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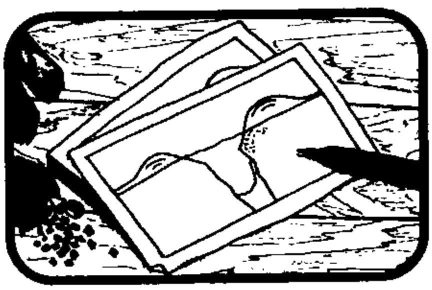

Kimberlites in the Slave Craton, Northwest Territories, Canada

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SUMMARY

A significant new kimberlite province, which hosts more than 150 kimberlite pipes and is centred in the heart of the Archean Slave Province, was discovered in 1991. By early 1998 Canada's first diamond mine is expected to be in production from this new kimberlite province. The principal diamond-bearing pipes occur in the Lac de Gras region, east-central Slave Province. Preliminary radiometric age determinations indicate that these pipes were emplaced in Late Cretaceous and Eocene time. Outside of the Lac de Gras area, Middle Jurassic-, Late Ordovician-, and Cambrian-aged kimberlites have been discovered, some of which also have good economic potential. The study of kimberlites in the Slave Province is at a very early stage and as work continues, a better understanding of their ages, petrology, and diamond potential will be gained. This paper summarizes what is known to date.

RÉSUMÉ

En 1991, une province à kimberlite d'importance et renfermant plus de 150 cheminées à kimberlites a été découverte au coeur de la Province archéenne de l'Esclave. On prévoit que les premières mines de diamants de cette province à kimberlites entreront en production au début de 1998. Les principales cheminées diamantifères sont situées dans la région du Lac de Gras, dans la portion centre-est de la Province de l'Esclave. Des datations radiométriques préliminaires indiquent que ces cheminées ont été mises en place à la fin du Crétacé et à l'Éocène. Mis à part les dépôts de la région du Lac de Gras, des gisements de kimberlites du Jurassique moyen, de l'Ordovicien supérieur et du Cambrien ont été découverts, et certains d'entre-eux présentent un bon potentiel économique. L'étude des gisements de kimberlites de la Province de l'Esclave n'en sont qu'aux premiers stades et nos connaissances quant à leurs âges, leurs pétrologies et leurs potentiels diamantifères augmenteront au fur et à mesure de la progression des travaux. Le présent article présente un résumé des connaissances acquises à ce jour.

INTRODUCTION

The Slave Structural Province of the Northwest Territories, Canada, 400 km x 750 km in size and an integral part of the North American Craton, has remained stable since the end of Archean time. Although it is a classic environment in which to find kimberlites and diamond deposits, none were known until a few years ago. Diligent work by explorationists has resulted in the discovery of a significant new kimberlite province centered in the heart of the Slave Province, the extent of which is, as yet, unknown. Since 1991, more than 150 pipes have been discovered and in early 1998 Canada's first diamond mine is expected to be in production.

Most of the kimberlites in the Slave Province do not crop out at surface; they have been identified using a combination of heavy mineral sampling, geophysical techniques, and drilling. Many of the pipes are characterized by either high- or low-magnetic anomalies and resistivity lows; however, some pipes have very weak or no geophysical signatures and have been discovered solely by tracing indicator mineral trains.

The principal diamond-bearing pipes occur in the Lac de Gras region, in the east-central Slave Province. Crater and massive, hypabyssal facies kimberlites are common, and some diatreme-facies kimberlites are also present. Macrocrysts of olivine (up to 1 cm) and chrome diopside (>2 cm) are ubiquitous, and garnet (to 0.5 cm), chromite, and ilmenite are also common. Preliminary U-Pb and Rb-Sr radiometric age determinations indicate that pipe emplacement occurred in the Late Cretaceous and Eocene at 81-73 Ma and 52 Ma. Paleontological studies on mudstone chips and wood fragments in volcaniclastic breccia and crater facies deposits lend further support for these young ages. Middle Jurassic (172 Ma) and Cambrian (540 Ma) kimberlites have been discovered in the eastern Slave Province, outside of the Lac de Gras area. Late Ordovician (*circa* 450 Ma) kimberlites have been discovered in the southwestern part of the Slave Craton.

The study of kimberlites in the Slave Province is at a very early stage. As exploration continues, it is likely that more

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kimberlites will be found and a better understanding of their ages, petrology, and diamond potential will be gained. Much of the information on the mineralogy, petrology, indicator mineral chemistry, age, and even location of individual kimberlites is still proprietary. This study is an attempt to summarize and interpret what is publicly known to date.

GEOLOGICAL SETTING OF THE SLAVE PROVINCE

The Slave Structural Province of the Northwest Territories, northern Canada, is an Archean segment of the North American Craton that is composed of granites, gneisses, and supracrustal rocks. Sialic basement remnants, well documented in the Slave, include some of the oldest rocks in the world: the Acasta gneisses in the western part of the province, which have been dated at 3.96 Ga (Bowring and Housch, 1995). Metasedimentary and lesser metavolcanic rocks of the Yellowknife Supergroup, deposited mainly between 2.71 Ga and 2.61 Ga, are the most abundant rocks of the supracrustal sequences; some *circa* 2.8 Ga supracrustal rocks are also present locally. Syn- to post-volcanic granitoid plutons comprise approximately 65% of the Slave (Padgham and Fyson, 1992; Fyson and Padgham, 1993). Late Archean carbonatites (2.60-2.59 Ga) are known from two localities (Relf *et al.*, 1995; Stubley and Tyler, 1996; Villeneuve and Relf, in press). *Circa* 2.18 Ga Proterozoic peralkaline granite-syenite (Squalus and Blatchford Lake, Bowring *et al.*, 1984; Stubley, 1996) and alkaline carbonatite-related (Big Spruce Lake, Cavell and Baadsgaard, 1986) complexes have intruded Archean strata in the southwestern part of the Slave Province. At least five swarms of Proterozoic diabase dykes cut the older units in the central Slave Province near Lac de Gras, the most important of which are the northeast-trending Malley dykes (2.23 Ga), the east-trending MacKay dykes (2.21 Ga), the northerly trending (010°) Lac de Gras swarm (2.02 Ga), and the dominant north-northwest-trending (330°) Mackenzie swarm (1.27 Ga) (LeCheminant and van Breemen, 1994; LeCheminant *et al.*, 1996). Other dyke swarms, not yet dated, intrude the southwestern part of the Slave Province, and two younger sets of dykes, associated with the 0.78 Ga Gunbarrel and the 0.72 Ga Franklin magmatic events, penetrate the northern and western margins of the craton (LeCheminant *et al.*, 1996).

On isotopic evidence (Davis and Hegner, 1992; Thorpe *et al.*, 1992) the Slave Province can be subdivided into an eastern and a western domain (Fig. 1). Lead isotopes for galena from volcanogenic massive sulphides, syn-volcanic veins, and breccias in the western part of the Slave Province are characterized by high $^{207}Pb/^{204}Pb$ ratios and those from the eastern Slave, by low $^{207}Pb/^{204}Pb$ ratios. It has been interpreted that the high $^{207}Pb/^{204}Pb$ ratios in the west reflect derivation of a significant component of lead from an ancient upper crustal source and the low $^{207}Pb/^{204}Pb$ elsewhere in the Slave suggest a mantle source and juvenile crust (Thorpe *et al.*, 1992). Neodymium isotopic studies of supracrustal and granitoid rocks in the Slave Province support this interpretation. Granitoids and supracrustal rocks in the central and eastern part of the province have positive ε_{Nd} values consistent with derivation from juvenile sources, whereas those from the western part of the province have negative ε_{Nd} values suggesting contamination from older crust (Davis and Hegner, 1992). The isotopic subdivision of the Slave province is supported by the observation that quartz arenites of *circa* 2.8 Ga occur only in the western domain, and that granitic and gneissic rocks with zircon U-Pb dates older than the Yellowknife Supergroup sequences have also only been identified from the western part of the province.

Further support for a distinct difference between the eastern and western Slave Province comes from preliminary magnetotelluric studies in the Slave, which indicate, among other things, that the lithosphere beneath the western Slave Province is laterally homogeneous, thicker, and more resistive than lithosphere to the east (Jones and Ferguson, 1997; Jones *et al.*, 1997). Kusky (1989) proposed the name "Anton terrain" for the part of the Slave Province underlain by this older continental crust and its associated sediments. In this paper, the area west of the lead isotopic boundary underlain by old continental crust (Fig. 1) will simply be referred to as the western or southwestern Slave, while the juvenile terrain east of the lead isotopic boundary will be referred to as the eastern Slave.

Kimberlites intrude granites, metasedimentary rocks and, in some cases, diabase dykes (Pell, 1995a) in both the eastern and western parts of the Slave Province. The Slave is a classic setting for diamondiferous kimberlites: a stable Archean craton with, as suggested by seismic tomography (Anderson *et al.*, 1992), a cool mantle root, which is necessary for the development of the diamond stability field (Clifford, 1966; Haggerty, 1986; Janse, 1993, 1994).

Subsequent to kimberlite emplacement, the area was covered by Laurentide ice during the Late Wisconsinan glaciation, which climaxed about 20,000 years B.P. Local and regional ice flow patterns show considerable variation throughout the Slave, and in the Lac de Gras area there appear to have been at least four ice movement directions (Ward *et al.*, 1996).

HISTORY OF DIAMOND EXPLORATION IN THE SLAVE PROVINCE

Much has already been written on the history of the diamond discoveries in the Northwest Territories (Ashley *et al.*, 1995; Carlson *et al.*, 1996; Duval *et al.*, 1996; Fipke *et al.* 1995a; Gibbins and Atkinson, 1992; Hurburgh, 1994; Jennings, 1993; Pell, 1994a; 1994b; Pell and Atkinson, 1993). This history is briefly summarized in the following paragraphs.

Workers in the late 1940s and early 1950s noted that some garnet and pyroxene populations in esker and beach deposits at Exeter Lake north of Lac de Gras could not have been derived from the surrounding metasedimentary-granitic terrain (Folinsbee, 1948, 1955). Similarly, geochemical surveys by the Geological Survey of Canada in the early 1970s defined chromium and nickel anomalies around Lac de Gras that could not be attributed to any source (Allan *et al.*, 1973). The significance of these observations was not recognized until much later.

The work which directly led to the discovery of the first kimberlite in the central Slave Province began in the late 1970s when Diapros, a De Beers subsidiary, prospected for diamonds in the Mackenzie Mountains approximately 800 kilometres to the west of Lac de Gras. Other geologists heard of this work and, in 1981, a consortium consisting of Chuck Fipke (C.F. Minerals), Hugo Dummet (with Superior Oil), Chris Jennings (with Falconbridge), and Stu Blusson began exploring in the Mackenzie Mountains–Blackwater River area. Some kimberlitic indicator minerals were found in this area, but it was realized that they must have been transported from the east by glaciers. After this effort was discontinued, independent exploration programs were intermittently carried out by Fipke and Blusson and by Jennings throughout the 1980s,

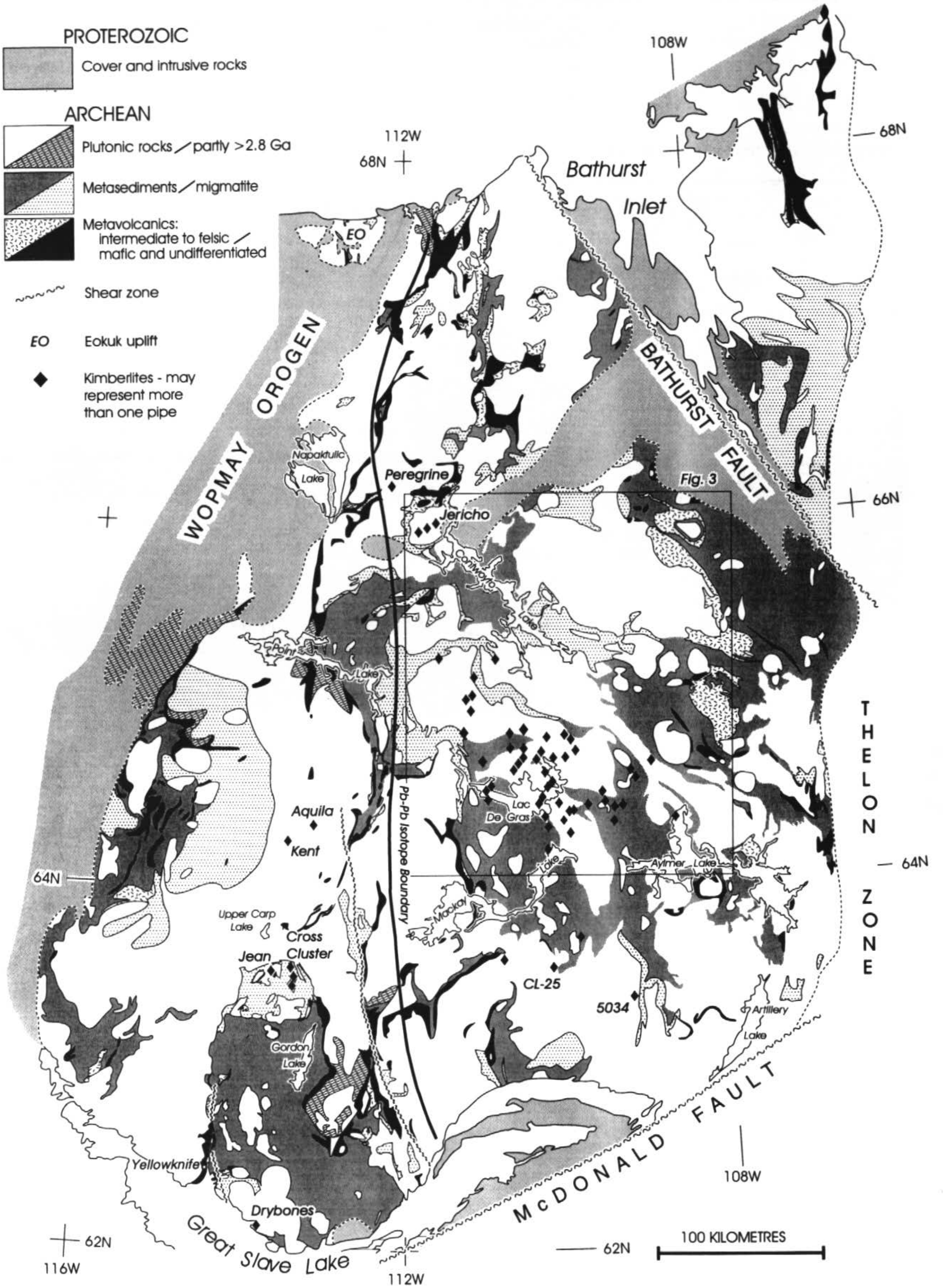

Figure 1 *Distribution of kimberlites in the Slave Province. Pb-Pb isotopic boundary from Thorpe* et al., *1992; geology from Fyson and Padgham (1993). Area outlined in right centre is shown in Figure 2.*

and the diamond indicator minerals were eventually traced eastward toward their source. In 1989, large and abundant indicator minerals were found in regional till and esker samples in the Lac de Gras area by Chuck Fipke and his son, Mark.

In 1990, Fipke and the company he had founded to help fund his exploration efforts, DiaMet Minerals, entered into a joint venture with BHP Minerals, with whom Hugo Dummet was now employed, to explore the ground they had staked in the Lac de Gras area. In 1991, two diamonds, one a 0.83 mm gem-quality stone, were discovered in esker samples. Later that year, a hole drilled to test a geophysical and heavy mineral anomaly just north of Lac de Gras intersected diamondiferous kimberlite, the "Point Lake" pipe. In November 1991, it was announced that a 59-kg core sample from the Point Lake pipe had yielded 81 diamonds, and a staking rush began. During February and March, 1992, a 160-tonne bulk sample of the

Table 1 Bulk sampling result summary, Slave kimberlites. Compiled from Dierker and Dyke, 1997; Pell, 1995b; and company news releases.

Pipe	Weight (tonnes)	Carats	Carats per 100 tonne	$ US per Carat	$ US per tonne	Current Status	Company
LAC DE GRAS							
Fox	8223	2199	27	$125	$ 34	Development Plan	BHP/DiaMet
DO-27	4261	1095	26	$ 25	$ 7	Abandoned	Kennecott/DHK
Panda	3402	3244	95	$130	$124	Development Plan	BHP/DiaMet
Koala	1550	1465	95	$122	$116	Development Plan	BHP/DiaMet
A-154 South	2585	11739	454	$ 59	$269	Evaluation	Aber/Diavik
Sable*	1096.1	1070.3	98	$ 64	$ 63	Development Plan	BHP/DiaMet
Misery	1030	4313	419	$ 26	$109	Development Plan	BHP/DiaMet
Leslie	608	223	33	$ 89	$ 30	On hold	BHP/DiaMet
Falcon	426	120	28	$ 17	$ 5	Abandoned	BHP/DiaMet
Jay	237.6	476.8	201	n/a	n/a	Evaluation	BHP/DiaMet
Point Lake	161	101	63	n/a	n/a	Abandoned	BHP/DiaMet
Pigeon	154	60	39	$ 51	$ 20	Abandoned	BHP/DiaMet
A-154 North	71.72	156.81	219	n/a	n/a	Evaluation	Aber/Diavik
A-418	62.31	247.5	397	$ 64.10	$255	Evaluation	Aber/Diavik
Misery South	36	27	75	$ 37	$ 28	Unknown	BHP/DiaMet
Ranch Lake	28	5	19	n/a	n/a	Abandoned	Lytton
Torrie	25	<1	3	n/a	n/a	Abandoned	Tanqueray
A-21	6.9	21.49	311	n/a	n/a	Evaluation	Aber/Diavik
DO-18	6.88	0.10	1.5	n/a	n/a	Abandoned	Kennecott/DHK
ELSEWHERE							
Jericho	95.4	~98.3**	103	$ 95	$ 98	Evaluation	Lytton/New Indigo
5034	104	~257**	247	n/a	n/a	Evaluation	Mountain Province

*Average value of diamonds from Sable pipe drops to $48 per carat if a 9-carat gem that was recovered is excluded. In February 1997, the Sable Pipe replaced Leslie in BHP's Development Plan.
** Stones >2 mm only.

Table 2 Statistics on some producing and past producing diamond mines. Compiled from Duval *et al.*, 1996; Janse, 1993.

Pipe	Area (hecatres)	Tonnage (million tonnes)	Grade carats* per tonne	Ave. Value $ per carat	$ per tonne	Total Value** (billion $)
Mwadui	146	143	0.2	$150	$30	4.3
Orapa	106	117.8	0.68	$60	$41	4.8
Yubileynaya	40	98***	1.0	$100	$100	9.8
Venetia	12.7	66	1.2	$100	$120	7.9
Jwaneng	45	110***	1.4	$95	$133	14.6
Mir	6.9	17***	2.0	$100	$200	3.4
Kimberley	3.7	9***	1.0	$200	$200	1.8
International	1.7	4***	4.0	$120	$480	1.9

* one carat of diamonds weighs 0.2 grams
** total value of reserves in the ground
*** tonnage estimated to 120 m depth.

Table 3 Statistics on BHP/DiaMet development pipes. Compiled from DiaMet news release, 6 March 1997.

Pipe	Tonnage* (million tonnes)	Grade (carats per tonne)	Ave. Value $ US per carat	$ US per tonne	Total value** (billion $ US)
Fox (pit)	16.7	0.4	$125	$ 50	0.84
Koala (pit)	14.6	0.76	$122	$ 93	1.36
Koala (u/g)	2.8	1.63	$122	$199	0.56
Misery (pit)	5.5	4.26	$ 26	$111	0.61
Panda (pit)	12.6	1.09	$130	$142	1.79
Panda (u/g)	0.8	0.97	$130	$126	0.09
Sable	12.9	0.93	$ 64	$ 60	0.77

* proven and probable reserves
** total value of reserves in the ground; for all 5 pipes is just over $ US 6 billion.

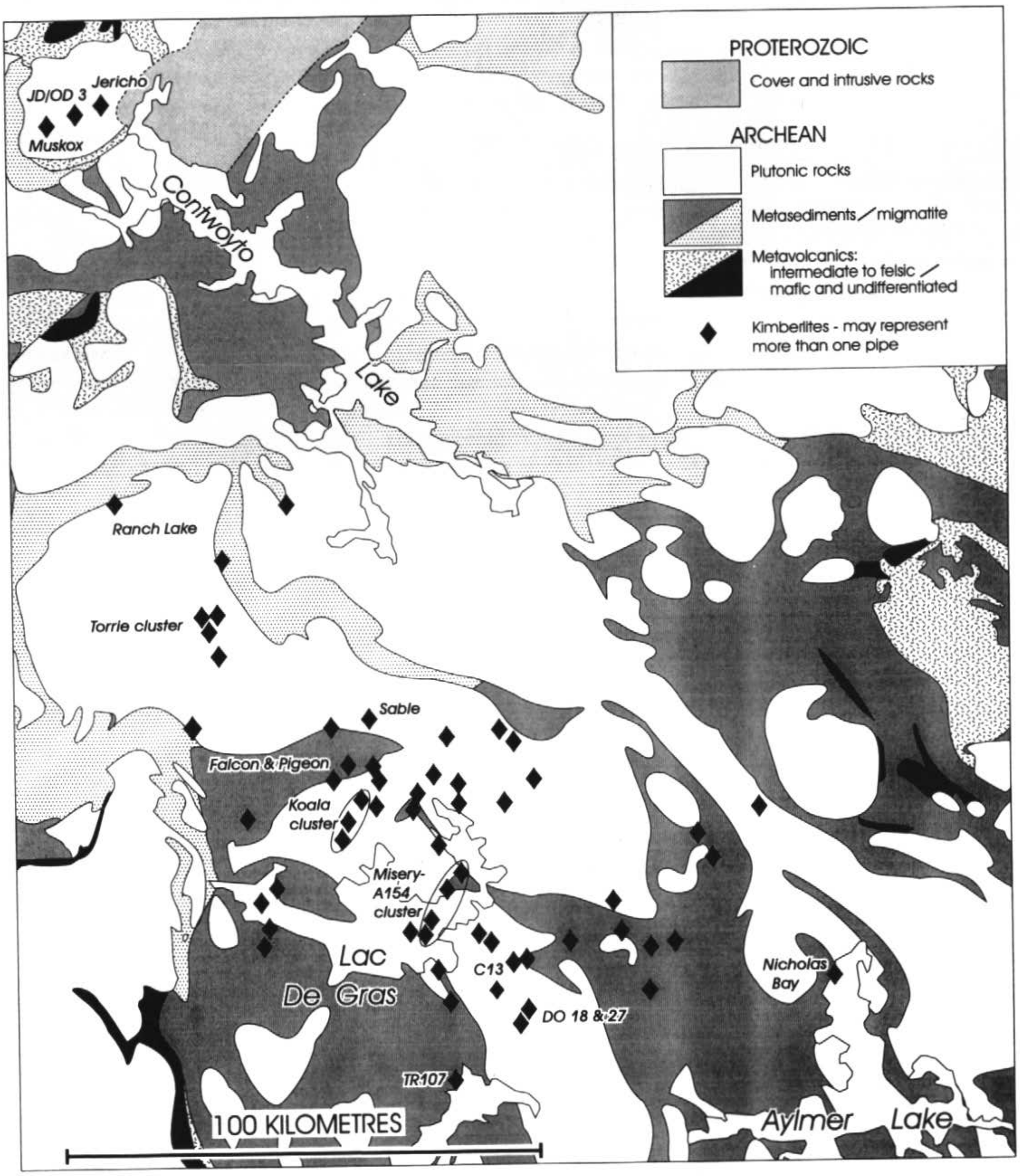

Figure 2 *Kimberlites in the Lac de Gras area. The Misery–A154 cluster comprises the Point Lake, Misery North, Misery South, A154 North, A154 South, A 418, A21 A5 and C42 pipes. The Koala cluster comprises the Fox, Leslie, Koala and Panda pipes. Torrie, Sputnik and Sue pipes make up the Torrie cluster.*

Point Lake pipe was obtained by drilling and trucked to Fort Collins in Colorado for testing. The announcement that this sample contained 101 carats, approximately 25% of gem quality and with some stones up to 3 carats in size, gave additional impetus to the staking rush. Half a dozen major companies and at least 100 junior companies became involved. Between the beginning of 1992 and the end of 1994, mineral claims covering nearly 22 million hectares of the Northwest Territories were recorded, mostly in the Slave Province. Since that time, claims have changed hands but few have been dropped.

Subsequent to the discovery of the first kimberlite in the Slave Structural Province in 1991, more than 150 pipes have been found. By early 1996, bulk samples (>1000 tonnes) had been collected from seven pipes, and minibulk samples (2-500 tonnes) from 12 others (Table 1 and Pell, 1995b). Excellent results were obtained from four pipes in the Lac de Gras area — Panda, Koala, Misery and A-154 South — all of which contain ore valued at >$100 per tonne. This is well within the range of economic deposits (Table 2; Table 3), even in Canada's north where open pit mining costs have been estimated at approximately $30 per tonne. A minibulk sample of the Jericho pipe north of Contwoyto Lake (Figs. 1, 2), which yielded a grade of approximately 120 carats per 100 tonnes, is also estimated to have ore worth >$100 per tonne.

In early November, 1996, the Canadian Federal Government gave final approval for BHP–DiaMet to open Canada's first diamond mine. Five kimberlite pipes are planned for development, namely Panda, Misery, Koala, Fox and Sable. Pre-stripping operations will begin in the spring of 1997 and initial production is expected by the second half of 1998. Exploration and evaluation of other pipes is continuing and it is possible that additional mines will be found.

BACKGROUND: KIMBERLITE DEFINITIONS AND CLASSIFICATION

Kimberlite Mineralogy

Kimberlites are volatile-enriched, potassic ultrabasic rocks that commonly exhibit a distinct inequigranular texture resulting from the presence of mineral and rock fragments set in a fine-grained matrix. They are hybrid rocks consisting of components derived from four distinct sources: the primary phenocrysts and groundmass minerals (cognate phases); the megacryst or discrete nodule suite; mantle-derived xenoliths and xenocrysts; and crustal xenoliths and xenocrysts (Fipke *et al.*, 1995b; Kirkley *et al.*, 1991; Mitchell, 1986; 1991; Scott Smith, 1992; 1996). Archetypal Group I kimberlites (as defined in Mitchell, 1995, 1996a; Smith, 1983; Smith *et al.*, 1985) are believed to form from partial melting of the asthenospheric mantle. Group II kimberlites (also referred to as micaceous kimberlites or orangeites; Mitchell, 1995, 1996b; Smith, 1983; Smith *et al.*, 1985) are believed to be derived from metasomatized lithospheric mantle (Mitchell, 1995).

Olivine, phlogopite and chromite may occur as primary phenocrysts (liquidus phases) in Group I kimberlites. Matrix (groundmass) minerals include microphenocrysts of olivine and one or more of: monticellite, perovskite, spinel (Mg-ulvöspinel), phlogopite, apatite and primary carbonate and serpentine (Mitchell, 1996a; Scott Smith, 1996). Primary groundmass clinopyroxene does not occur in pristine hypabyssal Group I kimberlites; however, it can crystallize from contaminated magmas that have had their compositions modified by xenolith digestion (Scott Smith, 1996). Group II kimberlites are characterized by the presence of phlogopite macrocrysts and microphenocrysts together with groundmass micas (phlogopite to tetraferriphlogopite). Euhedral, primary olivine is common, but not always a major constituent. Primary groundmass phases can include diopside, spinel (Mg-chromite to Ti-magnetite), Sr- and REE-rich perovskite, Sr-rich apatite, REE-rich phosphates, Nb-rutile, Mn-ilmenite, calcite, dolomite, rare earth carbonates, serpentine and zirconium silicates. Unlike Group I kimberlites, Group II kimberlites do not contain monticellite, Mg-ulvöspinel or Ba-rich micas (Mitchell, 1995; 1996b).

The megacryst or discrete nodule suite consists mainly of large (1-20 cm) single crystals or polycrystalline aggregates of magnesian ilmenite, Cr-poor titanian pyrope, diopside, enstatite, phlogopite and zircon; intergrowths of ilmenite and pyroxene are also common. Megacrysts are common constituents of Group I kimberlites but are rarely present in Group II kimberlites. The origin of this suite, whether it be from protokimberlitic magma or a mantle magma unrelated to the kimberlite, is uncertain (Mitchell, 1986, 1991; 1995; Smith *et al.*, 1985).

Mantle-derived xenoliths in kimberlites commonly consist of lherzolites and harzburgites of the peridotite-pyroxenite suite, ecologites, metasomatized peridotites, glimmerites and mica-amphibole-rutile-ilmenite-diopside (MARID) nodules. Fragmentation of mantle xenoliths during transport in kimberlite results in the addition of xenocrysts to the magma. Some of these, such as chrome diopside and chrome pyrope, which are commonly derived from lherzolites and jadeitic pyroxenes and grossular-rich garnet derived

Table 4 Textural-genetic kimberlite classification. After Clement, 1982; Clement and Skinner, 1985; Mitchell, 1986; Scott Smith, 1996.

All Facies					
OLIVINE		XENOLITHS			
macrocrystic (0.5-10 mm)	aphanitic (<0.5 mm)	lithic	heterolithic	autolithic	xeoncrystic
Crater-Facies					
(EXTRUSIVE) VOLCANICLASTIC KIMBERLITE					
pyroclastic			epiclastic (resedimented)		
Use standard particle size and textural terminology					
Diatreme-Facies					
XENOLITHS				INTER-CLAST MATRIX	
tuffisitic kimberlite		tuffisitic kimberlite breccia		pelletal	uniform
<15% >4 mm clasts		> 15% >4 mm clasts			
Hypabyssal-Facies					
XENOLITHS				GROUNDMASS	
kimberlite		kimberlite breccia		uniform	segregationary
<15% >4mm clasts		>15% >4mm clasts			

from eclogites, are easily recognized due to their unique chemistry. Other xenocrystic phases, such as olivine and phlogopite may be indistinguishable from phenocryst minerals. Xenocrystic chrome-poor garnets and magnesian ilmenites may themselves be indistinguishable from those derived from the megacryst suite. When they are large (0.5-10 mm), olivine, phlogopite, chrome-poor garnet, and ilmenite grains, irrespective of origin, are commonly referred to as macrocrysts (Mitchell, 1986, 1991).

Kimberlites are often altered by deuteric, metasomatic or weathering processes. In the case of deuteric alteration (which is often manifested as serpentinization) the changes are a direct result of crystallization, and alteration products are considered to be primary. Weathering and metasomatic alteration can obscure the original mineralogy by the formation of secondary serpentine, calcite, dolomite, chlorite, and clay minerals (Mitchell, 1986).

Kimberlite Morphology

Kimberlite magma is derived from the mantle at depths greater than 150 km and is emplaced in the upper crust as small volcanic pipes, dykes and sills. The generally accepted kimberlite pipe model (Fig. 3), which is derived from observations from a number of kimberlites in southern Africa, comprises three dominant zones, each with distinctive morphology: the crater, diatreme and hypabyssal or root zones (Clement, 1982; Hawthorne, 1975; Kirkley *et al.*, 1991; Mitchell, 1986; Scott Smith, 1992, 1996). A textural-genetic classification scheme has been developed (Clement, 1982; Clement and Skinner, 1985; Mitchell, 1986; Scott Smith, 1996) to describe kimberlites in these zones (Table 4).

Hypabyssal-facies kimberlites are "non-fluidized magmatic rocks that form from the intrusive emplacement of 'normal' kimberlite magmas that have not breached surface" (Scott Smith, 1996). They may, or may not, have associated diatreme and crater zones. Hypabyssal kimberlites commonly contain crystals (phenocrysts and xenocrysts) and xenoliths set in a finer-grained igneous matrix formed from the crystallization of kimberlite magma (Mitchell, 1986; Scott Smith, 1996).

Kimberlite diatremes are cone-shaped bodies with vertical axes and steeply inward dipping (80-85°) margins. In some regions, such as Yakutia, multiple intrusions can coalesce and form a single, complex bi- or tricuspid-shaped body (Mitchell, 1995). Kimberlite diatremes generally overlie the root zone and are infilled with structureless "tuffisitic" kimberlite and "tuffisitic" kimberlite breccia, which is considered to be the end-product of the complex intrusive gas-solid fluidized systems that form the diatremes themselves (Mitchell, 1986; Scott Smith, 1996). As Scott Smith (1996) pointed out, "it is important to use the term 'diatreme' with care....diatreme is not synonymous with 'volcanic vent' or steep-sided pipe"; in kimberlite literature, it has a genetic connotation. "Tuffisites" are intrusive fragmen-

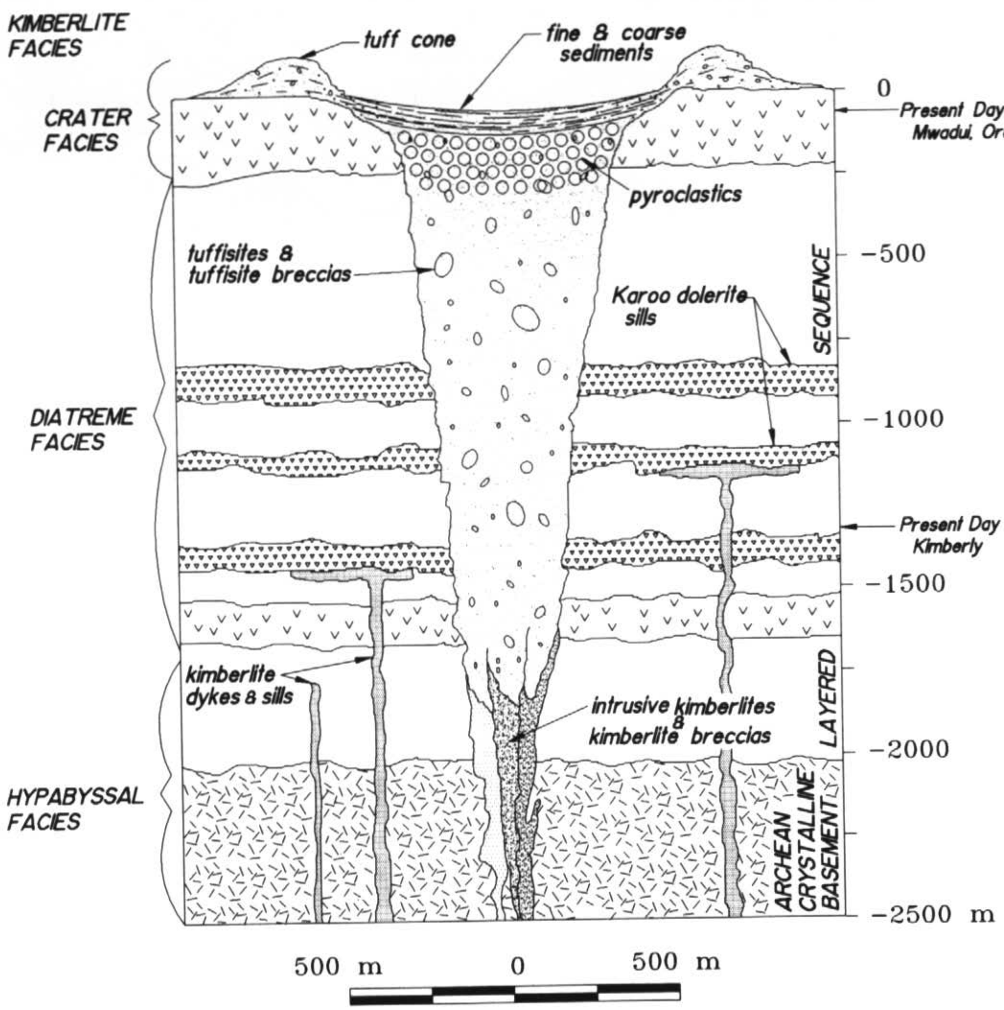

Figure 3 *Idealized model of a Southern African kimberlite pipe. Modified from Hawthorne (1975) and Mitchell (1986).*

tal rocks containing kimberlitic, mantle and abundant crustal country rock fragments. Mitchell (1995) argued that the term "tuffisite" should be abandoned as a general term for diatreme-facies kimberlite because of its genetic connotations (implication of formation by gas-solid fluidization), and be replaced by "volcaniclastic kimberlite." Scott Smith (1996), on the other hand, suggested that the term "tuffisite" as defined in the AGI Glossary, simply refers to an intrusive tuff (fragmental rock) with no implications as to how it formed, and should be retained because "volcaniclastic kimberlite" is a term that can be applied to crater-facies rocks and thus, if used for diatreme-facies lithologies, will lead to confusion.

Kimberlite craters are usually basin-shaped excavations formed at the surface by explosive volcanic eruptions, and may have external flanking tuff rings preserved. Crater-facies lithologies comprise primary pyroclastic deposits (including explosion breccias) and secondary, resedimented epiclastic rocks (Mitchell, 1986, Scott Smith, 1996). If depositional processes are not understood, Scott Smith (1996) suggests that the term crater-facies volcaniclastic kimberlite be used. Recent work has shown that the southern African kimberlite model may not be applicable to all kimberlites; in some regions (*e.g.*, Saskatchewan) kimberlite craters or kimberlite tuff cones can form without an associated diatreme, and thus new pipe models must be developed for these occurrences (Kjarsgaard, 1996a, 1996b; Leckie *et al.*, 1997; Lehnert-Thiel *et al.*, 1992; Scott Smith, 1995, 1996; Scott Smith *et al.*, 1995).

DISTRIBUTION, GENERAL CHARACTERISTICS AND AGES OF SLAVE PROVINCE KIMBERLITES

Few of the kimberlites in the Slave Province are exposed at surface; most have been discovered using a combination of heavy mineral sampling, geophysical techniques, and drilling. Many of the pipes have well-developed indicator mineral trains within the glacial tills that cover the region and/or are characterized by magnetic anomalies (either highs or lows) and resistivity lows. Some pipes have very weak or no geophysical signatures and have been discovered solely by tracing indicator mineral trains; others have very subtle indicator mineral signatures and their discovery has relied more heavily on geophysics (Ashley *et al.*, 1995; Buckle, 1993; Buckle *et al.*, 1994; Carlson *et al.*, 1995; Cookenboo and Foulkes, 1996; Doyle and Stephenson, 1995; Dupuis et. al, 1996; Fipke *et al.*, 1995a; Jennings and Barker, 1994; Schiller and Chartier, 1995; Stewart, 1994).

Lac de Gras Kimberlites

The majority of kimberlites in the Slave Province (>120) occur in an arcuate kidney-shaped zone which trends northwest from Lac de Gras for approximately 135 km and northeast from the lake for approximately 100 km (Figs. 1, 2). The northwest trend roughly parallels the Bathurst Fault and the northeast trend is roughly parallel to the MacDonald Fault, both of which are Proterozoic structures related to the docking of the Slave Province with the Rae (Churchill) Province (Hoffman, 1989). Some of the pipes in the Lac de Gras area form clusters that appear to be aligned along north-northeast trends (*e.g.*, Koala Cluster and Misery-A154 cluster; see Fig. 2). Many pipes occur at lineament intersections (*e.g.*, DO27, Doyle and Stephenson, 1995). Major fractures, contacts, faults, and Proterozoic dykes may all have had some influence on the location of individual pipes.

Kimberlites in the Lac de Gras area are characterized by abundant macrocrysts of olivine (or serpentine pseudomorphs after olivine), which can comprise up to 50 volume % of the rock. Chrome diopside, phlogopite, pyrope garnet, chromite, and picroilmenite are commonly present. Eclogitic garnets and enstatite have also been reported and some pipes contain xenocrysts of quartz, feldspar, and biotite, derived from the country rock. Serpentine, calcite, monticellite, perovskite, spinel and magnetite are groundmass minerals. Peridotite and eclogite xenoliths and autolithic fragments are found in some pipes (Carlson, *et al.*, 1995; Cookenboo, 1996a, 1996b; Doyle and Stephenson, 1995; Dynes, 1994; Kennecott Canada Inc., 1993; Lytton Minerals Ltd., 1994; Scott Smith, oral presentation, GAC–MAC short course on alkaline rocks, Winnipeg, 1996).

Kimberlite pipes in the Lac de Gras area generally resemble the classical southern African pipe model (Fig. 3) in terms of overall shape and wall rock slopes; however, they do exhibit some significant differences in morphology and petrology. Most Lac de Gras kimberlites are small, generally ranging from less than 2 hectares to slightly more than 12 hectares in surface area (Pell, 1995b), which is similar to the present day Kimberley pipes; however, many of the pipes in the Lac de Gras area have their craters intact, while at Kimberley, the pipes are deeply eroded (Doyle and Stephenson, 1995; Kirkely, 1995a, 1995b). Furthermore, to the limits of current exploration, many Lac de Gras pipes contain only crater or crater and hypabyssal-facies kimberlite (BHP Diamonds display, Prospectors and Developers Association Convention, 1997; I. Graham, oral presentation, Yellowknife Geoscience Forum, 1996; Scott Smith, 1996); diatreme-facies kimberlites are not as common, but have been reported in some instances (Fig. 4). Some pipes have oversteepened walls and actually taper upward: A154-North has a cross-sectional area of 0.90 ha at 50 m below surface, 1.40 ha at 250 m below surface, and 1.32 ha at -650 m; A418 increases from 0.83 ha at 65 m beneath the surface to 1.10 ha at -215 m (Diavik Diamond Mines Inc., 1997).

Crater facies kimberlites (as defined by Scott Smith, 1996) comprise both primary pyroclastic deposits and resedimented epiclastics. Lithologies recognized include ash tuffs, olivine macrocrystal tuffs, lapilli-bearing crystal tuffs, lapilli tuffs, lithic tuffs, and tuff breccias as well as kimberlitic mudstones, siltstones and sandstones. Unsorted to weakly sorted beds are common; occasionally well-defined layering and/or reverse grading is displayed. In some pipes, gravel, silt and clay layers of sedimentary origin are interbedded with kimberlite tuffs to depths of more than 400 m (Carlson, *et al.*, 1996; De Beers display, Prospectors and Developers Association Convention, 1997; I. Graham, oral presentation, Yellowknife Geoscience Forum, 1996; Kennecott Canada Inc., 1994). Laminated crater infill sediments, which overlie the kimberlitic tuffs, are preserved in some pipes.

Volcaniclastic crater facies breccias commonly contain wood fragments and siltstone and mudstone lithoclasts from which dinoflagellates, pollen, spores, and teleost fish remains have been recovered. Mudstone fragments from 13 of the pipes north of Lac de Gras contain fossils that range in age from Early Cretaceous (Albian, 97 Ma) to Tertiary (Paleocene, 56 Ma) and are the first evidence of a pre-existing Cretaceous and Tertiary cover in the Slave Province. Thermal maturation studies indicate that wood entrained in kimberlites at Lac de Gras has been subjected to temperatures up to about 100°C (Stasiuk and Nassichuk, 1995, 1996), which is lower than the temperatures recorded by charred wood in the 79 A.D. pyroclastic flows from Vesuvius, which were around

300°C (Fisher and Schminke, 1984).

A Rb-Sr isochron age of 52±1.2 Ma from phlogopite and whole-rock, on two of the pipes in the central part of the Lac de Gras area, closely supports the paleontological evidence (Carlson *et al.*, 1995; Nassichuk and McIntyre, 1995, 1996). A slightly younger Rb-Sr phlogopite macrocryst-whole rock isochron age of 47.5±0.5 Ma has been obtained from another of the pipes north of Lac de Gras (Davis and Kjarsgaard, 1997). A U-Pb age of 74±3

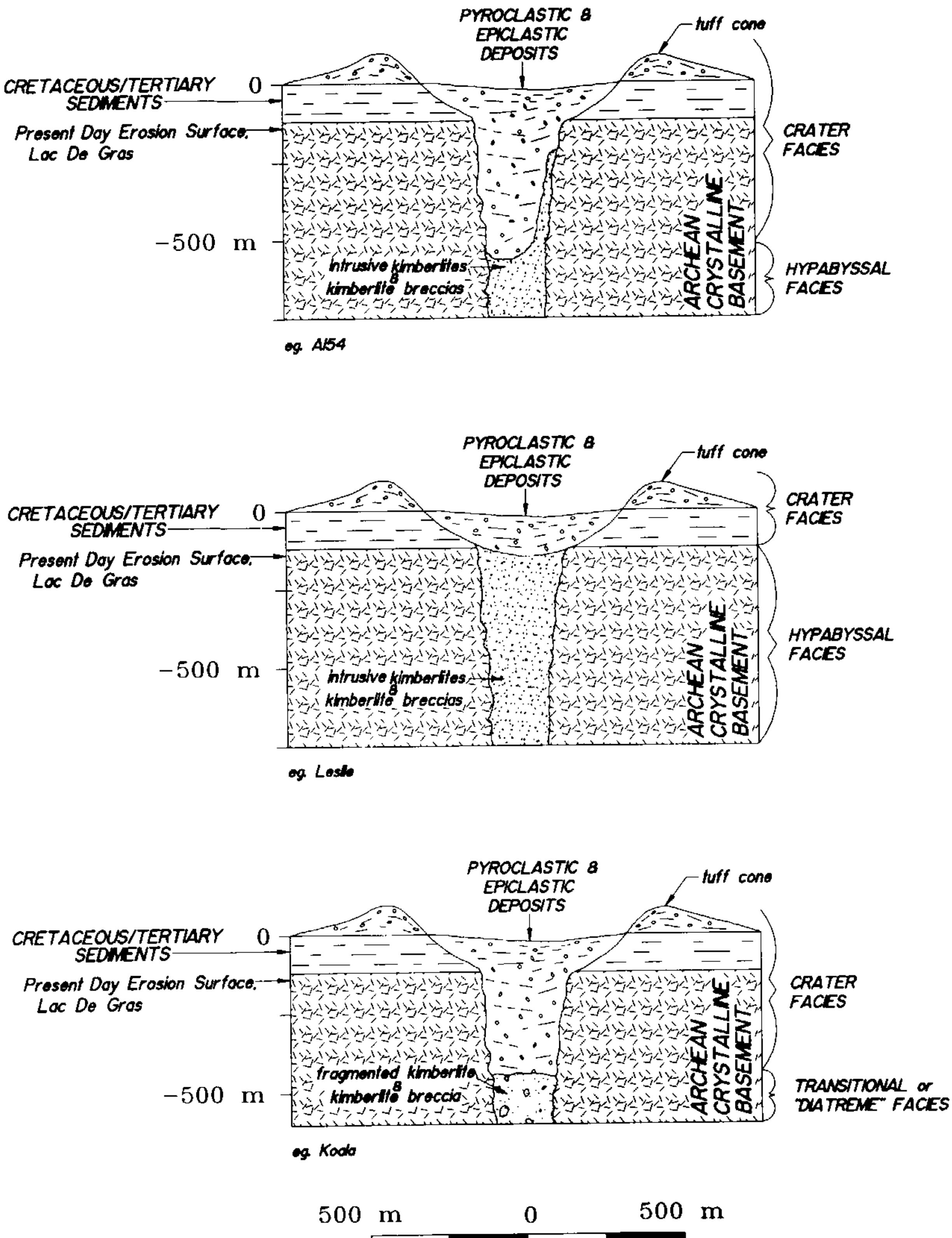

Figure 4 *Schematic models of Lac de Gras kimberlites. Compiled from company data supplied in talks, poster displays and core displays.*

Ma was obtained from perovskite from the C13 pipe, southeast of Lac de Gras (Heaman *et al.*, 1997) and an age of approximately 81 Ma has been reported from another pipe in that area (E.Thomas, pers. comm., 1995). These data indicate that in the Lac de Gras area, kimberlites were emplaced in both Cretaceous and Tertiary time.

Hypabyssal kimberlites in the Lac de Gras area have a mineral assemblage typical of South African Group I kimberlites (Carlson, *et al.*, 1995, 1996). They are generally massive, with olivine macrocrysts, which can comprise up to 50% of the rock, set in a uniform groundmass. Monticellite is common in many pipes and, in some cases, segregationary textures are developed (De Beers display, Prospectors and Developers Association Convention, 1997; Kjarsgaard, pers. comm., 1993). Hypabyssal kimberlites can occur in narrow dykes or within pipes, and are sometimes found within the upper parts of the pipe (Carlson *et al.*, 1995; Doyle and Stephenson, 1995).

Although less common, diatreme or incipient diatreme-facies kimberlites have been identified in some pipes (BHP Diamonds display, Prospectors and Developers Association Convention, 1997; Carlson *et al.*, 1995, 1996; Doyle and Stephenson, 1995). They are typically fragmental and olivine rich; locally pelletal textured kimberlites or kimberlite breccias, containing more than 15 volume % country rock fragments, are developed (BHP Diamonds display, Prospectors and Developers Association Convention, 1997; Carlson *et al.*, 1995, 1996). It is not clear if these diatreme-facies rocks were developed through fluidization processes, similar to South African diatremes, or by other mechanisms.

Other Eastern Slave Province Kimberlite Pipes

Kimberlites have been discovered in the eastern Slave Province outside the Lac de Gras area (Fig. 1) and some contain diamonds. The Jericho pipe, at the north end of Contwoyto Lake and the 5034 (or Kennedy Lake) pipe, south of Aylmer Lake both have returned encouraging initial results in terms of diamond potential (Table 1). Like kimberlites in the Lac de Gras area, these pipes are only a few hectares in size.

Contwoyto North Area

The Jericho (or JD/OD 1) kimberlite, near the north end of Contwoyto Lake (Figs. 1, 2) is a multiphase intrusion consisting of a precursor dyke and at least two pipes. The precursor dyke extends to a small satellite pipe 300 m north of Jericho, and is characterized by olivine and phlogopite macrocrysts and microphenocrysts in a fine-grained groundmass of euhedral spinel, calcite, and serpentine with minor perovskite and apatite. Pyrope garnet, chrome diopside, and ilmenite are also commonly present. Later phases are more fragmental, have different relative percentages of the various indicator mineral phases, and have been subjected to differing degrees of serpentinization. They also contain chlorite and have fewer oxides in the matrix resulting in lower magnetic susceptibilities (Cookenboo, 1997; Kopylova *et al.*, 1997a). All phases at Jericho contain autoliths and abundant mantle xenoliths including eclogites, peridotites (harzburgites, lherzolites and wherlites) and some pyroxenites (Kopylova *et al.*, 1997b). Fossiliferous limestone xenoliths containing faunal assemblages of Middle Devonian age are common in the Jericho pipe and the JD/OD 3 kimberlite, 7 km to the west (Cookenboo *et al.*, 1997). A Rb/Sr model age of 172±2 Ma has been determined from phlogopite from the Jericho pipe and is interpreted as the age of emplacement (Cookenboo *et al.*, 1997; Heaman *et al.*, 1997).

The Muskox pipe, 15 km southwest of Jericho (Figs. 1, 2), contains hypabyssal facies, macrocrystic, spinel-rich, carbonate-monticellite kimberlite and transitional hypabyssal to diatreme-facies, serpentine-carbonate-pyroxene kimberlite breccia. The Peregrine pipe, 43 km northwest of Jericho, contains bedded, crater-facies volcaniclastic kimberlite and kimberlite breccia. Carbonate rock fragments are also common in these pipes (De Beers display, Prospectors and Developers Association Convention, 1997) and represent the only evidence for Paleozoic cover on this part of the craton.

Aylmer Lake Area

Diatreme and hypabyssal-facies kimberlites have been recognized (H. Bird, pers. comm., 1994; Pell, 1995c) in the Nicholas Bay pipe on Aylmer Lake (Fig. 2). Heterolithic tuffisitic kimberlite breccias are characteristic of the diatreme facies. They contain abundant Archean country rock fragments (granitoids, metasediments, mafic metavolcanics), and spherical structures (pelletal lapilli, which are characteristic of diatreme-facies kimberlites) are common. Hypabyssal rocks are massive and contain approximately 10-15% olivine crystals, generally less than 5 mm in size. The groundmass consists predominantly of serpentine, carbonate, and spinels±perovskite and varies in texture from uniform to segregationary. In the latter case, carbonate and opaques rim olivine crystals, and light-brown serpentine comprises the segregations. Atoll spinels are common. Indicator minerals (pyropes, chrome diopsides, ilmenites) are not abundant in either facies. No information on the age of this pipe is available; however, geochronological studies are ongoing (Heaman *et al.*, 1997).

Southeastern Slave Province

The 5034 (Kennedy Lake) pipe in the southeastern Slave Province (Fig. 1) is a hypabyssal-facies kimberlite characterized by olivine (or serpentinized pseudomorphs after olivine) and lesser orthopyroxene macrocyrsts in a groundmass of serpentine, calcite, Ti-Ba phlogopite, perovskite, chrome spinel, apatite, barite, and other minor phases. Mantle xenoliths are rare. Country rock fragments, predominantly Archean granitoids, are locally abundant and often show evidence of partial resorption by the magma (Cookenboo, 1996b; Cookenboo and Foulkes, 1996). Whole-rock chemistry of 5034 shows some similarities with both Group II kimberlites and micaeous (madupitic) olivine lamproites (Cookenboo, 1996b). Isotopic studies on groundmass phlogopite separated from whole-rock samples yielded a precise Rb-Sr age of 538.6±2.5 Ma, indicating that this pipe was emplaced in the Cambrian period (H. Cookenboo, pers. comm., 1996).

The CL-25 kimberlite, which is also located in the southeastern part of the Slave Province has been described as "intensely altered kimberlite breccia" containing chrome-rich pyrope and eclogitic garnets, picroilmenites, chrome spinels, and chrome diopsides (Pokhilenko *et al.*, 1996). Kimberlite dykes and sills have been discovered in other areas in the southeastern Slave Province; however, no geological information is available on them.

Kimberlites in the Western Slave Province

Kimberlite pipes have also been found in the southwestern part of the Slave province. These include the Aquila and Kent kimberlites north of Upper Carp Lake, approximately 200 km north of Yellowknife, the Cross cluster and Jean kimberlites south of Upper Carp Lake, and a single pipe in the Drybones Bay area on Great Slave Lake, southeast of Yellowknife (Fig.

1). Diamonds have been found in some of these pipes and their evaluation is continuing.

Upper Carp Lake Area

The Cross pipe was the first pipe discovered in the Cross cluster, which also includes the Ursa and Orion pipes and Winny dyke. It is slightly less than 2 hectares in size and contains hypabyssal and diatreme-facies heterolithic kimberlite breccias. Ilmenite, commonly rimmed by pseudobrookite, is abundant (W. Hillier, pers. comm., 1994); tetraferriphlogopite and red spinels are also common. Olivine grains are generally serpentinized. Granitoid clasts and mid-Paleozoic carbonate rock fragments are abundant in these breccias. The carbonate rock fragments are evidence that there was once Paleozoic cover in this area; presently the nearest Paleozoic rocks are 150 km to the southwest. A radiometric age of 450 Ma has been obtained for the Cross Lake pipe (W. Hillier, pers. comm., 1995).

The Jean kimberlite, west of Cross, comprises hypabyssal, macrocrystic, spinel-rich serpentine kimberlite and diatreme-facies tuffisitic kimberlite breccias with pelletal juvenile lapilli. The Kent kimberlite, north of Cross, contains hypabyssal-facies macrocrystic spinel-rich monticellite kimberlite microbreccia. Both of these pipes contain (Paleozoic?) carbonate rock fragments (De Beers display, Prospectors and Developers Association Convention, 1997).

Great Slave Lake Area

The Drybones Bay kimberlite, on Great Slave Lake southeast of Yellowknife, has a surface area estimated at 22 hectares and is the largest pipe discovered so far in the Slave Province. It has a positive magnetic signature and appears to be a composite, multiphase intrusion. The main, western part of the pipe consists predominantly of medium green, crater-facies volcaniclastic kimberlite and minor kimberlite breccia. Some sections display a subtle-to-distinct layering and grain-size variation (grading). These strata overlie structureless, possible diatreme-facies kimberlite (Kretschmar, 1997). Breccias, dominated by fragments of the host granitoids, are best developed near the edge of the pipe. Spherical lapilli are common and most are cored by serpentinized olivine or phlogopite grains, or by small rock fragments. In the eastern part of the pipe, epiclastic strata are preserved, comprising kimberlite tuffs which grade upward into sandy kimberlites, kimberlitic sands, and semi- to unconsolidated quartz sands in units from a few metres to tens of metres thick. Locally, these units are repeated over an apparent cumulative thickness of >150 m. Dolostones and red siltstone/sandstone fragments, similar to Proterozoic Great Slave Supergroup strata in the East Arm Graben, are locally present (pers. observ., by author). Throughout the intrusion, olivine (or serpentine pseudomorphs after olivine) and ilmenite dominate the phenocryst–xenocryst suite; tetraferriphlogopite, pyrope garnet, eclogitic garnet, green high-calcium, high-chromium garnets, red spinel, chromite, and chrome diopsides are also present. The groundmass is dominated by serpentine, chlorite, calcite, clay minerals; minor spinel, pyrite, pyrrhotite and chalcopyrite occur locally. Some mantle xenoliths (peridotites and possible eclogites) are present (Kretschmar, 1996, 1997; pers. observ., by author). Presumed mantle zircons rimmed with badellyite are common in the Drybones Bay pipe. Isotopic studies of these zircons have yielded U/Pb ages of *circa* 480 Ma, 447-434 Ma and 270 Ma; a significantly older model Rb-Sr phlogopite age of *circa* 1035 Ma was also obtained (Heaman *et al.*, 1997; Kretschmar, 1997). Additional isotopic studies are necessary to unequivocally establish the emplacement age of this pipe.

DISCUSSION AND CONCLUSIONS

The more than 150 kimberlite pipes discovered since 1991 demonstrate that the Slave Province has experienced intermittent kimberlite intrusive events for nearly 500 million years (>90% of the Phanerozoic). In the Lac de Gras region, the preliminary evidence suggests that there are at least two periods of kimberlite emplacement: Tertiary (Eocene) and Late Cretaceous. Elsewhere in the eastern Slave, Middle Jurassic and Cambrian kimberlites have been identified. Late Ordovician kimberlites have been found in the southwestern part of the Slave. As pointed out by other workers (Kjarsgaard, 1996c; Kjarsgaard and Heaman, 1996), Slave kimberlites form a Type 3 kimberlite province (*i.e.*, kimberlite fields of different ages in the same region; Mitchell, 1986). Most of the pipes that have been discovered in the Slave Craton are typical Group I kimberlites, with the exception of 5034, which is significantly more micaceous and has an anomalous chemical signature. Some of the kimberlites in the Slave Province do not conform to the standard South African pipe model with respect to their morphology or distribution of lithological facies, which may be due in part to the physical characteristics of the near-surface lithologies into which they were emplaced.

Kimberlites in the western part of the Slave Province display some differences with those in the east, most notably with respect to their indicator mineral suites. Pyrope garnet and chrome diopside are predominant in the mineral assemblage of the eastern pipes, whereas ilmenite and tetraferriphlogopite are more common in the west. To date, the only economic pipes have been found in the eastern Slave. Kimberlites in the eastern Slave have apparently passed through a more juvenile crust than those that were emplaced in the western part of the Province, which might account for some of the differences. Alternatively, the variations may be attributed to differences in the lithospheric mantle under a juvenile *versus* evolved ancient crust, as sampled by the kimberlites.

Cretaceous and Eocene pipes around Lac de Gras contain wood and mudstone fragments of similar ages which are the only record of Mesozoic and Cenozoic cover in this part of the Slave. The Cross Lake kimberlite, in the southwestern Slave, and the Jericho pipe, near Contwoyto Lake, are older than the pipes at Lac de Gras area. Both of these pipes, and others in their immediate vicinity, contain carbonate rock fragments that constitute the only record of Paleozoic cover in their respective parts of the Slave. The study of these entrained crustal xenoliths will greatly add to our understanding of the Phanerozoic history of the region.

The history of kimberlite discoveries in the Slave craton dates back to 1991, and by 1998 Canada's first diamond mine should be in production in the Lac de Gras area. Many companies are currently active in the ongoing search for additional economic deposits. As exploration continues, it is likely that more kimberlites will be found and a better understanding of their ages, petrology and diamond potential will be gained.

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