Exploration and Geology of the Attawapiskat Kimberlites, James Bay Lowland, Northern Ontario, Canada

J.M. KONG[1], D.R. BOUCHER[2] and B.H. SCOTT SMITH[3]

1. Monopros Limited, Waterpark Place, 10 Bay Street, Suite 1510, Toronto, Ontario M5J 2R8, Canada
2. Monopros Limited, 185 des Distributeurs, Val d'Or, Quebec J9P 6Y1, Canada
3. Scott-Smith Petrology Inc., 2555 Edgemont Boulevard, Vancouver, British Columbia V7R 2M9, Canada

ABSTRACT

Sediment sampling and airborne magnetic surveys proved to be excellent methods for finding the Attawapiskat kimberlite cluster in the James Bay Lowland. The mantle-derived mineral suite recovered from sediment sampling included ilmenite, garnet, chrome diopside and chromite. Their compositions suggest they were derived from kimberlite(s) that is probably diamondiferous. Sixteen pipes were found and tested by drilling. Fifteen pipes are diamondiferous. Evaluation is ongoing. The ages determined for the kimberlites range from 155 to 180 Ma. The pipes are composed of spinel carbonate kimberlite with less common monticellite kimberlite. They were formed by (i) pipe excavation without the development of a diatreme and (ii) subsequent pipe infilling. Two textural types occur: macrocrystic uniform to segregationary textured hypabyssal kimberlite and macrocrystic pyroclastic kimberlite (lapilli tuffs).

Keywords: exploration, emplacement, crater-facies, geophysics, kimberlite, petrology, Ontario

1. INTRODUCTION

Diamonds recovered from Wisconsin and in the Great Lakes area are postulated to be glacially transported from the James Bay Lowland (Brummer, 1978). During 1960, Selco Exploration Company Limited discovered kimberlitic indicator minerals in the Moose River Basin, the southern extent of the James Bay Lowland (Brown, 1967). Subsequent mapping completed in 1966 by the Ontario Department of Mines identified indicator minerals as well as ultramafic lamprophyre and "kimberlitic" sills and dykes at Coral Rapids. The regional setting and the presence of indicator minerals prompted BP Selco and Esso Minerals to commence an exploration program in 1979. Using low level airborne magnetic surveys and detailed ground geophysics to define targets, BP Selco and Esso Minerals undertook a drilling program that yielded 34 melnoitic pipes (Scott Smith, 1995) from 64 geophysical anomalies (OGS Assessment Work Files; Janse *et al.*, 1989; Reed and Sinclair, 1991).

In 1984 Monopros Limited, a subsidiary of De Beers Consolidated Mines Ltd., started a regional sediment sampling program to the west-northwest of the Selco melnoites. The combination of sediment sampling, indicator mineral chemistry and geophysics was effective in locating diamondiferous kimberlites in the Attawapiskat River area. This paper describes the discovery and nature of the kimberlites.

The kimberlites are located near the Attawapiskat River in the James Bay Lowland, 350 km north of the town of Hearst and 100 km west of the coast of James Bay (Fig. 1). The James Bay Lowland is located on the west side of James Bay and lies on the Hudson Platform. It is characterized by a low, swampy plain with subdued glacial features and a belt of raised beaches along the coast of the bay (Bostock, 1976). Shallow pools of standing water are crossed by strands of floating muskeg forming string bogs (Suchy and Stearn, 1993). These bogs and small lakes are connected by small shallow streams. The area is drained by several large well incised rivers that flow into James Bay. Near these large rivers, the drainage is better and the land can support small trees. In the summer, access is only possible by helicopter. However, in the winter fixed winged aircraft fitted with skis can be used on the frozen muskeg.

2. GEOLOGICAL SETTING

The Attawapiskat area is part of the Hudson Platform that consists of flat-lying Palaeozoic sedimentary rocks unconformably overlying the Precambrian plutonic and metamorphic rocks of the Superior Province. The Superior Province, the largest Archaean craton in the world, is characterized by east-west linear fault bounded terranes that were accreted together in the Late Archaean. Isotopic ages range from 3.1 Ga in the north to 2.6 Ga in the south (Card, 1990). The accretionary model of the Superior Province by Williams *et al.* (1992) suggests that the kimberlite pipes are located on the oldest part of the craton (the protocraton). The teleseismic study by Grand (1987) confirms

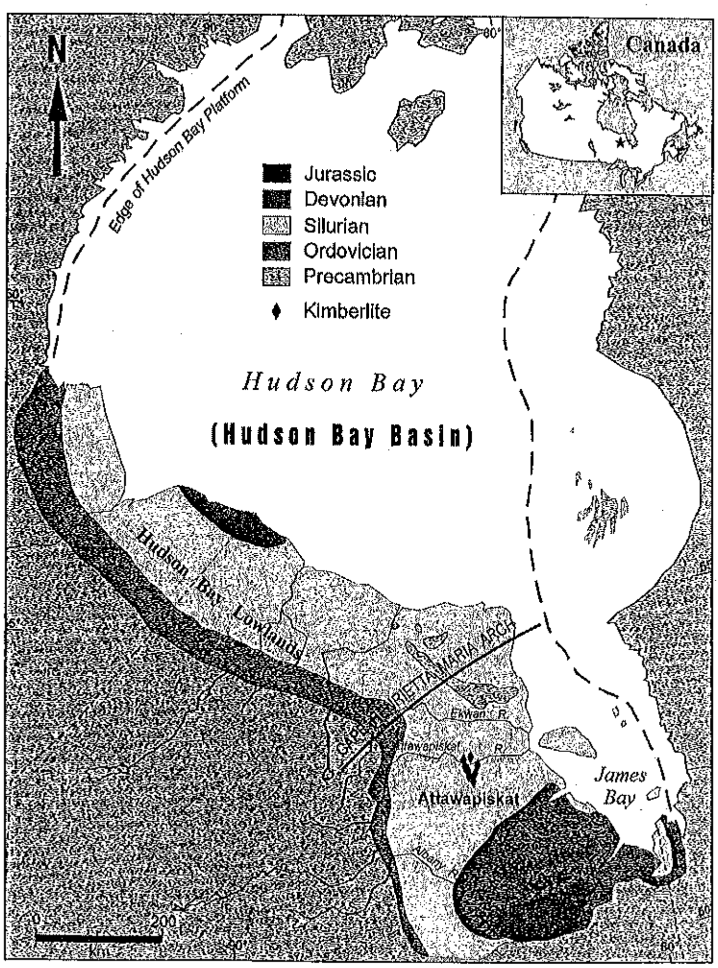

Figure 1. Regional geological setting and location of the Attawapiskat kimberlites (Norris, 1986).

the presence of a lithospheric root extending to depths of at least 200 km in the area.

The Cape Henrietta Maria Arch trends southwest to northeast, cutting through the northern part of the area and exposing Proterozoic basement rocks known as the Sutton Inlier (Donaldson, 1986). The kimberlites are located on the southern flank of the arch (Fig. 1) that separates the erosional remnants of two adjacent cratonic basins, the Hudson Bay Basin and the Moose River Basin (Norris, 1986). The Attawapiskat area is transected by a set of minor faults striking northwest-southeast and northeast-southwest. The major structure in the area is the Winisk River Fault system that is clearly visible on the Canadian Geological Survey map of regional airborne magnetic data. Two sets of dykes are also visible on the magnetic data, dykes that strike northwest to southeast (possibly belonging to the Mackenzie dyke swarm) and the Matchewan/Hearst dykes that trend north-south.

The basins were the depositional centres for Palaeozoic sediments of the Hudson Platform (Johnson *et al.*, 1991). The Palaeozoic rocks thin towards the arch but can attain thicknesses of up to 800 m in the Moose River Basin and up to 1 800 m in the Hudson Bay Basin (Norris and Sanford, 1968). These rocks range in age from Ordovician at their western limit to Jurassic in the centre of the basins (Fig. 1). The basins consist predominantly of limestones and dolomites with some shales, siltstones and sandstones. Based on regional data, the sediments in the Attawapiskat area are ~250 m thick. The uppermost limestone sediments are Silurian reef and bioherm deposits of the Attawapiskat Formation (Suchy and Stearn, 1993). These sediments are upfaulted in the immediate area of the Attawapiskat kimberlite cluster and are exposed in 30 m high cliffs in the banks of the Attawapiskat river.

The Palaeozoic bedrock is covered by frost heaved brecciated carbonate bedrock, followed by thin Pleistocene till sheets that are overlain by thin marine and coastal Holocene deposits. The till sheets were deposited by glaciers flowing north to south with a northeast to southwest flow in the eastern part of the area. Two units have been recognized: an upper brown to reddish brown till and a lower grey till. The Holocene deposits consist of marine and coastal beach deposits formed during the regression of the early post glacial Tyrrell Sea (Martini, 1988). Till and coastal Holocene deposits overlying the Attawapiskat kimberlites vary in thickness from 0 to 30 m.

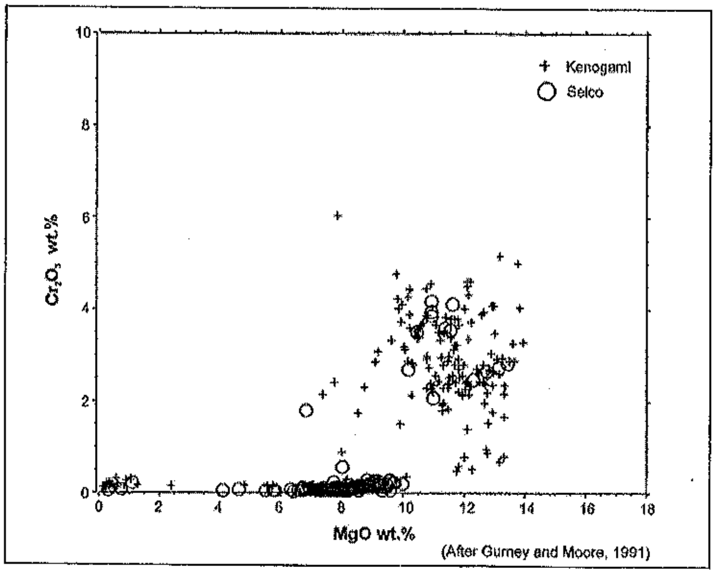

Figure 2. Comparison of ilmenite compositions from the Kenogami River and from the vicinity of the Selco bodies.

3. EXPLORATION

3.1 Heavy Mineral Sampling

Extensive wetlands restricted sampling to streams and rivers that have intersected glacial and marine deposits. The streams and rivers concentrated heavy minerals along gravel bars that were the main sample medium. Specifically, the heads of the bars were preferentially sampled as tests showed that this material contained the highest concentration of heavy minerals. When exposed along the banks of rivers, till was also collected.

In 1984, reconnaissance stream sampling of the Kenogami River yielded mantle-derived ilmenites, garnets, spinels, and rare clinopyroxenes. Comparisons of the ilmenite mineral compositions from the Kenogami River to those from the vicinity of the Selco bodies show striking differences. Ilmenites in the Kenogami River have higher Cr_2O_3 and MgO contents (Fig. 2). As the predominant ice direction is from the northeast, it was postulated that a new source of the indicator minerals should occur to the northeast. The mantle-derived indicator minerals found during the 1985 and 1986 systematic regional stream sediment sampling program from the Kenogami River north to the Ekwan River have similar mineral compositions. The Ekwan River was devoid of indicator minerals and provided a good "cut-off" (Fig. 3). The majority of the garnets are peridotitic falling in the garnet cluster groups G9 and G10 of Gurney (1984). The ilmenites recovered in the Attawapiskat area are "kimberlitic" with Cr_2O_3 contents of 1.5 to 8 wt% and MgO values from 7 to 15 wt% (Fig. 4). Low Fe_2O_3 values suggest good diamond preservation (Gurney and Moore, 1991). Although rare, the spinels have "kimberlitic" compositions. The chrome diopsides appear to originate from garnet lherzolite sources (Sobolev *et al.*, 1992).

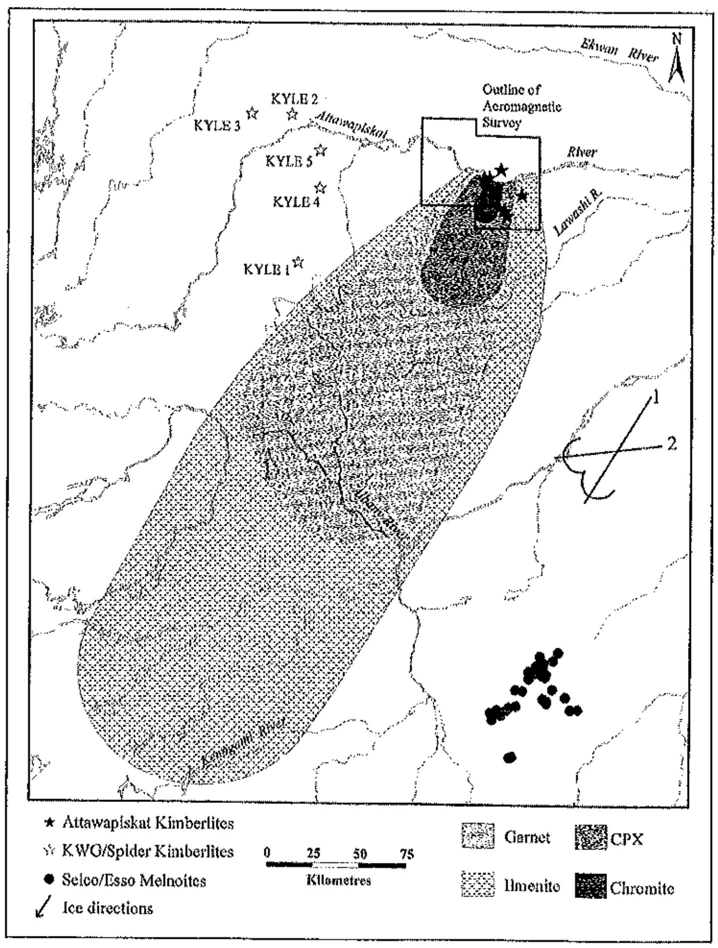

Figure 3. Indicator mineral dispersion from the Attawapiskat kimberlites.

The indicator mineral compositions suggest derivation from diamondiferous kimberlites. In 1987, detailed sampling along the Attawapiskat River and its tributaries yielded super-abundant mantle-derived mineral grains and kimberlite clasts.

The indicator mineral grains in the kimberlites had been transported to the south and southwest by the advancing Nouveau Quebec glacial ice and deposited in the till sheets during its retreat. After the retreat of the ice sheet, much of the Hudson and James Bay Lowlands were inundated by the Tyrrell Sea. In some areas, the regression of the post glacial Tyrrell Sea concentrated the indicators in north-south trending beach ridges. The east-flowing rivers draining into James Bay crossed and cut into both the glacial till and beach ridges, re-concentrating the indicator minerals in the gravel bars within the river system. Care was taken to identify sample sites near beach ridges as they gave anomalous results due to concentration of the heavy minerals. In general, the number of grains recovered per sample decreased to the south and southwest of the kimberlites. The abundance of indicator minerals in the sediments and the distance of glacial transport of the grains is directly proportional to the abundance of the minerals within each of the kimberlites. Ilmenite grains, that are by far the most abundant mineral in the kimberlites, are also the most abundant mineral in the samples and they were dispersed over 300 km from their source. Spinels are the least abundant indicator mineral within the kimberlites and are rare in the samples, with transportation distances of less than 20 km (Fig. 3). Detailed stream sampling along the Attawapiskat River also indicated that the size and surface texture preservation decreases down river from the kimberlites.

3.2 Geophysics

The kimberlite boulders recovered from the Attawapiskat River prompted an aeromagnetic survey covering 2 900 km^2 (Fig. 3). Kenting Earth Sciences completed a total intensity and measured vertical gradiometer aeromagnetic survey over the area outlined by Monopros Limited. Flight lines were orientated true north-south and spaced at 250 m intervals with a tolerance of 375 m for 3 km. Readings were taken every 0.25 seconds. The aircraft ground clearance was 100 m. This detailed aeromagnetic survey proved to be the most effective method of detecting kimberlites in this area (Fig. 5). The 250 m of non-magnetic Palaeozoic sedimentary rocks are an ideal filter of the magnetic response from the basement rocks. The kimberlites penetrating the cover rocks were easily detected. The vertical gradient modeling further emphasized the signature of the near surface kimberlites and delineated the contacts of the pipes (insert in Fig. 5). This survey identified 31 targets.

Detailed ground magnetic surveys were conducted over the 31 targets. Survey grids were established on all anomalies with a line spacing of 100 m and stations at 25 m intervals. Readings were taken every 12.5 m along all lines and base lines. Modeling of the geophysical response suggested 16 anomalies represented near surface steeply dipping prisms at a depth of 5 to 20 m and 15 anomalies represented basement features at a depth of 200 to 250 m. The possible kimberlites represented by the near surface anomalies range from 0.4 ha to 15 ha in size. These anomalies follow the northwest trend of dykes similar to the kimberlites in the "Corridor of Hope" of the Slave province. Fifteen of the near surface anomalies (A1, A1 North, B1, C1, D1, G1, I1, T, T

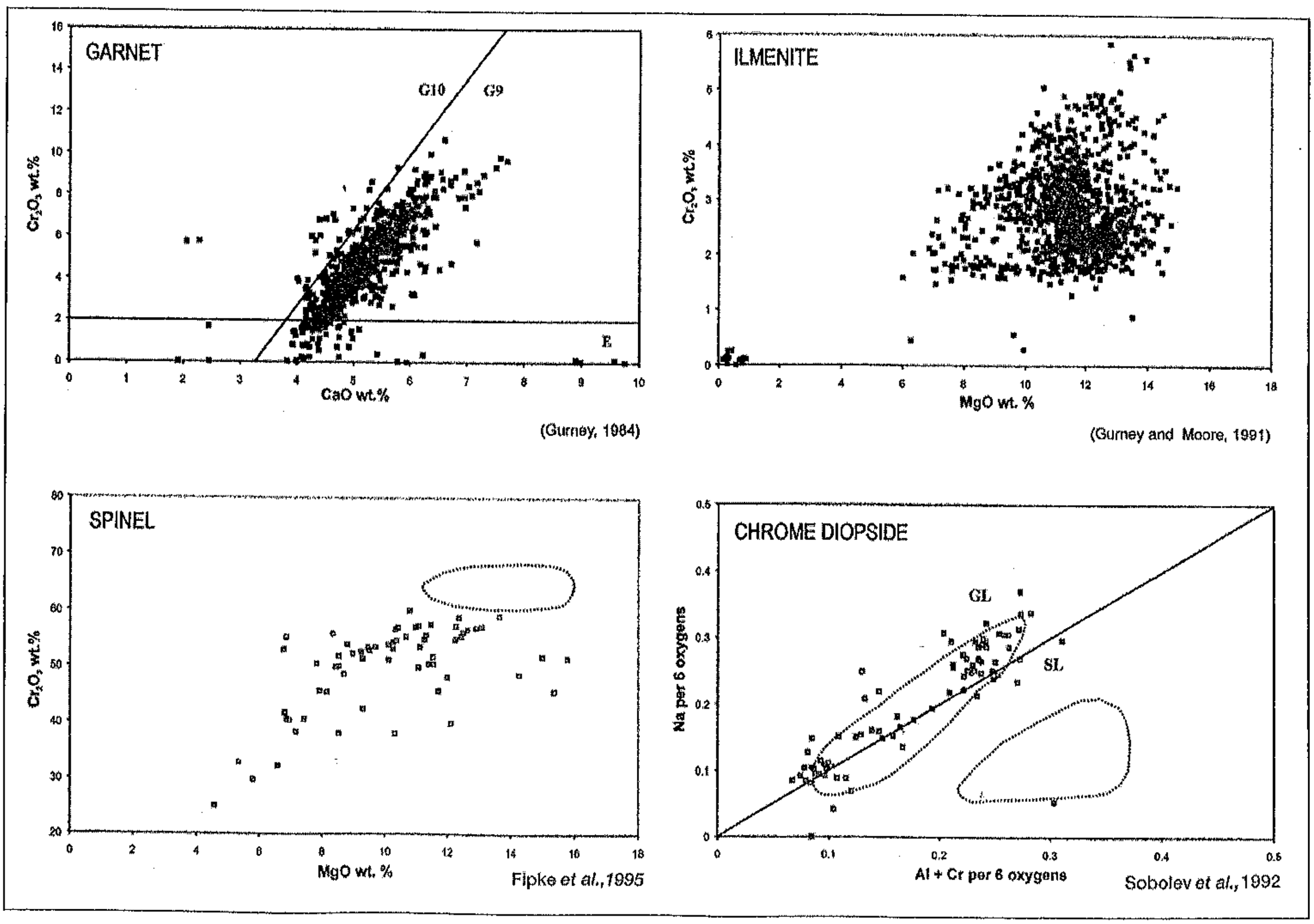

Figure 4. Composition of garnet, ilmenite, spinel and chrome diopside recovered from sediment samples down ice from the kimberlites.

Extension, V, W, X, X1, Y, and Z) are normally polarized with the negative pole oriented to the north (e.g. kimberlite B1 in Fig. 6). The intensity of the magnetic response range from 150 nT to 1200 nT. One anomaly, U, has strong remnant magnetization (Fig. 6). It consists of a strong magnetic low (-750 nT) with a weak positive oriented toward the magnetic north. The strong

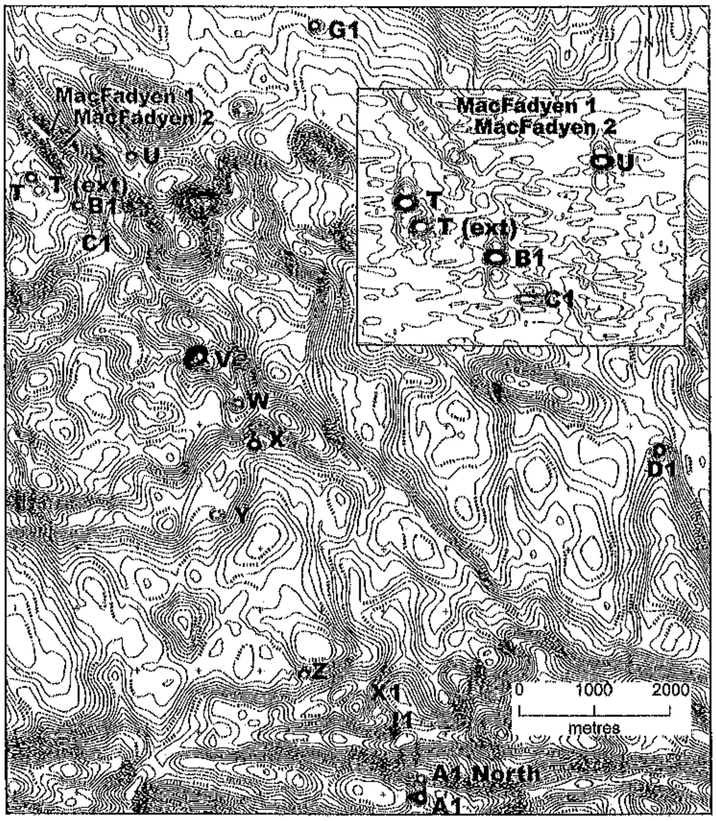

Figure 5. Aeromagnetic survey over the Attawapiskat kimberlites. The measured vertical gradient (inset) enhances the contacts of the kimberlites.

remnant magnetization demonstrates that this causative body intruded at a different time during a period of reversal in the Earth's magnetic field. The magnetic signatures for 12 of the anomalies have simple shapes that suggest each body reflects a single centre of intrusion. However, the signatures for 4 anomalies (A1 North, D1, T and the largest, V), are more complex and the bodies may be formed by a composite of 2 or 3 largely discrete intrusion centres. As shown in Fig. 7, the original aeromagnetic signature over V was resolved into two discrete anomalies (V South and V North) by the detailed ground magnetic survey. The large magnetic gradient on the south side of the anomalies suggests that the contacts are steep. Lower gradients on the north and west sides suggest more gradually dipping contacts. In the northwest, shallow gradients and weaker magnetic response may represent a separate blind intrusion or a buried extension of the exposed kimberlite to the immediate southeast.

Magnetic susceptibility readings were taken at 1 to 2 m intervals along the full length of all the core drilled from the kimberlites. The country rock limestone was found to be non-magnetic with no detectable susceptibility. Significant variations in susceptibility were observed in the kimberlite that could tentatively be correlated with the observed geology. Sections of the drillcore containing uncontaminated kimberlite gave average susceptibility readings of 1 X 10^{-4} SI units, while in kimberlite intersections with abundant country rock limestone fragments, the readings decreased by an order of magnitude. Thus, the individual readings were extremely variable highlighting the changes in xenolith content within the kimberlite.

Ground electromagnetic surveys and vertical electric soundings were completed over kimberlites A1, V, W, and X to evaluate the effectiveness of these methods to help locate kimberlites in this area. Borehole resistivity logging was completed for four holes in the W and V kimberlites. A Geonics EM34-3 Terrain Conductivity meter in a horizontal dipole configuration with readings recorded for intercoil spacings of 10, 20 and 40 m was used. Readings were taken at 25 m intervals along lines that are

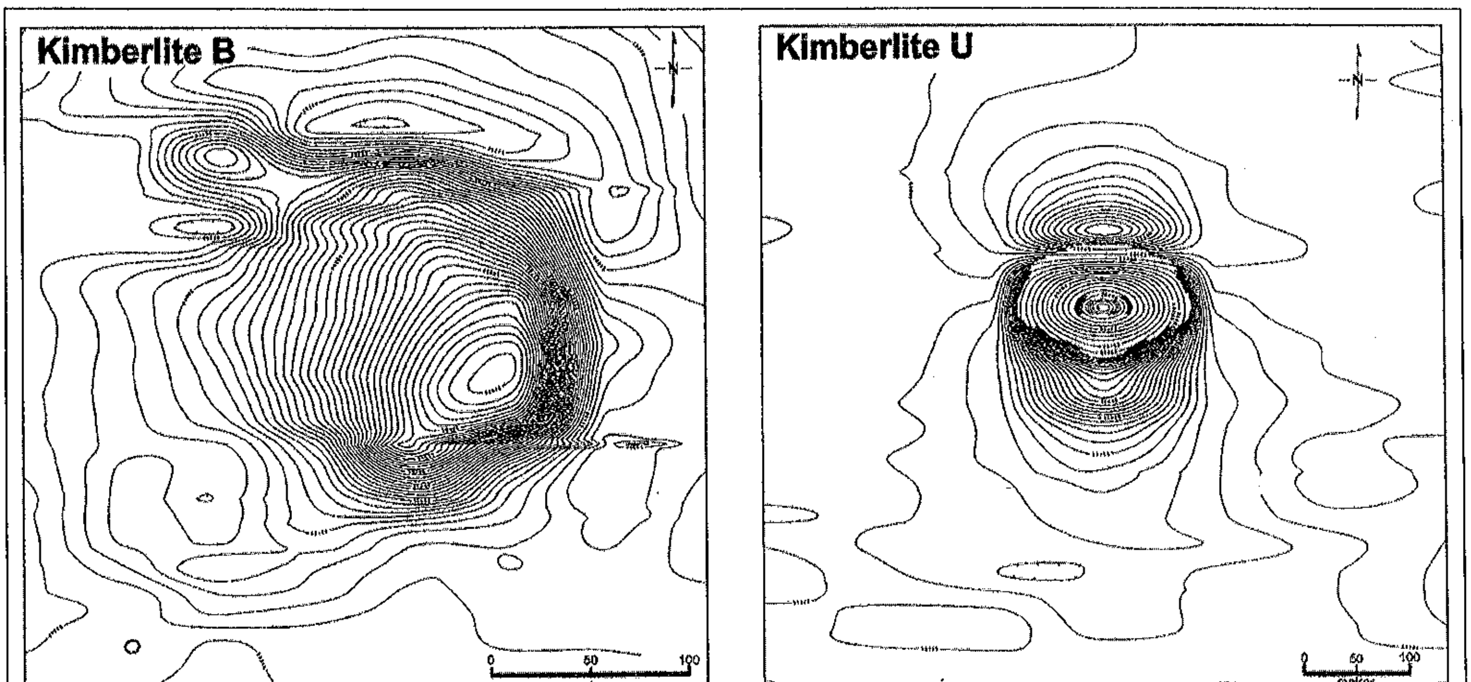

Figure 6. Detailed ground magnetic survey over kimberlites B1 and U. The magnetic signatures from the majority of the kimberlites are similar to the signature from Kimberlite B, which is normally polarized with the negative pole oriented to the north. Kimberlite U is reversely polarized with the negative pole oriented to the south.

spaced 100 m apart. No correlation exists between the mapped EM34-3 conductivity and the magnetic highs defining the kimberlite. An EDA IP-PLUS instrument was used for the electric soundings at 16 locations on and off the kimberlite bodies. Resistivity values for V, W, and X kimberlites are lower than those obtained from the surrounding sediments (211 ohm-m versus 670 ohm-m). While there are differences in resistivity between the kimberlite and the limestone, the background variability due to changes in overburden thicknesses and conductivity does not permit the successful use of electromagnetic surveys for detecting kimberlites in this area.

Detailed gravity surveys were conducted over the D1, T, and V kimberlites by Rideau Geophysics to test gravity as a viable cost effective method for detecting non-magnetic anomalies. Readings using a LaCoste and Romberg model G gravimeter were taken at 25 m intervals along 100 m spaced north-south lines. Both the D1 and V kimberlites produced good gravity anomalies that coincided with magnetic anomalies. A 0.5 mgal Bouguer gravity anomaly defined D1 and a model of an oval shaped body that is 300 m in diameter in the long axis and 250 m diameter in the short axis best represents the anomaly. A 0.4 mgal gravity anomaly coincided with kimberlite V. This anomaly modeled as 3 vertical cylinders with diameters of 125, 300 and 140 m. The T kimberlite was not detected because the density contrast between the limestone and the kimberlite is highly variable. Thus, gravity surveys are an ineffective method of searching for non-magnetic kimberlites in this area due to the density contrast variability and the high cost of the survey.

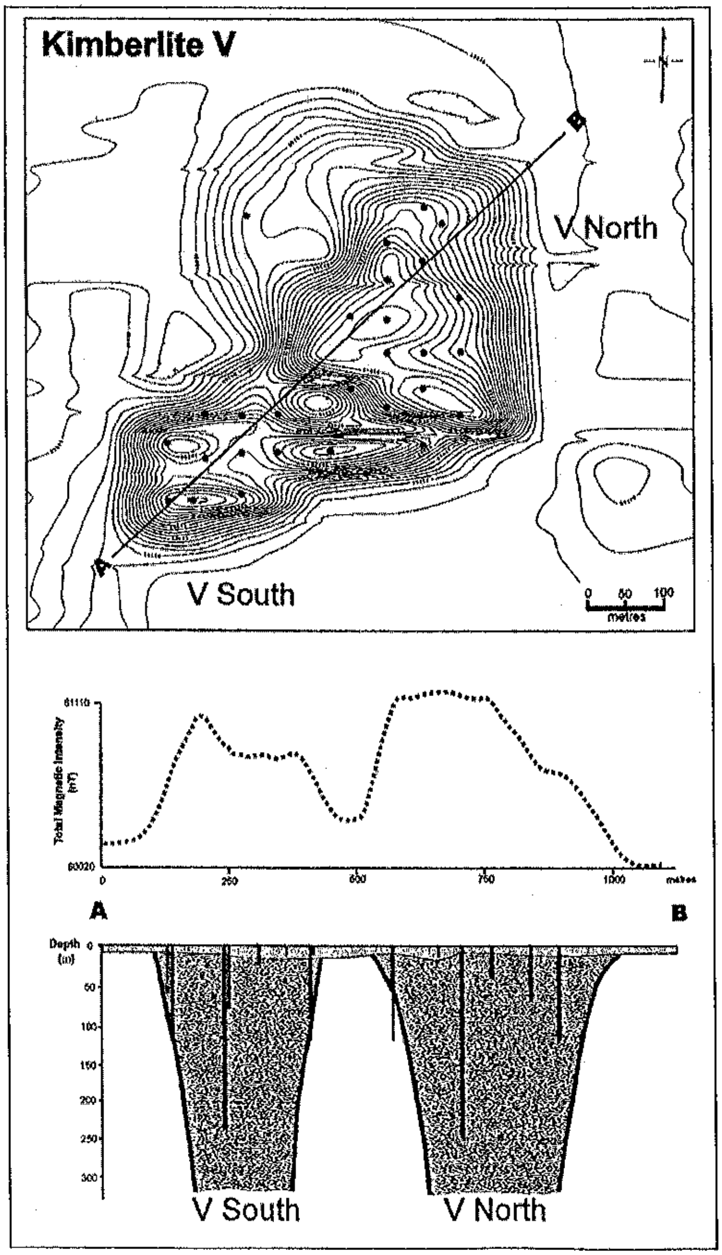

Figure 7. Detailed ground magnetic survey over Kimberlite V showing drillhole locations. The A-B cross section shows the magnetic profile, drillhole information, and inferred kimberlite contact.

3.3 Drilling and Results

The drilling in 1988 and 1989 confirmed 16 kimberlite pipes. In addition, 3 of the 15 anomalies modeled as basement features were drilled to test the geophysical modeling. These 3 holes encountered only limestone to a depth of 200 m where the holes were abandoned. A total of 29 holes was drilled into the kimberlites. At least 1 hole was drilled into each kimberlite. Two holes were drilled into A1 North, D1, and C1. Eight holes were drilled into V to ensure that representative samples would be obtained from the different intrusions suggested by the geophysics. The majority of these holes are vertical. Four holes, angled at 45° and drilled outwards from the centre of the pipe tested the size of the kimberlite W. The kimberlite was smaller than estimated from the ground magnetics. Two kimberlites (U and X) outcropped while the overburden, consisting of glacial sediments and limestone boulders, ranges from 5.5 to 54 m for the other pipes. Over 100 kg of core from each of 16 kimberlites were analysed for microdiamonds. All but one kimberlite (Y) proved to be diamondiferous.

Using the micro-diamond results, the petrographic and mineral chemistry rating, and the size, kimberlites B1, V, X and Z were bulk sampled for macro-diamonds in the spring of 1997. A total of 64 tonnes was collected using a reverse circulation drill.

KWG-Spider Resources subsequently conducted an airborne survey over the Attawapiskat kimberlites to calibrate their signatures and then flew additional surveys to the west-northwest. They discovered 7 additional kimberlites. Two, MacFadyen 1 and 2, are small bodies within the Attawapiskat cluster and 5 kimberlites, Kyle Lake 01 to 05, are scattered over an area 110 km to the west and southwest of the Attawapiskat cluster (Fig. 3). The Kyle Lake kimberlites are capped by 68 to 130 m of overburden and *in situ* Palaeozoic sediments and are not part of the Attawapiskat cluster.

Attawapiskat drillcore was made available to a number of geoscientists for research purposes. Moser and Krogh (1995) dated lower crustal xenoliths from the kimberlites. Over 60 xenoliths including tonalitic and amphibolitic gneiss, garnet-bearing amphibolite and tonalite, and garnet + clinopyroxene ± plagioclase mineral assemblages were studied. Preliminary results yielded a concordant U-Pb age of 2668 ± 2 Ma from monazite and a discordant minimum age of 1625 ± 100 Ma from a single grain of zircon. Schulze (1996) described mantle xenoliths from the Attawapiskat kimberlites that include coarse and deformed garnet, garnet-spinel and spinel peridotites, and rare eclogites. Also present is a newly identified type of mantle xenolith consisting of garnet, diopside and ilmenite megacrysts. Hetman (1996) studied 35 composite ilmenite-silicate xenoliths from the kimberlites. Ilmenite compositions between ilmenite-silicate megacrysts and macrocysts are similar and the rims of the grains contain high MgO. Sage (1997, pers. comm.) carried out an extensive study of the kimberlitic indicator mineral compositions and geochronology. Microprobe analyses were completed for approximately 200 grains of garnets, and 50-75 grains of ilmenite, chrome diopside and chromite, from all of the James Bay Lowland kimberlites.

4. GEOLOGY OF THE KIMBERLITES

4.1 Geochronology

Rb/Sr dating on phlogopite for five kimberlites was completed by C.B. Smith and E.S. Barton, at the University of Witwatersrand. Results gave model ages between 155 to 170 Ma and an emplacement age of 156 ± Ma for the A1 North and G1 kimberlites. More recent work supported by R. Sage (Ontario Geological Survey) and carried out by L. Heaman at the University of Alberta used U/Pb isotope dating techniques on perovskite that yielded the following ages: 179.9 ± 1.6 Ma for C1, 179.4 ± 2.2 Ma for B1, and 177.1 ± 2.0 and 177.3 ± 1.8 Ma for the MacFadyen 1 pipe (Sage, 1997). Kimberlite magmatism appears to have occurred over a relatively short period of approximately 15 Ma compared to the Lake Temiscaming-Kirkland Lake and Fort a la Corne kimberlite magmatism that spanned approximately 30 Ma (Sage, 1997; Scott Smith *et al.* 1998). To the south of the Attawapiskat pipes, the Selco intrusives yielded ages of 152 and 180 Ma using K/Ar techniques (Reed and Sinclair, 1991). The Kyle Lake kimberlites are much older with one body (Kyle Lake 01) dated at 1100 ± 40 Ma using Rb/Sr isotopic dating techniques on phlogopite (Sage, 1997). The other Kyle Lake bodies are assumed to be the same age based on their geological similarities and location below Palaeozoic cover rocks. The Bachelor Lake kimberlites in Quebec are of similar age and their emplacement may relate to the collision of the Grenville and the Superior Provinces and the development of the Midcontinent rift.

4.2 Rock type classification

The Attawapiskat bodies are composed of rocks that have macrocrystic textures. Olivine macrocrysts (mostly <5 mm, up to 10 mm in size) are common to abundant and frequently unaltered. These grains are mostly anhedral to rounded in shape. They are often polycrystalline and/or display features such as undulose extinction that indicate most of these grains are xenocrysts derived from mantle peridotites. Other mantle-derived xenocrysts are also common and include ilmenite, garnet, chrome diopside, mica and spinel as well as occasional megacrysts (>1 cm) of chrome diopside, olivine and mica. Mantle-derived xenoliths are present but are not common. The two generations of olivine that are diagnostic of kimberlites are present. In addition to the olivine xenocrysts described above, there are common smaller (typically <0.5 mm) euhedral phenocrysts. The above constituents are set in fine grained groundmasses that contain carbonate, serpentine, spinel and lesser monticellite, mica, apatite and perovskite. The carbonate occurs as tabular lath-like grains and/or as an equigranular mosaic in interstitial areas. Both types of carbonate appear to be primary groundmass constituents of the rocks. Spinels occur as fine cubic grains (<0.1 mm), some of which have atoll textures. Serpentine is typically isotropic or cryptocrystalline. Monticellite is often fresh but may be altered to serpentine. The fine monticellite grains (<0.05 mm) impose a sugary texture on the areas of the groundmass where this mineral is abundant. Perovskite occurs as small brown grains (<0.2 mm) but is not common and locally is atypically coarse grained (up to 0.7 mm). Based on their mineralogy the rocks at Attawapiskat are classified as kimberlites (sensu stricto, Woolley *et al.*, 1996).

4.3 Mineralogical classification

The kimberlites within the Attawapiskat province have remarkably uniform groundmass mineralogies within the context of the generally wide range of modal mineralogies of kimberlites. The Attawapiskat rocks are mostly dominated by groundmass carbonate and spinel ± serpentine. Monticellite, mica and perovskite are usually less common. The two main mineralogical rock types are spinel carbonate kimberlite and monticellite kimberlite. The most common rock type is spinel carbonate kimberlite. The abundance of carbonate throughout the kimberlites within this province is unusual compared to kimberlites worldwide.

4.4 Mantle-derived Indicator Minerals

Most of the Attawapiskat kimberlites contain abundant ilmenites, and moderate quantities of garnets, chrome diopsides and spinels. However, there are exceptions. Kimberlites A1 North, B1, C1 and T have indicator mineral suites consisting mainly of garnet and spinels with only rare ilmenites present. There is no correlation between indicator mineral variability and microdiamond results.

The garnets in these kimberlites are predominantly xenocrysts but a significant number of garnet megacrysts are present. The kimberlites contain peridotitic garnets that fall along the lherzolite trend and are classified as G9 and G10 varieties (Gurney, 1984). As calcium saturation in garnets is dependent on pressure, the G10 grains are most likely high pressure lherzolite garnets (Fipke *et al.*, 1995). No harzburgitic garnets with very low CaO contents were recovered (Fig. 8). Eclogitic garnets are rare. The ilmenites contain very high MgO (9 to 14 wt%) and Cr_2O_3 (2 to 10.5 wt%), and low Fe^{3+}/Fe^{2+} ratios. According to Gurney and Moore (1991), such compositions indicate a potential for good diamond preservation. The kimberlites contain high Cr-Ti chromites and moderate to high Cr and low Ti chromites that are usually associated with kimberlites (Fipke *et al.*, 1995). A few grains with compositions similar to diamond inclusion chromites were found. The presence of sub-calcic garnets and chromites similar to diamond inclusions indicates that the kimberlites have sampled within the diamond stability field. However, the low abundance of high interest grains suggests only limited sampling within the diamond window. All major element analyses were completed at the De Beers Geoscience Centre in Johannesburg using an ARLSEMQ microprobe. The indicator minerals were selected from heavy mineral concentrates, set in epoxy mounts and analysed for 10 seconds.

Application of the garnet nickel thermometer of Griffin *et al.*, (1989) suggests derivation of the garnet xenocrysts from areas within the mantle. Temperatures range from 426 to 1314 °C. However, the majority falls within 750 to 1200 °C and poorly defines a geotherm of 37 mW/m^2. A similar conclusion was reached by Schulze and Hetman, 1998 who analyzed ten mantle xenoliths. A low geotherm for the Attawapiskat area is indicated. In terms of incompatible trace element compositions, the garnets are not depleted. Although they are enriched in Y and Ga, no obvious correlation exists between Y and Zr to suggest late stage melt metasomatism.

4.5 Textural classification

The terminology used in this section is that of Field and Scott Smith (1998b). Most of the kimberlites are medium grained macrocrystic rocks but less common coarse grained macrocrystic rocks and some sparsely macrocrystic rocks are also present. The kimberlites contain conspicuous angular country rock xenoliths but they are seldom abundant. The xenoliths are dominated by limestone. Only minor parts of the intrusions can be termed limestone-lithic kimberlite breccias. The kimberlites can be subdivided into two groups that have different textures.

The first group of rocks is composed of uniformly distributed, matrix supported olivines set in magmatic groundmasses that are relatively well crystallised and composed of carbonate, spinel, serpentine and lesser monticellite, mica, apatite, and perovskite. These rocks are hypabyssal kimberlites (HK, Fig. 9 e,f). They have uniform to fine irregular segregationary groundmass textures. The latter rocks commonly contain irregular pool-like segregations that are composed of serpentine and/or carbonate. This group of rocks mostly can be classified as medium grained macrocrystic uniform to segregationary textured hypabyssal kimberlites.

The second textural group of rocks (Fig. 9 a-d, 10, 11) is composed of abundant clast supported discrete olivine grains and less common magmaclasts (discrete small bodies of magma). These rocks are considered to be pyroclastic (see later discussions). The olivine grains are fresh, even in the more altered rocks. The discrete grains of olivine are predominately anhedral macrocrysts but some olivine phenocrysts (euhedral grains) are present. Relative to the abundance of macrocrysts, the proportion of olivine phenocrysts present is lower than that in most kimberlites. However, in the hypabyssal kimberlite and within the pyroclastic kimberlite magmaclasts the olivine size distribution is typically kimberlitic. The magmaclasts are round to ovoid in shape and mostly less than 1cm in size (up to 3 cm). Some magmaclasts have more irregular curvilinear shapes. The magmaclasts are composed of two generations of olivine set in groundmasses composed mainly of carbonate, serpentine and spinel. Some magmaclasts contain kernels, usually an olivine grain. The magmaclasts are set in an inter-clast matrix composed mainly of magma-derived minerals specifically isotropic serpentine ± carbonate. This group of rocks can be classified as medium grained macrocrystic magmaclastic kimberlites. From a genetic point of view, interpretation of these magmaclastic textures is not straightforward.

A number of features of the Attawapiskat kimberlites show that these rocks are not classical tuffisitic kimberlite breccias that typically infill the diatreme zones of kimberlite pipes (Field and Scott Smith, 1998a). These features include the presence of fresh olivine, the presence of primary carbonate within the magmaclasts and in the inter-clast matrix, the paucity of country rock xenoliths, and the absence of both pelletal lapilli and quenched microlitic clinopyroxene. The magmaclastic textures at Attawapiskat fall in the difficult area of petrographic textural overlap between globular segregationary hypabyssal kimberlite (HK) and pyroclastic kimberlite (PK). In general, features that might aid in the textural classification of these rocks are poorly developed.

The groundmasses within some of the magmaclasts contain well crystallized tabular grains of carbonate and cubic grains of spinel. The apparent well crystallized nature of these components is a feature typical of hypabyssal kimberlites. This feature, the generally rounded shape of the magmaclasts, and the presence of a magmatic inter-clast matrix result in these rocks resembling hypabyssal globular segregationary textured kimberlites. However, carbonate can crystallise very rapidly relative to the silicate minerals in kimberlites, and the texture observed here need not be formed in a hypabyssal environment. Also, some features in these rocks are not characteristic of globular segregationary kimberlites. Most importantly, discrete grains of olivine are common, often occurring in greater abundances than the magmaclasts, and the spherical magmaclasts are composed predominantly of carbonate. In globular segregationary kimberlites most, or all, of the carbonate occurs in the inter-globule matrix and the olivines are confined to within the globules where they are set in a carbonate-poor, relatively silica-rich, groundmass. Thus, the magmaclasts at Attawapiskat do not appear to be

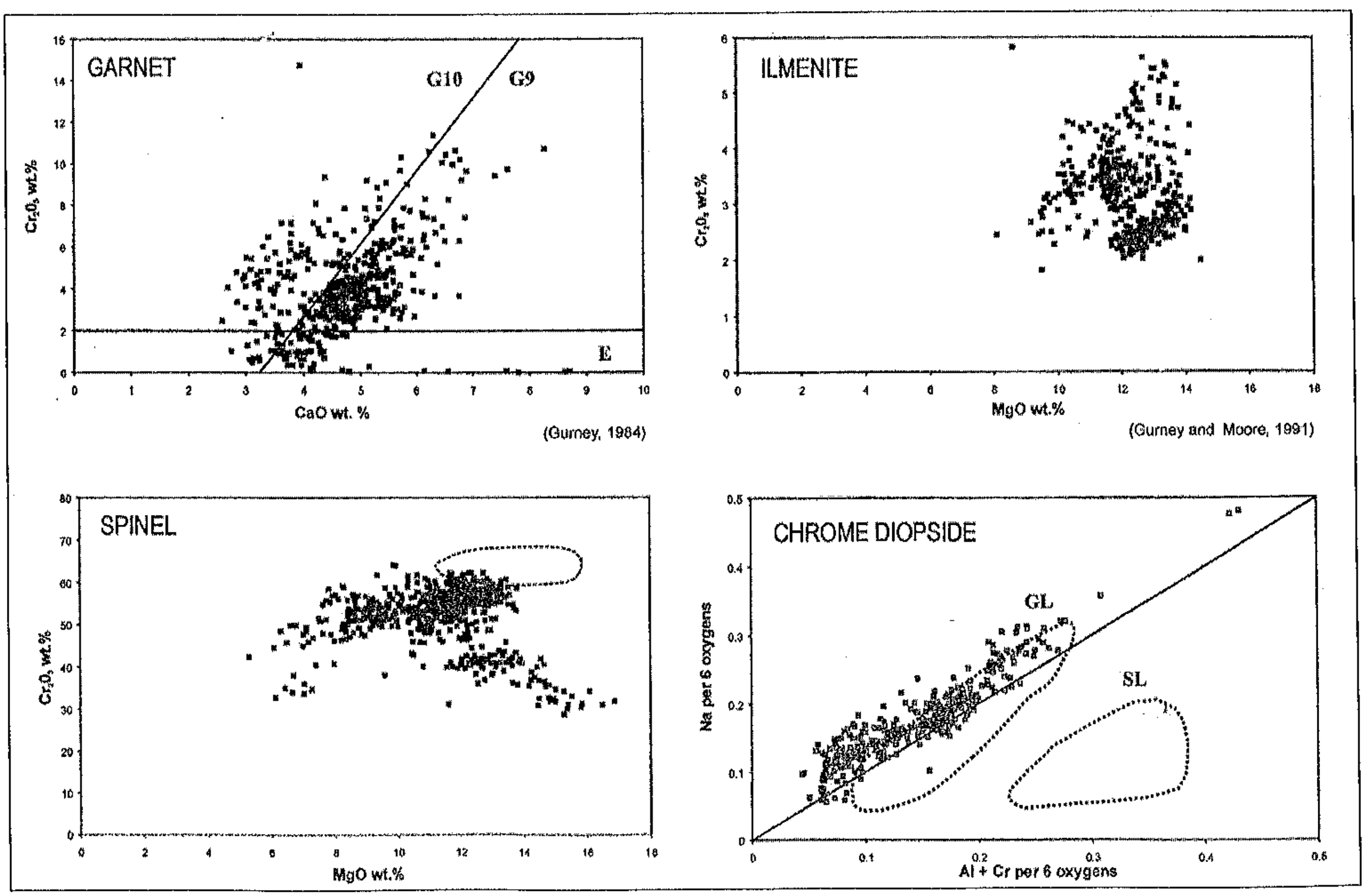

Figure 8. Composition of garnet, ilmenite, spinel and chrome diopside recovered from the Attawapiskat kimberlites.

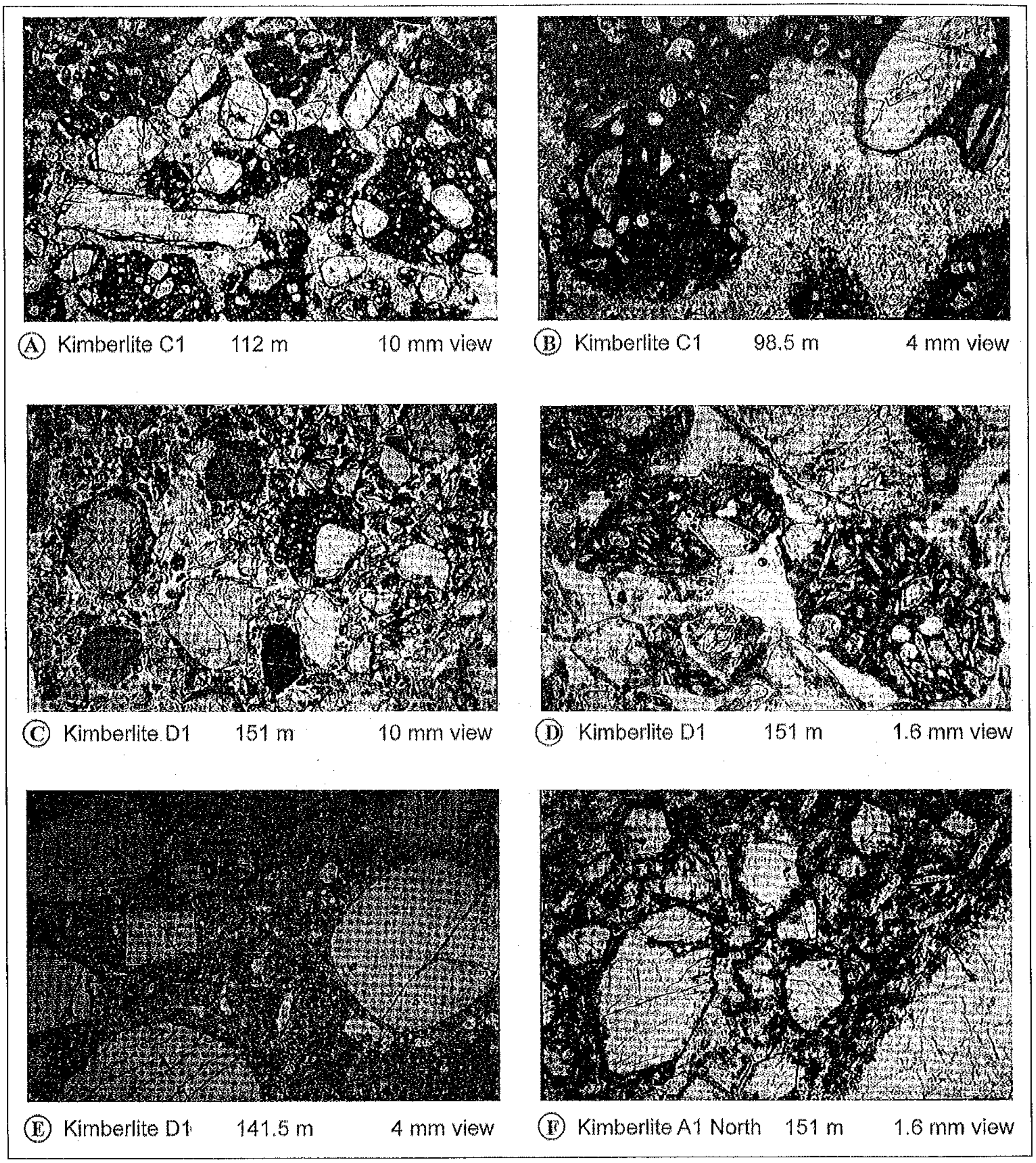

Figure 9. Ⓐand ⒷPyroclastic monticellite kimberlite with common amoeboid juvenile lapilli, rare single olivine xenocrysts, interclast carbonate, and minor serpentine. In Ⓑ, the lapillus contains a few vesicles and phlogopite.

Ⓒ and Ⓓ Pyroclastic spinel carbonate kimberlite composed of discrete olivine grains and less common rounded juvenile lapilli. The kimberlite has clast supported, loosely packed texture. The juvenile lapilli contain abundant carbonate (as laths and as interstitial base), spinel and some vesicles. No monticellite is present. The interclast matrix is serpentine.

Ⓔ and Ⓕ Typical hypabyssal kimberlite with 2 generations of olivines: anhedral macrocrysts and anhedral phenocrysts set in groundmass composed of spinel, carbonate laths and interstitial carbonate.

globular segregations formed in a hypabyssal setting. Other features consistent with this conclusion are the overall lack of reaction in the country rock xenoliths and the clast supported textures. It should also be noted that globular segregationary textured kimberlites are not a common rock type and are unlikely to form the main infill of any pipe or be a major rock type in a kimberlite province.

Some features of the Attawapiskat kimberlites are more characteristic of volcaniclastic kimberlites and are difficult to explain by processes other than those responsible for infilling volcanic craters. These features include :

(1) the *presence of* irregular curvilinear and more amoeboid-shaped magmaclasts (Fig. 9a,b) with re-entrant embayments that are a hallmark of certain pyroclastic kimberlites (Scott Smith *et al.*, 1998); clast supported textures; quenched groundmasses (e.g. cryptocrystalline carbonate); vesicles within the magmaclasts; the presence of small and large scale sorting; the occurrence of normally graded beds (Fig. 10) up to 1-2 m thick (clast sizes in different areas vary from <0.5 to >10 mm); the variation in proportion of magmaclasts within one phase of kimberlite; rare broken lapilli; and the presence of xenoliths of now eroded country rock, and

(2) the *lack of* kimberlite selvages on most limestone xenoliths and the paucity of fine single grains of olivines.

The features listed above suggest that the magmaclastic rocks at Attawapiskat are volcaniclastic kimberlites (VK). The magmaclasts are interpreted as juvenile lapilli that formed from pyroclastic eruptions. The same process liberated the single grains of olivine that are prominent components of this group of rocks. Some of the above features and other observations suggest that the final deposition of most of this material was by primary pyroclastic processes. The latter features include :

(1) the *presence of* common horizontal fabrics; the occasional moulding of magmaclasts against xenoliths; concentrations of finer clasts on top of, but not below, large clasts such as xenoliths (i.e. draping, Fig. 11); rare examples of *in situ* impact brecciation of country rock xenoliths, magmatic inter-clast matrices often with textures suggestive of crystallisation in voids; the overall uniform nature of this rock type; loosely packed textures; one possible impact sag; a single probable composite juvenile lapillus, and

(2) the *absence of* fines (whether juvenile ash or derived from exotic material), widespread sorting and common sedimentary structures, breakage of fragile constituents, country rock material that should have been present in crater rim deposits.

This group of the Attawapiskat rocks is interpreted as magmaclastic kimberlites. They are classified as lapilli-bearing olivine crystal pyroclastic kimberlites. If standard volcanic terminology is applied to these rocks they can be described as lapilli-bearing crystal or olivine tuffs. There is no evidence of resedimentation involving reworking of crater rim deposits.

Based on the available evidence and the above discussion, it is tentatively concluded that the Attawapiskat bodies are composed of both hypabyssal kimberlite (HK) and pyroclastic kimberlite (PK) but it must be noted that some aspects of the geology of these bodies are not understood. Although the list of features suggesting the volcaniclastic and pyroclastic nature of some of

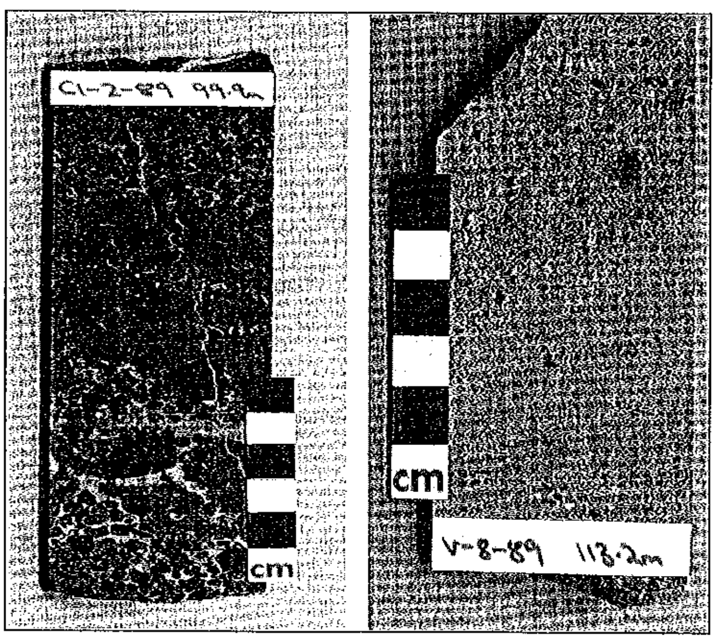

Figure 10. Graded bedding found in Kimberlite C1 and V.

Figure 11. Sorting and draping of fine grained olivine phenocrysts in pyroclastic monticellite kimberlite. Note the amoeboid shapes of the lapilli at the bottom of the micrograph.

the Attawapiskat kimberlites is convincing, none of the features described is as well developed as those observed in some other pyroclastic kimberlites such as the Fort a la Corne pipes (Scott Smith *et al.*, 1998). Furthermore, in a few instances at Attawapiskat, it appears that PK occurs below HK (although the latter might reflect younger sill-like intrusions). Such observations suggest that the textural interpretations may be more complex than is proposed in this paper.

4.6 Country rock geology

In the vicinity of the kimberlites, regional data suggest that the flat lying Palaeozoic sediments are approximately 250 m thick (Norris, 1986). Composite information from Monopros drill hole data and regional data suggests that the country rock sediments consist mainly of light grey to tan coloured massive microcrystalline Ordovician limestone and dolostone with a basal sandstone-siltstone unit that unconformably overlies basement rocks (Fig. 12). Between 55 to 123 m from surface, tan to brown fossil-

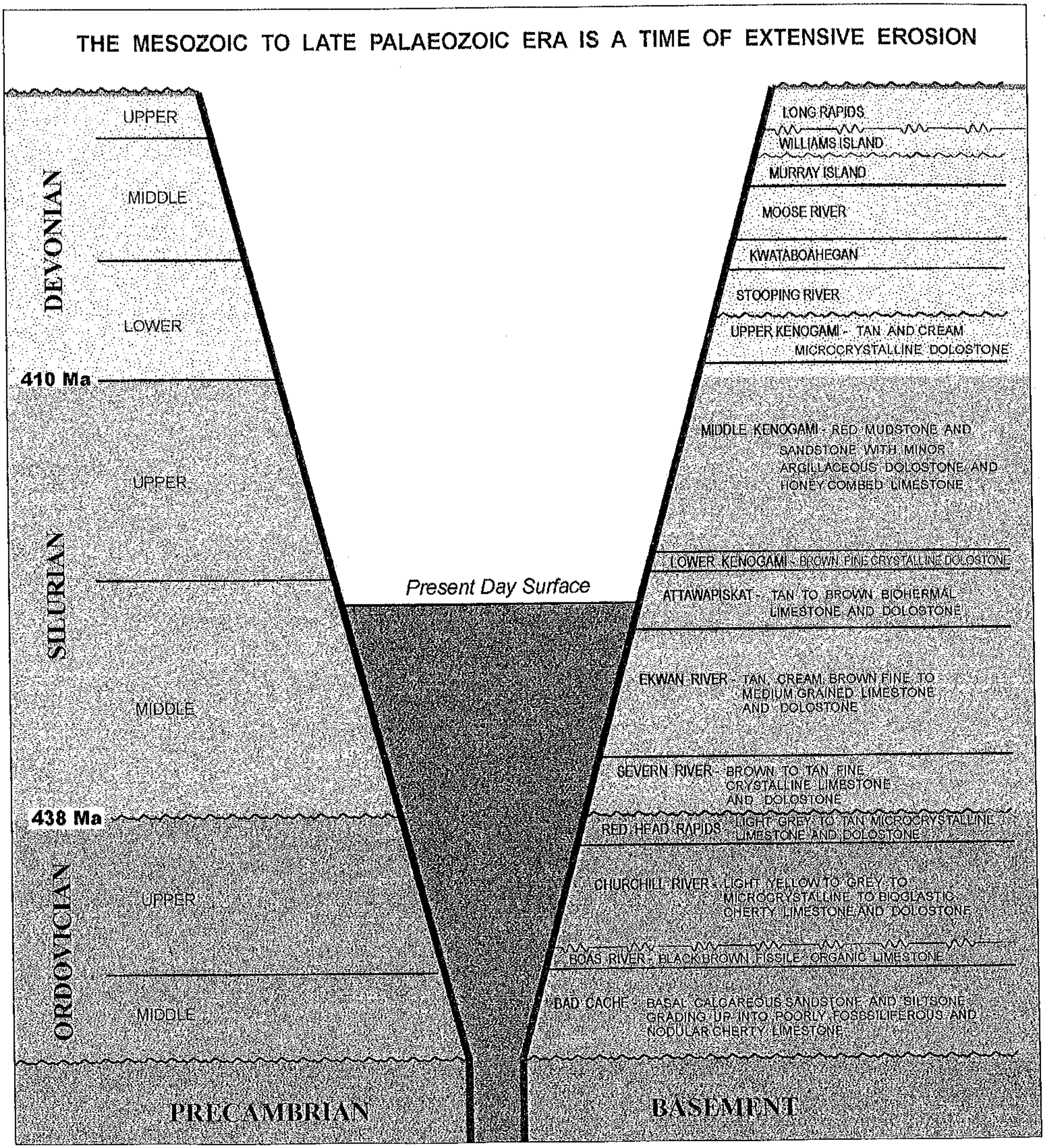

Figure 12. Stratigraphy in the vicinity of the Attawapiskat kimberlite pipes.

iferous limestone of the Attawapiskat Formation; tan, cream and brown fine to medium grained limestone and dolostone of the Ekwan Formation; brown to tan fine crystalline limestone of the Severn River Formation and, probably a basal green mudstone and shale unit unconformably overlie the Ordovician sediments. The Kenogami formation (consisting of brown crystalline dolostone, red mudstone/sandstone and tan to cream microcrystalline dolostone) must have once overlaid the now exposed Attawapiskat Formation as xenoliths from the Kenogami Formation are preserved in some of the Attawapiskat kimberlites. Devonian sediments were once present in the area but have been eroded due to the continued uplifting of the Cape Henrietta Maria Arch (Norris, 1986). The late Palaeozoic to Mesozoic era was a time of extensive erosion in this area (Johnson *et al.*, 1991). As the pipes intruded in the Jurassic, the kimberlites were apparently emplaced in subaerial conditions.

4.7 Pipe geology

Each body within the Attawapiskat province is dominated by one of the two mineralogical types of kimberlites. For example, bodies A1 North, A1, B1, G1, I1, V North and V South are spinel carbonate kimberlites while bodies C1 and U are monticellite kimberlites. Both mineralogical varieties occur as PK and HK, the two main textural types found at Attawapiskat. At least six of the bodies are composed of fairly uniform HK, for example A1, A1 North, B1, U, X1 and Y. These bodies range in apparent size up to 6-7ha. In a few instances typical HK grades into volumetrically minor magmaclastic textures. Where this occurs in the uppermost part of the body it appears to reflect a gradation from HK to PK towards surface. In other areas of the bodies, a similar gradation appears to reflect a change from uniform to segregationary hypabyssal textures. Textural differences between these two types of magmaclastic rocks support the contrasting interpretations.

At least eight of the bodies are composed mainly of PK. These bodies are C1, G1, T Extension, X, V South, and the largest V North. Bedding is best developed in bodies V North and C1 (Fig. 10 and Appendix 1). Bodies V North and V South are composed of spinel carbonate PK (Appendix 1), a major rock type in the Attawapiskat province. The carbonate rich juvenile lapilli in these rocks have consistently rounded shapes (Fig. 9c,d). In contrast, the monticellite PK contains juvenile lapilli that frequently have distinctive amoeboid shapes (Fig. 9a,b). Monticellite PK is a minor rock type at Attawapiskat but is the main rock type in body C1 (Appendix 1). Based on geophysics, body C1 appears to be less than 1ha in size. Interestingly, body C1 is one of the smallest bodies in the Attawapiskat province yet it is composed of PK to a depth of at least 125 m. This body also includes some of the best evidence that the magmaclastic rocks at Attawapiskat are PK (Appendix 1).

The internal geology of most of the Attawapiskat bodies is simple. Variations in the proportion of macrocrysts and the nature of the groundmasses are among the few features that suggest both textural types of bodies may have been formed by more than one phase of kimberlite. A few pipes do display more complex internal geology such as D1 which is briefly described in the Appendix. Body D1 is a rare example where both mineralogical varieties of kimberlite occur together within the same body. Furthermore, each mineralogical variety has a different texture; spinel carbonate PK and monticellite HK.

The xenoliths at Attawapiskat are dominated by angular limestone that occurs in a variety of colours and textures suggesting that they derive from different stratigraphic horizons in the country rock. The xenoliths are most commonly pale cream coloured limestone (mostly <10 cm but frequently larger) that vary in modal abundance. These pale coloured xenoliths are probably derived from the uppermost country rock limestone, that have been eroded subsequent to kimberlite intrusion. The limestone xenoliths in HK include a higher proportion that display zonal alteration due to reaction with the host magma than those in the VK. Minor dark basement xenoliths are present and often zonally altered. Small green xenoliths appear to be composed of shale. In body G there are frequent distinctive xenoliths of red mudstone between 63-105 m from surface. The likely source of these xenoliths is the Kenogami Formation which in the Attawapiskat area must have been eroded after kimberlite emplacement (Fig. 12). Kimberlite G1 contains most of the rare examples of autoliths of HK within PK. One +/-30 cm autolith of coarse grained VK occurs in the upper part on one of the HK bodies (A1).

5. EMPLACEMENT MODEL

5.1 Volcaniclastic kimberlites

Individual pipes infilled predominantly with PK vary from <1 ha up to 15ha in size for V North. Limited information suggests that the pipe walls are steep and in kimberlite V they appear to dip at ~70° (e.g. Fig. 7). PK occurs to a depth of at least 240 m in this pipe. Country rock xenoliths are not abundant in the Attawapiskat kimberlites. This feature suggests that the pipes must have been excavated prior to being infilled by juvenile-rich PK. Thus there are two separate processes: (1) pipe excavation and (2) pipe infilling. The nature of these two stages is considered further below.

The cause of the pipe excavation is not easily determined. Following the concepts proposed by Field and Scott Smith (1998a) for kimberlites, there are two end member processes by which kimberlite pipes form: (1) by phreatomagmatic driven maar-like processes as found in Saskatchewan that form only craters with no underlying diatreme and (2) the intrusive-extrusive fluidisation processes driven by juvenile gases, mainly carbon dioxide, that form diatremes with overlying explosion craters, as commonly found in southern Africa. At Attawapiskat, there is no direct evidence to indicate which of these processes was responsible for excavating these pipes. The apparent steep sided pipe shapes may be comparable with the southern African diatremes. However, diatreme-facies kimberlites or any similar pyroclastic products have not been encountered at Attawapiskat. Importantly, the juvenile lapilli are composed dominantly of carbonate at Attawapiskat which contrasts with the distinctive lack of carbonate in the typical infilling of kimberlite diatremes and the associated craters that reflects the pervasive degassing from the fluidised system that forms the diatreme. The PK that infills the Attawapiskat pipes does not appear to have passed through the fluidisation process. Also, some pipes are infilled with HK. If any diatreme-forming fluidisation process occurred at Attawapiskat, all or most of the products formed by this process must have been removed from the pipes.

The pipes are infilled predominantly with PK suggesting that they are explosion craters. Therefore, the pipes may have formed by phreatomagmatic processes. This type of process is generally thought to be driven by meteoric water that typically derives from an aquifer in the country rock. During phreatomagmatic crater or maar excavation, the resulting disrupted country rock material is deposited mainly outside the crater. The crater rim material is composed mainly of base surge deposits with specific characteristics that provide the main evidence for the crater excavation process. Given the lack of preserved crater rim deposits at Attawapiskat, there is no direct evidence to allow evaluation of the crater forming process. The nature of the country rock and parts of the pipe infill are, however, relevant in providing indirect evidence of pipe formation.

The main country rock at Attawapiskat is well consolidated Palaeozoic limestone. Some different overlying strata appear to have been eroded since emplacement but the amount of erosion is not known. Aquifers can only accumulate in limestone when it is porous or fractured. From the limited information on the nature of the local limestone neither of these possibilities appear to pertain to this area. In phreatomagmatic eruptions the excavated craters flare from the area where the magma interacts with water in an aquifer. The deepest PK recovered derives from 240 m. This is close to the suggested, but poorly constrained, interface of the Palaeozoic sediments and the underlying basement. The limited data also suggest that a basal unit of calcareous sandstone and siltstone unconformably overly the Precambrian basement (Fig. 12) as well as in the deeper parts of the overlying sediments, shale and sandstone are intercalated with the limestone (Johnson, 1991 and Cumming, 1975). These rocks may have included an aquifer. Another possibility is that local aquifers could be formed in fractured limestones formed by the long lived faults that are known to occur in this area (e.g. Suchy and Stearn, 1993).

If the Attawapiskat bodies are phreatomagmatic maar-like craters they appear to have steeper walls and lower diameter to depth ratios than are typical of maars. The available information for two separate pipes at V suggests steep kimberlite to country rock contacts (>60-75°). One of these bodies has a diameter of ±350 m with pyroclastic kimberlite present to 240 m. The apparent diameters of the smaller bodies and the depth to which kimberlite has been encountered within them suggests that they are similar steep sided pipes. In contrast most maars are shallower basin-shaped craters.

The second and separate stage of maar-like pipe formation, after crater excavation, is the pipe infilling. The features observed in body C1 (Appendix 1), especially when compared to the Fort a la Corne kimberlite (Scott Smith *et al.*, 1998) suggest that these rocks are primary pyroclastic deposits which are considered to result from sub-aerial Hawaiian style eruptions (lava spatter to lava fountains). The paucity of fines could reflect the fact that such constituents were not produced and/or the fines were lost from the dry eruption cloud by wind processes. Although the VK in some of the other bodies is also thought to have been produced and deposited by pyroclastic processes, insufficient evidence precludes comment on the styles of eruption.

In the light of the processes postulated above, it is interesting to consider the nature of the erupting magma further. The Attawapiskat kimberlites are unusual in that they are dominated by groundmass carbonate. Petrographically this carbonate appears to be primary but consideration needs to be given to the possibility that this carbonate may be derived by assimilation of the limestone xenoliths into the kimberlite magma. Firstly the limestone xenoliths are not abundant. Also, many of the xenoliths may not have been resident in the kimberlite magma as most of them appear to be derived from the upper crater walls and to have been incorporated in PK after crater excavation. Although some zonal alteration is evident among these xenoliths, overall they display a notable lack of reaction with the host kimberlite. This feature also holds for the Attawapiskat HK where the limestone xenoliths must have been resident in the magma even if only for a short time prior to consolidation. It is therefore deemed unlikely that any of the groundmass carbonate derives from this, or any other secondary source. In turn this suggests that the erupting magma was composed mainly of xenocrysts enclosed in a melt that ultimately crystallised mainly as carbonate.

Given the high primary carbonate content of the Attawapiskat kimberlites, it would seem likely that this type of magma has the greatest potential amongst kimberlites generally to form diatremes. Diatremes form by processes that involve the extensive degassing of carbon dioxide from magmas temporarily trapped below surface under barriers of cap rocks (Field and Scott Smith, 1998a). The lack of diatremes sensu stricto may reflect two different aspects of the Attawapiskat situation. The first aspect is related to the nature of the country rock. The absence of an igneous barrier and the presence of faults did not allow subsurface buildup of juvenile volatiles and the development of diatremes. The second aspect of the Attawapiskat province is the nature of the magmas and the abundance of carbonate itself. The magma, when it reached near surface, carried a large proportion of xenocrysts and early formed phenocrystal olivines enclosed in a melt that crystallised mainly carbonate. The melt fraction of the magma could be classified as a carbonatite if based only on the simple definition that carbonatites contain more than 50 % carbonate. The fluidal part of the erupting Attawapiskat magma is comparable to carbonatite magmas and their eruption products. From a volcanological point of view, there is probably a similarity between the Attawapiskat carbonate-rich kimberlites and carbonatites. In this sense it is noteworthy that carbonatites often erupt without extensive degassing of carbon dioxide. This feature appears to contrast with the more typical kimberlites that are richer in silica and that degas near surface (Dreibus *et al.*, 1995).

Carbonatitic melts differ significantly from silicate magmas since they contain little silica, alumina or water. It has been suggested that carbonatitic magmas have very low viscosities, near that of water or light machine oil (Treiman, 1989). This feature explains the dominantly rounded shape of the Attawapiskat juvenile lapilli that are comparable to the tear-drop lapilli found in carbonatites (e.g. Fig. 4.1 of Keller, 1989) and that contrast strongly with the often amoeboid shaped juvenile lapilli in more silicate-rich pyroclastic kimberlites such as at Fort a la Corne (Scott Smith *et al.*, this volume). In this context it is no coincidence that the best development of amoeboid shaped lapilli at Attawapiskat is in body C1. Body C1 is one of the few kimberlites, especially among the PK, that contains significant modal proportions of groundmass monticellite reflecting a more 'normal' relatively silica-rich kimberlite magma than is typical of the Attawapiskat province. The nature of the erupting magmas and the lack of degassing of carbon dioxide from them together would also explain the general lack of vesicles in many of the Attawapiskat kimberlites.

Lorenz *et al.* (1997) report the occurrence of spherical vesicle-poor 'carbonatitic' pyroclasts in pipes in the Gross Brukkaros volcanic field in Namibia. The pyroclasts here also indicate a lack of exsolution of volatile phases during formation and before quenching. Lorenz *et al.* (1997) interpret these, and other features, as suggesting that degassing was not responsible for the formation of the pyroclasts but rather that they formed by fragmentation of the explosive magma. The surface tension of these fluidal magmas forced them into a spherical shape. The origin of these pyroclasts is very similar to that proposed here for Attawapiskat. Keller (1989) noted that in other carbonatites 'drop-shaped' lapilli represent near surface vent-facies deposits of moderately explosive activity that can be compared to Hawaiian and Strombolian-style eruptions of silicate magmas.

These styles of eruption have also been proposed for the Fort a la Corne kimberlites (Scott Smith *et al.*, 1998). Such eruptions are likely to have produced the PK rocks found at Attawapiskat. Keller (1989) also noted that some carbonatites appear to have formed by maar-like phreatomagmatic processes and that such processes may be widespread among carbonatites. Erupting carbonatitic magmas are extremely fluid (Keller, 1989) which allows them to flow at surface. It is interesting to consider whether any of the HK that occurs within PK in the more internally complex bodies (such as body D1, Appendix 1) could perhaps be magmatic kimberlite that either invaded the PK or formed a lava lake over PK during pipe infilling. Such possibilities are consistent with the horizontal fabric that often occurs in the HK. Interestingly, these discussions imply that carbonate-rich kimberlite magmas such as those that occurred at Attawapiskat have the greatest potential among known kimberlite compositions of forming kimberlite lavas.

It must be emphasized that the above comparison of the volcanological aspects of carbonatites and the carbonate-rich kimberlites at Attawapiskat does not imply any petrogenetic relationship between the two. The Attawapiskat rocks show none of the other features given in definitions of carbonatites (Bell, 1989). The Attawapiskat rocks are carbonate-rich kimberlites. Haggerty (1989) concludes that kimberlites and carbonatites may be distant relatives but they are not brethren. Mitchell (1986) notes that the presence of primary groundmass carbonates in both kimberlites and carbonatites is indicative, not of a genetic relationship, but of their common origin within the upper mantle. Wyllie (1989) concurs with Mitchell's views and suggests that the petrogenetic link between kimberlites and carbonatites lies in their paths through the peridotite-kimberlite-nephelinite-carbonatite system. Further discussion of this aspect of kimberlites and carbonatites is beyond the scope of this paper (cf. Barker, 1989). It would be interesting to consider why the more typical silicate kimberlites are so poorly represented at Attawapiskat compared to most other kimberlite provinces. Very carbonate-rich kimberlites most often are extreme mineralogical varieties within provinces of kimberlites and are volumetrically minor relative to the more typical kimberlites in such provinces.

The Selco pipes to the southeast are similar in age to the Attawapiskat pipes. Both groups of pipes are composed of carbonate-rich rocks that often fall within the overlap of kimberlite and melnoites (Scott Smith, 1995). Interestingly, the Attawapiskat pipes are true kimberlites while the Selco pipes are melnoites. Another large area of carbonate-rich rocks has been recognised in West Greenland (Mitchell *et al.*, 1998). The latter were initially thought to be kimberlites but are now considered to be melnoites.

5.2 Hypabyssal kimberlites

Hypabyssal kimberlites form pipes of a significant size (up to ~6-7 ha) at Attawapiskat. Some of the HK bodies appear to be larger than the smallest PK-infilled bodies such as pipe C1. It was suggested above that the PK dominated pipes are formed by two separate processes, pipe/crater excavation and pipe infilling. In this context it is interesting to consider the emplacement of the HK pipes. The HK clearly occur at the same elevations within the country rock where the PK bodies occur. The HK infilled apparently similar steep sided bodies as the PK-containing pipes. As with the PK, the HK contain only low proportions of country rock xenoliths. It seems unreasonable that similar pipes formed at the same time in the same area by different processes. If so, HK must have infilled previously excavated pipes. The low viscosity nature of the magma may be an important factor in this process. In contrast, truly intrusive kimberlites take advantage of weaknesses in the country rock and typically form small tabular bodies. In the root zones of diatreme-bearing pipes HK is associated with large scale brecciation and often contains high proportions of xenoliths derived from the local country rock.

Although the depth of erosion is not known, these HK must have reached areas that were reasonably near the original surface at the time of emplacement. There is one case of HK hosting a large autolith of coarse grained graded VK. This observation suggests that crater-facies kimberlite had formed in this pipe prior to the emplacement of the HK.

6. CONCLUSIONS

Stream sediment sampling and geophysics, particularly vertical gradient modeling of the aeromagnetic data, proved to be excellent methods for finding kimberlites in the James Bay Lowland area of northern Ontario. Sixteen kimberlite pipes were discovered. Fifteen of them are diamondiferous and evaluation is ongoing. Mineral compositions of the mantle xenoliths and xenocrysts indicate that the kimberlites sampled mainly lherzolitic mantle within the diamond window and that the geotherm was 37 mW/m^2. Mineralogically, the Attawapiskat bodies are composed of spinel carbonate kimberlite with less common monticellite kimberlite. Texturally, both hypabyssal and pyroclastic kimberlites are present within the cluster. Geochronological studies suggest that the kimberlites intruded at ~155-170 Ma, during an interval of approximately 15 Ma. This conclusion should be verified by further work, particularly for pipe U which has been shown by geophysics to have intruded at a different time compared to the other pipes.

The Attawapiskat bodies appear to be steep sided pipes up to 15 ha that were excavated into ~250 m of Palaeozoic sediments which overlie the basement. The dominance of carbonate-rich magmas throughout the kimberlite cluster is unusual. Given that there is no evidence of diatreme-facies kimberlite, the pipes may have been excavated by phreatomagmatic processes and subsequently infilled by subaerial pyroclastic lapilli tuffs and/or hypabyssal kimberlite.

ACKNOWLEDGEMENTS

The authors are grateful to Monopros Limited and De Beers Consolidated Mines Ltd. for permission to publish this paper. Constructive comments by C.R. Clement, J.A. Fowler, R. Sage and R.H. Mitchell are much appreciated. Analytical and petrological work completed by staff at the De Beers Geoscience Centre are important contributions to this paper. I. Schmitt, M. Shoari and J. Adam are thanked for preparation of the illustrations and poster.

APPENDIX 1

Geology of body C1

The single drill core from this apparently small kimberlite consists of clast supported magmaclasts (Fig. 9 a, b). In addition to the magmaclasts, less common discrete mineral grains also occur. Olivine is the most abundant of these grains, with macrocrysts being more common than phenocrysts. Less frequent grains of phlogopite and garnet occur. The rocks display sorting and in some areas bedding is easily discerned. The magmaclasts have variable shapes from rounded to more commonly irregular, curvilinear as well as frequent examples of amoeboid shapes with re-entrant embayments. The shapes reflect the plastic nature of the clasts during their formation. No angular autoliths were found. The magmaclasts are composed of two generations of partly altered olivine set in a very fine grained groundmass. Olivine and, less commonly, mica grains in some instances protrude from the magma clast surfaces.

The groundmass of the magmaclasts contains minor amounts of fine grains of spinel, perovskite, phlogopite and apatite, and probable monticellite. These minerals are set in an extensive base that is composed mainly of isotropic serpentine but also contains variable amounts (rarely abundant) of very fine grained carbonate. In a few instances aggregates of carbonate grains suggest incipient crystallisation of carbonate laths. The groundmass can be described as poorly crystalline verging on quenched. No true glass, however, is present. The groundmasses commonly contain vesicle-like structures. These structures vary from spherical shapes to less common coalescing examples with dumb-bell shapes or to more irregular segregationary-like bodies. These structures are infilled with carbonate and/or serpentine. The carbonate in some cases occurs as fine needles that are arranged radially or in sheaf-like aggregates along the margins of the vesicle. The juvenile lapilli can be classified mineralogically as spinel- and perovskite-bearing serpentine and/or monticellite kimberlites with variable proportions of carbonate.

Xenoliths are not common and only very minor parts of the drillcore can be termed breccias. Basement xenoliths are more common than the adjacent country rock limestone. In this respect body C is different from most of the other Attawapiskat bodies. The xenoliths are mostly <2-3 cm in size but range up to 6 cm. The basement xenoliths are varied in type and often have kimberlite selvages. Most of the limestone xenoliths are unaltered and have no kimberlite selvages. The limestone xenoliths have different colours to those observed within the hypabyssal kimberlite elsewhere at Attawapiskat.

The nature of the inter-clast matrix is variable along the length of the core. In many areas it is composed mainly of carbonate and serpentine. Carbonate in the matrix is typically more abundant and often coarser grained than that within the magmaclasts. Two forms of inter-clast carbonate are present. One variety is very fine grained with a turbid appearance. This type of carbonate appears to be the first to have crystallised as it typically forms rims on all the clasts. The main areas of most of the inter-clast matrix are composed of coarse grained clear carbonate that is closely associated with green isotropic serpentine. The carbonate within these areas often occurs as lath to needle-like crystals that form distinctive sheaf-like or stellate aggregates. The proportion of this type of carbonate and serpentine varies considerably from place to place. The textures of the inter-clast matrix suggest crystallisation from volatile-rich fluids percolating through voids in the pyroclastic deposits. The mineralogy of the inter-clast matrix is similar to that of late stage pools in magmatic kimberlites.

Modal analyses of volcaniclastic rocks are of limited use. However modal analyses of samples from body C1 indicate that they consist (as modal % of the total rock) of 15-20 % xenocrystic olivine, 15 % olivine phenocrysts, 3-4 % phlogopite macrocrysts/phenocrysts and within the magmaclast groundmasses, 4-5 % spinel, 1-2 % mica, <1 % perovskite, <0.5 % apatite, and 30-40 % of a base composed of carbonate, serpentine and monticellite with the inter-clast matrix carbonate forming 5-20% with <10 % serpentine.

The magmaclasts may or may not have a kernel. Those without kernels can range in size up to 30 mm in size. Magmaclasts with a kernel of a xenolith can be larger. There is a wide range in size of the magmaclasts down to microscopic proportions but fine material is rare. Overall the rocks can be described as poorly sorted, clast supported and loosely packed. There is a relatively high proportion of inter-clast matrix. There is some sorting with coarser and finer areas throughout the hole. The clast size in different areas varies from less than 2 mm to greater than 10 mm. In some cases normally graded beds up to 1-2 m thick can be discerned (Fig. 10). Xenoliths are often concentrated at the base of the graded beds together with the larger magma clasts. Thinner beds of up to 10-20 cm are composed of finer clasts. All the bedding and fabrics are horizontal. Magmaclasts in some instances are moulded against xenoliths. Frequently smaller magmaclasts are concentrated above and lack below larger clasts such as xenoliths (effectively draping). (Fig. 11).

Geology of body D1

Based on two vertical drill cores of this 7-8 ha body the kimberlite in this pipe is texturally complex. One drillcore is dominated by magmaclastic kimberlite for which the preferred interpretation is PK (Fig. 9 c, d). However, there is insufficient evidence for a conclusive interpretation. Between 91-161.5 m in this drill core a complex zone of limestone and aphanitic to macrocrystic hypabyssal kimberlite occurs (Fig. 9 e). Some of the proposed PK occurs below this material. The second, more complex, drillcore appears to be composed of the following: 24.5 m of probable VK with minor horizontal bedding near the top, 15 m of macrocrystic HK, 15 m of aphanitic HK with horizontal flow fabrics, 1.5 m of hypabyssal macrocrystic kimberlite (which contains large spherical segregations of serpentine), 7.6 m of altered ?VK, 6.1 m of limestone, 10.7 m of altered ?VK, 3 m of HK similar to the last intersection of HK, 24.5 m of juvenile lapilli-rich VK (possibly PK) before intersecting 24.5 m of limestone. The deepest kimberlite contains the most common magmaclasts and the most convincing evidence to suggest this material is VK. This evidence includes the presence of adjacent fragments of one zonally altered limestone, curvilinear to amoeboid shaped lapilli, some vesicles in the juvenile lapilli, moulding of juvenile lapilli, draping of fines over coarse clasts and the nature of inter-clast matrix. This kimberlite also has lower abundances of indicator minerals and different ilmenite compositions than the uppermost VK suggesting that it represents a different phase of eruption. The HK is variable in character over short distances of core. Too little information is available to obtain a clear understanding of the internal geology of this pipe.

Geology of body V

The V body consists of two separate lobes (termed V North and V South), (Fig. 7) that nearly coalesce at the present surface. Both bodies are composed of similar kimberlite that megascopically, and to a large extent macroscopically, appears to be fairly uniform in character. Overall only a low proportion of xenoliths are present. However, some parts of the pipes can be termed kimberlite breccias. The limestone xenoliths are mainly less than a few centimetres in size. Much of the xenolithic material derives from the upper parts of the pipe wall. Most of the xenolith-rich areas appear to be close to the contacts and/or in the lower half of the two deepest holes. These breccias occur where any debris falling back into the crater after its formation are expected to be found.

The kimberlite is composed mainly of poorly sorted, clast supported discrete grains of olivine and magmaclasts. There is a paucity of the fine discrete grains of olivine. Magmaclasts are mainly less than 1 cm in size but rarely range up to 2-3 cm. The magmaclasts are mostly round in shape but examples occur which are ovoid, more irregular to curvilinear in shape. Vesicles are frequently present in the magmaclasts but are not abundant. These vesicles are often infilled with serpentine. The magmaclasts are composed mainly of the olivine set in a fine grained groundmass that usually contains laths of carbonate, interstitial carbonate of variable grain size, spinel and perovskite. There are often variations in the nature of the groundmass between adjacent magmaclasts. In some cases these differences are sufficient to suggest that the magmaclasts derived from different phases of kimberlite eruption. The interstitial carbonate within the magmaclasts is typically cryptocrystalline suggesting that it has been quenched. The magmaclasts vary in abundance from place to place but they are usually modally less abundant than the single grains of olivine. The interclast matrix is composed predominantly of isotropic serpentine although it can contain variable proportions of carbonate. In some parts, typically deeper in the body, another turbid amorphous inter-clast matrix is present.

Although the drillcores are generally very uniform in character, there are variations in the nature, proportion and sizes of the clasts showing that some sorting has occurred. In some places there are limited bedding features including normal grading (<1-2 m thick), (Fig. 10). The bedding is best displayed in hole V-8-89 where the clast size within beds varies from <2 mm to 10 mm and the bedding planes dip at 10-45°. Most of the fabrics in this hole and elsewhere in V are horizontal (generally defined by elongate phlogopite grains and limestone xenoliths). There is minor evidence for impact sags. One example of a composite lapillus was observed suggesting pyroclastic recycling.

In contrast to the main part of the pipe V, the drill core from hole V-3-88 in the northwest part of the anomaly (Fig. 7) is composed mainly of HK. The groundmass is composed of carbonate (that can occur as lath-like grains), brown perovskite (relatively coarse grained), spinel, phlogopite (that occurs as small plates and laths), less common serpentine and possibly minor altered monticellite. The presence of brown perovskite in the groundmass distinguishes this kimberlite from that forming the main lobes V North and V South and suggests that the kimberlite in V-3-88 is a separate phase of intrusion. This kimberlite occurs under 42 m of what is presumed to be in situ limestone. This part of V may represent a separate body of HK that has not reached surface.

REFERENCES

BARKER D.S., 1989. Field relations of carbonatites. In Bell K., ed., *Carbonatites: Genesis and Evolution,* Unwin Hyman, London. pp. 38-69.

BELL K.(Ed.), 1989. *Carbonatites: Genesis and Evolution.* Unwin Hyman, London. 618 pp.

BOSTOCK H.S., 1964. A Provisional Physiographic Map of Canada, *Geological Survey of Canada,* Paper 64-35, pp. 24.

BROWN D.D., BENNET G. & GEORGE P.T., 1967. The sources of alluvial kimberlite indicator minerals in the James Bay Lowland. *Ontario Department of Mines,* **MP 7,** pp. 35.

BRUMMER J. J., 1978. Diamonds in Canada. *C. I. M. Bulletin* **71,** no. 798, pp. 64-79.

CARD K.D. 1990. A review of the Superior Province of the Canadian Shield, a product of Archean accretion. *Precambrian Research* **48,** pp. 99-156.

CUMMING L.M., 1975. Ordovician strata of the Hudson Bay Lowlands. *Geological Survey of Canada* Paper 74-28.

DONALDSON J.A., 1986. Precambrian Geology. In Martini I.P., ed., *Canadian Inland Seas,* Elsevier, New York, pp. 494.

DREIBUS G., BREY G. & GIRNIS A., 1995. The role of carbon dioxide in the generation and emplacement of kimberlite magmas: new experimental data on CO_2 solubility. *Extended Abs. 6th Internaional Kimberlite Conference, Novosibirsk, Russia.* Published by Siberian Branch of Russian Academy of Sciences, pp. 138-140.

FIELD M. & SCOTT SMITH B.H., 1998a. Near surface emplacement of kimberlites: contrasting models and why. *Extended Abstracts of the Seventh International Kimberlite Conference, Cape Town, South Africa, 1998.*

FIELD M. & SCOTT SMITH B.H., 1998b. Textural and genetic classification schemes for kimberlites: a new perspective. *Extended Abstracts of the Seventh International Kimberlite Conference, Cape Town, South Africa, 1998.*

FIPKE C.E., GURNEY J.J. & MOORE R.O., 1995. Diamond exploration techniques emphasizing indicator mineral geochemistry and Canadian examples. *Geological Survey of Canada.* Bulletin 423, p. 86.

GRAND S.P., 1987. Tomographic inversion for shear velocity beneath the North American plate. *Journal of Geophysical Research* **92,** no. B13, pp. 14065-14090.

GRIFFIN W.L., COUSINS D.R., RYAN C.G., SIE S.H. & SUTER G.F., 1989. Ni in chrome pyrope garnets: a new thermometer. *Contributions to Mineralogy and Petrology* **103,** pp. 199-203.

GURNEY J.J., 1984. A correlation between garnets and diamonds in kimberlite; in Glover, J.E ,& Harris, P.G., ed., *Kimberlite Occurrence and Origin: A basis for conceptual models in exploration, Geology Department and University Extension, University of Western Australia,* Publication **8,** pp. 143-166.

GURNEY J.J. & MOORE R.O., 1991. Geochemical correlation between kimberlitic indicator minerals and diamonds as applied to exploration. *Extended Abstracts of Fifth International Kimberlite Conference, Brazil,* Special Publication 2/91, pp. 125-126.

HAGGERTY S.E., 1989. Mantle metasomes and the kinship between carbonatites and kimberlites. In Bell K., ed., Carbonatites: *Genesis and Evolution,* Unwin Hyman, London. pp. 546-560.

HETMAN C., 1996. The ilmenite association of the Attawapiskat kimberlite cluster, Ontario, Canada. *MSc. Thesis,* Dept. of Geology, University of Toronto.

JANSE A.J.A., DOWNIE I.F., REED L.E. & SINCLAIR I.G.L., 1989. Alkaline Intrusions in the Hudson Bay Lowlands, Canada: Exploration methods, petrology and geochemistry, in Ross J., ed. Kimberlites and Related Rocks Volurme 2 Their Mantle Crust Setting Diamonds and Diamond Exploration, GSA, Victoria, Australia. pp. 1192-1203.

JOHNSON M.D., ARMSTRONG D.K., SANFORD B.B., TELFORD P.G. & RUTKA M.A., 1991. Paleozoic and Mesozoic geology of Ontario. *Geology of Ontario,* Ontario Geological Survey, Special Volume 4, Part 2, pp. 907-1008.

KELLER J. 1989. Extrusive carbonatites and their significance. In Bell K., ed., *Carbonatites: Genesis and Evolution,* Unwin Hyman, London. pp. 70-88.

LORENZ V., KURSZLAUKIS S., STACHEL T. & STANISTREET I.G., 1997. Volcanology of the carbonatitic Gross Brukkaros volcanic field, Namibia. *Proceedings of the Sixth International Kimberlite Conference, Russian Geology and Geophysics* **38,** No. 1, pp. 40-49.

MARTINI I.P., 1988. The Hudson Bay Lowland: major geologic features and assets. *Geologie en Mijnbouw* **68,** pp. 25-43.

MITCHELL R.H., 1986. *Kimberlites: Mineralogy, Geochemistry and Petrology,* Plenum Press, New York. 442 pp.

MITCHELL R.H., SCOTT SMITH B.H. & LARSEN L.M., 1998. Mineralogy of ultramafic dikes from the Sarfartoq, Sisimiut and Maniitsoq areas, West Greenland: Kimberlites or melnoites. *Extended Abstracts of the Seventh International Kimberlite Conference, Cape Town, South Africa, 1998.*

MOSER D.E. & KROGH T.E., 1995. A U-Pb dating study of lower crustal xenoliths from the Attawapiskat kimberlite pipes, Sachigo subprovince. *Lithoprobe Western Superior Transect, Second Annual Workshop,* Lithoprobe Report no. 53, pp. 54.

NORRIS A.W., 1986. Review of Hudson Platform Paleozoic stratigraphy and biostratigraphy. In Martini, I.P., ed., *Canadian inland seas,* Elsevier, New York. 494 pp..

NORRIS A.W., 1993. Hudson Platform. In Stott D.F., ed., *Sedimentary Cover of the Craton in Canada, Geology of North America.* Volume D-1, The Geological Society of America Inc. 655pp.

NORRIS A.W. & SANFORD B.V., 1968. Palaeozoic and Mesozoic geology of the Hudson Bay Lowlands. In Hood P.J., ed., *Earth Science Symposium on Hudson Bay,* Geological Survey of Canada, Paper 68-53, pp. 169-205.

REED L.E. & SINCLAIR I.G.L., 1991. The search for kimberlite in the James Bay Lowlands of Ontario. *C. I. M. Bulletin* **84,** no. 947, pp. 132-139.

SAGE R.P., 1997. Project Unit 93-12. Kimberlites of Ontario. *In Summary of Field Work and Other Activities 1997.* Ontario Geological Survey, Miscellaneous paper 168, pp.37-40.

SCHULZE D.J., 1996. Ultramafic xenoliths and xenocrysts in kimberlite and alnoite: Windows to the upper mantle. LeCheminant A.N., Richardson D.G., DiLabio R.N.W., and Richardson K.A., eds.; *Searching for Diamonds in Canada,* Geological Survey of Canada, Open File 3228, pp. 129-133.

SCHULZE D.J. & HETMAN C.M., 1998. Mantle xenoliths from the Attawapiskat kimberlites. In press.

SCOTT SMITH B.H., 1995. Petrology and diamonds. *Explor. Mining. Geol. C.I M* **4,** no. 2, pp. 127-140.

SCOTT SMITH B.H., ORR R.G., ROBERTSHAW. P. & AVERY R.W., 1998. Geology of the Fort a la Corne kimberlites, Saskatchewan. *Extended Abstracts of the Seventh International Kimberlite Conference, Cape Town, South Africa, 1998.*

SOBOLEV N.V., POKHILENKO N.P., GRIB V.P., SKRIPNICHENKO V.A. & TITOVA V.E., 1992. Specific composition and conditions of formation of deep-seated minerals in explosion pipes of the Onega peninsula and kimberlites of Zimnii coast in the Archangelsk province. *Soviet Geology and Geophysics* **33,** No. 10, pp. 71-78.

SUCHY D.R. & STEARN C.W., 1993. Evidence of a continent-wide fault system on the Attawapiskat River, Hudson Bay Platform, northern Ontario. *Can. J. Earth Sci.* **30,** pp. 1668-1673.

TREIMAN A.H., 1989. Carbonatitic magma: properties and processes. In Bell K., ed., *Carbonatites: Genesis and Evolution,* Unwin Hyman, London. pp. 89-104.

WILLIAMS H.R., STOTT G.M., THURSTON P.C., SUTCLIFFE R.H., BENNETT G., EASTON R.M. & ARMSTRONG D.K., 1992. Tectonic evolution of Ontario: Summary and synthesis. In Thurston P.C., Williams H.R., Sutcliffe R.H., Stott G.M., eds., *Geology of Ontario,* Ontario Geological Survey, Special Volume 4, part 2, pp. 1255-1332.

WOOLLEY A.R., BERGMAN S.C., EDGAR A.D., LE BAS M.J., MITCHELL R.H., ROCK N.M.S & SCOTT SMITH B.H., 1996. Classification of the lamprophyres, lamproites, kimberlites and the kalsilite-, melilite- and leucite-bearing rocks. (Recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks). *Can. Mineral.* **34,** pp. 175-186.

WYLLIE P.J., 1989. Origin of carbonatites: Evidence from phase equilibrium studies. In Bell K., ed., *Carbonatite: Genesis and Evolution,* Unwin Hyman, London. pp. 500-545.

The

J.B. DAWSON

VOLUME

PROCEEDINGS OF THE VIIth INTERNATIONAL KIMBERLITE CONFERENCE

Editors

J.J. Gurney, J.L. Gurney, M.D. Pascoe & S.H. Richardson

VOLUME 1

Authors

A~K

Contents

Volume I

Page