplift followed by rifting and accompanied by the Coppermine River flood basalts in the north of the Slave Province. 1.27 Ga Mackenzie dyke swarms developed south as a result of rift propagation across the domal hotspot. The dyke swarms intrude from vertical above the plume, to horizontal within the brittle upper part of the lithosphere (figure 45). Helmstaedt and Gurney (1995) determined that this type of lateral structures are generally mantle-root friendly and could carry economic proportion of diamonds.

It is thus possible that what Griffin et al. (1999) called "Plume lithosphere" under the Slave Craton, corresponds to a large volume of plume material intruded laterally as dyke swarms. This model is more coherent with a preservation of diamondiferous mantle-root. Diamonds would have not been preserved in the model of Griffin et al. (1999) under excessive thermal heating from the plume.

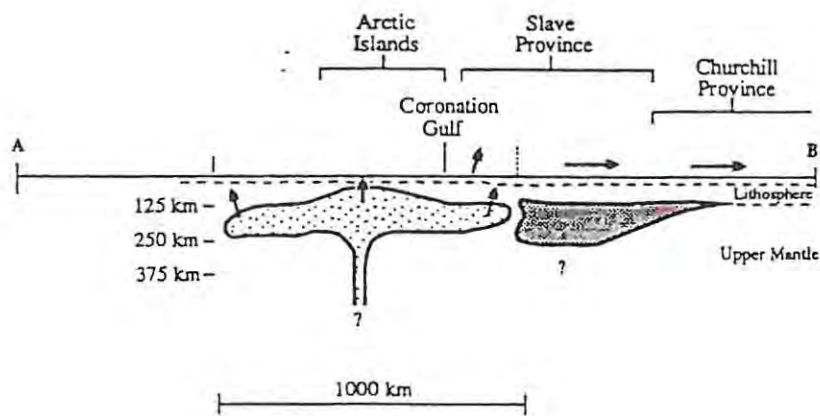
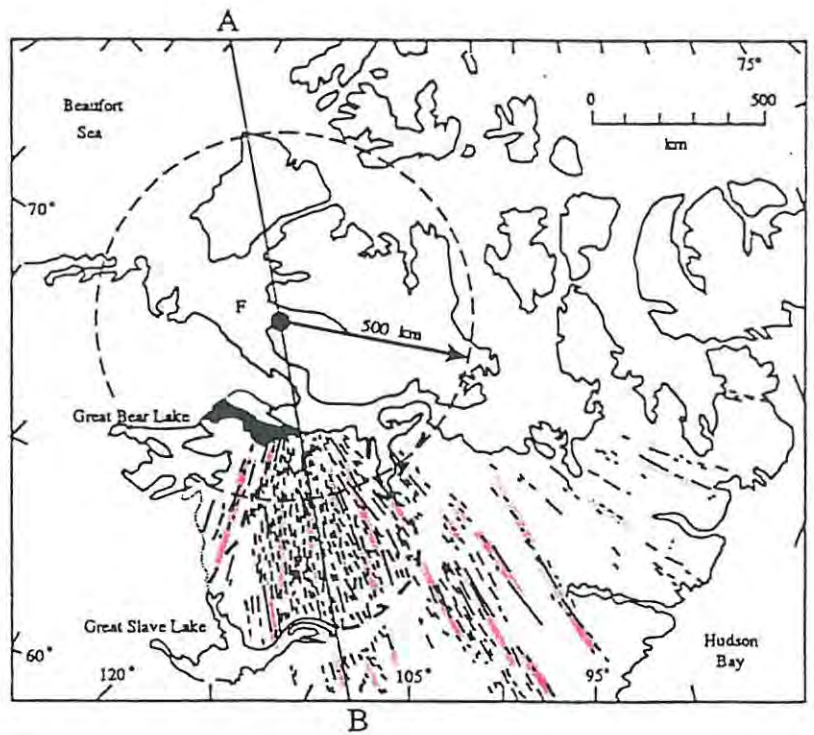


Figure 45: (Top) Map showing the distribution of Proterozoic MacKenzie dyke swarm along an approximate NS trend (after LeCheminant and Heaman, 1989); (F): inferred plume axis. (Bottom) Hypothetical cross-section through MacKenzie plume along line A-B in upper map. Shaded area under the Slave Province represents remnant of lithospheric root that was thermally eroded from the north by the plume. Arrows above line represent change in flow direction in dykes from vertical to horizontal south of plume margin. (after Helmstaedt and Gurney, 1995).

It is therefore proposed here that the lithospheric mantle under the Lac de Gras area, is according to the seismic profile geometry and the previous developments, composed possibly of slices of trapped Archaean mantle, underlain by ultra-depleted subducted oceanic lithosphere at shallow depth, itself underlain at 140-150 km by Mackenzie dyke swarms (figure 46).

This complex scenario, introducing plume material and subducted material under the craton, would thus accounts for the diversity of age and composition of diamond source rocks in the Slave Craton. This hypothesis would need further verifications.

The Slave Craton case is thus profoundly different from the other diamondiferous cratons, like the Siberian Craton, where individual terranes have retained their lithospheric keels during their amalgamation into the craton. The difference maybe lies into the fact that Siberian terranes were continental fragments, whereas the Slave Craton apparently assembled by island-arc-type activity along a continental margin (Griffin et al., 1999).

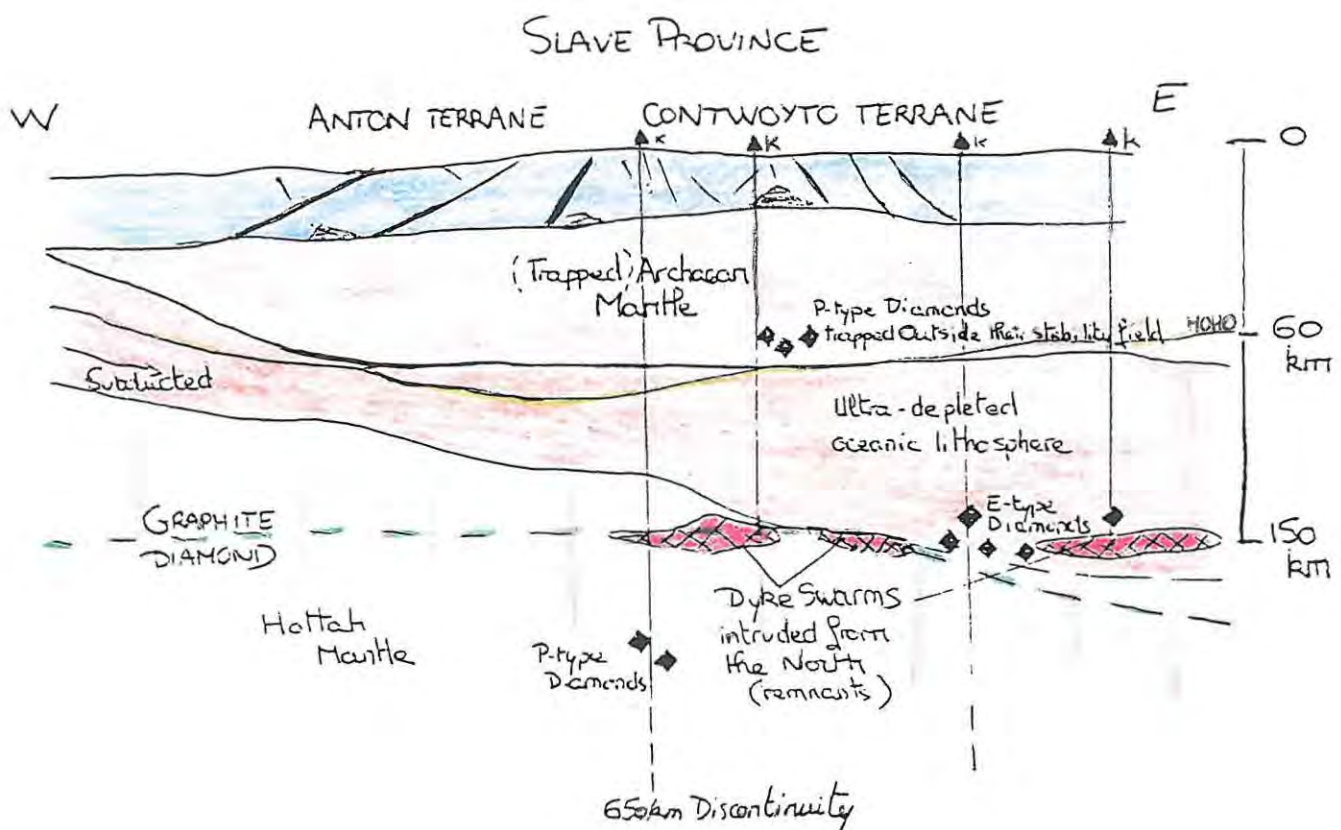


Figure 46: Cartoon illustrating proposed lithospheric mantle under the Contwoyto terrane.

## 4.6. Southern Africa

As Southern Africa contains the highest known concentration of kimberlites in the world, with 865 occurrences, and the more ancient discoveries of kimberlite pipes back to the 19<sup>th</sup> century, Southern African kimberlites and diamonds are thus the more studied in the world. Most of the theories concerning diamonds origin and kimberlites formation and emplacement controls, have been formulated from South Africa cases and have been detailed previously. Therefore, in this part, we will just review briefly the more recent theories and try to articulate the different ideas into one or two possible integrated models.

### Tectonic setting

All known diamondiferous kimberlites occur within the boundaries of the Zimbabwe/Kaapvaal Craton. This cratonic block is bounded in the north and northeast by the Pan African (~600 Ma) Zambezi and Mozambique belts respectively, in the west, by the early-Proterozoic (1800 Ma) Kheis belt, in the south by the mid-Proterozoic (1100 Ma) Namaqua belt, and in the east by the Jurassic (200 Ma) Lebombo monocline (Skinner et al., 1992, figure 47). The Craton has an ancient root, formed earlier than 3 billion years ago, composed mainly of peridotites, strongly depleted in basaltic components, and thought to derived from harzburgite rocks (Cf. Herzberg, 1993). The asthenosphere boundary shelves from depths of 170-190 km beneath the craton to approximately 140 km beneath the mobile belts (Boyd and Gurney, 1986).

The Zimbabwe Craton collided with the Kaapvaal Craton between approximately 2.7 Ga and 1.95 Ga. The combined craton, called also Kalahari Craton, underwent a complex late and post-Archaean history, detailed further on.

### Distribution of kimberlites

Distribution of kimberlites in southern Africa has been divided into Group I and Group II kimberlites. Six provinces are recognized for the Group I and one or two for the Group II. Some overlap between Group I and Group II provinces is noticed in South Africa (figure 48).

The kimberlite magmatism ranges in time from the Proterozoic to the late Mesozoic. An earlier diamondiferous event, possibly during the Archaean, is probable, indicated by the occurrence of detrital diamonds in the Witwatersrand Basin. Four emplacement periods are recognized: Lower Proterozoic (Kuruman), Middle Proterozoic (Premier), Middle Cretaceous and Upper Cretaceous. The mid-Cretaceous event is far beyond the most widespread, in South Africa like in the rest of the world.

Group II kimberlites and some Cretaceous Group I kimberlites (Kimberley province) exhibit more or less northeast trends over distance of more than 1000 km. A decrease in the kimberlite emplacement ages along this trend from the northeast to the southwest is noticeable for both of the kimberlite groups (Skinner et al., 1992). The oldest Group II kimberlites in the NE are about 200 Ma, the youngest in the SW are 110 Ma, the oldest kimberlites from the Kimberley Province (Group I) are similarly around 100 Ma in the NE, and the youngest, around 70 Ma in the SW. These northeast trends extend across the craton edge.

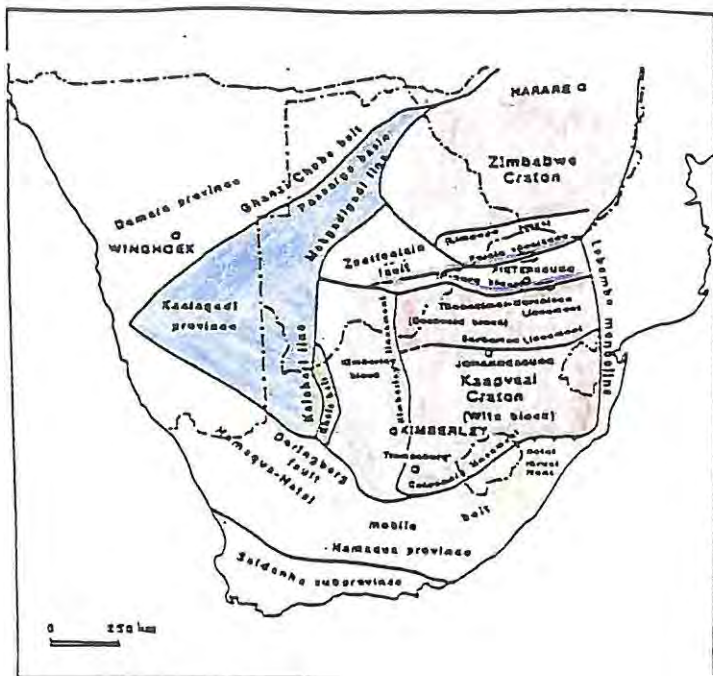
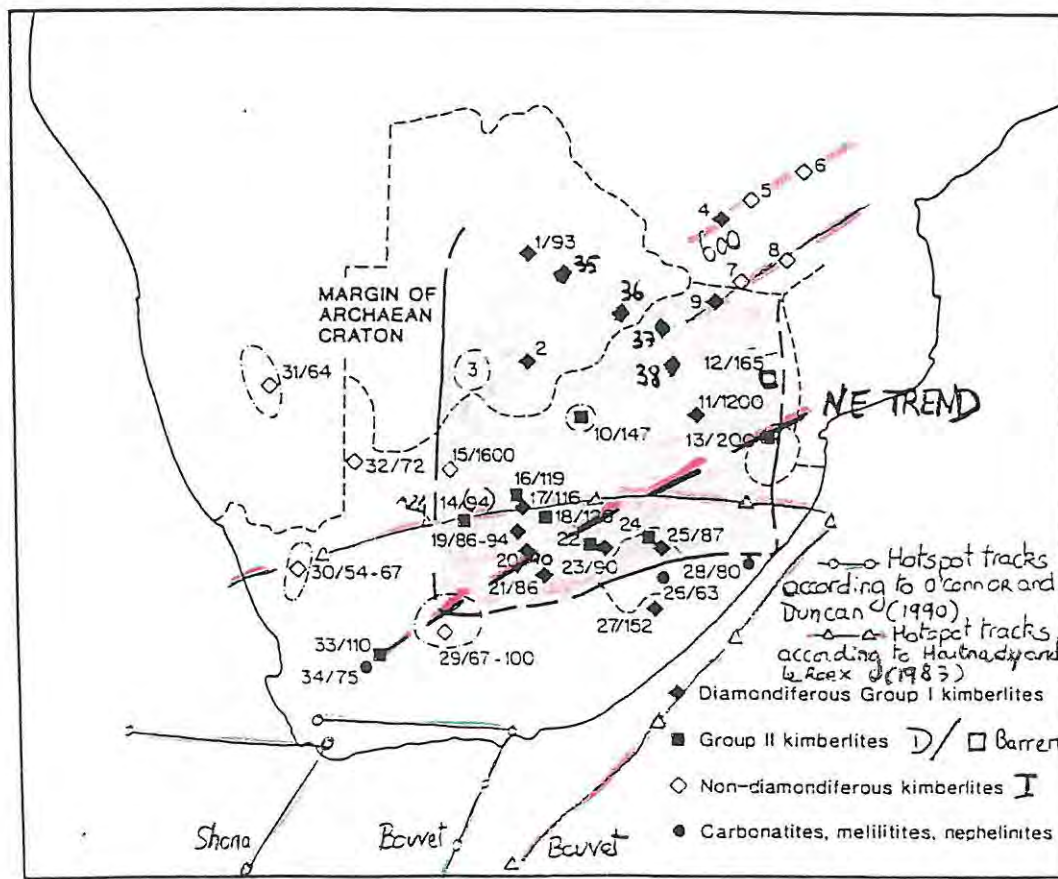


Figure 47: Simplified tectonic reconstruction of Southern Africa (after Skinner et al., 1992).



1. Orapa; 2. Jwaneng; 3. S.W. Botswana; 4. Colossus and Wesseis; 5. Clare; 6. Charter; 7. River Ranch;
8. Shingwize; 9. Venetia; 10. Swartuggens; 11. Premier; 12. Dullstroom (Elandskloof); 13. Dokolwayo;
14. Finsch; 15. Kuruman; 16. Bellsbank; 17. Barkly West (Newlands, Mayeng, Frank Smith); 18. Boshof area (New Elands, Roberts Victor, Blaauwbosch); 19. Kimberley area (Bultfontein, Dutoitspan, De Beers, Wesselton);
20. Koffiefontein; 21. Jagersfontein; 22. Winburg area (Star, Lion Hill); 23. Monastery; 24. Marakabei, Lesotho;
25. Mothae, Lesotho; 26. Melkfontein carbonatite; 27. Mzongwea; 28. Eshowe melilitites; 29. Victoria West (Lushof, Uintjes Berg); 30. Namaqualand (Platbakkies, Brakfontein); 31. Gibeon-Keetmanshoop area, Namibia (Deutsche Erde, Mukorob); 32. Rietfontein; 33. Eendekuil; 34. Sutherland melilitites
35. Letlhakane; 36. Tswaing; 37. The Oaks; 38. Marsfontein

Figure 48: Distribution and ages of southern African kimberlites (after Dawson, 1986). Proposed Hotspot tracks from different sources.

## Structural analysis

If we look at the internal tectonic boundaries within the craton, and at the major known geophysical lineaments, it appears that major structural trends have little influence on the distribution of kimberlite provinces and fields. Trends are not apparently related to prominent geologic features and could only be imposed by structures at depth (Zhang and Lutz, 1989). The only apparent structural controls are local trends of kimberlite clusters related to minor faults and dykes directions (Dawson, 1970). It is possible that in certain cases these trends correspond to deeper structures, like the east-west 'Lesotho trend' recognized as a major fracture trend, parallel the foliation in the basement granite-gneiss.

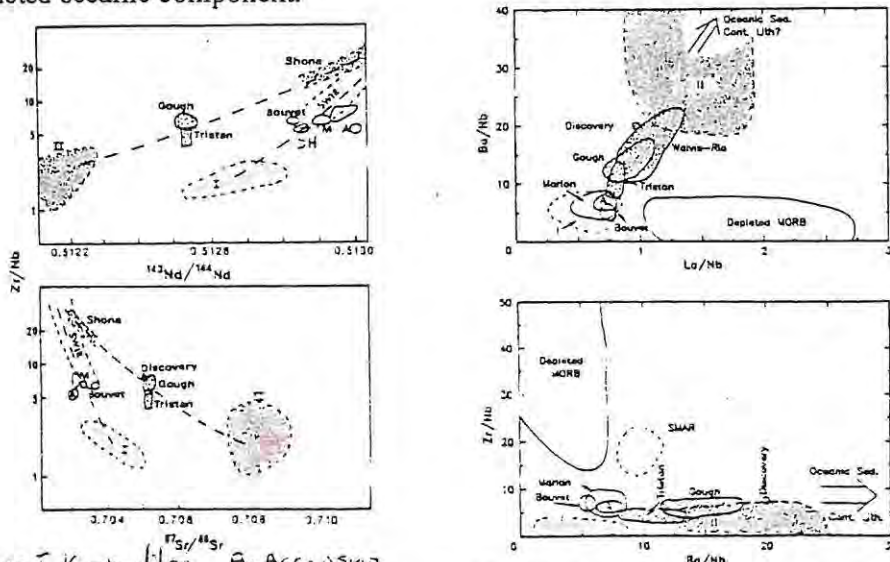
More recently, Friese (1998) identified major, possibly trans-lithospheric Archaean terrane boundaries (suture zones) within the Kaapvaal Craton, which would have some control on the kimberlite emplacement. Neotectonic analysis of Southern Africa reveals two major compressive stress orientation: NNE trends which would correspond to the orientation of the East African Rift system, and NW-WNW trends of pre-Cretaceous age, called Wegener Stress Anomaly (Friese, 1998). The stress field is dominated later, during the Late Cretaceous, by the NE-directed ridge push. This NE trend, characterized by major fracture zones, would also correspond to the on-shelf continuation of oceanic transform faults as previously proposed by Marsh (1973).

Friese (1998) shows thus that the majority of the kimberlite clusters within the Kaapvaal Craton occur at the intersection of the NE and the NW trends (figure 49, next page).

## Geochemical and isotopic signatures

Isotopic studies of South African kimberlites reveal (figures 50) that Group I kimberlites are derived from undifferentiated to slightly depleted sources relative to bulk Earth (Sr and Nd systematics), with relatively high U/Pb ratio. Group II kimberlites are derived from enriched sources with high Rb/Sr and Nd/Sm, but low U/P ratios. The enrichment event is likely to have occurred more than 1000 Ma ago (Smith, 1983).

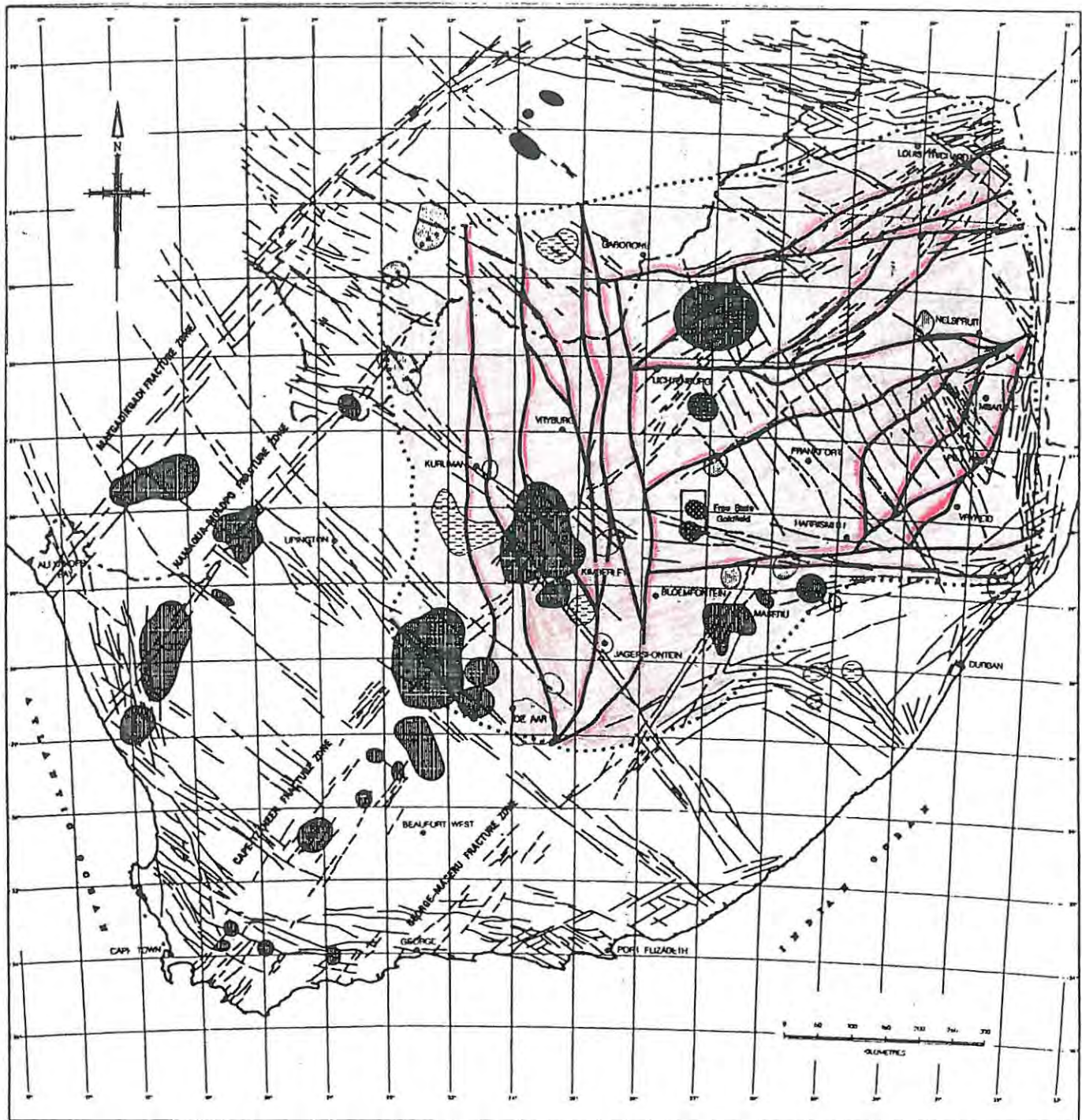
It has been deduced that Group I kimberlites have an asthenospheric origin, while Group II are derived from the subcontinental lithosphere, with possibly involvement of a subducted oceanic component.



I Group I Kimberlites A: Ascension  
 II Group II Kimberlites M: Marion  
 SH: St Helena

SWIR: Southwest Indian Ridge  
 SMAR: Southern Mid-Atlantic Ridge

Figures 50: Isotopic ratios of South Atlantic basalts compared to Group I and Group II kimberlites (after Le Roex, 1986).



**LEGEND**

Kimberlite pipe cluster at intersection of

- Trans-Indian and Cape-Tzaneen fracture systems
- Trans-Indian or Cape-Tzaneen fracture systems and Archaean terrane boundaries
- Trans-Indian or Cape-Tzaneen fracture systems and crustal fault systems
- Trans-Indian fracture system and shear zones with Central Zone Terrane of Limpopo Province
- Kimberlite pipe clusters within Trans-Indian fracture system (at no obvious intersection with other major fracture systems)

- Kaapvaal Craton with major terrane boundaries
- Ergo of Archaean (at ~2.0 Ga) Kaapvaal Craton
- Archaean crustal suture zone / terrane boundary
- International border

Figure 49: Position of Cretaceous kimberlite clusters in relation to lineament patterns across South Africa (after Friese, 1998).

## Models of kimberlite emplacement

### -The hotspot theory-

Such isotopic signatures are similar to those generated by hotspots, with two 'end-member' types: one from the upwelling of primordial material and the second from possibly a boundary layer of recycled material (Ringwood et al., 1982). The isotopic signatures of southern African kimberlites have thus been compared with those of recognized mantle plumes of the South Atlantic Ocean. Le Roex (1986) determined that Cretaceous Group I kimberlites have geochemical similarities with the Bouvet hotspot and Group II kimberlites with the Shona hotspot. It has also been suggested that the Group II kimberlite isotopic signatures are similar to the Tristan hotspot (Hatton, 1998), or to the St Helena hotspot (personal communication). However, a study of different ratios and isotopic signatures of both groups of kimberlites compared to South Atlantic hotspots (Cf. figure 50) does not show such similarities.

Lack of precision in the data and possible contaminations for the kimberlite samples, are probably source of errors.

In the case of southern African kimberlites, the hotspot theory is however interesting by the relative positions of hotspot tracks in the African continent and the NE trend of Cretaceous Group I and Group II kimberlites.

The decrease in age of Group II kimberlites along a northeast-southwest zone from Dokolwayo (200 Ma) to Eendekuil (110 Ma) would correlate quite nicely with the drift of the African plate over the Shona hotspot. M. Skinner (personal communication) shows in parallel that the precise age and distance difference between two end-member of Group I cretaceous kimberlites (93 Ma and 65 Ma, separated by 1200 km) corresponds exactly to the African plate movement of 4cm/yr, deduced from paleomagnetic data.

In fact, much of the uncertainties remain in the validity of the hotspot tracks and relative plate motions data (Baksi, 1999). Predicted hotspot palaeo-tracks from Hartnady and LeRoex (1983) or O'Connor and Duncan (1990) do not really match the kimberlite repartition (Cf. figure 48). The fact that a significant number of kimberlite ages do not fit the apparent hotspot tracks and the uncertainties as to the location of plumes does not support therefore a simple plume model for the kimberlite magmatism in South Africa (Friese, 1998).

### -The subduction theory-

Stratigraphic records in South Africa indicate that a large-scale subsidence of the paleo-Pacific plate beneath the Gondwana take place during the Late Carboniferous to the Early Triassic, prior to its break-up. This subduction event is responsible for the formation of the Cape fold belt and the development of the Karroo Basin. Pysklywec and Mitrovica (1999) described the process of subduction leading to subsidence and the cessation of subduction leading to uplift and subsequent erosion in the case of the Karroo Basin. If active subduction stopped in the Early Triassic, the subducted slab may have persisted at least until the 130 Ma break-up of the Gondwana.

Believing that a deeply subducted plate would provide the hydrous and carbonaceous material necessary to the formation of the source rock of diamond-bearing kimberlites, Sharp (1974) suggests a direct link between subduction and Cretaceous kimberlite magmatism despite the age timing difference.

Helmstaedt and Gurney (1984) reviewed this hypothesis, suggesting that shallow subduction under Gondwanaland was probably active much longer far beneath the continent, and provided the widespread upper mantle metasomatism under Southern Africa.

If the size of the subducted plate could account for the large distribution of kimberlites over southern Africa, it is however controversial to pretend that kimberlite distribution lies parallel to the Gondwanide belt, corresponding to the subduction front, as proposed by Sharp (1974) and Helmstaedt and Gurney (1984). In fact, the kimberlite distribution follows a northeast trending, and only some kimberlites of the 'Lesotho trend' would have the appropriate direction.

McCandless (1999) supposed that the south-westward younging trend of kimberlites corresponds to the heating up migration of the foundered oceanic lithosphere from its deepest end consecutive to the opening of the Atlantic Ocean (Cf. figure 15). However it is unlikely that the subduction front was off the west coast of Gondwana, but more likely off the south coast of Gondwana. In that case the kimberlite age repartition in southern Africa cannot match a hypothetical southward younging trend.

If subduction is thus unlikely to have a direct control on kimberlite magmatism, the ensuing volatile-rich metasomites produced by the shallow-subduction would be however a good candidate to Group II kimberlite magmatism (Smith, 1983) after partial melting, triggered by low heat flux (Dawson, 1989; Egglar, 1989).

It is thus proposed that the subduction of the paleo-Pacific plate beneath the Gondwana is responsible for the metasomatic enrichment of the southern African lithosphere, and the accumulation of subducted material and its contribution to the garnetite layer near the base of the lithosphere (Ringwood et al., 1992). But another subsequent heating mechanism is needed to induce partial melting and further kimberlite magmatism.

#### **- Other possibilities-**

Skinner et al. (1992) have reviewed the different hypothesis pertaining to the distribution of kimberlites in southern Africa.

**Rifting** seems unlikely to contribute to kimberlite magmatism as few rifting events occur in southern Africa (absence of rock-types). Previous rifting lineaments are also unrelated spatially with kimberlite distribution.

**Deep-seated fracture zones** (pre-existing and newly formed intra-cratonic weaknesses) are considered to be favourable zones of kimberlite emplacement as previously noticed (Friese, 1998b). It is probable that kimberlites may have followed these structural discontinuities on their ascent to the surface. However, Friese (1998) argues for a primary control of these faults on kimberlite magmatism by stress release and decompressional melting during extensional reactivation. In that case it is difficult to interpret the age progression of kimberlites along a fault. Bailey (1993) proposed that the apparent age progression could also reflect progressive structural readjustments into the craton, following continental break-up.

## - Synthesis-

The different geochemical and isotopic signatures of Group I and Group II kimberlites suggest rapid spatial or temporal composition gradients in the upper mantle. If we look precisely at the timing of Mesozoic kimberlites (Cf. table 1.1, Dawson, 1989), it is striking to note that Group II kimberlite magmatism is restricted to 115-200 Ma with a peak at 120-118 Ma whereas Group I kimberlite magmatism is restricted to 80-95 Ma with a peak at 86 Ma, with only two exceptions for Mayeng and Frank Smith yielding age of 116 Ma.

This age repartition suggests a major change in kimberlite magmatism around 100 Ma. Analysis of garnets composition by Brown et al. (1998) reveals dramatic modification of the lithosphere underlying the Kaapvaal Craton by 90Ma (figure 51). Kimberlites erupted prior to 90 Ma, essentially belonging to Group II, sampled a harzburgite-rich lithosphere ca 210-220 km thick, with a geotherm near 34 mW.m<sup>-2</sup>. Kimberlites erupted after 90 Ma, belonging exclusively to Group I, sampled a strongly modified and thinner lithosphere affected by melt-related metasomatism. This thermo-chemical change of the lithosphere at 90 Ma would also correspond to the major regional uplift of the Kaapvaal Craton.

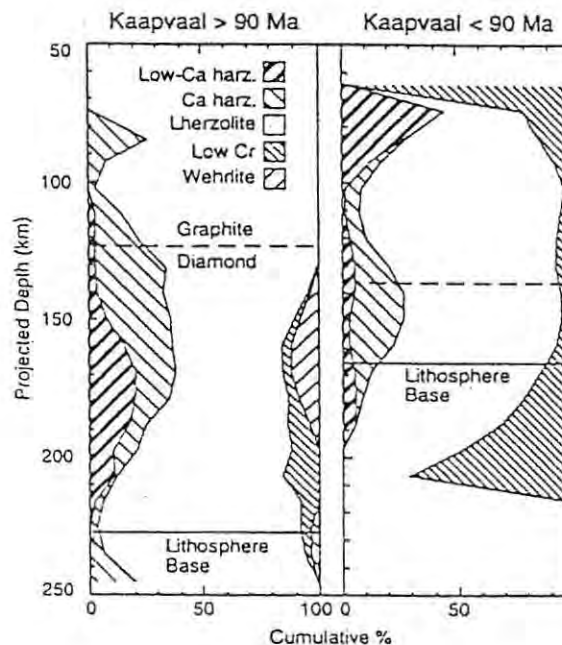


Figure 51: Lithospheric sections beneath the Kaapvaal craton (before and after 90Ma), showing the lithosphere thinning at ca 90 Ma (After Brown, et al., 1998).

From the precedent results, it could be proposed that the 86 Ma peak of Group I kimberlite magmatism is related to a major change in the lithospheric mantle of the Kaapvaal Craton around 90 Ma, due possibly to a plume activity. This timing is also coherent with the reconstructed hotspot tracks of different authors, which despite their disparities favour all a hotspot activity around 100 Ma, under southern Africa (Bouvet hotspot, Cf. Duncan, 1981). The plume may have impinged the base of the lithosphere and triggered kimberlite magmatism near the transition zone. The further ascent of kimberlites may have been controlled essentially by prominent deep-seated fracture zones, which would explain the roughly linear repartitions of Group I kimberlite clusters in the Kaapvaal Craton and their disparity with the hotspot tracks.

Concerning the formation of Group II kimberlites, much debate is also remaining. They are often linked to the break-up of Gondwanaland and the opening of the South Atlantic Ocean by 130 Ma. It has been proposed that rifting was initiated at about 200 Ma, followed by the intrusion of flood-basalts along major fracture zones between 180 and 130 Ma (Karoo volcanics, 182 Ma; Etendeka, 120-130 Ma), as a consequence of plume activity (Haggerty, 1999).

It has been noticed previously (Cf. section 3.3.2), that rifting and flood-basalt eruptions possibly occur away from the vertical ascent of the plume, in 'thinspot' areas (Thompson and Gibson, 1991) whereas kimberlite magmatism could possibly be triggered at the vertical of the plume (Gibson et al., 1999). Hatton (1998) inferred that the position of the Tristan Plume at 130 Ma would be situated in the middle of the Kaapvaal craton and not beneath the Etendeka flood-basalt, as it was proposed by O'Connor and Duncan (1990). This position of the plume would fit with the 120 Ma peak of Group II kimberlite magmatism in the middle part of the craton. It is also noticed that the supposed initiation of the plume started around 200 Ma, which would correspond to the first Group II kimberlite magmatism in the northeast of the craton (Dokolwayo kimberlite, 200Ma).

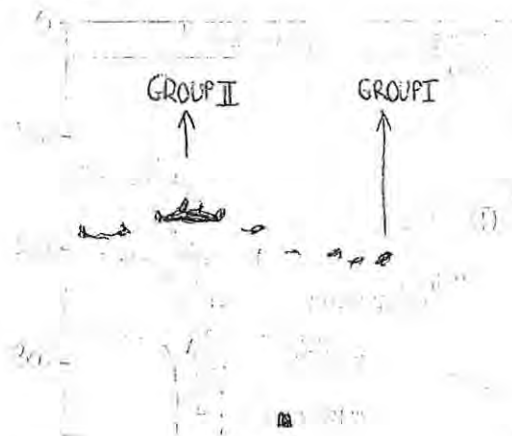
This hypothesis does not exclude the contribution of subducted material to the formation of group II kimberlite magma near the transition zone (Ringwood et al., 1992), but a direct link between the Permian-Triassic active subduction and the Jurassic-Cretaceous kimberlite magmatism is unlikely. The Group I kimberlite however does not show a similar geochemical signature involving subducted material. It is possible that the shallower plume event, accounting for the Group I kimberlite, raised the asthenosphere/lithosphere boundary (Cf. figure 51) and finished to destroy the previous foundered oceanic lithosphere by excessive heating.

At this stage, a single plume model has been proposed. Linking both Group I and Group II kimberlites to hotspot activity would avoid to derive spatially juxtaposed kimberlites of slightly different ages from two tectonically different source regions (Gurney, 1989). However, it would remain to explain the different compositions between the two kimberlite groups and why, for example, only Group I kimberlites sample the full megacryst suite and the hot-deformed peridotites (Gurney, 1990).

Alternatively, a same trigger mechanism, such as plume activity, could possibly allow the formation of two distinct sources of magma of different compositions, as proposed by Wyllie (1988) (figure 52). Migration of fluid-rich melts derived from a plume, at the asthenosphere/lithosphere boundary to form lateral magma chambers has been also proposed by Davies et al. (2001) for the formation of the Gibeon Kimberlites, Namibia (Cf. figure 14).

In this model, the emplacement age difference between Group I and Group II kimberlites in the craton could be explained by the time gap between magmatism above the plume and magmatism induced as the plume diverged.

Figure 52: Plume model for kimberlite genesis (modified after Wyllie, 1988).



However, the fact that the Kaapvaal Craton lithosphere underwent a strong modification around 90-100 Ma (Cf. in Brown et al, 1998, figure 50) would rather support a distinct event for the origin of Group I kimberlites between 80 and 95 Ma.

### Diamondiferous Mantle-Root

The diamondiferous-root of southern Africa has been well documented by Gurney (1990). We will only review here the main ideas.

South African kimberlites are situated for most of them in areas underlain by Archaean Cratons. Occurrences of kimberlites in the "mobile belt" of Limpopo (e.g. Venetia) do not contradict this rule since the Zimbabwe and the Kaapvaal Cratons appear as a single Archaean structure with an intercraton destructive zone established before 2.5 Ga with a common lithospheric mantle (Sobolev et al., 1992). The diamondiferous mantle-root has thus survived under the combined Kaapvaal and Zimbabwe cratons, where it was further sampled by kimberlites (figure 53).

The diamond content of each kimberlite could be estimated by the analysis of its G10 garnets and high-Cr chromites content, reflecting the quality of the diamondiferous mantle root (Helmstaedt and Gurney, 1995). It appears (table 7) that the more diamondiferous kimberlites are situated in the middle of the craton, where the mantle-root signature is stronger, whereas off-craton kimberlites are barren with a weak mantle-root signature.

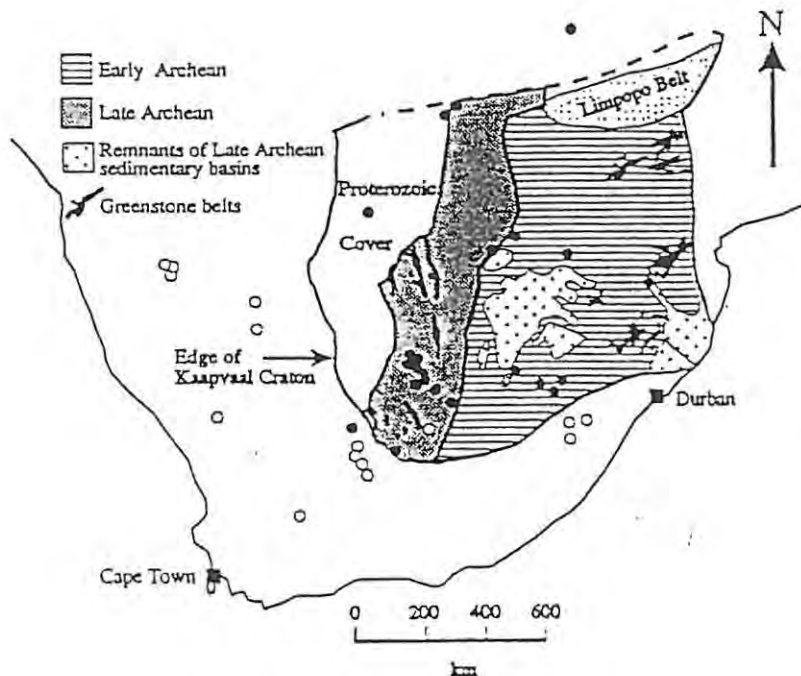


Figure 53: Outline of the Kaapvaal Craton showing distribution of diamondiferous (filled dots) versus non-diamondiferous (open dots) kimberlite clusters (after Helmstaedt and Gurney, 1995).

Strength of Mantle Root Signature				
strong *	medium *	weak *	barely visible **	absent ***
GO25	Orapa	Jwaneng Area but not Jwaneng	Khukong Region	Gibeon
Jwaneng	Lethakane		Kang Region	Grundoon
Dokolwavo	River Ranch	Schuller	M-1	Hanaus
Venetia	Premier	Franspoort	Wessels Sills	Louwrencia
Sekameng	Zwartuggens	Montrose	Palmietfontein	Mukarob
Finsch	Dullstrom	Kao	Markt	S. Namibia Reg.
Bellsbank	Zero	Pipe 200	Paardeberg	Noenieput
Bobbejaan	Star	Goedgevonden	Lovedale	Louwrencia
Sover	Driekoppies	Kaal Vallei	Kimberley West	Rietfontein
Newlands	Makganyane	Monastery	Andriesfontein	Pofadder Reg.
Kimberley Area	Loxton	Leicester		Bushmanland
Roberts Victor	Frank Smith	Borrels Kop		Uintiesberg
New Elands	Saltpetre Pan	Victoria		Meltonwold
Biesiesdam		Washington		Lekkerfontein
		Balmoral		Hebron

\* Kimberlites are on-craton, all but Zero are diamondiferous; \*\* most kimberlites are near craton margin, some are weakly diamondiferous; \*\*\* all kimberlites are off-craton and non-diamondiferous. G-10 and chromite data from unpublished concentrate analyses by J.J. Gurney.

Table 7: Mantle root signature of selected southern African kimberlites based on G10 garnets and high-Cr chromites in concentrates (after Helmstaedt, 1993).

Studies of inclusion-bearing diamonds reveal the presence of three generations of diamonds (Richardson et al., 1993), the more common being peridotitic diamonds and eclogitic diamonds. For the age repartition of diamond inclusions for southern African kimberlites in comparison to kimberlite age emplacement, we refer to figure 5.

Peridotitic diamonds are believed to form by 3.3 Ga from a cool reduced harzburgitic keel formed itself by 3.5 Ga (Gurney, 1990), while eclogitic diamonds could possibly reflect further episodic mantle events during the Proterozoic. It has been pointed out that eclogite formation involves an oceanic crustal source, which was subducted into the asthenosphere, probably remobilised by melting and underplated onto the base of the lithosphere. The study of Archaean tectonics from Helmstaedt and Schulze (1986) indicates the existence of low-angle subduction processes during the Archaean. It has been proposed that a Limpopo ocean was subducted beneath the Kaapvaal Craton prior to 2700 Ma, during the collision between the two cratons (figure 54). Lateral underplating of the continent by oceanic lithosphere results in a tectonic imbrication showed in figure 53. This material would thus have been the source rock for eclogite xenoliths dated at 2400-2700 Ma (Cf. figure 5). It is remarkable that no eclogite xenolith or eclogitic diamond of age prior to 2700 Ma has ever been recovered in South Africa.

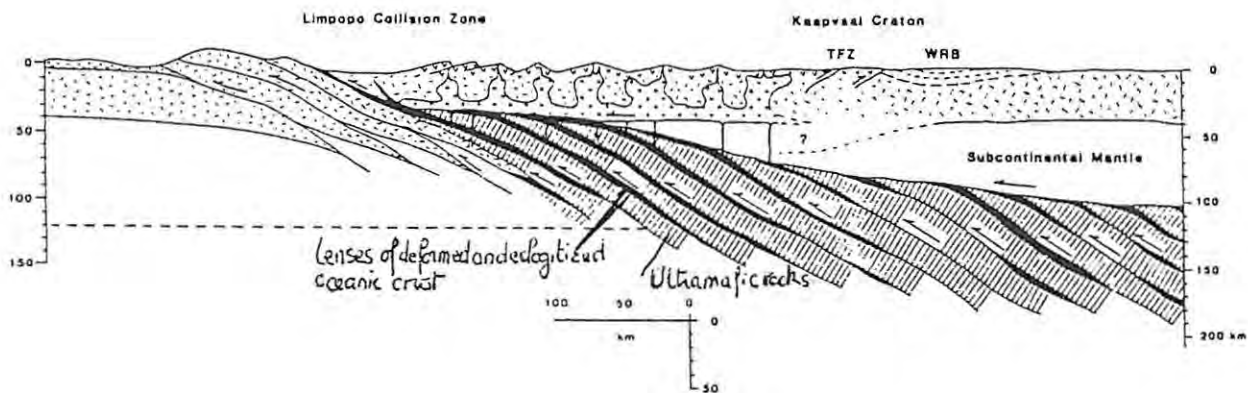


Figure 54: Plate tectonic model of collision between Zimbabwe and Kaapvaal cratons. This model shows the imbrication of the subducted slab (after Helmstaedt and Schulze, 1986).

In the Kalahari Craton, about 25% of the diamonds recovered are eclogitic. Radiogenic isotopic studies indicate old, but different ages for eclogitic inclusions in diamonds from Orapa (990 Ma), Premier (1150 Ma), and Finsch (1580 Ma). This diversity of eclogitic diamond ages in southern Africa is however still lacking to be correlated with specific events such as subduction, in the evolution of the Kalahari Craton (Gurney, 1990). A direct relation between subduction events during the Archaean and sampling of E-type diamonds only from the mid-Proterozoic is thus difficult to establish.

Studies of inclusion suites in diamonds on the Kalahari Craton reveal that both peridotitic and eclogitic diamonds are present in every single locality. The respective population of P-type and E-type diamonds vary considerably from one locality to another within adjacent kimberlite clusters, and even within adjacent pipes (Gurney and Harris, 1992).

Exceptional lateral and vertical variations in age and composition of diamond source rocks in the lithosphere within the craton are thus expected to account for the diversity of kimberlite sampling.

This result supposes a complex lithospheric keel, formed by stacking of probably subducted/obducted oceanic plates or island arcs (Carlson et al., 1998). It is thus believed that diamondiferous eclogite periodically underplated the pre-existing peridotitic keel and accumulated at the base of the lithosphere during the Proterozoic (Gurney, 1990).

The diversity of kimberlite sampling could be resumed in the following figure 55:

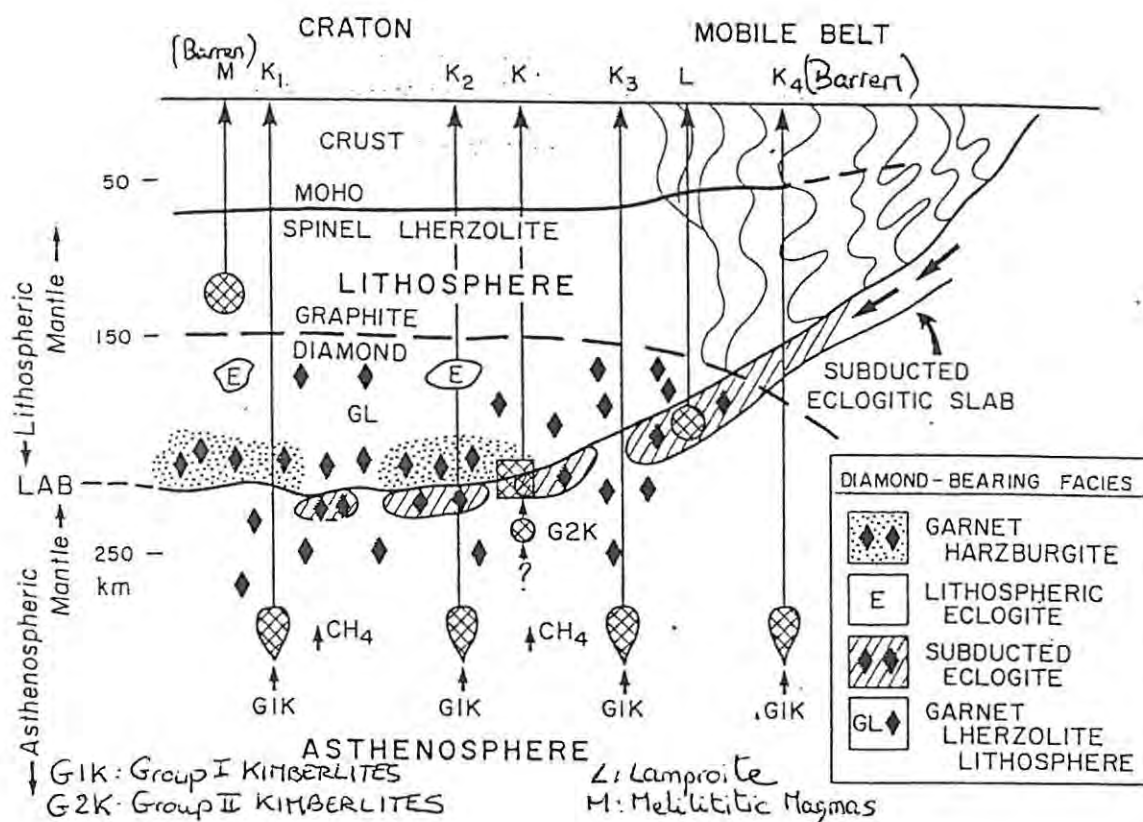


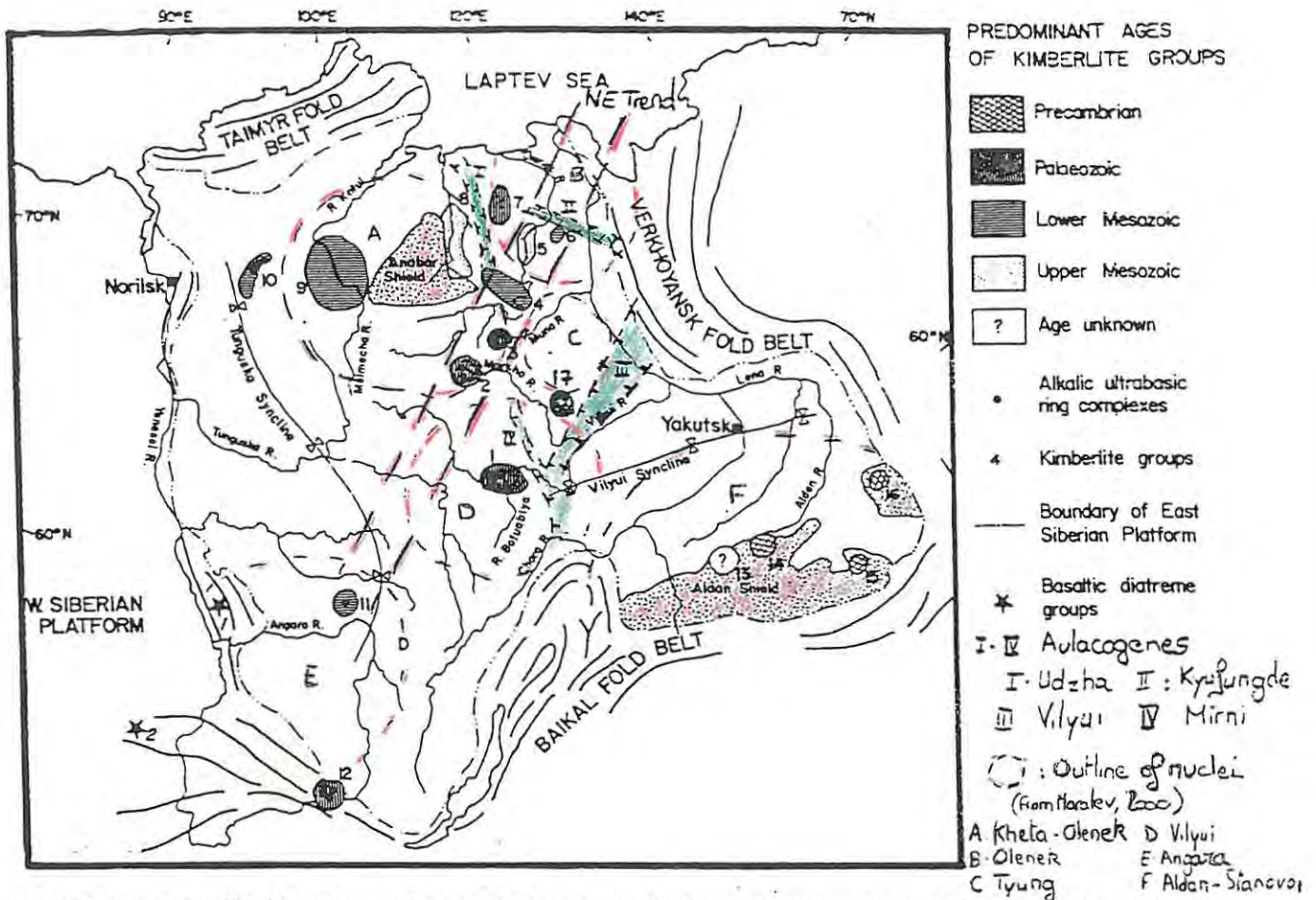
Figure 55: Hypothetical cross-section of an Archaean craton and adjacent mobile belt, showing the influence of a subducted eclogitic slab at the base of the lithosphere upon the different sampling by kimberlites and lamproites en route to the surface (after Mitchell, 1991).

The exceptional sampling of diamonds over a time span ranging from the mid-Proterozoic to the Cretaceous, suggested a particular good preservation of the southern Africa mantle-root. Preservation could have been favoured by the relatively small size of the craton (Cf. chapter 3.8 this dissertation). It is also suggested that late to post-Archaean magmatic events on the craton were "mantle-root friendly" (Helmstaedt and Gurney, 1991).

This would not match with a hypothetical hotspot origin for kimberlites, as plumes are considered to destroy mantle-roots. However plumes may have occurred on the craton margins. Alternatively, it is possible that sufficiently deep plumes would not affect the diamond content of the sub-continental lithosphere.

## 4.7. Yakuta Province

The Siberian Platform consists of crystalline basement rocks overlain by thick, flat-lying sedimentary (Paleozoic and Mesozoic formations) and volcanic sequences (Permo-Triassic Trapp formations). Two major Archaean cratonic regions are exposed, surrounded by younger mobile belts. About 90 % of the Siberian kimberlites are located in the northern cratonic part of the Siberian platform (figure 56).



Generalized map of the Siberian platform showing the distribution of kimberlites and alkalic rocks modified after Dawson (1970). Kimberlite groups: 1—Malo-Berubinsk, 2—Daldya Alakit, 3—Mura, 4—Middle-Olenek, 5—Lower-Olenek, 6—Pri-Lena, 7—Udschinsk, 8—Kuonamsk (Anabar), 9—Meimecha-Kotui, 10—Kamensk, 11—Chadobets, 12—Pri-Sayan (Oka), 13—Chomiolinsk, 14—Tobusk (Aldan), 15—Arbarastakh, 16—Ingili, 17—Naryn.

**Figure 56:** Map of the Siberian platform showing the distribution of kimberlites (after Dawson, 1970; Erlich, 1985), the rifting structures (after Kaminsky et al., 1995) and the outlines of the ancient sialic nuclei (after Moralev and Glukhovskiy, 2000).

On the basis of mosaic geophysical properties, the northern cratonic region could be divided into different cratonic blocks, characterized by domal or ring structures. It has been recognized recently that these structures are complex granite-gneiss domes, believed to be ancient sialic nuclei or terranes originated in the Early Archaean (Moralev and Glukhovskiy, 2000). These ancient sialic nuclei have a rather thick consolidated crust, whereas internuclear belts have a relatively thin crust.

## Geotectonic controls on kimberlites

The kimberlite magmatism in the Siberian Craton occurred in the Precambrian in the Aldan Shield, and repeatedly during the Palaeozoic and Mesozoic in the centre of the northern Siberian platform.

Amongst the theories presented for the distribution of the Palaeozoic and Mesozoic kimberlite fields in Yakutia, Helmstaedt and Carmichael (1978) presented a possible subduction along the margins of the craton. Kushev et al. (1992) believed that kimberlite emplacement is controlled by deep-seated basement structures reactivated in response to the development of the Verkhoyansk Mobile belt, which is believed to be a south eastern extension of the Polar Mid-Ocean Ridge. Milshtein et al. (1998) favoured a rifting-related (Middle Paleozoic Sredinno-Sibirskaya Rift System) origin for the diamondiferous kimberlites (figure 57).

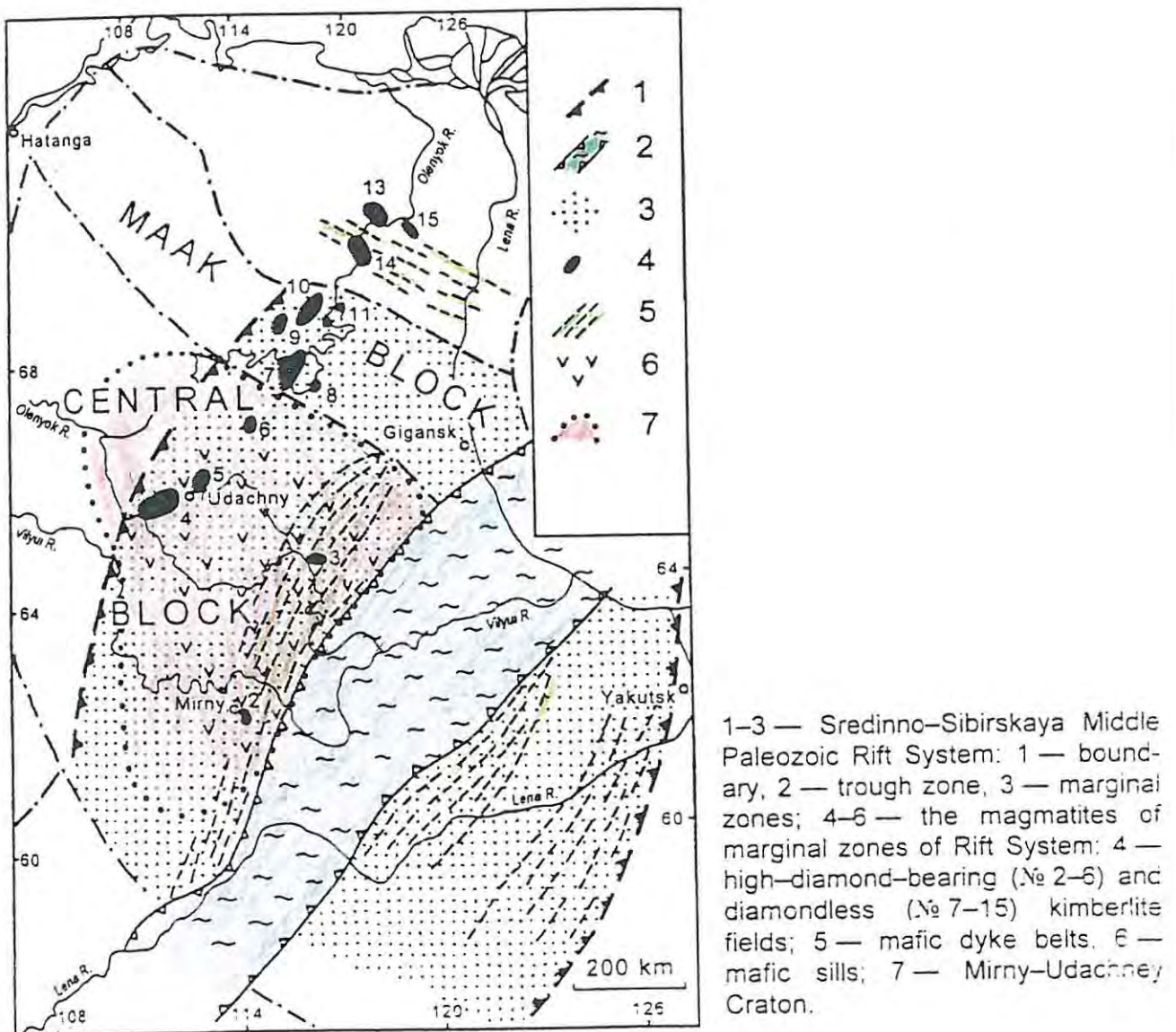


Figure 57: Tectonic relation between the middle Paleozoic kimberlites and the Sredinno-Sibirskaya Rift System (after Milshtein et al., 1998).

These theories oppose generally a hotspot model, presented below.

The general repartition of the kimberlites in the Siberian craton shows a linear distribution of kimberlite fields in a NE direction from the Upper Vilyui River to the Lower Lena River. This zone includes kimberlites from Lower Palaeozoic to Cretaceous, and seems to transect all the geological lineaments (figure 58). This trend is believed to be a zone of deep-seated feature, called *zone of anomalous mantle*, because it corresponds to particular geophysical lineaments (positive anomaly of the regional gravity field) (Cf. figure 6 from Kaminsky et al., 1995). These zones would correspond to sub-Moho accumulation of dense and highly magnetic magmatic rocks, which partly penetrated into the base of the Earth's crust.

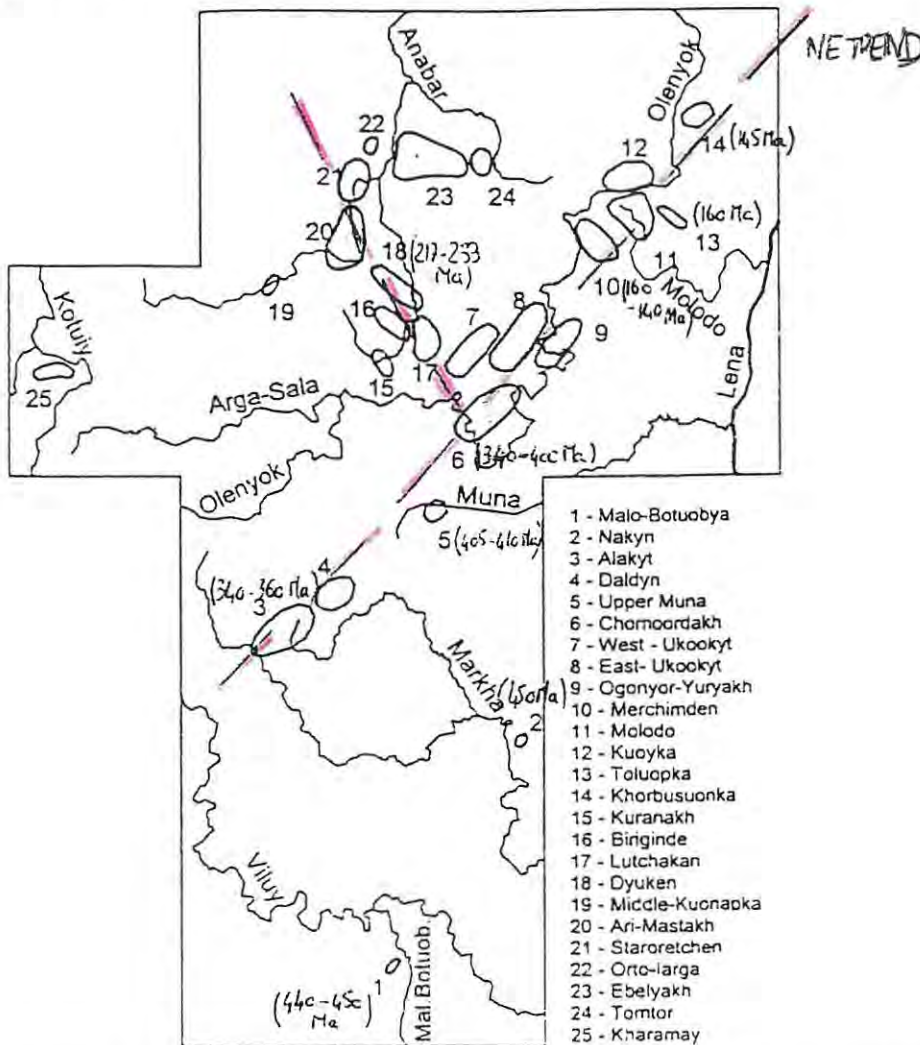


Figure 58: Distribution of Yakutian kimberlites (after Shamshina and Zaitzev, 1998). Ages (U-Pb dating on zircons) from Kushev et al. (1992).

Age repartition (U-Pb dating on zircons, Kushev et al., 1992) shows a roughly linear trend from older kimberlite fields (420 Ma) to the southwest to younger kimberlite fields (340 Ma) to the northeast. This feature, together with palinspastic reconstitutions of the Siberian Plate movement, suggests that kimberlite magmatism is linked to a passage of a hot spot, which could be at present located under the Azore islands (Natapov and Griffin, 1998). A Central-Asia province of hotspots is recognized (Zonenshain et al., 1991), and the hypothesis of mantle plume activity under the Siberian Plate is highly probable.

The Palaeozoic-Mesozoic times are characterized by the development of the platform cover, by the formation of domal uplifts and intense magmatism (Trapp volcanics). Kimberlite fields are situated within the nuclei, whereas flood basalts are predominantly localised in the internuclear zones (Moralev and Glukhovskiy, 2000). If we consider that these internuclear zones constitute "thin spots", this particular disposition agrees with the hotspot theory of Thompson and Gibson (1991, cf. figure 13). Flood basalts triggered by the plume activity, erupted where the lithosphere is thinner in an extensional geodynamic environment, whereas kimberlites intruded at the vertical of the hotspot. The third stage of the extension could possibly be characterized by minor rifting activity as it is proposed by Natapov and Griffin (1998). The Vilyui rift, parallel to the NE kimberlite trend (figure 57), developed following the plume activity, in the SE part of a low-angle detachment fault (Cf. figure 19). Kimberlite magmatism on one side of the rift, used possibly this fault that we can identify as being a tectonic suture of NE stretch described by Zuev et al. (1998).

This type of fault can be considered to be previous structural zone of weakness in the basement located at the periphery of the sialic nuclei, which were reactivated in the extensional environment, following the rotation events in the drift history of the Siberian Plate (Moralev and Glukhovskiy, 2000). Kimberlite fields are observed to be located generally at the intersections of these radial and concentric faults zones. These deep-seated faults defined thus the structural position of both rift structures and kimberlite fields (see also Erlich, 1985).

To resume, mantle plume activity produced flood basalts and kimberlite magmatism in an extensional geodynamic environment, with restricted development of linear rift structures. Reactivated deep-seated basement faults, located at the margin of the Archaean terrains, were then used by kimberlite magma as a passive pathway to the surface. Kimberlite fields of the same age form thus elongated trends accompanied by extension structures such as grabens, dykes swarms and faults zones.

This scenario, applied to Palaeozoic times, is also possibly applicable to the late Proterozoic times, marked by intense rifting along the same radial and concentric fault zones of nuclei and by ultramafic-alkaline and kimberlite magmatism (Moralev and Glukhovskiy, 2000). Some Precambrian kimberlites have been conserved in the Aldan Shield in the southeast of the Yakutia province (Cf. figure 56).

In terms of diamonds, only the Middle Palaeozoic and Early Mesozoic kimberlite events are diamondiferous. Kushev et al. (1992) recognize two main petrochemical types of kimberlites represented in the Yakutian province. Kimberlites 1 are more potassic, with dominantly harzburgite xenoliths and are enriched in diamonds, whereas kimberlites 2 are more subalkaline with eclogitic xenoliths and are depleted in diamonds. Kimberlites 1 are located within Archaean terrains and are associated with local gravity anomalies and magnetic lows. These anomalies correspond to the seismically recognized lenses of high-density rock masses on the crust-mantle boundary (Moralev and Glukhovskiy, 2000). These lenses do not exist under diamond-barren kimberlite fields. Age determination of diamonds and xenoliths shows an age interval between 2 and 2.9 Ga. These rock masses have been interpreted as early Precambrian high-pressure diamond-bearing eclogitic and peridotitic residues.

The formation of such diamond-bearing rocks could be attributed to different processes reviewed in the first part of this dissertation. However, it seems that subduction-related processes during the Archaean evolution stage is favoured (Moralev and Glukhovskiy, 2000). This theory is supported by the isotopic studies of E-type diamonds from Siberia (Jacob et al., 1994).

The fact that Mesozoic kimberlite fields are barren in the NE part of the Siberian platform could possibly be explained by the replacement of the Archaean or Proterozoic lithosphere by younger less depleted mantle during the upper Proterozoic rifting that led to the development of the Udzha aulacogens (Natapov and Griffin, 1998). This thermal erosion would have thus led to the destruction of the diamondiferous mantle-root. These barren kimberlites, called kimberlites 2 (Kushev et al., 1992), form linear zones that were believed to correspond to longitudinal grabens in the sedimentary cover and to downwarps of the crystalline basement (change in the Moho depth). In fact, the geophysical anomalies do not reflect an abrupt change in the Moho depth, but a sub-Moho accumulation of the previously identified dense rocks masses (see also Kaminsky et al., 1995). Such kimberlites, e.g. those situated on the eastern border of the Anabar shield, are situated at the proximity to aulacogens and are believed to be triggered by rifting by Kushev et al. (1992). However, it seems unlikely that the major Proterozoic rifting stages influence kimberlite magmatism in the Mesozoic. The formation of these barren kimberlite fields are more in acquaintance with the previous theory and emplacement of kimberlites along reactivated previous zones of weakness (e.g. Udja fault zone, see also Erlich, 1985).

## 4.8. Synthesis

Acknowledging the fact that the subject presented here, e.g. Geotectonic Controls on Primary Diamond Deposits, is still very new, badly published and subject to a number of controversies, it would be preposterous to provide here with a single exploration model. The case studies previously described align the fact that each diamondiferous province, even each kimberlite field sometimes carry their own characteristics and exploration criteria.

However, despite their differences, the kimberlite provinces and super-provinces described previously do show some similar trends. In order to establish a prospective model for diamondiferous primary deposits exploration in terms of area selection, the following geotectonic criteria could be distinguished:

- Diamondiferous domains: a thick cool reduced lithosphere is generally needed for diamond formation and preservation. The Clifford's Rule, modified by Janse (1984), stating that diamondiferous kimberlites occur on Archons (> 2400 Ma), and diamondiferous lamproites occur preferentially on Protons (> 1600 Ma), seems not to be valid anymore as diamondiferous kimberlites have been found in mobile belts. Mobile belts surrounding Archaean cratons are also favourably sites of lamproite intrusions (Cf. Australia Case Study). It is noticed that diamondiferous Archaean mantle-roots are not always apparent on surface and could be detected efficiently by seismic profiles or by analysis of G10 garnets (Cf. Wyoming Block, fig. 28).

It appears that small size cratons, with a single layer lithosphere (simple lithospheric keel) and with a thick cover, are substantially more diamondiferous (e.g. Kaapvaal Craton). Kimberlites occurring at the centre of cratons are often the more diamondiferous, although lamproites are generally of lower grade.

- Kimberlites and Lamproites Provinces: kimberlites and lamproites deposits do show some apparent trends at a craton-size scale. These trends often cross tectonic boundaries and could be interpreted as hotspot tracks. Prospecting kimberlite provinces along these major trends is thus suggested.

As a result of plume activity, rifting structures or aulacogens, and flood-basalts are also expected to occur in the same Super-province than kimberlite intrusions.

- Kimberlites and Lamproites fields: kimberlites and lamproites provinces distributed along a major trend, can show particular smaller-scale trends, corresponding to major regional structures. These structures are often reactivated deep-seated basement faults or newly formed fault zones, in response to a stress in an extensional environment. These structures are parallel to the main rifting structures or perpendicular as continental extension of transform faults. Kimberlite and lamproite fields follow generally these structural trends (Cf. Lac de Gras kimberlite province, Wilkinson et al., 2001; Kaapvaal Craton, Friese, 1998; Argyle, Deakin and White, 1991; Yakuta kimberlite province, Moralev and Glukhovskiy, 2000).

Intersection of the deep-seated faults with arch structures is also characteristic of kimberlite location. The geophysical signature of a diamondiferous field is thus possibly identified by local crust-mantle arch doming, resulted from the plume activity. Such features are identified on surface by zones of dome-shaped uplift or block-shaped uplift.

- Kimberlites and Lamproites clusters: second-order faulting controls generally the emplacement of kimberlite clusters inside a province. Traditional prospecting methods at the intersections of fault systems are suggested. Different shapes of cluster according to the kimberlite nature (Group I or Group II), and distance to the faults are topic still under examination.
- Kimberlites and Lamproites pipes: With the increase notably of geophysical tools depth resolution and with the multiplication of active structural projects around kimberlite pipes in the world, it has been more and more apparent that kimberlites and lamproites intrusions do not always occur as a single pipe. Dyke kimberlites on surface have their corresponding at depths, called fissure kimberlites. Precisely fissure kimberlites consist of group of align pipes connected at depth up to 200m (Cf. Merlin, Australia, Lee et al., 1997). Whether the intrusion follows pre-existing shallow structures or propagates itself in a certain direction is still under debate. The single-intrusion and biggest pipes are often the more diamondiferous. The near-surface geology, controlling the shape of the pipes, would have more effect on the exploitation costs, than on the diamond grades. The level of erosional sections is also important, as the larger volumes are situated in the crater-facies.

These criteria should be considered in relation with the timing of the kimberlite and lamproite intrusions. On a large scale, kimberlite intrusions are closely related in time with major tectonic events or global activation stages, also associated with continental break-up, subduction, rifting, and trap magmatism.

Correlation between fields or provinces along a particular trend is relevant only if the intrusions correspond to the same event (age spanning < 200 Ma and similar geochemical signature). Age of kimberlite and lamproite events is thus on primordial importance in identifying the structures link with the intrusions and also in determining the diamond potential of these deposits.

Areas (what Mitchell, 1989, called "type III kimberlite provinces"), which host several diamondiferous kimberlite fields of completely different ages and petrological characters (e.g. Kaapvaal Craton), have been particularly stable cratonic areas over a considerable time-span, and represent the best diamond producing provinces in the world.

# Conclusion

Through a study of the fundamental processes involved in diamond formation, preservation and transport to the surface, and in the light of different diamondiferous occurrences around the world, some criteria for area selection of primary diamondiferous deposits have thus been suggested.

Amongst them, Archaean cratons, hotspot tracks, and structural lineaments seem to play a major role in the distribution of kimberlites and lamproites in all diamondiferous provinces.

It is reminded that the concepts presented in this dissertation are for the majority still very new and under discussions. It is thus probable that further studies and discoveries will constraint better the models of diamondiferous mantle-roots and kimberlite/lamproite intrusions controls.

The complexity of the mantle-root preservation and the kimberlite/lamproite emplacements highlights the necessity to integrate all geophysical, petrologic, geochemical and structural information for a successful diamond exploration program.

The results of such methods of prognostication and tectonic analysis in diamond exploration have already been demonstrated with success in China, Canada and Brazil, where traditional methods of prospecting are not possible or easy.

In a close future, one could expect that large alluvial diamond producers, such as Brazil, West Africa or Central Africa, where the vegetation or sand cover does not permit easy direct investigations, would be able to identify their primary deposits using such geotectonic analysis.

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