MINERALOGY AND PETROLOGY OF KIMBERLITE FROM WEMINDJI, QUEBEC

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INTRODUCTION

Exploration by Majescor Resources in the Wemindji area of Northern Quebec has resulted in the discovery of several sub-horizontal sills of kimberlite emplaced in a granitic-gneiss terrain.

The Wemindji kimberlites occur as thin dike/sill-like bodies, ranging from about 8 cm to 1 meter in thickness, in vertical drill core samples. They exhibit an extremely wide variation in their macroscopic appearance, ranging from fine grained macrocryst-free aphanitic dolomitic hypabyssal kimberlite to ilmenite/garnet macrocryst-dominated hypabyssal kimberlite. Flow differentiation features and multiple intrusion within a given dike/sill are characteristic. Regardless of the extreme macroscopic and microscopic variation in mode and texture, the kimberlites are all simply variants of single mineralogical type of kimberlite; namely macrocrystal spinel-ilmenite-apatite-phlogopite-dolomite hypabyssal kimberlite. Crater- and diatreme facies kimberlites are not present.

Macroscopic Character

Macroscopically, the Wemindji kimberlite dikes/sills typically exhibit fine grained macrocryst-free margins and internal crystal size grading. This feature is particularly well-seen in core 02-10, in which an 8 cm thick dike is intrusive into granite. At the contacts the fine grained phase is 1 cm and 0.5 cm in thickness at the upper and lower margins of the dike, respectively. The bulk of the dike exhibits normal grading with a decrease in the size of olivine macrocrysts from the bottom to the top of the dike. Grading is particularly evident in the macrocryst-rich dike 02-26. Here the bottom portion of the sill contains close-packed ilmenite, garnet and olivine macrocrysts, with gradation upwards into macrocrystal kimberlite containing fewer and smaller macrocrysts. In the closely-packed macrocryst-rich portions of this unit the kimberlite matrix comprises less than 10% of the rock. Other discrete intrusions in the lower composite sill of core 02-09 exhibit similar size grading.

The lower composite sill encountered in core 02-09 also contains (at 15.3 - 15.6m) multiple thin units of fine-grained carbonate-rich aphanitic hypabyssal kimberlite. Individual bands range from 0.25 - 1 cm in thickness, and differ modally with respect to the opaque mineral to carbonate ratio. Thin black bands (0.1-0.2mm) of oxide-rich material are common within this unit. Erosional contacts between modally-different bands of kimberlite within composite sills are commonly found. Because of the extreme modal variation between and within sills It is not possible to correlate intrusions between the various drill holes.

Small (<1 cm) xenoliths of granite, phlogopite-pyroxenite, and harzburgite occur within the sills. The upper portion of core 02-26 (from 22.70-23.20m) contains many such xenoliths. A large (4 cm) rounded harzburgite xenolith occurs at 23.2 m in this core. Reactions of the kimberlite with the host granitic rocks range from none to bleaching and chloritization.

All of the diverse macroscopic textural features result from flow differentiation of very fluid, low viscosity carbonate-rich kimberlite. Unusual aspects of the Wemindji kimberlites are: (1) the presence of complex, composite, flow-differentiated dikes/sills; (2) the exceptional concentration of large (1-2 cm) macrocrysts in some of the sills. With regard to the latter, such macrocryst-rich kimberlites are rare, one notable example occurring in one of the kimberlite units at the Monastery Mine (RSA). Flow differentiated carbonate-rich sills are known from the Benfontein and Wesselton Mines (RSA). These intrusions have many similarities with the Wemindji sills, in particular the flow-differentiation, “graded bedding”, and erosional features. Unlike the Wemindji sills they are characterized by diapiric segregations of carbonate. Although carbonate segregations are present in the Wemindji sills they tend to be small, irregular and elongated by flow.

Petrographic Character
Macrocrysts

Angular xenocrysts of quartz are common in many samples. These do not exhibit any reaction margins. Olivine is the dominant macrocryst in all of the kimberlites. It forms rounded-to-anhedral crystals which can be concentrated by flow differentiation. All macrocrystal olivines are completely pseudomorphed by pale yellow lizardite. Typically, the olivines contain at their margins many small subhedral-to-euhedral crystals of deep red rutile. Such inclusions are absent from the cores of the grains suggesting that originally the macrocrystal olivines possessed mantles of a different composition, *i.e.* similar to that of the groundmass olivine (see below). Some macrocrystal olivines have been replaced by quartz plus serpentine. This style of pseudomorphing is evident in the thin contaminated sill occurring at 12.5 - 13.0 m in core 02-09. Despite the abundance of carbonate in these rocks prograde pseudomorphing by carbonate is rare.

Many of the kimberlites contain irregular plates of colourless-to-pale orange pleochroic phlogopite. Typically these are altered along cleavage planes to green chlorite.

Magnesian ilmenite occurs as rounded macrocrysts up to 2 cm in size in cores 02-22 and 02-26. Typically, these are single crystals but mosaic-textured examples also occur. In terms of their composition they contain from 7 - 13 wt.% MgO and <2 wt.% Cr_2O_3. Magnesian ilmenite also occurs as irregular microcrysts throughout the groundmass of the kimberlites (Table 3) These can contain up to 23 wt.% MgO and are typically mantled by either pure ilmenite, Mn-Nb-ilmenite (Table 3) and more rarely by spinel.

Garnets are common in cores 02-22 and 02-26. They are rounded and/or elongated and have well-developed kelyphitic rims consisting of mica and spinel. The crystals analysed were low Ti, low chrome (2-3 wt.% Cr_2O_3) pyrope (*i.e.* G1/G9 garnets). In core 0-26, fresh orthopyroxene is common as large rounded macrocrysts.

Groundmass

In addition to olivine and magnesian ilmenite microcrysts the groundmass is composed of: microphenocrystal olivine, spinel, ilmenite, Mn-Nb ilmenite, rutile, apatite, phlogopite - barian phlogopite, baddeleyite, REE-phosphate, serpentine, calcite and dolomite.

Microphenocrystal olivine forms small euhedral-to-subhedral crystals. The majority of the crystals are now completely pseudomorphed by lizardite. Typically the crystals contain randomly-orientated inclusions of deep red rutile. Similar inclusions occur in the outer margins of the olivine macrocrysts suggesting that the latter have been mantled by olivine of the type which forms the microphenocrysts. Rarely olivine is replaced by dolomite and apatite. Relict olivines (Table 1) are typically uniform in composition with Mg#'s of 0.89 - 0.91, rarely irregular cores of Mg-rich material are found (Mg# 0.93).

Spinel occurs as euhedral-to-subhedral opaque crystals 5 - 60 microns in size. The majority of the *bona-fide* groundmass spinels are Cr-poor members of the qandilite (magnesian ulvöspinel) - ulvöspinel magnetite series with significant contents of $MgAl_2O_4$ spinel (10 - 14 mol.%). (Table 1). The qandilite content can range from 20 - 50 mol. Mg_2TiO_4. Individual sills contain spinels of differing composition. Discrete, anhedral Cr-rich relict cores are rarely present. In some samples spinels have relatively Mg-poor, Fe-rich cores which are zoned to Mg-rich, Fe-poor rims, *i.e.* towards qandilite enrichment. However, typically groundmass spinels are of uniform composition and are Fe-rich. The overall trend of compositional change is from Al-bearing spinels through qandilite-rich examples to ulvospinel-magnetite and ultimately to magnetite (Table 2). Baddeleyite inclusions are common in the spinels. The spinels have Fe/Fe+Mg ratios of 0.55 - 0.72, Ti/(Ti+Cr+Al) > 0.49, and Cr/Cr+Al < 0.1, *i.e.* they plot of the back face of the reduced spinel prism and follow spinel compositional trend 1. The spinel compositions indicate that these rocks are highly-evolved kimberlites. The presence of a $MgAl_2O_4$ component coupled with very low Cr suggests that the magma could have been contaminated with Al derived from the country rocks. Also rarely present are large rounded microcrysts (< 0.5mm) belonging to the solid solution series $(Fe,Mg)Cr_2O_4$ - Fe_3O_4 with only small amounts of qandilite (< 6 mol.%).

Phlogopite occurs as euhedral zoned microphenocrysts (50 x 25 um), ragged skeletal microphenocrysts (20 x <10 um), and fine grained laths (<5 um x 1 um) in interstices between carbonates. The distribution is very irregular, *e.g.* some dolomite-rich samples do not contain any phlogopite, whereas other petrographically-similar samples contain 10-20 vol. % phlogopite. Zoned crystals consist of a rounded discrete core of phlogopite and a euhedral mantle of barian phlogopite (5 - 9 wt.% BaO), *i.e.* phlogopite-kinoshitalite solid solutions (Table 2). Different samples contain micas of differing composition.

Ilmenite is common as anhedral-to-subhedral groundmass crystals and as reaction mantles upon magnesian ilmenite microcrysts. This groundmass ilmenite (Table 3) is typically relatively-pure $FeTiO_3$ with < 1.0 wt.% MgO. However, some crystals are enriched in MnO (up to 12 wt.%) and Nb_2O_5 (3 - 6 wt.%). Mantles of magnetite occur on some crystals.

Deep red-coloured rutile is common as anhedral microcrysts in the groundmass. This mineral is probably derived principally from altered olivine crystals and is strewn throughout the groundmass during the serpentinization process. Typically the crystals are small (< 20 um) and of subhedral-to-rounded habit. Niobium contents can range up to 5 wt.% Nb_2O_5.

The major components of the groundmass in which all of the above are set are dolomite and apatite. The former is the principal carbonate found in these rocks and occurs an anhedral interlocking plates. In some samples dolomite is intergrown with calcite. The dolomite contains < 0.5 wt.% FeO or MnO, and the calcite <0.4 wt.% MgO, <0.2 wt% FeO and MnO. Apatite is abundant (10 -20 vol.% in some samples) and forms large late-stage anhedral plates (100 - 200 um). Prismatic apatite appears to be absent. The apatite contains minor (1 -2 wt.%) to significant (10 - 12 wt.%) amounts of SrO, depending upon sample. In core 02-09 Sr-apatite (5- 10 wt.%) coexists with abundant late-stage REE-phosphate (25.1 wt.% Ce_2O_3, 14.8 wt.% La_2O_3, 13.4 wt.% Nd_2O_3, 2.3 wt.% SrO, 6 wt.% CaO, 1.3 wt.% FeO, 4.7 wt.% SO_3, 25.3 wt.% P_2O_5. Wemindji kimberlites are relatively-poor in serpophitic serpentine although this material is rarely present in the groundmass.

These rocks are unlike most kimberlites in that perovskite does not appear to be present as a groundmass primary mineral. Other minerals which are absent in the sections examined include: melilite and/or its alteration products; andradite garnet; clinopyroxene; nepheline; pectolite and other calcium silicates.

Concluding Comments

The Wemindji rocks are dolomite-rich highly-differentiated hypabyssal kimberlites. In terms of kimberlite nomenclature they range from dolomite spinel kimberlite through macrocrystal dolomite apatite kimberlite to garnet - magnesian ilmenite macrocrystal kimberlite. The diverse modes and textural features result from flow-differentiation and multiple intrusions of many batches of genetically-related kimberlite magma. The kimberlites have been contaminated by reactions with country rock prior to their emplacement.

Table 1. Compositions of Olivine

wt.%				
SiO_2	40.24	39.83	40.93	40.18
FeO_T	7.02	10.54	6.64	10.63
MnO	0.0	0.21	0.24	0.13
MgO	51.12	48.46	51.39	48.11
CaO	0.08	0.07	0.04	0.0
	98.46	99.11	99.24	99.05
Structural formula (O=4)				
Si	0.99	0.99	1.00	1.00
Fe	0.14	0.22	0.14	0.22
Mn	-	-	-	-
Mg	1.87	1.79	1.86	1.78
Ca	-	-	-	-
	3.00	3.00	3.00	3.00
mg#	0.93	0.89	0.93	0.89

Table 2 Representative Compositions of spinels

wt.%	1	2	3	4	5	6	7	8	9	10	11
MgO	9.35	10.02	15.38	21.74	18.94	14.29	10.19	7.59	3.91	1.16	0.85
Al_2O_3	0.92	0.50	8.46	9.51	5.28	13.04	3.12	1.83	1.28	1.75	0.43
TiO_2	8.01	6.57	16.57	18.73	18.45	18.11	14.44	13.41	14.22	14.25	0.73
Cr_2O_3	41.64	46.77	0.49	0.71	0.36	1.60	0.37	0.70	0.0	0.26	0.11
MnO	0.42	0.53	0.43	0.43	0.88	0.42	0.71	0.82	0.40	0.79	0.17
FeO_T	40.39	34.13	56.13	46.43	52.74	57.04	67.67	71.34	74.89	76.76	89.46
Recalculated Fe											
FeO	25.23	21.96	24.14	16.67	19.20	22.89	29.06	31.37	37.77	41.66	29.81
Fe_2O_3	16.85	13.52	35.55	33.62	37.27	34.15	43.53	44.42	41.33	39.00	66.29
Total	102.42	99.87	101.02	101.42	100.38	101.06	99.78	100.14	98.84	98.88	98.39
Mol.% End member molecules											
$MgAl_2O_4$	1.53	0.87	11.35	12.19	6.90	12.02	3.34	2.60	1.88	2.63	0.66
Mg_2TiO_4	25.42	21.91	30.61	43.69	41.76	34.15	23.23	18.47	9.48	1.33	1.97
$MgCr_2O_4$	3.78	14.06	-	-	-	-	-	-	-	-	-
$MnCr_2O_4$	1.00	1.33	-	-	-	-	-	-	-	-	-
Mn_2TiO_4	-	-	0.62	0.59	1.24	0.40	0.92	1.25	0.63	1.28	0.16
$FeCr_2O_4$	41.52	39.27	0.44	0.61	0.32	0.29	0.26	0.67	-	0.26	0.10
Fe_2TiO_4	-	-	11.31	1.65	3.14	10.89	13.91	16.68	29.86	38.37	-
Fe_3O_4	26.75	22.56	45.66	41.26	46.64	42.25	56.23	60.33	58.14	56.12	97.09

1-2 relict chromite-qandilite-magnetite cores; 3-4 core (spinel- ulvospinel-qandilite-magnetite) and rim (spinel-qandilite-magnetite) of zoned spinel; 5- 11 isolated euhedral-to-subhedral spinels in core 02-09 illustrating the very wide range in spinel compositions.

Table 3 Representative Compositions of Ilmenite

wt.%	1	2	3	4	5	6	7	8
MgO	19.30	15.73	12.87	0.30	0.60	0.13	0.15	0.12
Al_2O_3	0.19	0.0	0.47	0.13	0.39	0.14	0.53	0.07
TiO_2	55.00	54.61	53.21	51.15	47.91	49.46	93.48	94.37
Cr_2O_3	1.61	2.14	0.75	0.0	3.16	0.0	0.0	0.0
MnO	0.59	0.69	0.27	1.17	5.26	11.18	0.0	0.10
FeO_T	22.51	25.70	33.23	46.60	41.50	36.30	3.76	1.48
Nb_2O_5	0.20	1.28	0.0	0.51	0.32	2.84	0.63	2.61
Recalculated Fe (2 cations/3 oxygens)								
FeO	14.66	21.75	24.63	44.84	37.04	36.00	-	-
Fe_2O_3	8.72	4.39	9.56	1.96	4.96	0.33	4.18	1.64
Total	100.27	100.59	101.76	100.06	99.64	100.08	98.97	98.91
Mol.% End Member Molecules								
Al_2O_3	0.25	-	0.63	0.19	0.58	0.22		
Cr_2O_3	1.40	1.93	0.67	-	3.17	-		
Fe_2O_3	7.22	3.77	8.14	1.87	4.73	0.33		
Nb_2O_5	0.10	0.66	-	0.29	0.18	1.69		
$MnTiO_3$	1.10	1.33	0.52	2.52	11.30	24.89		
$MgTiO_3$	63.30	53.48	43.43	1.14	2.27	0.51		
$FeTiO_3$	26.60	38.83	46.62	93.99	77.78	72.37		

1-3 macrocrystal Mg-ilmenite; 4-6 ilmenite occurring as mantles upon groundmass spinels and ilmenite macrocrysts; 7-8 rutile.

Table 4. Representative Compositions of Phlogopite and Barium Phlogopite

wt.%	1	2	3	4	5	6	7	8	9
SiO_2	42.37	33.38	41.50	32.58	42.38	32.58	36.96	35.89	33.74
TiO_2	0.0	0.97	0.0	0.33	0.90	0.25	0.40	0.59	0.63
Al_2O_3	10.71	18.62	10.21	17.91	10.25	19.28	15.65	17.18	18.21
Cr_2O_3	0.12	0.08	0.81	0.09	0.19	0.11	0.22	0.21	0.07
FeO_T	3.59	2.00	4.72	1.55	4.74	1.65	2.82	1.83	2.25
MnO	0.08	0.26	0.0	0.25	0.37	0.0	0.0	0.0	0.0
MgO	27.30	24.28	27.33	23.82	25.89	25.16	26.79	25.97	24.94
Na_2O	0.39	0.53	0.09	0.27	0.23	0.35	0.37	0.20	0.17
K_2O	10.82	7.61	9.47	6.96	9.30	6.64	8.85	8.55	8.16
BaO	0.21	8.45	0.16	10.30	0.0	12.10	4.04	5.58	6.99
Total	95.51	96.25	94.12	95.06	94.23	97.87	96.06	96.01	95.16
Structural formulae based on 22 atoms of oxygen									
Si	6.02	4.96	5.98	4.96	6.08	4.85	5.34	5.22	5.01
Al	1.79	3.26	1.73	3.21	1.73	3.38	2.66	2.94	3.18
Ti	-	0.11	-	0.04	0.10	0.03	0.04	0.06	0.07
	-	-	0.09	0.01	0.02	0.01	0.03	0.02	0.01
Fe	0.43	0.25	0.57	0.20	0.57	0.21	0.34	0.22	0.28
Mn	-	0.03	-	0.03	0.05	-	-	-	-
Mg	5.78	5.38	5.87	5.63	5.53	5.59	5.77	5.63	5.52
Na	0.11	0.15	0.03	0.08	0.07	0.10	0.10	0.06	0.05
K	1.96	1.44	1.74	1.35	1.79	1.26	1.63	1.59	1.54
Ba	0.01	0.49	0.01	0.61	-	0.71	0.23	0.32	0.41
	16.11	16.10	15.99	16.11	15.83	16.10	16.14	16.06	16.07

1-2, 3-4, 5-6, rounded cores and euhedral overgrowths (02-09); discrete groundmass euhedral-to-subhedral crystals (02-22).