The Tli Kwi Cho (DO27 and DO18) Diamondiferous Kimberlite Complex, Northwest Territories, Canada

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ABSTRACT

The Tli Kwi Cho kimberlite complex was discovered in the Lac de Gras area of the Archean Slave Craton in 1993 by drill testing the paired geophysical anomalies, DO27 and DO18. This body is a complex kimberlite which was emplaced into the Slave craton after 74 Ma, probably during the early Tertiary. At this time the basement was covered by Cretaceous marine shales. Core drilling showed that this body consists of four main rock types which occur in different areas of the body: HK (hypabyssal kimberlite), PK (pyroclastic kimberlite), VK (shale-rich volcaniclastic kimberlite) and XVK (xenocryst-rich volcaniclastic kimberlite). All four rock types have distinct colours, mineralogies, textures, mantle xenocryst contents and compositions, diamond contents and xenolith contents. The different rock types are considered to represent separate emplacement events. The HK is a subsurface intrusive sheet complex that was emplaced in association with extensive brecciation of the adjacent country rock granite. Some individual sheets are unusually thick (up to 22 m). The other three rock types are extrusively formed kimberlites which appear to have infilled separate pipes during terrestrial conditions. The PK rocks are suggested to be juvenile lapilli-bearing olivine (crystal) tuffs that formed by subaerial pyroclastic processes. Resedimentation may have been involved in the final deposition of the VK and XVK. Both the PK and VK kimberlites must have formed by a two phase process, pipe excavation and subsequent pipe infilling. The Tli Kwi Cho kimberlite complex contrasts to the 'classic' kimberlite pipe model with no evidence for the formation of a diatreme (sensu stricto) infilled with tuffisitic kimberlite breccia. The different geology and emplacement model for Tli Kwi Cho created additional challenges during exploration that utilised pre-existing kimberlite models. Although the Tli Kwi Cho kimberlites contain significant quantities of diamonds, this occurrence is considered sub-economic.

Keywords: kimberlite, pyroclastic, volcaniclastic, sill, hypabyssal, diamond, exploration, emplacement, crater-facies

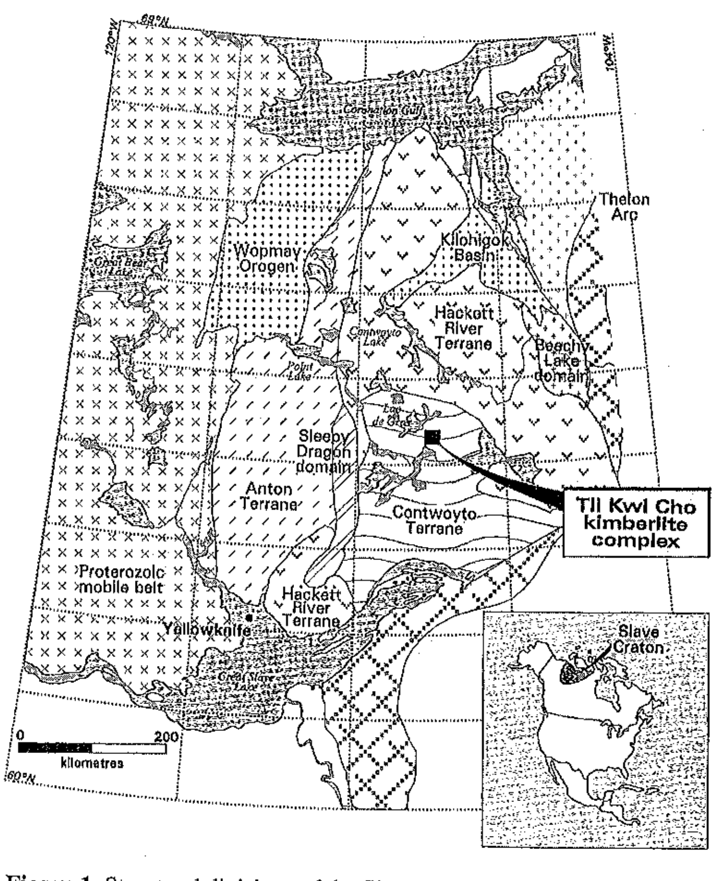

Figure 1. Structural divisions of the Slave craton (after Griffin *et al.* in press) and location of the Tli Kwi Cho kimberlite complex.

1. INTRODUCTION

The Tli Kwi Cho diamondiferous kimberlite complex occurs in the Lac de Gras kimberlite field located 360 km north east of Yellowknife at latitude 64° 19' N and longitude 109°48' W in the Northwest Territories of Canada. The complex is held under mineral claims belonging to the DHK joint venture whose ownership consists of 40 % Kennecott Canada Exploration Inc., 10 % SouthernEra Resources Inc., 15 % Aber Resources Ltd. and 35 % DHK (Dentonia Resources Ltd., Horseshoe Gold Mining Inc. and Kettle River Resources Ltd.).

2. GEOLOGICAL SETTING

The Tli Kwi Cho kimberlite complex lies within the Slave Structural Province (Fig. 1), an Archean craton that totals 210,000 sq km. in area. Like most Archean cratons worldwide, the Slave craton consists predominantly of granitoid intrusive rocks with greenstone belts consisting of mafic to intermediate volcanic rocks and flysch supracrustal metaturbidites (Padgham and Fyson, 1992).

The Slave craton was assembled between 4.0 to 2.58 Ga. Table 1 summarizes the main geological events. There have been numerous attempts at a tectonic synthesis for the Slave. The most recent (Yamashita *et al.*, 1998) describes the Slave craton as an assemblage of terranes based on the latest geological and isotopic evidence. Rocks in the west contain an older isotopic signature whilst rocks to the east have juvenile isotopic signatures (Thorpe *et al.*, 1992; Davis and Hegner, 1992). The 2.9-4.0 Ga basement rocks of the Anton terrane are probably remnants of a rifted continental block. Mafic-intermediate volcanic rocks of the western Slave Province could have been generated in a single back arc system. The felsic-dominated Hackett River volcanic belt may represent a fore-arc system. Yamashita *et al.* (1998) compare this setting to the size and composition of the Sino-Korea/Japan system as a modern day analog. This setting of continent, back-arc, fore-arc is also characterized by significant accumulations of turbidites, both in the fore and back arc basins (Contwoyto terrane). Intrusion of the syn- and post-deformation plutons around 2.58 to 2.62 Ga signified a period of crustal thickening and the cratonization of the province. Formation of the lithospheric keel, essential in hypotheses for the formation and preservation of diamonds, may have occurred at this time. After this time the craton appears to behave as a cold brittle body that fractures under stress, behaviour consistent with a tectonically coupled crust and keel.

After assembly of the craton in the Archean, its geological evolution continued through to the Proterozoic. From ~2.2 to 1.92 Ga the Slave craton was involved in a continent/continent collision with the Churchill structural province to the east. The Thelon Orogen was created in the process along the eastern side of the Slave. Commencing at ~1.97 Ga early Proterozoic island arcs accreted to the Slave thrusting foredeep and shelf sediments on to its western margin (Wopmay Orogen). Subsequently the Great Bear continental arc developed over east dipping subduction (1.88-1.86 Ga). The Kilohigok basin also formed around this time in the north centre of the Slave due to lithospheric flexure caused by the collision with the Rae. By 1.65 Ga most of the collisional activity had ceased and the Slave Craton had now been incorporated into the supercontinent Laurentia (Hoffman, 1989).

The Slave craton is notable for its numerous and prolific diabase dyke intrusions, as summarized in Table 1. Each dyke emplacement episode is suggested to either represent a rift event along the margins of the Slave and Laurentia or a mantle plume (Fahrig, 1987).

Throughout the Phanerozoic, the Slave craton appears to have oscillated between depositional and erosional regimes. Mid-Paleozoic carbonate xenoliths occur in kimberlites from the southwestern portion of the Slave craton (e.g. at Drybones Bay near Yellowknife, Pell, 1997). Middle Devonian fossiliferous limestone xenoliths are abundant in the Jericho pipe approximately 150 km north of Lac de Gras (Cookenboo, 1997). These occurrences are the only remnants of what must have been a carbonate platform that once extended over much of the craton which has since been removed by erosion. Unpublished work by Kennecott at the Tli Kwi Cho occurrence and by others (Nassichuk and McIntyre, 1995; McKinlay *et al.*, 1998) have shown that the Slave craton was once covered by marine shales and mudstones of Cretaceous and Tertiary age. Xenoliths found in the numerous kimberlite bodies of the Lac de Gras cluster are the only known remaining evidence of this Cretaceous-Tertiary cover over the Slave.

Table 1. Summary of geological events for the Slave craton.

Type	Geology	Age	Comments	References
Basement rocks	Intrusives and gneiss	>2.8 Ga	Oldest rocks 3.6-4.0 Ga occur W of Long.111°W	1, 2
Early cover	Orthoquartzite	>2.72 Ga	Stratigraphically beneath greenstone belts	1, 2
Mafic to intermediate volcanic rocks	Greenstone belts	2.72-2.66 Ga		1, 2
Sedimentary rocks	Metaturbidites	2.71-2.66 Ga	Contwoyto & Itchen Formations in central part & the Beechey Lake in NE	1, 2
Synvolcanic intrusives	High and low Al_2O_3 trondhjemites and diorite	2.7 - 2.65 Ga	Spatially associated with volcanics. Calc-alkaline	1, 2
Younger sedimentary rocks	Metaturbidites	2.61 Ga & 2.59 Ga		1, 2
Syndeformational intrusives	Trondhjemites, hornblende-biotite monzodiorite to granodiorite	2.62 - 2.59 Ga	Meta-aluminous, calc-alkaline	1, 2
Postdeformational intrusives	Muscovite-biotite granites, biotite granites	2.59 - 2.58 Ga	From partial melting of metasedimentary protoliths	1, 2
Metamorphism & deformation	Amphibolite & greenschist	2.62 - 2.59 Ga	2-6 kb from 400-700°C	3
Alkaline intrusions	Carbonatites	2.60 - 2.59 Ga	Two localities	4
Malley dykes	Diabase dykes	2.23 Ga	NE trending	5
Mackay dykes	Diabase	2.21 Ga	E trending	5
Proterozoic intrusives	Peralkaline granite-syenite, alkaline-carbonatitic complexes	2.18 Ga		6
Lac de Gras dykes	Diabase	2.02 & 2.03 Ga	010° NNE trending	5
Proterozoic cover	Foredeep & shelf sediments	2.2 - 1.86 Ga	Wopmay in W of craton; Kilohigok centre N.	7
Mackenzie dykes	Diabase/gabbro	1.27 Ga	NNW trending	8
Gunbarrel dykes	Diabase	0.78 Ga	Northern edge of Slave	9
Franklin dykes	Diabase	0.72 Ga	Northern edge of Slave	9
Paleozoic cover	Platform carbonates	Mid-Devonian	Probably craton wide	6
Mesozoic cover	Marine and minor late terrestrial sediments	Mid-early Cretaceous	Probably craton wide	10, 11
Cenozoic cover	Terrestrial sediments	Tertiary		10, 11

References: 1 - Kusky (1989), 2 - Padgham and Fyson (1992), 3 - King *et al.* (1992), 4 - Relf *et al.* (1995), 5 - Le Cheminant *et al.*(1995), 6 - Pell (1997), 7 - Hoffman (1989), 8 - Le Cheminant *et al.* (1989), 9 - Fahrig (1987), 10 - Nassichuk and McIntyre (1995), 11 - McKinlay *et al.* (1998).

3. COUNTRY ROCK GEOLOGY

The bedrock geology in the Tli Kwi Cho area is known from the mapping of Lord and Barnes (1954). The local geology consists of metamorphosed granitoid rocks including quartz diorite, quartz monzonite, granodiorite and granite, with zones of granite gneiss, migmatite and mixed gneiss involving rocks of the Yellowknife Supergroup. These coarse grained intrusive rocks are surrounded by belts of cordierite- plus andalusite-bearing knotted schists of the Yellowknife Supergroup (Lord and Barnes, 1954).

The kimberlite complex has intruded into a medium grained two-mica aluminous garnetiferous granite. The granite probably belongs to the syndeformational intrusives described by Hoffman (1989). Based on correlations with similar rocks at Contwoyto Lake, it is suggested that the granites were emplaced at 2.58 to 2.60 Ga (van Breeman *et al.,* 1992). The granites have partially to totally assimilated the supracrustal turbidites, with relict roof pendants, xenoliths, xenocrysts and enclaves present. Compositionally, these rocks contain quartz, potash and low An- or high Ab-feldspar and subordinate biotite, muscovite, hornblende, epidote, apatite, chlorite, with rare sillimanite and garnet. Minor zones of migmatite and pegmatite are also present locally.

4. GLACIAL GEOLOGY

The Slave craton was covered by a 2-4 km thick ice sheet 18,000 years ago during the height of the Wisconsinan cycle of the last ice age. This ice sheet retreated eastwards and by 9,000 years ago the Lac de Gras area was ice free (Dyke and Prest, 1987). Most of the present day surface features and landforms were created by the advance and retreat of this ice sheet. Outcrop in the area around the Tli Kwi Cho kimberlite is limited to 10-20 % exposure; the rest of the area is covered by a 5-50 m thick till blanket. The glacial till consists of a well-compacted silt, containing angular to subangular clasts of country rock fragments and a lesser amount of cobbles and pebbles. A train of mantle xenocryst material is detectable for over 20 km down-ice of the Kwi Cho kimberlite. The predominant direction of ice movement was 290°. Unloading after the 2-3 km thick ice sheet retreated encouraged the formation of a horizontal joint set in the basement rock. These joints are spaced approximately 1m apart with the spacing decreasing at depth. Permafrost is generally found to a depth of 50 to 60 cm on land, with no permafrost under the lakes. The kimberlite complex appears to have been partially gouged by an ice sheet advance, which left up to 50m of till covering the southern part of the complex.

5. KIMBERLITE GEOLOGY

The Tli Kwi Cho kimberlite complex was discovered in 1993 as a result of a helicopter-borne magnetic/electromagnetic/VLF survey that was flown over the property at 200 m line spacing (Aerodat survey). Two geophysical anomalies were recognized and designated DO27 and DO18 (south and north respectively; Fig. 2). A ground magnetic survey confirmed and enhanced the anomalies. A total of forty-three NQ/HQ holes were drilled into anomaly DO27 and thirteen NQ/HQ holes were drilled into anomaly DO18 (Fig. 3). The drilling indicated the approximate outline of the Tli Kwi Cho kimberlite (Fig. 3). Within the drill-core four main rock types with distinct characteristics have been recognized:

i. HK – dark grey hypabyssal kimberlite.
ii. PK – green pyroclastic kimberlite.
iii. VK – black volcaniclastic kimberlite.
iv. XVK – grey-green xenolith- and xenocryst-rich volcaniclastic kimberlite.

The four main rock types dominate different areas of Tli Kwi Cho (Fig. 4). Two cross sections are shown in Figs. 5 and 6 (location of sections are shown in Fig. 3). There are a number of minor kimberlite dykes and sills that traverse the area between DO27 and DO18. The kimberlite is overlain by glacial till and/or a lake (Fig. 4 - 6).

5.1 HK: Hypabyssal Kimberlite

The HK rock type dominates the central part of DO27 at Tli Kwi Cho (Fig. 4). HK occurs only between 70 and 160m depth below the present surface (Fig. 5). Within this zone, drill cores usually comprise alternating intersections of HK and relatively long intersections of granite (Fig. 5). Individual intersections of HK range up to 22 m vertical thickness. Contact relations, which include flow features within the kimberlite, suggest that much of the granite is in situ. In contrast to the surrounding country rock, the extensive areas of granite between and above the HK is highly fragmented (Fig. 5). The brecciated granite contains no kimberlite matrix. All the fragments can be fitted back together showing that they have not been transported any significant distance and must represent contact breccias comparable to those

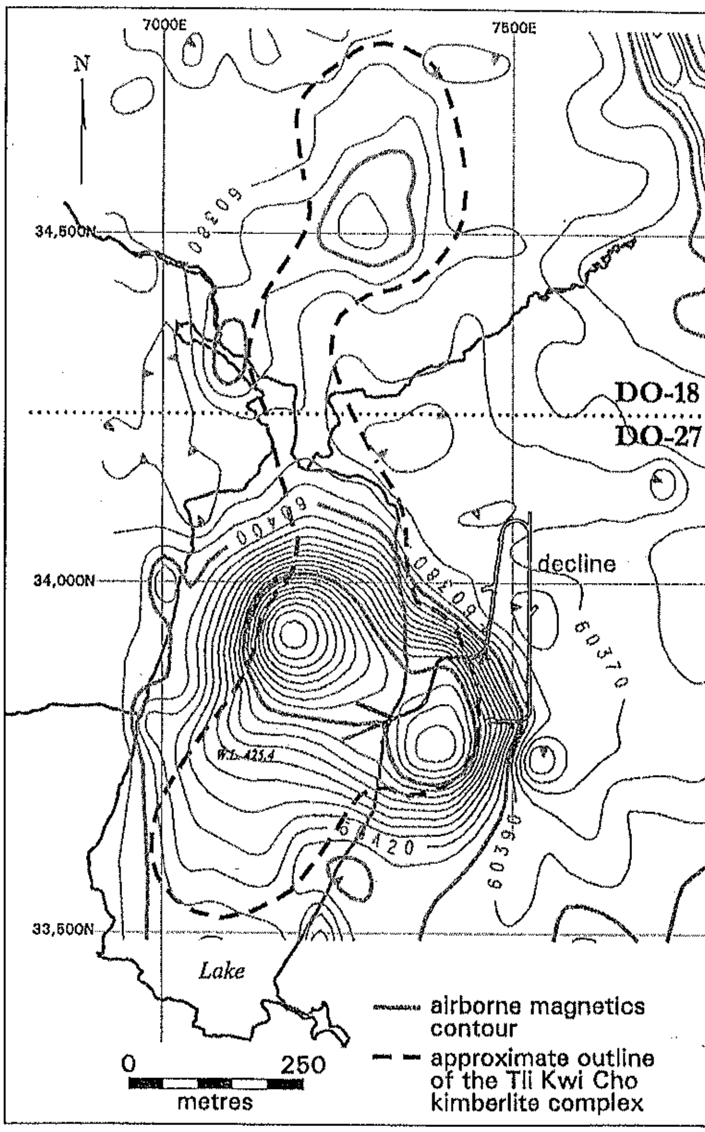

Figure 2. Airborne magnetics for Tli Kwi Cho (outline from Fig. 3).

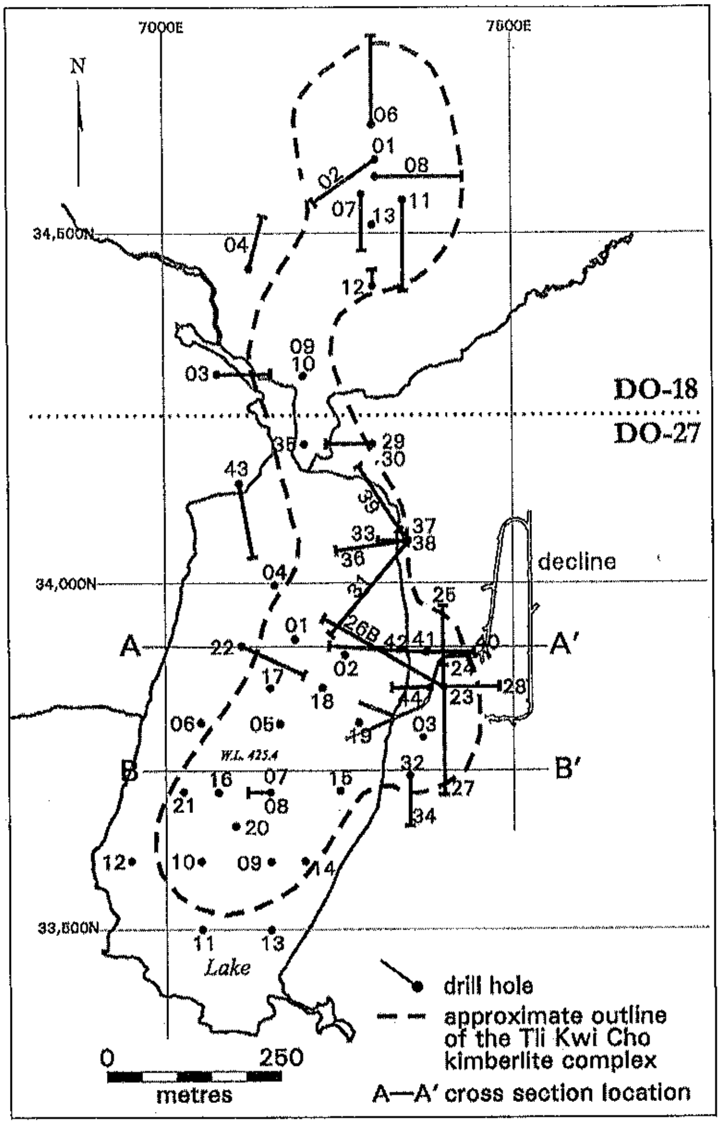

Figure 3. Location of drill holes in Tli Kwi Cho.

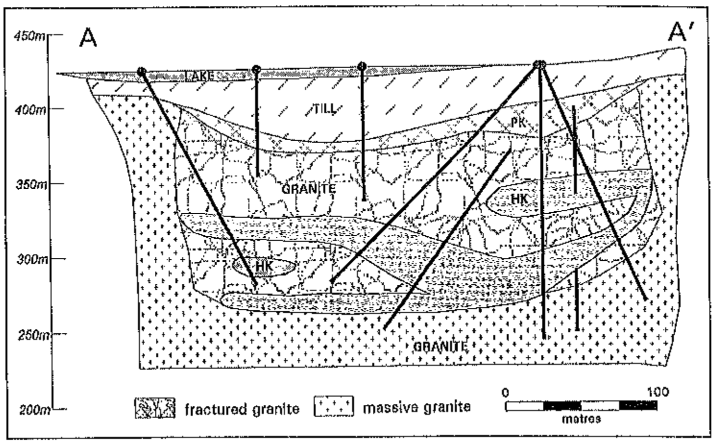

Figure 5. Cross section A-A' (Fig. 3) showing flaring edge of PK pipe and sheets of HK within the zone of fragmental granite.

described by Clement (1982). The sericite alteration of the mica and feldspar in the brecciated granite has given this rock a pale bleached colour.

The HK is composed of the two generations of olivine characteristic of kimberlites. The anhedral olivine macrocrysts or mantle-derived xenocrysts are mainly less than 10 mm in size but they range up to 20 mm in size. Numerous smaller euhedral olivine grains are less than 0.5 mm in size and are interpreted as phenocrysts. Other mantle-derived xenocrysts include chrome diopside, garnet, chromite and ilmenite (listed in decreasing order of abundance). Xenocrysts derived from the country rock granite, mainly mica and more rarely feldspar, are also present. The previously described coarser constituents are set in a fine grained (<0.1 mm) uniform groundmass which is composed of abundant spinel, fresh or altered monticellite and cryptocrystalline serpentine and carbonate. No perovskite is apparent. The proportions of the groundmass minerals vary, especially the carbonate and serpentine. Most of the HK can be classified as fresh hypabyssal macrocrystic carbonate-bearing, spinel-rich monticellite kimberlite. The groundmass spinels show a variation in composition from chromite to alumino-spinel and titano-magnetite which plot on Trend 1 of Mitchell (1995). Spinels occur as individual grains or as atoll-textured spinels with chromite cores. In the latter, outer zones of alumino-spinel are coated by phlogopite/serpentine followed by titano-magnetite rims. High barium phlogopite-kinoshitilite mica was recognized in backscatter images using an electron microprobe. Rare grains of biotite and feldspar derived from the country rock show reaction rims of this mineral.

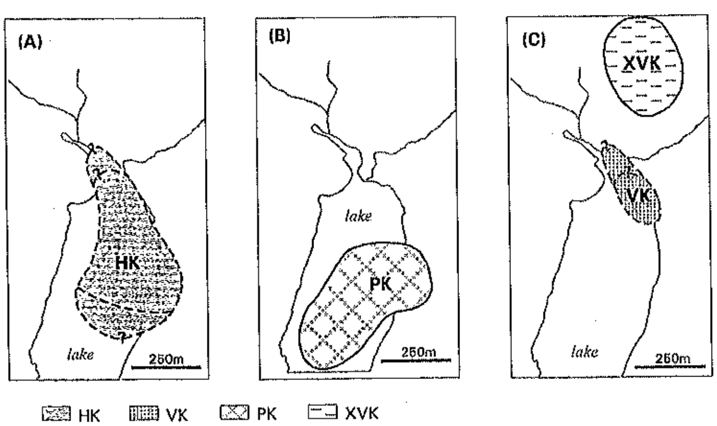

Figure 4. Plan view of the distribution of the four main rock types which comprise the Tli Kwi Cho kimberlite complex.

Country rock xenoliths are present in the HK but are usually not abundant. The xenoliths comprise granites which vary in size, abundance, colour and alteration (from darker grey green to a more altered very conspicuous white colour). Xenoliths <10 mm are common and locally the kimberlite can be termed a microbreccia. The smaller granite clasts are altered to green serpentine-like material and typically have thin white reaction rims. The larger xenoliths (>10 mm, up to 30 cm in size) are usually less altered. In rare instances the larger granite xenoliths are more altered and have a conspicuous white colour induced by moderately intense sericite and clay mineralization. Where larger altered granite xenoliths are common, the rocks can be termed kimberlite breccia. In contrast to all the other kimberlites at Tli Kwi Cho, shale xenoliths were not found in the HK.

The hypabyssal nature of the HK, the absence of shale xenoliths, the three dimensional distribution of this rock type (Figs. 4 and 5) and the adjacent brecciation of the country rock (Fig. 5) together show that the HK is an intrusive hypabyssal sheet complex which invades *in situ* granite. The HK probably never reached surface. Variations in the xenolith content and olivine grain size within the HK indicate that up to four different phases and/or sheets of kimberlites are present. The broad sub-horizontal zones of granite and hypabyssal kimberlite (Fig. 5) suggest that the HK forms an overall sill-like complex of sheets, possibly somewhat similar to that at Mayeng in South Africa (Apter *et al.*, 1984). The Tli Kwi Cho sills, which range up to 22 m in vertical thickness, are unusual in that sheets greater than 1-2 m thick are rare among reported kimberlites. Mitchell (1986), however, reports that kimberlite sills can range up to 10m thick in granitic country rocks and rarely up to 45 m.

5.2 PK: Pyroclastic Kimberlite

The rock type PK dominates the 9 ha area of the southern part of Tli Kwi Cho (Fig. 4). This type of kimberlite forms a distorted bowl-shaped deposit (Fig. 6) that has a northern extended lip that covers the area above the HK (Fig. 5). In the lip area, the PK ranges from 1m to 30 m in thickness and the kimberlite/country rock contacts have shallow dips of 5-10°. The main part of the rest of the body forms an elongate bowl with steeper dipping pipe walls (50-70°) which is greater than 200 m deep (Fig. 5).

The PK is an altered, pale green-grey, volcaniclastic kimberlite which overall is uniform, poorly sorted, loosely packed and appears to be mainly clast supported. Only rare examples of finer grained zones, coarser grained areas containing more common olivines in the size range 5-10 mm and possible graded bedding (~17 and 5.5 m thick) are present. Lapilli-like structures are present in the PK. These lapilli-like structures are mostly less than 10mm in size, or are occasionally larger if they incorporate a xenolith. Some lapilli have a kernel such as an olivine grain, with a thin kimberlite selvage while many others contain no coarse constituent. The lapilli-like structures are composed of two generations of olivine set in a fine grained groundmass which appears to have been quenched. The groundmass of the lapilli typically contains common crystals of fine grained spinel, less common mica and/or carbonate laths and possible monticellite pseudomorphs set in a base of cryptocrystalline serpentine and/or carbonate. The lapilli vary in shape from sub-rounded or ovoid to more irregular and sometimes curvilinear. These shapes and the quenched nature of the groundmass show that these structures are extrusively formed juvenile lapilli. Rare examples of armoured lapilli were observed. The nature of the juvenile lapilli together with the nature of bedding, or lack of it, strongly suggest that these rocks represent pyroclastic deposits. The proportion of juvenile lapilli is difficult to determine due to alteration, but in some fresher rocks it appears to be approximately 10-20 %.

The PK contains abundant fresh or altered olivine. Olivine modal proportions are typically ~40-50 %, locally ranging up to 70-80 %. Macrocrysts of olivine are common and are mostly less than 5 mm in size, but occasionally range up to 10mm. Some of the grains display features such as undulose extinction which show that they have undergone strain at elevated pressures and are therefore probably mantle-derived xenocrysts. Discrete olivine grains are more abundant than the juvenile lapilli so these pyroclastic rocks can be termed juvenile lapilli-bearing olivine (crystal) tuffs. In many instances, among the discrete olivine grains the proportion of the finer grained phenocrysts is less than that typically found in hypabyssal kimberlites. In contrast to the discrete grains of olivine described above, the proportions of the two generations of olivine within the lapilli are typical of hypabyssal kimberlite. This contrast suggests that sorting occurred and that fines have been lost from the volcaniclastic material forming the drillcore. Common garnet and less common chrome diopside, chromite and ilmenite occur as macrocrysts or mantle-derived xenocrysts. Xenocrysts of mica and feldspar derived from the country rock are also present.

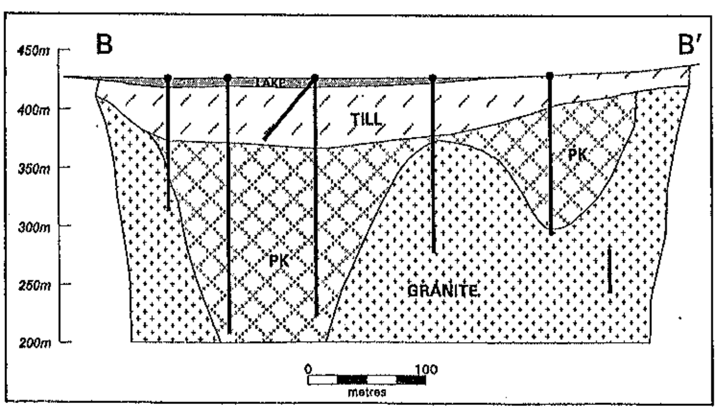

Figure 6. Cross section B-B' (Fig. 3), showing the upward flaring of the PK pipe.

The inter-clast matrix is a structureless green serpentine-like material or brown cryptocrystalline material which is probably serpentine and/or clay minerals after altered serpentine. Some small euhedral grains of carbonate are scattered throughout the matrix. Fine ash, whether of exotic or juvenile origin, is not recognized and is considered to be probably low in abundance. The PK kimberlite body has been altered to clay minerals. X-ray diffraction analysis shows that smectite and illite are present in these rocks and that the clay content increases towards the centre of the body.

Xenoliths are present, but seldom abundant, and most of the PK cannot be termed a breccia, i.e. it contain less than 15 % xenoliths. The PK contains frequent shale clasts which are mostly <2 cm in size, but occasionally reach 5cm and rarely 30 cm. The shale clasts vary in colour from black to pale grey to brown. Some shale clasts also display features which show that they were poorly consolidated at the time they were incorporated into the kimberlite. These features include deformed laminae and the incorporation of kimberlitic olivine along the margins of the xenoliths. This material is interpreted as being derived from the upper country rock, which has subsequently been removed by erosion. Most of the shale xenoliths have no kimberlite selvages and show no reaction or alteration haloes suggesting that they were not resident in the kimberlite magma. Rare fragments of wood were also observed. Xenoliths and xenocrysts derived from granite (<30 cm) are less common than shale. Kimberlite selvages were observed on some granite clasts suggesting that at least some of them were kimberlite transported clasts. Some granitic clasts, especially those <1 cm in size, have been serpentinized. In minor areas either the shale or the granite clasts increase in abundance. Granite xenoliths and coarser olivines are more abundant towards the centre of the PK. In contrast, shale xenoliths as well as larger (1-3 m) granite xenoliths are concentrated near the margins of the body.

Observed features such as the lack of breakage of many internally fragmented fresh olivines and garnets as well as of fragile lapilli and shale clasts, the lack of fines, lack of sorting and sedimentary structures and the presence of loosely packed, clast supported textures suggest that resedimentation processes cannot have been significant in the final deposition of this material. This volcaniclastic material, therefore, is considered to have been deposited mainly by primary pyroclastic processes (hence termed PK). The overall lack of juvenile and exotic ash-sized particles including discrete olivine phenocrysts, the paucity of sedimentary material, poor sorting, absence of sedimentary structures, the shape of the juvenile lapilli and the paucity of armoured or accretionary lapilli, suggests that the eruption and deposition of the PK occurred in subaerial conditions. This suggestion is supported by the presence of wood (also see section 6.0 below). The presence of coarser kimberlitic constituents and more common granite near the centre of the main PK body (near drillhole DO27-07 in Fig. 3) may reflect primary pyroclastic deposition of coarser material nearer the likely vent. This part of the pipe is coincident with the relatively small area of the pipe where the lower limit of the PK has not been reached. More common shale and occasional concentrations of larger (1-3 m) granite xenoliths, which occur along the margins of the pipe, may represent contributions from pipe wall collapse or some resedimentation from crater rim deposits. This material probably represents early debris falling into the pipe.

5.3 VK: Volcaniclastic kimberlite

The rock type termed VK occurs in the northeastern part of DO27 (Figs. 3 and 4). The distribution of VK is relatively limited and not well constrained by the drilling in this area of the pipe. The VK occurs over at least 92 m vertical thickness with relatively steep kimberlite/country rock contacts. The VK occurs above part of the HK. The VK is a massive volcaniclastic kimberlite composed of variable proportions of poorly sorted olivine set in a black, fine grained, shale-like matrix. In thin section this matrix appears to be turbid and it contrasts in nature to the structureless material forming the inter-clast matrix of the PK. Macroscopically, most areas appear to be composed of matrix supported sparse olivine grains less than 5 mm in size (~20-30 modal %, mostly <2-3 mm). Some less common areas are composed of moderate or very abundant olivine grains (~40-50 or ~80 modal % respectively). The olivine-rich areas are clast supported and typically contain olivine grains in the 2-5 mm size range as well as rare grains up to 10 mm. All the olivine is totally altered to light coloured secondary material, which contrasts with the dark inter-clast matrix. The olivines occur both as discrete grains and within juvenile lapilli. Garnet, chrome diopside, chromite and ilmenite macrocrysts are present.

Locally juvenile lapilli (<10 mm) can be seen to be common. Elsewhere their presence is not clearly discernible. These lapilli are typically composed of two generations of olivine set in a quenched groundmass, which may contain rare spinel in a base of cryptocrystalline carbonate and/or serpentine. Some examples contain common vesicles, which appear void or are infilled with carbonate and/or serpentine. The lapilli have variable shapes ranging from sub-rounded to irregular. Some are composed of olivine with only a thin selvage of kimberlitic material.

The most striking feature of the VK is the presence of abundant xenoliths of shale which are mainly less than 5 cm in size, but may be occasionally larger (20-50 cm). The shale xenoliths have varied colours including examples that are similar in colour to the black inter-clast matrix as well as lighter grey and brown types which contrast in colour with the black inter-clast matrix. The lighter brown sediments contain gypsum. Some of the shale xenoliths were poorly consolidated when incorporated into the kimberlite. Plant material is also present. Volumetrically minor granitic xenoliths (mostly <5 cm, rarely up to 20 cm) and granite-derived xenocrysts are present. Some granite xenoliths have kimberlite selvages.

The VK is a volcaniclastic kimberlite composed mainly of juvenile lapilli and olivine. The presence of irregular curvilinear quenched vesicular lapilli suggest that the kimberlitic constituents formed by subaerial pyroclastic processes. Only rare possible armoured lapilli were observed. In contrast to the PK, the VK contains more common shale xenoliths and has an inter-clast matrix dominated by fine grained black shale-like material. These features show that different processes and/or environments of deposition allowed greater influx of shale both as clasts and as disaggregated material when compared to the PK (and XVK). The VK at Tli Kwi Cho was probably deposited by secondary resedimentation processes as suggested for similar kimberlites in Hardy Lake 01 and 02 (McKinlay *et al.*, 1998). However, given the absence of supporting evidence for resedimentation such as bedding, this rock type is described using the less specific term volcaniclastic kimberlite (VK).

5.4 XVK: Xenocryst-rich volcaniclastic kimberlite

This rock type occupies a separate ~6 ha body (DO18) north of DO27 (Figs. 2-4). Drilling to 250 m has shown that DO18 is a steep sided pipe-like body which has kimberlite/country rock contacts that dip at angles greater than 80°. Overall the XVK is a uniform, medium grey coloured, kimberlite breccia. Megascopically and macroscopically the kimberlite consists of 10-30 modal % granite-derived xenocrysts and granite micro-xenoliths mostly <5 mm in size and the kimberlitic constituents are difficult to discern. Microscopically, it can be seen that the XVK is a poorly sorted, fairly closely packed, volcaniclastic rock which contains common pseudomorphed discrete grains of olivine and some juvenile lapilli. The proportion of kimberlitic constituents to xenocrystic material is greater in the upper parts of the body but decreases with depth. Below approximately 150 m the granitic material generally is more common than kimberlitic constituents. The abundance of olivine in the XVK varies from more than 50 to 20 modal %. The olivine grains are mostly <3 mm but range up to 7 mm. Two generations of olivine typical of kimberlites occur within some lapilli. Chrome diopside, garnet and opaque black oxide macrocrysts are not common and are mainly <2-3 mm in size. Primary groundmass minerals in the lapilli include fine grained spinel, mica, carbonate, possible serpentine and, in rare examples, possible monticellite. The inter-clast matrix occurs in low proportions and is altered. No fabric or bedding was observed.

In addition to the fine xenocrystic and xenolithic material described above, in most areas of the drill core, granite and shale commonly form small xenoliths which are mainly less than 3 cm in size. Many intersections of the core can be termed kimberlite breccias. In contrast to the shale, the granitic xenocrystic and xenolithic material sometimes has selvages of kimberlite. Larger intersections of granite ranging from 0.5 m to 1.5 m in size can form up to 35 % of the core and are considered to be xenolithic rather than in situ country rock. Sedimentary rock clasts 20-30 cm in size are also common and consist predominantly of mudstone but rare sandstone and wood were also observed. Rarely the sedimentary clasts range up to 10 m in size. The larger mudstone xenoliths contain bedding planes which show variable dips but they display only minor rotations from horizontal (<15°). There is no reaction between the xenolithic material and the host kimberlite except in one case where granite micro-xenoliths occurs within a large lapillus. This reaction halo includes clinopyroxene.

In the XVK the granitic material is angular and highly fragmented while breakage of kimberlitic constituents does not appear to be extensive. The vast fragmentation of the granitic material must be related to pipe formation and explosive eruptions. Large rafts of mudstone also occur at different levels in the pipe. The lack of local disruption and sub-horizontal bedding suggest that the rafts sunk gently downwards into the pipe. The abundance and size of the shale clasts is greatest in the deepest parts which may represent early pipe infill. The thorough mixing of the granitic material as well as the presence of more common fines contrasts with the other volcaniclastic kimberlites and suggests a different mode of eruption and/or deposition for the XVK than for the PK and VK. Observed features are more consistent with infilling the XVK pipe by pipe wall collapse and resedimentation of crater rim material. However, the lack of supporting evidence such as sedimentary structures suggests that primary depositional processes cannot be ruled out so the rock type is described using the less specific term volcaniclastic kimberlite.

5.5 Mantle-derived xenocrysts

The size, abundance and alteration of the olivine macrocrysts, as well as the abundance and nature of the other mantle derived xenocrysts vary in each of the rock types (Table 2, abundances based on visual estimates of grains greater than 0.5mm in size derived from crushed and concentrated 15 kg samples). Unlike the other rock types, the garnets in the HK can have 300μm thick kelyphite coronas and the diopsides occur as rounded ovoids rather than square laths as found in the other rock types. Not only does the type vary, but also the composition of the mantle-derived xenocrysts incorporated into each kimberlite, suggesting that separate batches of magma sampled different zones of the lithospheric mantle. The differences in garnet compositions for three of the rock types are shown in Fig. 7 as an example. The diamond contents of each rock type are also

Table 2. Mantle-derived minerals in the different kimberlite types at Tli Kwi Cho

Rock type	HK	PK	VK	XVK
Olivine Size	<20mm	<5mm	<2-3mm	<2-3mm
Olivine Alteration	Minor	Partly	Total	Total
Abundances (>0.5mm)*				
Garnet	P	C	P	P
Chrome Diopside	R	C	P	P
Chrome Spinel	P	P	R	R
Ilmenite	R	R	R	R

* C = common, P = present, R = rare.

Table 3. Summary of caustic fusion diamond recovery results (diamonds > 0.015 mm)

	Rock Type	Sample wt (kg) diamonds	No. of Micro* diamonds	No. of Macro*	Stones /100 kg	Bulk sample grade carats/tonne
DO27	PK	1307	1032	353	106	0.36
DO27	HK	405	94	24	29	0.013
DO27	VK	358	136	21	44	not determined
DO18	XVK	1682	636	115	45	0.09

* Macrodiamonds have at least one dimension >0.5mm. Microdiamonds are smaller.

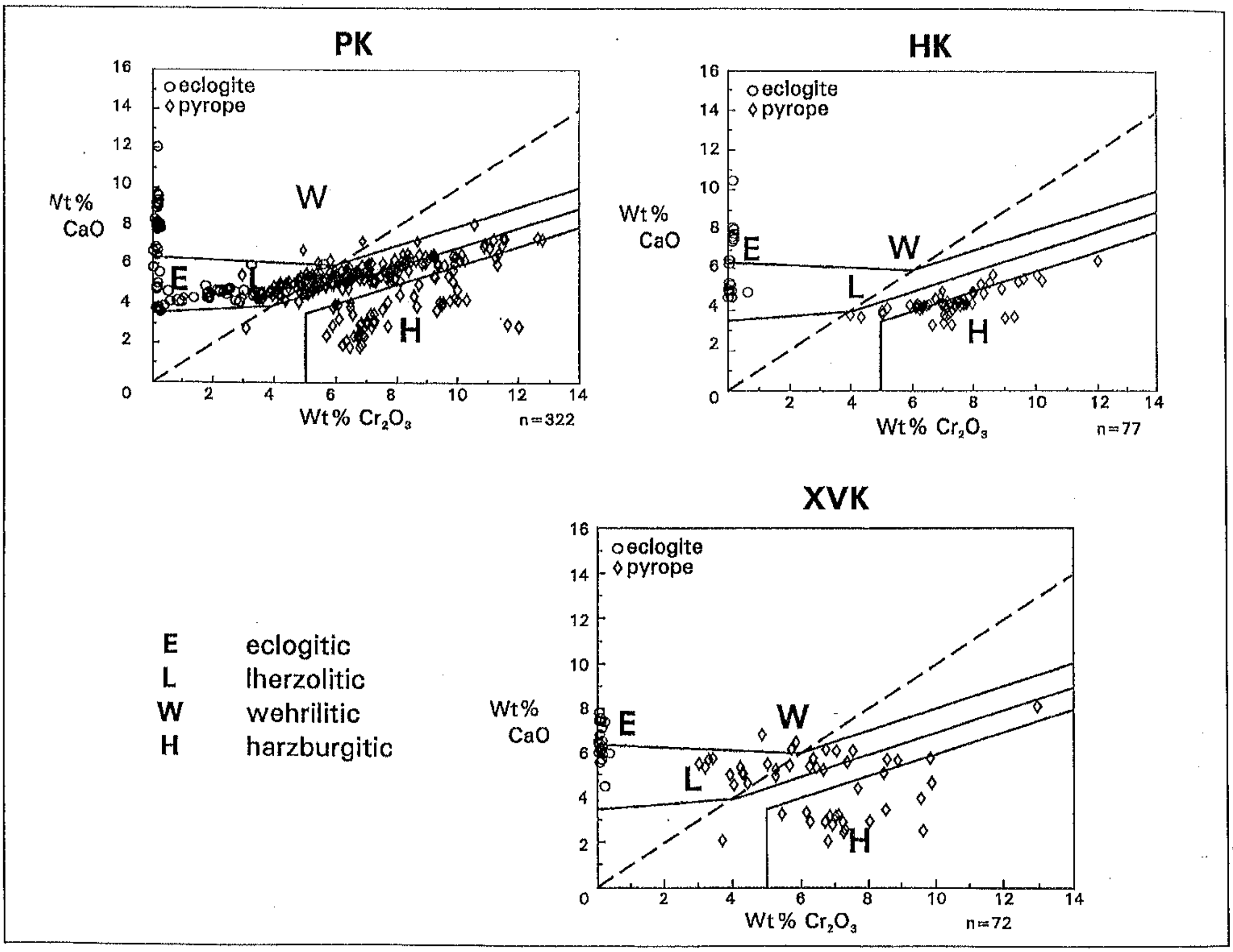

Figure 7. Cr_2O_3 vs. CaO for garnet xenocrysts from three different rock types at Tli Kwi Cho (after Sobolev, 1974).

different, as shown in Table 3. The PK contains the most mantle derived xenocrysts and diamonds while the HK contains the least diamonds.

6. AGE AND ENVIRONMENT OF EMPLACEMENT

The Tli Kwi Cho complex has proven difficult to date due to the scarcity of minerals suitable for isotopic age determinations such as perovskite and phlogopite. Palynology of the exotic mudstone and shale fragments indicates a maximum age for kimberlite emplacement of Maastrichtian or 74 Ma (Table 4). A Paleocene-Eocene age for the Tli Kwi Cho kimberlites, however, can be assumed from the younger ages obtained during the palynological investigations (Table 4). These investigations show the presence of the Paleocene pollen Triporopollenites mullensis in the DO18 XVK. Also the coal fragment from the DO27 VK contained fern and fungal spores such as Laevigagatosporites ovatus (fern) and Dicellaesporites popovii, D. aculeolatus, D. ovatus (fungus) which correlate to flora found in Paleocene-Eocene coaly outcrops along the Mackenzie River. Early Tertiary isotopic ages have been determined for other kimberlites in the Lac de Gras area (e.g. Nassichuk and McIntyre, 1995; Davis and Kjarsgaard, 1997). The shale xenoliths analysed show a major Albian to Cenomanian component with less abundant Maastrichtian and Santonian components. These sediments appear to have been deposited in mainly marine to near shore environments while the younger components are mainly terrestrial (including cypress and mesosequoia species of wood). This suggests that a marine transgression had taken place and the kimberlites were emplaced in terrestrial conditions and that the surface was probably forested. These palynological results are similar to those found by Nassichuk and McIntyre (1995) and McKinlay *et al.* (1998).

7. EMPLACEMENT MODEL

The four rock types recognized at Tli Kwi Cho are petrologically and texturally distinct, indicating that they result from different phases and styles of kimberlite emplacement. Firstly, the hypabyssal kimberlite (HK) is an intrusive subsurface sheet complex while the other three rock types are extrusive volcaniclastic kimberlites. The HK also has a much higher magnetic susceptibility than the other rock types (Fig. 2). The suggestion of at least four main phases of kimberlite emplacement is strongly supported by the contrasting nature of the mantle-derived xenocrysts (Section 5.6, Table 2, Fig. 7). Differences among the volcaniclastic kimberlites include, for example, the observation that the juvenile lapilli in the VK contain more vesicles and less common and finer grained groundmass spinel than those in the PK. These differences strongly suggest that the juvenile lapilli in these two rock types formed during different pyroclastic events. Other differences between the three types of volcaniclastic kimberlite include the proportion, type and alteration of the xenoliths and the nature of the inter-clast matrices. The PK contains low abundances of granite and shale xenoliths and the inter-clast matrix lacks fine constituents and is composed of clearer serpentine +/- carbonate. The VK contains common shale xenoliths and the inter-clast matrix is composed of fine material that resembles disseminated shale. In contrast in the XVK, there has been a thorough mixing of more abundant granitic material. The contrasting inter-clast matrices and xenoliths indicate that different types of eruption and/or deposition must have been involved in the formation of each of the volcaniclastic rock types. It is considered that the PK is a primary pyroclastic kimberlite while resedimentation may have been involved in the final deposition of the other two volcaniclastic rock types. The incorporation of contrasting types of exotic material suggests that different eruption and/or deposition processes must have occurred for the VK and XVK.

Table 4. Palynology results for selected samples from Tli Kwi Cho

Sample No.	Rock Type	Sample type	Palynology	Environment	Age
DO18-2 121.8 m	XVK	Wood and small black mudstone fragments in kimberlite	Fern spores, conifer and angiosperm pollen, dinocysts, wood is from the cedar group	Mixture in kimberlite	Maastrichtian -Danian (pollen) Paleocene (pollen) Albian-Early Cenomanian (dinocysts)
DO18-1 87 m	XVK	Wood	Meso-sequi	Terrestrial	Probably Paleocene
DO18-2 116 m	XVK	Black mudstone	Conifer pollen, dinocysts	Marine, warm temperate	Albian-Cenomanian (dinocysts)
DO18-1 165 m	XVK	Black mudstone	Fern spores, conifer and angiosperm pollen, dinocysts	Strong terrestrial component suggests near shore flood plain, warm temperate to sub-tropical	Albian-Cenomanian (dinocysts) Maastrichtian (dinocysts)
DO27-26 166 m	VK	Grey claystone	Fern spores, conifer and angiosperm pollen, dinocysts	Strong terrestrial component suggests near shore flood plain, warm temperate to sub-tropical	Albian-Cenomanian (dinocysts) Santonian (dinocysts)
DO27-30 60 m	VK	Black claystone	Fern spores, conifer and angiosperm pollen, dinocysts	Strong terrestrial component suggests near shore flood plain, warm temperate to sub-tropical	Cenomanian (dinocysts)
DO27-30 72 m	VK	Coal/charcoal fragment	Detrital coal, fragments of fusinite, minor wood, granular vegetation material, fern and fungal spores	Wet/warm temperate peat swamps	Paleocene-Eocene

One of the most remarkable features of the PK and VK rock types is the relative lack of granitic and sedimentary xenolithic material when compared with the volume of material that must have been excavated to form the pipe. Pipe excavation, therefore, must have been a separate earlier event from the pipe infilling. Most of the country rock that once occupied this area must have been ejected from, and deposited outside, the crater. This amounts to many millions of tonnes of country rock. In these instances the pipe infill is mainly volcaniclastic kimberlite with overall minor contribution from the extra-crater material.

In the occasional drill hole, the HK occurs immediately below the PK and the HK was not observed invading the PK. These features suggest that the PK pipe was excavated into the granite which already contained the hypabyssal kimberlite sheet complex. Xenoliths of HK, therefore, should be expected to occur in PK. Dark grey kimberlitic xenoliths are present in the PK but further study is required to determine if these are comparable to the HK. There is no evidence for the PK "grading" into hypabyssal/magmatic kimberlite as suggested for other Lac de Gras kimberlites (e.g. Pell, 1997).

It appears that the VK was deposited into a separate pipe from the PK. Interestingly, in two drill holes the VK occurs below large intersections of granite. Although further work is required, it is possible that the drill holes skimmed approximately parallel to an irregular pipe margin and, that the VK

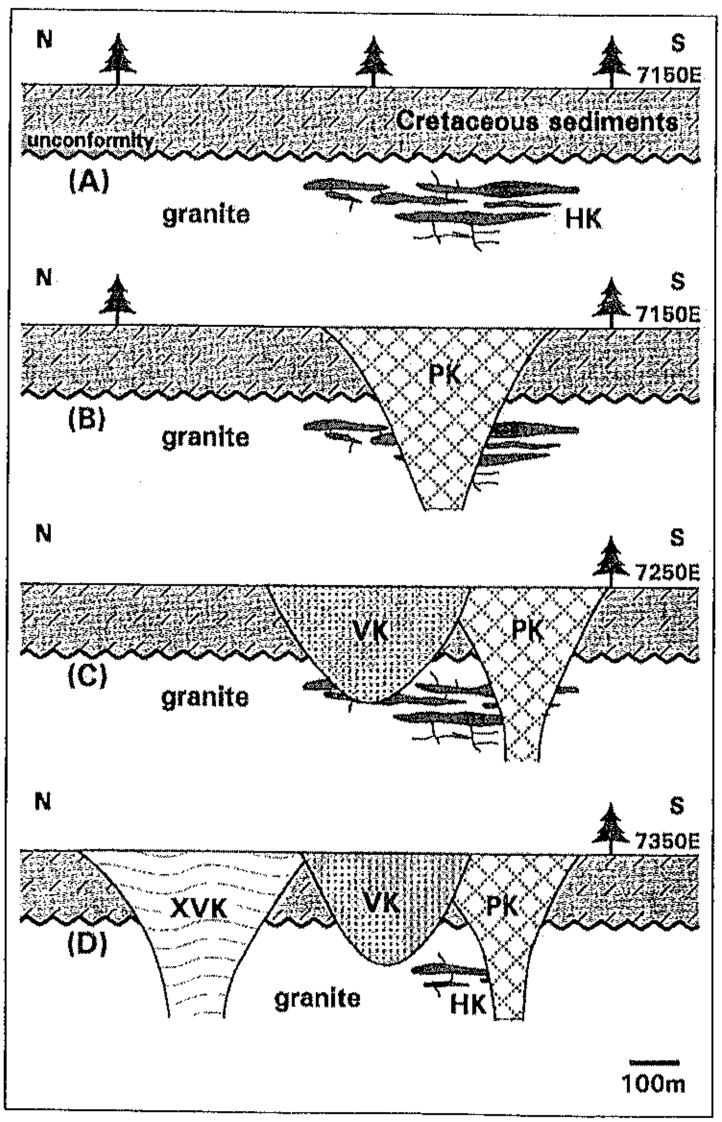

Figure 8. Emplacement model for the Tli Kwi Cho kimberlite complex.

occurs beneath a granite overhang or under a large granite xenolithic block. HK occurs directly below VK, but HK does not occur within the VK. Similar arguments to those presented for the PK suggest that the VK postdates the HK.

A schematic geological emplacement model is presented in Fig. 8. At the time of emplacement the basement was covered by poorly consolidated Cretaceous sediments, perhaps 50 to 200 m thick while the surface was forested. The HK is an intrusive sill-like sheet complex of hypabyssal kimberlite which invades in situ granite, mainly within a horizontal zone between 70-160 m below the present day surface. The rocks termed PK, VK and XVK are distinctly different types of volcaniclastic kimberlite that formed as a result of at least three separate eruptions at different volcanic centres forming separate pipes. The PK and VK pipes were excavated into areas of granite which had already being intruded by HK. The nature of the VK pipe is the least well constrained. The time relations between the pipe-forming events could not be determined. At Tli Kwi Cho, the excavation of each of the three pipes is clearly a separate earlier event to the pipe infilling. There is no evidence for the texturally specific diatreme-facies kimberlite, tuffisitic kimberlite breccia (sensu Hawthorne, 1975; Clement, 1982, Clement and Skinner, 1985) infilling. The absence of diatreme-facies kimberlites is comparable to other kimberlites in the Lac de Gras area (e.g. Graham *et al.*, 1998, McKinlay *et al.*, 1998). This shows that the emplacement of these kimberlite pipes is different to those described by Hawthorne (1975), Clement (1982) and Clement and Skinner (1985), which occur mainly in southern Africa.

8. IMPLICATIONS FOR EXPLORATION

The unusual geology and emplacement history of the Tli Kwi Cho kimberlite complex created challenges during exploration. Much of modern exploration is conducted with the aid of models because the explorationist often has limited information about the target to be tested. A geological model is used as a starting point, and is modified as new data are gathered. The classic 'carrot-shaped' pipe model of Hawthorne (1975) is traditionally the starting point for kimberlite-hosted diamond exploration. However, a contrasting 'champagne glass-shaped' pipe model is now known for lamproites (Scott Smith, 1996a) and some kimberlites (Demaiffe *et al.*, 1991; Scott Smith, 1996b).

The first hole drilled into DO27 (DO27-01, Fig. 3) was located at the centre of the magnetic anomaly below the lake and till (Fig. 2) but it only intersected 12 m of kimberlite (subsequently termed PK) and the hole ended in granite. Perplexingly, the kimberlite recovered had a low magnetic susceptibility and did not explain the magnetic anomaly. The second and third drill holes were completed again with only limited intercepts of similar kimberlite. Using the 'carrot-shaped' kimberlite pipe model, it was suspected that the lip of a crater had been intercepted and that a pipe-like body must lie near-by. This was confirmed when drill hole DO27-05 intersected the main PK kimberlite body as shown by subsequent 50m interval vertical holes drilled using an ice supported rig (Figs. 3 and 4). At this stage of the exploration, no kimberlite with a sufficiently high magnetic susceptibility had been intersected that could account for the DO27 magnetic anomaly (Fig. 2). As that spring progressed, the ice began to melt, and drilling had to be moved off-ice. Just prior to moving off the ice, drill hole DO27-22 was angled to intersect rock beneath drill hole DO27-01 (Fig. 3) to re-test the magnetic anomaly. This hole intersected a different type of kimberlite with a high magnetic susceptibility 30m below the end of the first drill hole DO27-01. Subsequent drilling showed that this rock type was responsible for the airborne magnetic anomaly shown in Fig. 2. Referring to the Hawthorne (1975) model of a kimberlite pipe, this deeper different rock type was erroneously considered to be diatreme-facies kimberlite containing abundant xenoliths as it appeared to occur below possible crater facies material. Later petrological work has shown this rock type to be the hypabyssal kimberlite sill complex described above (HK, Fig. 8). After the spring melt, the drill rig was moved to the lake shore, where it continued to drill angle holes. Then the first examples of VK were intersected in the northern part of DO27. In a separate drilling project, the DO18 geophysical target was tested. This target proved to be less complex as it is a single pipe-like body that occurs on land and is composed of one main rock type.

The Tli Kwi Cho case history shows that even after such extensive drilling (56 holes), model dependent interpretations of the geology can give vastly different ore reserve (tonnage) estimates. Estimates based on a 'carrot-shaped' diatreme-bearing pipe containing large granite xenoliths results in much more optimistic ore reserve estimates than those based on the model proposed here where the kimberlite diatreme is re-interpreted as a buried sill complex.

The first indication that the Tli Kwi Cho kimberlite complex is diamondiferous was the observation, while splitting core from the first drill hole, of a 2 mm-diameter diamond that caused the rock saw to jam. Encouraging results were also received from caustic fusion analysis (Table 3). In addition, the interpretation of the compositions of the diamond indicator minerals, especially from the PK rock type, suggested that Tli Kwi Cho had a high potential to be significantly diamondiferous (Fig. 7).

At this stage little was known about the grade or the ore value of the kimberlites. The multiple kimberlite types present at Tli Kwi Cho meant that each rock type had to be evaluated separately. The presence of the lake and till cover precluded surface sampling. Therefore, the available options for obtaining a larger sample were either to use a large diameter reverse circulation drill rig or to develop underground workings. These options had insignificant differences in projected costs. The RC drill rig option was rejected for a number of reasons (e.g. concern about poor drilling conditions as shown by the earlier core drilling, diamond recovery and breakage). The underground method also had the advantage of obtaining sufficient sample to provide a large enough parcel of diamonds on which to determine a more reliable estimate of the stone value. The main disadvantage of the underground sample was that it only sampled one level and one sector of the kimberlite complex. However, based on the geological model discussed above and the preliminary microdiamond results (Table 3), it was considered that this disadvantage was minimal for this phase of evaluation. The placement of the decline was planned to test two of the rock types at the DO27 anomaly, PK and HK (Figs. 3 and 4). A 1257.7 tonne sample was collected 90m below surface from one of the hypabyssal sills (HK). This sample returned a diamond grade of 0.013 carats/tonne (Table 3). The grade of the 3003.3 tonne sample of pyroclastic kimberlite (PK) was 0.36 carats/tonne. The stone value of the diamonds recovered from the pyroclastic kimberlite (PK) was $US 21.70 per carat at 1994 prices. The XVK (DO18) was tested in 1996 using large diameter (15 cm) drill core. A 6.88 tonne sample returned a grade of 0.09 carats/tonne. Based on the diamond grades determined and the stone values, the Tli Kwi Cho kimberlite complex is considered to be sub-economic. The contrast in grades supports the conclusion above that each of the rock types represents a different batch of magma emplaced in separate events.

9. CONCLUSIONS

The Tli Kwi Cho body is a complex kimberlite which was emplaced into the Slave craton after 74 Ma, probably during the early Tertiary. At this time the Archean granitic basement was covered by poorly consolidated Mid-Late Cretaceous marine to near shore shales, perhaps 50-200 m in thickness. It appears that a marine transgression took place and that kimberlite emplacement occurred in a terrestrial forested environment. Tli Kwi Cho contains at least four separate and distinct rock types that occur in different areas of the body:

i. HK- hypabyssal kimberlite
ii. PK- pyroclastic kimberlite or lapilli-bearing olivine (crystal) tuffs
iii. VK- shale-rich volcaniclastic kimberlite
iv. XVK- xenolith- and xenocryst-rich volcaniclastic kimberlite.

The contrasting nature of each rock type suggests that they formed in different emplacement events from distinct batches of magma at different eruptive centres. The HK was emplaced subsurface as a sill complex in a horizontal zone 70 to 160 m below the present day surface. This kimberlite may never have reached surface. Some of the sheets attained the unusually large vertical thickness of 22 m. This emplacement event was associated with extensive fracturing of the encompassing granite. The other rock types PK, VK and XVK occur in separate pipes which were excavated into the country rock in an approximately north-south line. Two of these pipes (PK, VK), in plan view, overlap with sill complex. The overall paucity of xenoliths within the kimberlite in the PK and VK pipes shows that they must have formed by two separate events, pipe excavation and subsequent pipe infilling. All three pipes were infilled by contrasting types of extrusively formed volcaniclastic kimberlite, the characteristics of which must reflect different styles of eruption and/or deposition. These processes include primary pyroclastic and probable resedimentation. It appears that the emplacement of the HK preceded the PK and VK pipe formation but other time relations between the different events are not known. As found in some other Lac de Gras pipes, there is no evidence for the development of any kimberlite diatreme (sensu stricto) at Tli Kwi Cho. Underground bulk testing of the PK and HK rock types and large diameter core drilling of the XVK rock type shows that the different rock types have different diamond grades. Although significant amounts of diamond are present, the Tli Kwi Cho kimberlite complex is not economic, mainly as a result of the low stone values. The different geology and emplacement model for Tli Kwi Cho created additional challenges during exploration and evaluation which utilised pre-existing kimberlite models that are now known to be inapplicable to this locality.

ACKNOWLEDGEMENTS

The continued encouragement and support for writing this paper received from George Stewart of Kettle River Resources Ltd. is much appreciated. Best regards to Bob Barnett for use of the electron microprobe analyses and back-scatter images. Dr. Glen Rouse is gratefully acknowledged for the palynological investigations. Bruce Kjarsgaard and Melissa Kirkley are thanked for their thorough reviews which improved this paper.

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