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# Kimberlite and related rocks from Garnet Lake, West Greenland, including their mantle constituents, diamond occurrence, age and provenance

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## ABSTRACT

Observations of thickness, orientation and morphology and mineral chemistry of the principal diamondiferous intrusive sheet and associated bodies in the vicinity of Garnet Lake, Sarfartoq, West Greenland are reported. The principal body dips to the east on a NE/SW (true) trend and reaches a maximum thickness of 4.25 m. Multiple intrusive events are identified within the main sheet including sub-parallel bands occasionally exhibiting grain size sorting, cross-cutting layers and late-stage carbonate-rich emplacement, particularly at the contacts with country rock.

Phenocrystic mineral assemblages and compositional measurements reveal two principal petrological types. The dominant type is an aillikite and the second rock type is a kimberlite. The kimberlite exhibits thin Ba-rich rims (towards kinoshitalite) on Al-rich phlogopite crysts, and an abundance of perovskite. Compositional zonation in groundmass spinels suggest a later transition towards an aillikite component. The aillikite is characterised by abundant phlogopite, heavily zoned with tetraferriphlogopite rims, transitional Type 1-Type 2 spinel compositions, rare Al,Ti-rich groundmass clinopyroxene and occasional exotic Sr-carbonate phases such as olekminskite.

The Garnet Lake main sheet is characterised by mantle phases occurring as individual grains, most strikingly as garnet xenocrysts up to 5 mm and disaggregated mantle olivine crysts. Xenoliths occur rarely and are typically garnet dunites and garnet lherzolites. Heavy mineral separation reveals an abundance of G10D garnets and, whilst peridotitic garnets dominate, eclogitic G3D and G4D garnets also occur. Trace element compositions of garnet crysts reveal sinusoidal REE patterns in harzburgitic garnets however a component of flat and REE enriched G11 garnets is apparent, reflecting significant mantle refertilisation.

Thermorbarometric calculations on assemblages in Garnet Lake main sheet garnet lherzolites reveal equilibrium conditions clustering closely around 1258 °C and 6.20 GPa, equivalent to a depth of 195 km along a  $41 \text{ mWm}^{-2}$  mantle geotherm. Garnet Lake xenoliths thus lie at the deepest extent of mantle samples recovered from western Greenland lamprophyric rocks and from well within the diamond stability field.

Diamonds are typically colourless and occur as fragments or with a dominant octahedral morphology. Crysts exhibit very high quantities of nitrogen (up to 2133 ppm N) and yet are not strongly aggregated to IaB centres (typically about 33% aggregation). This suggests either a short residence time, low residence temperature or likely a combination of both. Employing the restricted range of equilibrium conditions exhibited by mantle xenoliths, calculated diamond formation ages peaking around 583–593 Ma are favoured. This is a short time before the 568 Ma Garnet Lake main sheet emplacement age which coincides with the age of the nearby Sarfartoq carbonatite complex. A model of mantle refertilisation and diamond formation culminating in conditions favourable for creating carbonate-rich melts acting as carriers of mantle constituents to the surface is presented. Data suggest close temporal, chemical and geographic associations between kimberlite, aillikite and carbonatite.

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# 1. Introduction

Kimberlites, ultra-mafic lamprophyres (UML), carbonatites and related rocks occur abundantly in West and South-West Greenland (Larsen and Rex, 1992; Tappe et al., this issue) and are confined within both the re-worked and undeformed regions of the Archean craton. Emplacement ages range from the Archean through to the Oligocene (reviews in Larsen and Rex, 1992; Hutchison and Heaman, 2008;



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Secher et al., this issue). Aside from large intrusive carbonatite centres (Larsen and Rex, 1992), only a few pipe-like occurrences are known (e.g. the Oqaatsunnguit lamproite, Skjernaa, 1992). Otherwise lamprophyric bodies occur as sheets on a cm-scale up to ~4m thick rarely bulging up to 8m in lenses. Although often thin, many bodies can be traced for hundreds of metres.

Intrusive primary-carbonate bearing ultramafic bodies in West Greenland are of particular interest due to their diamond potential irrespective of their petrological classification. Indeed correct classification of diamond-bearing rocks from Greenland has proven to be controversial with carbonate-kimberlite, UML (aillikite) and orangeite identified (e.g. Mitchell et al., 1999; Hutchison, 2005; Nielsen and Sand, 2008; Tappe et al., this issue; Nielsen et al., this issue). In the vicinity of Garnet Lake, Sarfartoq, West Greenland (Appendix A Fig. 1), some outcropping rocks contain a high abundance of visually identifiable mantle material. Notably the Silly Kimberlite is a clast-supported 'xenolithite,' comprising dunites and garnet lherzolites, however the diamond contents acquired from such rocks are low (Hutchison, 2005). In contrast, kimberlite and kimberliteaffinity rocks occurring as a series of stacked, anastamosing, shallow (~24°), north-east (True) dipping sheets at Garnet Lake contain an abundance of diamonds (Hutchison, 2005; Hutchison and Heaman, 2008). The so-called Garnet Lake 'main sheet' (m.s.) is distinct in its higher concentrations of diamonds relative to other Greenlandic sources, including the nearby sub-parallel sheets. The principal surface expression of the main sheet is exposed at 66° 21.6126' N, 51° 40.2559' W (WGS84 datum, UTM22W 469979E,7360221 N). It lies within undeformed Archaean bedrock approximately 20 km south of the boundary with rocks affected by the 1.9-1.8 Ga (van Gool et al., 2002) Palaeoproterozoic Nagssugtoqidian Orogen.

Here we describe the physical and chemical characteristics and petrology of the rocks making up the Garnet Lake m.s. and use these observations to draw conclusions on the emplacement and genetic history of the body. Abundance, physical and chemical characteristics of discrete mantle minerals, including diamond and also xenoliths are also presented. Chemical concentrations of mantle components are used for geothermobarometric and diamond formation temperature/mantle residence calculations. Observations from samples from neighbouring rocks, particularly from sub-parallel sheets and from outcrops 10 km to the east of Garnet Lake are also included where they contribute to the interpretation of main sheet samples. The results are employed to gain insights into the ambient mantle conditions and conditions for diamond growth during and immediately prior to magma-hosted crustal emplacement.

# 2. Methodology

The dimensions, morphology and extent of the Garnet Lake m.s. were established by direct measurements and remote sensing. Direct data came from the mapping of near-situ float locations, surface backhoe and blasting excavations of in-situ rock and intersections of diamond drill core with the main sheet. Modelled continuation of the sheet to depth and interpolation between drill holes was achieved remotely by seismic reflection surveying. Sample locations discussed in the text are presented in Appendix A Table 1. The large collection of drill core samples provided the majority of textural observations, petrology and chemical characterisation however for diamond separation, larger samples of float and surface excavations contributed significantly. Mantle xenoliths were identified visually and prepared as thin sections. Mantle heavy mineral separates were prepared using dense media separation (DMS) at the Saskatchewan Research Council laboratories and diamonds were separated by caustic fusion at the same laboratory and also at SGS Lakefield.

Non-diamond mineral separates were mounted in epoxy and polished to  $1/4 \,\mu m$  with diamond paste. Major and minor element mineral compositions from polished thin sections and mineral separates were determined using the University of Copenhagen's JEOL JXA-8200

electron microprobe. Standardisation was achieved against natural and synthetic standards. Careful consideration was given to minimising spectral interferences, particularly for BaO. Detection limits (weight percent) for standard data follow those of Sand (2007): SiO<sub>2</sub>-0.024, TiO<sub>2</sub>-0.018, Al<sub>2</sub>O<sub>3</sub>-0.012, Cr<sub>2</sub>O<sub>3</sub>-0.02, FeO-0.03, MnO-0.0298, NiO-0.023, MgO-0.01, CaO-0.012, Na<sub>2</sub>O-0.01, K<sub>2</sub>O-0.01, BaO-0.01. Only mineral compositions with analysis totals within normal ranges for the mineral in question and providing good stoichiometry were considered to be acceptable. Trace element compositions were determined for mantle mineral separates using the Geological Survey of Denmark and Greenland's laser ablation ICPMS following the methodology of Ziemann et al. (2005); Liebscher et al. (2007). Representative phenocryst compositions are presented in Table 1 and mantle mineral compositions are presented in Table 2. Nitrogen concentration and aggregation in rough diamond crysts was determined using Thermo-Nicolet Fourier transform infra-red (FTIR) spectrometry units of the Universities of British Columbia and Alberta. Deconvolution of spectra was carried out using the methods of Boyd et al. (1994, 1995). Results are presented in Table 3.

# 3. Results

# 3.1. Morphology and emplacement

The extent of exploration work conducted so far has identified a true thickness of the Garnet Lake main sheet of up to 4.25 m and the body (Appendix A Fig. 1) has been shown to the limits of seismic reflection techniques available, to be largely continuous over 2.2 km down its 24° north-easterly (True) dip. The sheet has been traced 1.4 km along its NW–SE strike (Hutchison, 2005) although given the presence of glacial cover, particularly to the north, it may continue past the extent proven. Drill core evidence and surface excavations demonstrate that the thickness of the body can be variable and, whilst largely a single body, occasionally bifurcates.

The Garnet Lake m.s. was emplaced in the late Neoproterozoic (568 Ma, Hutchison and Heaman, 2008; Frei et al., 2008). Contact relationships, chilled margins within the main body, mineralogical and textural observations, described in the following, demonstrate that the Garnet Lake m.s. comprises two distinct but related mineralogies.

Garnet Lake area intrusives show clear evidence of emplacement controlled by crustal structural weaknesses such as shear zones and dykes. The Sarfartoq carbonatite complex, lying 21 km to the north-east of Garnet Lake, occupies a major east-west structural feature. Revised age determinations (Secher et al., this issue) demonstrate the carbonatite to be contemporaneous with ultramafic magmatism in the area, including the Garnet Lake m.s. Numerous ultramafic igneous sheets follow structures trending directly towards the carbonatite. Some structures were pre-existing such as for the 'M' and 'N' kimberlitic dykes (Jensen et al., 2004a), ~8 km north-west of Garnet Lake which run for several kilometres along strike of a considerably older Kangamiut dyke. However the stress on the crust during emplacement of such a large (8-12 km diameter) body as the Sarfartog carbonatite would have also created its own pattern of brittle deformation. In addition to trending directly towards the carbonatite, other bodies (Larsen, L.M., GEUS, pers. comm. 2006), including the Garnet Lake m.s., strike orthogonally to, and dip towards the carbonatite, reminiscent of a cone-structure. Indeed the Sarfartoq carbonatite hosts a kimberlitic intrusion within it (Jensen et al., 2004a). Stresses on country rocks are evident in the Garnet Lake m.s. where although contact relationships between the host rock and the m.s. are usually very sharp, near-contact brecciation of country rock gneisses is occasionally apparent. It is also common to observe significant carbonate infiltration into a network of brittle fractures within the host gneiss up to 10 m from even the thinner, 1 m pinches and this feature acts as a useful indicator of proximity to kimberlite. The style of emplacement, and aspects of mineralogy and texture described in the following, are strongly reminiscent of the Benfontein sills of South Africa (Dawson and Hawthorne, 1973).

118 Spinel Core 0.28 15.98 3.46 4.40 63.60 1.38 0.08 7.95 0.00 0.12 0.03 n.d. 97.28	M.T. Hutchison, D. Frei / Lithos 112.
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Table 1 Representative compositions of Garnet Lake main sheet phenocryst and groundmass phases.

Sample	05DS07_155a	05DS07_155a	05DS07_155a	05DS07_155a	05DS07_155a	05DS07_155a	05DS07_155a	05DS07_155a	05DS07_155a	05DS07_155a	MHG9_6a	MHG9_6a
Aillikite												
Grain	53	59	67	68	1	4	16	20	41	42	117	118
Phase	Phlogopite <sup>¤</sup>	Phlogopite¤	Phlogopite <sup>*</sup>	Phlogopite <sup>*</sup>	Ilmenite	Ilmenite	Ilmenite	Ilmenite	Olivine	Olivine	Spinel	Spinel
Location	Core	Core	Rim	Rim	Core	Core	Rim	Rim	Core	Core	Core	Core
SiO <sub>2</sub>	38.61	39.14	41.92	41.55	0.09	0.07	0.05	0.03	41.00	40.74	0.12	0.28
TiO <sub>2</sub>	4.04	3.96	0.48	0.46	21.80	20.09	12.50	11.80	bdl	bdl	19.55	15.98
Al <sub>2</sub> O <sub>3</sub>	14.38	14.29	1.55	1.22	4.60	4.46	1.32	1.30	0.04	0.01	6.35	3.46
Cr <sub>2</sub> O <sub>3</sub>	0.98	1.11	bdl	bdl	0.67	0.82	0.50	0.55	0.04	0.10	2.26	4.40
FeO¥	5.92	5.49	16.40	17.18	58.07	61.00	75.11	75.44	9.58	9.57	56.31	63.60
MnO	bdl	0.04	bdl	0.11	0.76	1.12	0.86	1.18	0.10	0.19	1.17	1.38
NiO	0.10	0.08	0.04	0.03	0.08	0.05	0.11	0.03	0.31	0.45	0.16	0.08
MgO	21.66	21.50	25.20	25.07	13.44	11.74	6.72	6.38	49.51	49.15	11.66	7.95
CaO	bdl	bdl	0.07	0.03	0.14	0.16	0.14	0.33	0.09	0.19	0.00	0.00
Na <sub>2</sub> O	0.22	0.22	0.15	0.12	0.03	0.03	0.06	0.03	0.02	0.01	0.10	0.12
K <sub>2</sub> O	10.30	10.24	9.94	10.28	0.00	0.00	0.04	0.00	0.00	0.01	0.03	0.03
BaO	0.33	0.25	0.04	0.03	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	96.54	96.32	95.79	96.08	99.68	99.54	97.41	97.07	100.69	100.42	97.71	97.28
Sample	05DS07_155b	05DS07_155b	05DS07_155b	05DS07_155b	05DS07_155b	05DS07_155b	05DS07_155b	05DS07_155b	05DS07_155b	05DS07_155b	05DS07_155b	
Kimberlite												
Grain	133	136	142	160	168	2	30	48	54	127	131	
Phase	Phlogopite ¤	Phlogopite §	Phlogopite §	Phlogopite §	Phlogopite §	Ilmenite	Ilmenite	Ilmenite	Ilmenite	Perovskite	Perovskite	
Location	Core	Core	Core	Rim	Rim	Core	Core	Rim	Rim	Core	Core	
SiO <sub>2</sub>	38.79	36.13	37.44	34.77	35.84	0.09	0.06	0.05	0.48	bdl	bdl	
TiO <sub>2</sub>	3.96	1.29	0.98	1.63	1.56	17.74	20.85	14.09	10.48	57.08	57.44	
Al <sub>2</sub> O <sub>3</sub>	13.93	18.11	17.36	18.41	18.6	5.39	4.53	3.15	1.38	0.34	0.23	
$Cr_2O_3$	0.68	bdl	0.02	0.03	0.06	3.26	2.70	0.61	0.38	bdl	bdl	
FeO <sup>¥</sup>	5.78	4.68	4.47	4.70	4.57	57.79	56.53	67.96	74.37	1.37	1.19	
MnO	bdl	0.07	0.06	0.06	0.05	1.08	0.79	1.10	1.15	bdl	bdl	
NiO	0.12	0.04	0.06	bdl	0.04	0.03	0.04	0.11	0.10	bdl	bdl	
MgO	21.55	22.66	24.14	22.05	22.96	13.22	13.51	10.25	7.75	0.07	0.06	
CaO	0.02	0.04	0.10	0.07	0.12	0.25	0.08	0.40	0.40	38.83	39.14	
Na <sub>2</sub> O	0.22	0.20	0.14	0.21	0.12	0.00	0.00	0.00	0.02	0.33	0.29	
K <sub>2</sub> O	10.38	9.77	9.99	9.41	9.46	0.02	0.01	0.01	0.09	0.01	0.03	
BaO	0.17	1.98	1.12	2.96	2.82	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	
Total	95.60	94.97	95.88	94.30	96.20	98.87	99.10	97.73	96.60	98.03	98.38	

¥= all Fe calculated as FeO, ¤ = High-Ti phlogopite, \* = Tetraferriphlogopite, § = High-Al phlogopite, bdl, below detection limit, n.d. = not determined.

Representative compositions of Garnet Lake mantle mineral separate phases.

	05DS10-30	05DS23-132	MHG9-5	MHG9-5	05DS12-26	05DS12-26	05DS10-30	05DS23-132	05DS12-26	05DS12-26	05DS12-26	05DS12-26	MHGB10	05DS12-26	MHG9-5	05DS25-63
Grain	102	043	C28	C47	121	109	124	059	055	157	181	192	109	041	C53	143
Phase <sup>a</sup>	G9	G9	G11	G11	G10D	G10D	G1	G1	G3D	G3D	G4D	G4D	Olivine	Olivine	Cr-Diopside	Cr-Diopside
#	2	2	2	2	4	2	2	2	4	3	2	1	2	4	2	3
SiO <sub>2</sub>	41.74	42.10	41.64	41.58	42.08	41.90	42.04	42.30	38.83	39.12	41.09	41.00	40.28	40.99	53.66	54.41
TiO <sub>2</sub>	0.20	0.06	0.78	0.70	0.28	0.31	0.63	0.91	0.51	0.51	0.56	0.63	bdl	bdl	0.18	0.19
$Al_2O_3$	17.32	19.04	18.20	19.36	18.70	18.82	21.40	22.54	22.50	22.61	22.70	22.62	bdl	0.01	1.61	1.99
$Cr_2O_3$	7.11	5.64	5.62	5.12	6.40	6.38	1.31	0.14	0.07	0.07	0.19	0.21	0.03	0.06	2.86	1.63
FeO <sup>§</sup>	7.14	6.20	7.02	8.80	6.19	6.38	11.33	8.10	17.90	17.82	14.76	14.33	6.84	7.49	3.75	3.53
MnO	0.42	0.30	0.31	0.42	0.31	0.27	0.42	0.32	0.40	0.38	0.27	0.27	0.12	0.10	0.11	0.12
NiO	bdl	bdl	bdl	0.02	bdl	bdl	bdl	0.03	0.02	bdl	0.03	bdl	0.39	0.38	0.07	0.51
MgO	20.21	21.63	20.40	19.54	22.07	22.14	19.26	21.86	11.37	11.74	17.84	18.20	51.94	51.08	13.81	15.90
CaO	6.36	5.26	5.27	5.18	4.44	4.40	4.50	4.42	8.22	7.73	3.46	3.36	0.01	0.02	19.20	20.12
Na <sub>2</sub> O	bdl	0.02	0.07	0.10	0.03	0.05	0.08	0.10	0.19	0.21	0.17	0.16	0.01	0.02	2.91	2.20
K <sub>2</sub> O	bdl	bdl	0.01	bdl	bdl	bdl	bdl	0.01	bdl	0.01	0.01	bdl	bdl	bdl	bdl	0.01
BaO	bdl	n.d.	n.d.	n.d.	0.02	0.01	0.02	n.d.	0.05	0.05	0.02	0.01	n.d.	0.01	n.d.	n.d.
Total	100.50	100.25	99.33	100.82	100.52	100.66	100.99	100.73	100.06	100.26	101.10	100.79	99.62	100.17	98.16	100.61
nnm <sup>b</sup>																
li	0.126	0.079	0.130	0.609	0.0610	0.067	0.611	0 270	3.26	2 680	412	3.67	1315	1 44	0.750	0.865
Sc	1914	187	138.6	125.2	146	144	139.8	103	59.9	64 5	49.6	51.1	1130	1.44	68.8	45 36
Ni	108.5	107	115 /	58.1	103.6	105.6	38.82	100 7	21.07	21.76	90.7	104 5	2022	2840	256.0	205 5
7n	13 03	107.1	12 10	15.02	10.5.0	11 0	10 55	1/1 8	124.8	110.0	023	05.0	117	18 /	11 11	14 71
C 1	8 13	5 3/	10.43	12.44	10.30	10.14	10.12	10.8	124.0	11.5.0	13.87	14 50	0.0460	0.0070	8 20	10.03
Ga Cr	0.625	0.800	0.022	12.44	0.678	0.600	711	70	100	14.44	15.07	14.55	0.0400	0.0370	440.0	10.55
V	2 100	2 17	16 72	20.09	5.16	5.0	7.11	7.2	155	4.71	20.5	20.9	<0.0042	<0.0087	19 40	2 5 9 0
1 7n	12.15	J.17	72.46	20.08	16.0	14.4	24.04	51	43.0	45.0	50.5	50.0	0.00184	0.00129	10.42	J.JOU 41.10
ZI Nb	12.15	4.47	75.40	99.41	0.220	14.4	0740	02	27.0	20.9	0.0296	0.0291	0.0890	0.0430	0.4170	41.19
IND Do	0.000	0.010	0.3710	40.2	0.239	0.238	0.745	14.5	15.90	1 790	1 254	0.0201	<0.00176	0.0440	1246	1150
Dd Le	0.0080	0.00700	0.00280	40.2	0.0150	0.0820	0.04	14.5	13.69	1.760	1.234	0.0615	<0.00176	0.00241	1.540	1.150
Ld	0.1192	0.0630	0.0551	0.0260	0.162	0.0400	0.504	0.114	0.175	0.0990	0.0415	0.0155	0.00026	<0.00090	12.00	3.500
Ce Du	0.978	0.013	0.597	0.2960	0.442	0.424	1.213	0.467	0.559	0.2760	0.1950	0.1306	0.00076	<0.00087	51.64	11.82
PT	0.2840	0.227	0.2115	0.1236	0.158	0.156	0.1834	0.128	0.1230	0.0707	0.0746	0.0696	DOI	<0.00089	9.60	1.913
INC	1.//1	1.85	2.098	1.437	1.60	1.58	1.359	1.26	0.930	0.678	1.210	1.180	Dai	< 0.0022	49.23	9.40
Sm	0.4/1	0.66	1.543	1.270	1.11	1.05	0.930	1.01	0.800	0.730	1.4/0	1.470	bdl	0.00125	11.09	2.111
Eu	0.1600	0.176	0.635	0.608	0.402	0.380	0.446	0.52	0.581	0.478	0.702	0.722	bdl	< 0.00094	3.140	0.613
Gđ	0.568	0.540	2.640	2.730	1.36	1.29	2.220	2.43	3./2	3.02	3.34	3.48	bdl	<0.0048	8.28	1.701
Tb	0.0753	0.061	0.4510	0.548	0.183	0.170	0.511	0.53	0.960	0.781	0.647	0.678	bdl	< 0.00074	0.959	0.2030
Dy	0.558	0.370	3.130	3.90	1.02	0.97	4.130	4.7	7.87	6.91	5.17	5.29	0.00093	<0.00155	4.970	1.021
Но	0.1185	0.110	0.615	0.777	0.198	0.183	1.011	1.16	1.70	1.61	1.160	1.180	bdl	<0.00089	0.740	0.1553
Er	0.449	0.460	1.807	2.110	0.590	0.58	3.230	3.9	4.93	5.02	3.59	3.66	bdl	<0.00080	1.616	0.2850
Tm	0.0785	0.098	0.2690	0.3050	0.099	0.093	0.523	0.62	0.740	0.762	0.536	0.564	0.00023	<0.00081	0.1692	0.0333
Yb	0.674	0.98	1.951	2.070	0.900	0.84	3.660	4.5	4.93	5.26	3.75	3.99	bdl	< 0.0029	0.993	0.1510
Lu	0.1348	0.196	0.3310	0.3150	0.187	0.178	0.571	0.70	0.710	0.792	0.590	0.589	0.00181	< 0.00067	0.1156	0.01640
Hf	0.380	0.099	1.807	2.370	0.405	0.370	2.153	1.78	0.660	0.730	0.980	0.980	0.00085	0.00350	7.58	2.609
Та	0.0769	0.0530	0.0396	0.02010	0.0228	0.0256	0.0469	0.0290	0.00490	0.00280	0.00294	0.00145	0.0296	0.00229	0.0343	0.02210
Th	0.0330	0.0173	0.01080	0.00509	0.0099	0.0117	0.0608	0.0153	0.0740	0.01200	0.0336	0.0163	bdl	< 0.00091	0.1038	0.0515
U	0.0364	0.0233	0.02110	0.01240	0.01210	0.0127	0.02190	0.0117	0.00284	0.0638	0.00342	0.00200	0.00112	< 0.00029	0.01840	0.00713

#= number of electron microprobe analyses, § = all Fe calculated as FeO, bdl = below detection limit, n.d. = not determined, < = concentration below stated ICPMS detection limit where this can be calculated.</li>
<sup>a</sup> G = Garnet, classification following Grütter et al. (2004).
<sup>b</sup> Trace element composition presented in ppm atomic as determined by ICP-MS and where the two least significant digits based on 1σ errors are presented.

## Table 3

Nitrogen characteristics of Garnet Lake main sheet diamond crysts and modelled residence times/temperatures.

Diamond	NT <sup>a</sup>	%IaB <sup>a</sup>	T(°C) <sup>b</sup>	t (Ma) <sup>b</sup>	Diamond	NT <sup>a</sup>	%IaB <sup>a</sup>	T(°C) <sup>b</sup>	t (Ma) <sup>b</sup>
05DS25 1	1686	17.1	1236	1.8	SGS Caustic 6	292	52.5	1338	56.2
05DS25_2	1474	64.3	1303	18.1	SGS_Caustic_8	701	39.0	1294	13.5
06DS04 1	1004	19.7	1255	3.6	SGS Caustic 9	1428	17.3	1241	2.2
06DS04_2	1066	19.7	1253	3.4	SGS_Caustic_10	617	53.6	1316	27.8
06DS13_1	1179	13.4	1238	2.0	SGS_Caustic_11	999	59.1	1308	21.4
06DS13_2	1429	25.6	1255	3.6	SGS_Caustic_12	679	19.0	1265	5.1
06DS13_3	1298	19.3	1247	2.7	SGS_Caustic_13	1474	67.4	1307	20.9
MHGB10_1	979	5.2	1214	0.8	SGS_Caustic_14	1227	43.7	1283	9.4
MHGB10_2	1507	19.0	1242	2.3	SGS_Caustic_15	1524	14.7	1233	1.7
MHGB10_3	981	22.2	1260	4.3	SGS_Caustic_16	697	38.6	1294	13.4
MHGB10_4	910	10.5	1237	1.9	SGS_Caustic_17	373	35.7	1309	22.1
MHGB10_5	1549	19.0	1242	2.3	SGS_Caustic_18	492	44.6	1312	24.3
MHGB10_6	1039	21.2	1257	3.8	SGS_Caustic_19	389	34.7	1306	20.3
MHGB10_7	1451	3.3	1191	0.4	SGS_Caustic_20	289	44.0	1328	40.5
MHGB10_8	1217	25.7	1260	4.2	SGS_DMS_2	801	71.6	1332	46.7
MHGB10_9	965	7.4	1225	1.2	SGS_DMS_3	694	49.2	1307	20.7
MHGB10_10	958	21.9	1260	4.4	SGS_DMS_4	826	49.5	1302	17.6
MHGB10_11	1297	32.8	1268	5.6	SGS_DMS_5	831	71.7	1331	45.2
MHGB10_12	743	2.9	1206	0.6	SGS_DMS_6	1368	70.6	1314	26.0
MHGB10_13	1731	70.4	1306	20.4	SGS_DMS_7	997	61.8	1311	24.1
MHGB10_14	591	0.0	1177	0.0	SGS_DMS_8	802	46.0	1298	15.8
MHGB10_15	1207	15.9	1243	2.3	SGS_DMS_10	534	28.4	1288	11.0
MHGB10_16	1024	0.4	1144	0.1	SGS_DMS_11	783	60.4	1317	28.9
MHGB10_17	728	0.0	1183	0.0	SGS_DMS_12	536	15.8	1265	5.2
MHGB10_18	1102	14.9	1243	2.4	SGS_DMS_13	644	44.6	1303	18.5
MHGB10_19	940	13.1	1243	2.4	SGS_DMS_14	700	60.8	1321	32.9
MHGB10_20	1233	10.8	1230	1.5	SGS_DMS_15	456	48.1	1318	30.1
MHGB10_21	815	40.4	1291	12.3	SGS_DMS_16	571	44.5	1307	20.8
MHGB10_22	413	49.7	1323	35.4	SGS_DMS_17	703	32.0	1285	9.9
MHGB10_23	1511	32.5	1263	4.7	SGS_DMS_19	913	53.2	1303	18.4
MHGB10_24	801	7.6	1231	1.5	SGS_DMS_20	1107	74.3	1326	38.7
MHGB10_25	1035	25.6	1264	4.9	SGS_DMS_21	696	41.1	1297	14.9
MHGB10_26	1463	30.7	1261	4.5	SGS_DMS_22	59	7.3	1305	19.7
MHGB10_27	1424	49.0	1285	10.0	SGS_DMS_23	1728	79.1	1321	32.5
MHGB10_28	915	17.8	1254	3.5	SGS_DMS_25	1164	60.5	1305	19.5
MHGB10_29	1251	39.1	1277	7.6	SGS_DMS_26	806	66.3	1324	36.2
MHGB10_30	1685	35.0	1263	4.7	SGS_DMS_27	1076	68.3	1318	29.7
MHGB10_31	1335	22.2	1251	3.2	SGS_DMS_28	852	75.9	1337	54.8
MHGB10_32	2133	18.8	1232	1.6	SGS_DMS_29	641	13.3	1255	3.5
MHGB10_34	1146	12.4	1236	1.8	SGS_DMS_30	802	36.6	1287	10.7
MHGB10_35	855	51.1	1303	18.1	SGS_DMS_32	929	35.0	1280	8.6
SGS_Caustic_1	1605	54.2	1287	10.9	SGS_DMS_33	1899	56.4	1285	10.1
SGS_Caustic_2	477	42.1	1309	22.6	SGS_DMS_34	1389	94.5	1377	184.7
SGS_Caustic_3	1041	33.3	1275	7.1					

 $N(T) = total nitrogen in ppm element the population having a 1\sigma uncertainty of <math>\pm 7.8\%$ ,  $\%laB = percentage of nitrogen atoms occupying laB centres the population having a 1\sigma analytical uncertainty of <math>\pm 15.8\%$ ,  $T(^{\circ}C) = modelled$  residence temperature based on a residence time of 4 Ma, t(Ma) = modelled residence time based on a residence temperature of 1258 °C. Data supplement analyses of an additional 32 stones from the Garnet Lake main sheet presented in Hutchison and Heaman (2008). Given the magnitude of uncertainties in nitrogen measurements, it is disingenious to calculate temperature and residence time uncertainties for individual diamonds, estimates of residence time and ambient temperature being made from subsets of the whole dataset. Typically, however, temperature uncertainties are of the order of  $\pm 10$  °C and residence times typically range from 37% above to 27% below the mean.

<sup>a</sup> Nitrogen concentration and aggregation calculations follow the methods described in Boyd et al. (1994, 1995).

<sup>b</sup> Residence time and temperature calculations follow the method described in Taylor et al. (1990).

#### 3.2. Mineral chemistry and petrography

Given that the petrological classification of West Greenland diamondbearing rocks has proven contentious, a summary of the discriminatory criteria of candidates for Garnet Lake rock-types is merited. Garnet Lake main sheet and vicinity rocks are ultramafic (with mafics typically>90% modal), intrusive, igneous rocks which are rich in xenocrystic olivine and ubiquitously contain cognate olivine, phlogopite, ilmenite and calcite. Unlike some lamprophyric rock types (Rock, 1991), primary feldspars and feldspathoids are completely absent from Garnet Lake samples studied. Furthermore, whilst carbonate-rich, typical Garnet Lake samples have modal carbonate of less than 50% and hence cannot be classified as carbonatites (Woolley et al., 1996). Compositions of the largely mineralogically similar Majuagaa kimberlite have K<sub>2</sub>O less than 3 wt.% (Nielsen and Sand, 2008), precluding these from classification as ultra-potassic rocks following Foley et al. (1987) or lamproites following Woolley et al. (1996). Indeed, Type I kimberlite is not an alkali-igneous rock (Kjarsgaard et al., this issue) as is commonly misconceived. By analogy and also given the ubiquitous presence of primary carbonate, neither can Garnet Lake samples be classified as lamproites. Although bulk rock compositions are not currently available for Garnet Lake rocks, given the degree of mineral segregation, coupled with the abundance of xenocrysts, bulk composition data for Garnet Lake rocks would not be expected to provide a quick fix to petrological classification,. It is for these reasons that bulk rock compositions as a classification tool for ultramafic lamprophyres, kimberlites and orangeites are generally considered disingenuous, authors typically preferring the mineral chemical approach to classification (Rock, 1991, Mitchell, 1995, Tappe et al., 2005).

As Garnet Lake rocks are neither pyroclastic, the remaining candidates are aillikite, kimberlite and orangeite as defined by Mitchell (1995). The updated IUGS classification scheme of Tappe et al. (2005), is favoured as a best first framework to classify Garnet Lake rocks. In the absence of Ti $\pm$ Zr-rich primary garnet, Tappe et al. (2005) argue that UML aillikites, orangeites and archetypal (Type I, Mitchell, 1995) kimberlites present the same associations of dominant mineral species and hence petrological classification must be achieved by inspection of



**Fig. 1.** Representative photographs of rocks from Garnet Lake main sheet and vicinity. The scale bar in each case represents 1 cm. (a) Hand sample MHG9-4 from the main sheet showing the fine knobbly texture typical of weathered surfaces. A black-rimmed kelphytised garnet xenocryst occupies the centre of the field of view and is the typical form evident for mantle material aside from disaggregated mantle olivine; (b) Sectioned core sample 06DS02-438 from the main sheet is unusual in that 1–2 cm scale rounded xenoliths being the features occupying most of the image are not disaggregated. This clast-supported 'xenolithite' texture is more typical of the nearby (0.5 km) Silly Kimberlite locality (Hutchison, 2005) which overlies the main sheet. Interstices between xenoliths in this sample are almost entirely calcite (white). Down-dip is to the right of the image; (c) Fine grained macroscopically relatively featureless broken core sample 06DS15-914 from the principal excavation site of the Garnet Lake main sheet. This absence of both strong carbonate segregation and cm-scale olivine and ilmenite xenocrysts is typical also of the kimberlite samples from the main sheet as identified by mineral chemistry; (d) In contrast to Fig. 1c, kimberlite sample MHG5-21, from 10 km east of Garnet Lake shows evidence of grain segregation and cm-scale xenocrysts of olivine (mid-grey) and ilmenite (dark grey, rounded); (e) Variably-textured main sheet core sample 06DS14-639 typical of Garnet Lake aillikite. Serpentinised olivine-rich (black rounded grains) accumulated band occupies the central strip of the image with an almost pure calcite carbonated band (grey) immediately to the right. Irregular thin diagonal white bands of late-stage calcite veining are evident as are white, irregular calcite bles (left of centre) possibly products of melts segregation. Occasional rounded crustal xenoliths (central 1 cm grain on far left side of image) are also apparent. Down-dip is to the left of the image; (f) Evenly-textured split core sample 0

spinel, clinopyroxene and phlogopite mineral compositions. This is certainly the case for aillikites and orangeites, however Mitchell (1995) argues that mineral *assemblage* criteria can be used in conjunction with mineral chemistry to achieve a robust classification between kimberlite and orangeite in many cases. Kimberlites may contain monticellite or Carich cognate olivine, which is also typically more Fe-rich than primary olivine in orangeites. Kimberlites also may exhibit 'atoll-textured' spinels typically of Mg-chromite and Mg-ülvospinel composition (the latter being rare in orangeites), perovskite (also rare in orangeite) and phlogopites with Ba-rich rims. In contrast, orangeite is typifed by a greater abundance of phlogopite, usually exhibiting tetraferriphlogopite rims (Ti and Al depleted) and primary clinopyroxene. Apatite and other (e.g. REE-rich) phosphates, barite and Ba-carbonate species and Zr-silicates are also more common in orangeites than in kimberlites.

The Garnet Lake m.s. lithology is hypabyssal and typically highly competent, fine grained (sub-mm) and dark green or blue. It has experienced little weathering except in areas where calcite  $\pm$  dolomite has been abundant as a groundmass phase or in veins, or in longexposed float (Fig. 1a and d). On hand-sample scale, variability in colour, mineral grain size and alteration is often apparent (Fig. 1). Segregation into layers is almost ubiquitous (Fig. 1e) and the accumulation of dense phases, particularly ilmenite and in some cases mantle xenoliths, in horizontal layers close to the base of intersections (Fig. 1b) suggests a common density segregation. Indeed the type sample for the Garnet Lake kimberlite, 05DS07-155b, given the very high abundance of perovskite and ilmenite, almost certainly arises from a degree of accumulation of dense phases and bears a strong resemblance to flowdifferentiated hypabyssal spinel perovskite calcite kimberlite from Benfontein (Mitchell, 1997). Occasionally fining upwards trends are clearly observed and xenoliths, when they occur (Fig. 1b), typically occupy positions approximately 2/3 down within the thickness of the sheet. Although bands are usually parallel to the edges of the intrusive body, occasionally they are cross-cut by subsequent intrusive layers both carbonate-rich and carbonate poor. Whilst it is very common to observe calcite-rich material up to several centimetres thick at the country rock interfaces, calcite veins and bands (often containing rounded olivine macrocrysts Fig. 1e) occur intermittently throughout the sheet. Diapiric calcite segregation (Fig. 1e) is also observed, another feature in common with kimberlite sills at Benfontein (Mitchell, 1997). Aside from the variability of carbonate component and a degree of cryst (particularly xenocryst) sorting, two separate rock types can be identified from both the Garnet Lake main sheet and the vicinity on the basis of mineralogy and mineral chemistry, as described in the following. Representative mineral compositions for these two rock types are presented in Table 1. Given that petrological distinction is made primarily on the basis of mineral chemistry rather than macroscopic characteristics, it is not possible at this stage to say what the physical interaction on emplacement of the two magma types has been at Garnet Lake. In particular, despite contact relationships between pulses of magma intrusion being seen, no clear contact between the two rock types has been identified. However as discussed in the following, some comments can be made as to the relative age of magmatic types on the basis of corerim compositional variation.

# 3.2.1. Aillikite

The dominant Garnet Lake m.s. rock is classified as an aillikite on the basis of mineral chemical criteria following Mitchell (1995) and Tappe et al. (2005), and as described in the following. The texture is macrocrystal consisting typically ~25% of mantle olivine (<3 mm), pyrope (Fig. 1a) and phlogopite macrocrysts. The groundmass mineralogy, which primarily determines rock classification, consists up to 30% opaques (mostly Mg-ilmenite and spinel) varying depending on the extent of density segregation, and on average 20% phenocrystic phlogopite (Fig. 2). The remaining groundmass is a mixture of primary olivine, calcite, dolomite, occasional clinopyroxene and minor phases. As an example, electron microprobe transects across thin section 07DS45-

96c revealed modal proportions of phases aside from olivine and evident xenocrysts as follows: phlogopite-24% (with an additional 3% of tetraferriphlogopite rims), dolomite-25%, serpentine-16%, calcite-12%, with the remainder comprising almost equal proportions of ilmenite, titanomagnetite, clinopyroxene, clays, chlorite and chromite. Whilst olivine comprises 24% of this whole rock sample, most of the olivine crysts are likely xenocrysts (c.f. Nielsen and Sand, 2008) however it is not clear what value can be assigned to the proportion of phenocrystic olivine. It should be noted that particular care should be taken in consideration of mineral proportions given the pervasiveness of density segregation. Hence reasonable melt compositions cannot be easily obtained from recombining mineral chemistry with mineral proportions. The same applies to kimberlite rock samples described in the following.

Discrimination between cognate olivine from xenocrystic olivine is a challenge given that due to xenolith disaggregation, xenocrystic material is so pervasive. Also by analogy with Majuagaa kimberlites (Nielsen and Sand, 2008), the compositions of phenocrystic olivine typically lie well within the range of xenocrystic compositions. The problem can be tackled however by characterising the compositions of known xenocrystic olivine (from xenolith phases), focussing on measurement of small euhedral groundmass olivines as candidates for phenocrystic compositions and identifying compositional trends where they occur. Fig. 3a presents olivine compositions for all Garnet Lake and vicinity rocks in terms of nickel concentration against forsterite content. The interpreted field of Majuagaa kimberlite melt compositions (dashed lozenge, Nielsen and Sand, 2008) is shown as context. As definitive identification of individual primary olivine crysts is difficult and given that groundmass olivines describe a wide compositional range, some analysed crysts likely at least include a xenocrystic core component. What is clear from Fig. 3a however is that some Garnet Lake main sheet groundmass phases describe a trend in composition with increasing Ni content within the range Fo87 to Fo89 (solid lozenge), parallel to and offset to more fayalite-rich compositions than those described by Nielsen and Sand (2008). A separate, more forsterite-rich, field (Fo90-Fo92) is also evident in Fig. 3a, a range which is particularly consistent with orangeite compositions described by Mitchell (1995) and with aillikite phenocrystic olivines (e.g. Tappe et al., 2006).

For ilmenite grains and after calculation of ferric iron by charge balance (Droop, 1987), components of end member pyrophanite (Mn), geikielite (Mg) and ilmenite (Fe<sup>2+</sup>) were calculated. Deviation from a 1:1 correlation between geikielite and ilmenite (Fig. 3b) is small and represents the small amount of pyrophanite component (the mode for all samples being 0.27 wt.% MnO). By comparison with the kimberlite compositional field of Mitchell (1995) all ilmenites fall within an acceptable range of Mn content. Garnet Lake main sheet aillikitehosted phenocrystic ilmenites have core compositions represented by 8-15 wt.% MgO and are typically at the lower Mg-end of the Mitchell (1995) kimberlitic field. Margin compositions typically overlap the core compositions however the small number of distinct rim compositions acquired demonstrates a relative Mg-depletion (down to 7 wt.% MgO) following the rough compositional trend annotated by the dashed line 'A' (Fig. 3b). This trend is consistent with both orangeites and aillikites (Mitchell, 1995; Mitchell et al., 1999).

Groundmass spinel compositions from Garnet Lake aillikites do not follow the magmatic trends of Mitchell (1995), rather cluster at high Ti number (Ti/(Ti + Cr + Al) cations) as shown in Fig. 3c. Following convention, Fig. 3c and d presents spinel compositions projected as ferric iron-free. Charge balance calculations (Droop, 1987) demonstrate that spinels from Garnet Lake main sheet aillikites do however contain significant ferric iron (up to 0.8  $Fe^{3+}/(Fe^{3+} + Fe^{2+})$ ). Dominantly, compositions of primary aillikite spinels lie between the 'Type 1 magmatic trend' of Mitchell (1995) and the 'Type 2 orangeitic trend' (Fig. 3c). The transition from core to rim compositions is always from Fepoor to Fe-rich as shown on Fig. 3c evolutionary trends 'B'. Compositions of xenocrystic spinel from mineral separates and thin sections are



Fig. 2. (a and b) Representative transmitted plane-polarised light and back-scattered electron images of Garnet Lake aillikites, where: (a) Plane polarised transmitted light image of sample MHG9-3. Field of view is 1.3 mm. Reasonably fresh olivine xenocrysts (OI) occur within a matrix of primary phlogopite (Ph) with distinct orange tetraferriphlogopite rims (TFP) also occurring as separate homogeneous crysts. Ilmenites (IIm) are characteristically irregular in morphology. The final crystallising phase in this sample is dolomite (D). (b) Back-scattered electron image of a portion of sample 05DS07-155c. Beam conditions used were 20 kV with a 6 micron rastered spot-size. The scale bar is 100 µm. The image shows a large phenocrystic olivine (OI) altered to secondary serpentine (Srp) and partly replaced by Sr(Sr,Ca,Ba)(CO<sub>3</sub>)<sub>2</sub> olekminskite (OIk). Separately, irregular ilmenite (IIm), chromite (Chr) and serpentine occur as phenocrysts within, in this case, a primarily dolomite-rich matrix (D). Separate phlogopite phenocrysts (Ph) show distinct zonation to bright backscattered tetraferriphlogopite rims (TFP) typical of aillikites and orangeites. (c and d) Representative transmitted plane-polarised light and back-scattered electron images of selected portions of Garnet Lake main sheet kimberlite sample 05DS07-155b, where: (c) Plane polarised transmitted light image. Field of view is 1.3 mm. Phlogopites (Ph) are relatively homogeneous and lack the distinctive tetraferriphlogopite rims of aillikite samples (e.g. Fig. 2a and b). The high abundance of opaque minerals suggests the influence of a mechanical concentration in this sample and hence modal proportions are not representative of the primary bulk magma composition. Ilmenites (Ilm) are typically euhedral and triangular shaped, whereas perovskite phenocrysts (Pvk) are typically square in section and subhedral. In this sample, euhedral primary olivine (OI) shows a brown colouration due to the onset of alteration. The principal carbonate matrix component in this sample is calcite (C). (d) Back-scattered electron image. Beam conditions used were 20 kV with a 6 micron rastered spot-size. The scale bar is 100 µm. The image shows euhedral phenocrysts of ilmenite (llm) occasionally with darker Mg-rich cores (Mg-llm) and apatite (Ap). The matrix comprises calcite (C) and dolomite (D). Perovskite phenocrysts (Pvk) exhibiting bright inclusions of monazite, rutile, baddelevite and dark toned ilmenite, partly altered phenocrysts of primary serpentine (Srp) and phlogopite phenocrysts (Ph) with little zonation are typical of Type I kimberlite (Mitchell, 1995). Whilst not shown here, some grains have very narrow (micron-scale), Ba-rich rims which is also a feature typical of Type I kimberlite.

usually chromites and plot on Fig. 3c at low Ti/(Ti + Al + Cr) values. Cores of anomalous groundmass spinels fall within the xenocrystic compositional range and are hence interpreted to be likely xenocrystic seed grains. These same grains have rims more typical compositions of Garnet Lake main sheet kimberlite spinel cores (Fig. 3d), as indicated by evolutionary trend 'A' (Fig. 3c) and suggest a remnant early kimberlite component to these samples.

Phlogopites in aillikite-classified samples are deep brown and strikingly zoned (Fig. 2a and b). Compositional variation is consistent from cores to rims in all samples measured (Fig. 3e). Compared to orangeites in general (Mitchell, 1995) cores in Garnet Lake samples are unusually high in Ti (up to 6.4 wt.% TiO<sub>2</sub>) however they are similar in this regard to some grains from mela-aillikites (Tappe et al., 2006). Tetraferriphlogopite rims are ubiquitous (Fig. 3e) and as  $Al_2O_3$  contents fall to around 1.5 wt.% concurrently FeO increases up to 16.8 wt.%. Measured compositional variations in phlogopite compositions are typical of classification of the host rock as either orangeite (Mitchell, 1995) or aillikite (Tappe et al., 2005).

Primary groundmass clinopyroxene has been observed in three main sheet samples (07DS45-54, 06DS15-875b1c1 and 07DS45-96c). As spinel and phlogopite compositions lie within the ranges seen amongst both aillikites and orangeites (Tappe et al., 2005) clinopyroxene compositions are crucial to any conclusion as to rock classification. Aluminium contents for groundmass clinopyroxene range from 1.92-6.06 wt.% Al<sub>2</sub>O<sub>3</sub> whilst titanium contents range from 1.74-3.15 wt.% TiO<sub>2</sub> where increased Ti correlates with increased Al. The atomic Al/Ti ratio averages 2.5 (varying from 1.7 to 3.2) and lies within the range seen in carbonatite clinopyroxene (~3) and from mela-aillikites, aillikites and damtjernites (~2, Tappe et al., 2006). Whilst not as enriched in Al and Ti as some aillikites (Mitchell et al., 1999 report values up to 10 wt.% Al<sub>2</sub>O<sub>3</sub> and 5 wt.% TiO<sub>2</sub>) Tappe et al. (2005) state that orangeite clinopyroxenes are nearly pure diopside. In terms of Al and Ti content, Garnet Lake groundmass clinopyroxenes are dissimilar to most orangeite-clinopyroxenes described by Mitchell (1995). Eleven clinopyroxene grains from three rock samples provide the deciding factor in favouring a petrological classification as aillikite

over orangeite for the dominant Garnet Lake main sheet rock. Such a classification is consistent with the conclusions reached for rocks described by Tappe et al. (2005) and Mitchell et al. (1999) for samples recovered also from the Sarfartoq area.

Finally baddeleyite and apatite occur as accessory minerals and the unusual carbonatitic Sr, Ba, Ca-carbonate mineral olekminskite appears along fracture surfaces in serpentinised olivine xenocrysts (Fig. 2b). Olekminskite has previously been recorded by Sharygin et al. (2008) in chloride-carbonate nodules from the Udachnaya-East pipe in Sakha. Mitchell (1995) consider the presence of Sr, Ba carbonates a strong indication of orangeite affinity, however such exotic species are also seen in aillikites (Tappe et al., 2006).

Classification of this rock type as 'aillikite' is favoured over 'kimberlite' given the presence of primary clinopyroxene, ubiquitous tetraferriphlogopite, exotic Ba,Sr-carbonate and the absence of monticellite (and Carich cognate olivine) and perovskite. The term 'aillikite' is also favoured over 'orangeite' given the presence of significantly elevated Ti and Al compositions in rare groundmass clinopyroxene. Given the small number of grains effecting the classification and the inconsistency of spinel compositions with recognised crystallisation trends, it is accepted that classification may prove controversial. It should be stressed that despite the terminology, the rock is demonstrably diamondiferous.

# 3.2.2. Kimberlite

The second component of the Garnet Lake m.s. is a bona fide Type I kimberlite as defined by Mitchell (1995). Similar rocks are described by Nielsen and Jensen (2005) at Majuagaa in West Greenland. The Garnet Lake kimberlite identified in the main sheet is aphanitic with striking fresh pyrope garnets (as in Fig. 1a) and disaggregated olivine being the principal mantle phases. Mineral proportions from the type sample 05DS07-155b (Fig. 2c. and d.) were calculated from thin section and electron microprobe transects. Ilmenite and perovskite comprise  $\leq$ 40% of the groundmass mineralogy with grains typically  $\leq$ 100 µm. Phlogopites (rarer than in aillikites and  $\leq$ 15% of primary mineralogy) are largely homogeneous and up to 1 mm in diameter and olivine phenocrysts (occasionally serpentinised) contribute an estimated further 15%. The remaining crystallised phases are carbonate (calcite dominates over dolomite, consistent with kimberlites from elsewhere, Mitchell, 1995) and apatite. Notably, primary clinopyroxene is absent. Kimberlite samples taken from 10 km to the east of Garnet Lake, whilst showing the same mineral assemblage and similar mineral chemical features as those from the Garnet Lake main sheet, are coarser grained, contain more xenocrystic material and show density segregation textures more distinctive on a macroscopic scale (Fig. 1d). Inclusion of these samples in the following discussion is instructive given that their kimberlite-affinity features are occasionally more extreme than seen in the Garnet Lake m.s. samples.

Whilst no systematic distinction between groundmass olivine compositions from aillikite and kimberlitic samples is clear, margins and rims to some olivine crysts present clues to the kimberlitic affinity of some samples. Garnet Lake main sheet olivines (Fig. 3a) are typically from aillikites however the data for other localities presented in Fig. 3a include olivine groundmass analyses from kimberlite samples. Although monticellite has not been observed in Garnet Lake and vicinity rocks, some olivine phenocrysts have Ca-rich margins with up to 0.69 wt.% CaO (main sheet sample 05DS25-203). Also of particular note is sample MHG5-21 from 10 km east of Garnet Lake where phenocrystic olivine compositions range from Fo<sub>88.9</sub>–Fo<sub>89.2</sub> and include crysts with Ca-rich rims up to 0.55 wt.% CaO. Both compositional characteristics are consistent with classification as *bona fide* kimberlite (Mitchell, 1995) and the presence of Ca-rich rims to olivines argues against an aillikite or orangeite classification (Mitchell, 1995; Nielsen and Sand, 2008).

Compositions of cores of phenocrystic ilmenites from kimberlite from samples 10 km east of Garnet Lake are presented in Fig. 3b. The range (shown by large grey circles, Fig. 3b) is greater than that seen in the associated aillikites however cores are distinctly lower in Mg (6–16 wt.% MgO) compared to margins (15–16 wt.% MgO) and describe a more convincing dominant compositional trend ('B' on Fig. 3b). Whilst thin Mg-rich rims (as distinct from margins) were not observed in kimberlite samples, compositions of cores cover the range of rims and cores measured from aillikites and although compositions are more Fe-rich, the compositional trend is consistent with that seen in the evolution of grains from the Majuagaa kimberlite (Nielsen and Sand, 2008). Cr contents of Garnet Lake vicinity kimberlites are relatively high (up to 5.8 wt.% Cr<sub>2</sub>O<sub>3</sub>) similar to matrix ilmenites from the Mayeng kimberlite (Mitchell, 1995).

Spinels from kimberlite samples are some of most Fe-enriched spinels recovered from Garnet Lake and vicinity rocks (Fig. 3d) and are Ti-rich. Typical compositions are similar to those from Tunraq reported by Mitchell (1995) and consist of ~60% haematite (Fe<sup>3+</sup>) component, the remainder being Mg-ülvospinel (Mg<sub>1.3</sub>Fe<sub>0.7</sub>TiO<sub>4</sub>) with small Mg,Alspinel and magnesiochromite components (2.5 and 5 mole%

Fig. 3. Selected mineral compositional features for Garnet Lake and vicinity rocks. (a) Compositions of olivine crysts from Garnet Lake and vicinity samples. Circles (solid – Garnet Lake main sheet, open – other samples) represent olivines from xenoliths and clearly identifiable xenocrysts. Grey symbols (triangles – Garnet Lake main sheet, diamonds – other samples) represent groundmass olivines which due to their small size and euhedral form may be phenocrysts. The dotted lozenge field highlights compositions crystallised from Majuagaa melts as interpreted by Nielsen and Sand (2008) whereas the solid lozenge, to lower forsterite content highlights the equivalent trend in compositions from Garnet Lake main sheet groundmass olivines. Nickel compositional data is presented in ppm weight. (b) Compositions of ilmenites from Garnet Lake and vicinity samples after removal of ferric iron and calculation of geikielite (MgTiO<sub>3</sub>), ilmenite (FeTiO<sub>3</sub>) and pyrophanite (MnTiO<sub>3</sub>) component. Geikielite component is plotted against ilmenite with deviation below a 1:1 correlation being attributable to pyrophanite. Circles represent phenocrystic ilmenites from kimberlites from samples 10 km east of Garnet Lake (grey – cores, white – margins). triangles represent phenocrystic Garnet Lake main sheet ilmenites from aillikite samples (grey – cores, white – margins, open – rims). Trends 'A' and 'B' represent the compositional variation from centre to edge for the two rock types. Small solid symbols represent xenocrystic ilmenite recovered as mineral separates and from thin sections from all Garnet Lake and vicinity samples. Fields of kimberlite ilmenites from Mitchell (1995) and ranges of Majuagaa ilmenite compositions (Nielsen and Sand, 2008) are included for reference. (c) Groundmass cognate spinel compositions (large symbols) and xenocrystic spinel primarily of chromite composition (small solid symbols) from aillikite samples. Large black symbols represent Garnet Lake main sheet spinel compositions with the arrows 'B' representing the dominant trend from core to rim compositions (solid - cores; open - rims). Grey symbols represent samples from locations aside from the main sheet. Some groundmass spinels (grey squares) are interpreted as having xenocrystic cores as they have closely similar compositions to spinel (chromite) from xenoliths and evident xenocrysts (small solid symbols). These same grains have more Cr-poor rims following compositional trend 'A' and corresponding to the cores of kimberlitic spinels (Fig. 3d). These anomalous grains may indicate a kimberlite component to these particular samples introduced through magma mixing or density segregation. Magnetites are not shown on this graph due to the large scatter that projecting to ferric iron-free compositions creates. T1 and T2 magmatic fields of Mitchell (1995) are shown where the T2 field for the compositions presented is also closely similar to Mitchell's (1995) 'orangeite' field. (d) Groundmass cognate spinel compositions from kimberlites. Black symbols represent Garnet Lake main sheet samples with the arrow representing the transition from core to rim compositions (solid - cores; open - rims). Grey symbols represent samples from locations aside from the main sheet. The field annotated 'M' encloses groundmass spinel compositions from the Majuagaa calcite kimberlite dike (Nielsen and Sand, 2008), (e) Compositions of phlogopites from aillikite samples from Garnet Lake and vicinity. Black symbols are from Garnet Lake main sheet samples (solid – cores, open - rims), grey symbols (solid - cores, open - rims) are from samples other than from the main sheet. Compositional variations from core to rim consistently follow the trend of decreasing Ti and Al as described by the arrows labelled 'A' and 'B'. Small solid symbols represent compositions of phlogopite phenocrysts from all Garnet Lake and vicinity samples. The rectangular field represents primary phlogopite core compositions from Mitchell (1995). (f) Compositions of phlogopites from kimberlite samples from Garnet Lake and vicinity in terms of Al<sub>2</sub>O<sub>3</sub> against TiO<sub>2</sub>. Solid triangles - Garnet Lake main sheet samples showing compositional trend ('A') from cores (solid black) to rims (open). Grey symbols represent samples taken elsewhere from the main sheet (solid – cores, open – rims). Whilst more subtle a variation than main sheet samples, some rocks (shown by trend 'B') describe the same trend of increased Al with decreased Ti typical of bona fide kimberlites (Mitchell, 1995). Ilmenites from an aberrant sample (trend 'C') exhibit a decrease of Al with Ti towards grain rims. The rectangular field represents primary phlogopite core compositions from Mitchell (1995). Compositional trends are markedly different from those of aillikite phlogopites (Fig. 3e) and are consistent with classification as kimberlite.

respectively). Whilst kimberlite-hosted spinels from Garnet Lake are on the whole not as Fe-rich as those from Majuagaa (field 'M' in Fig. 3d, Nielsen and Sand, 2008), spinels from kimberlites 10 km east of Garnet Lake have compositions of both cores and rims lying within the T1 kimberlite compositional trend of Mitchell (1995) and overlapping the Majuagaa field. These are some of the most Cr-rich sampled in the present study (atomic Cr/(Cr + Al)~0.8). Garnet Lake main sheet sample 05DS07-155b spinels also have T1 cores, however rims trend in composition towards T2 orangeite (arrow, Fig. 3d). Above the main sheet, sample 06DS05-64 spinels have core compositions falling within the T2 trend. Atoll-textured spinels have been observed in only one sample (07DS45-96a) showing T1 cores and T2 rims.

Phlogopites have largely homogeneous compositions. Where compositional variation is seen (Fig. 2c and d) margins reflect an increase in



Ti with a decrease in Al (Fig. 3f). Al and Ti compositional variation lies on the trend of bona fide kimberlites described by Mitchell (1995) and differs significantly from that seen in orangeites and aillikites (Tappe et al., 2005) where Ti depletion accompanies Al depletion (c.f. Fig. 3e). Whilst tetraferriphlogopite is almost entirely absent, a single sample (06DS05-64a), perhaps marginal in terms of classification as kimberlite, presents some rare tetraferriphlogopite grains. Striking, very thin (micron-scale) rims also commonly occur and are enriched in Ba. BaO has been measured up to 3.0 wt.% for Garnet Lake m.s. samples and up to 6.6 wt.% for sample MHG5-21 taken from an occurrence 10 km east of Garnet Lake. Ba-enriched rims are typical of Type I kimberlites (Mitchell, 1995).

Perovskite phenocrysts are abundant and compositions have been measured from five samples. They are usually fresh and homogeneous however occasionally contain inclusions of baddeleyite, monazite and rutile (Fig. 2d). The presence of perovskite is a robust indicator of kimberlite classification (Mitchell, 1995).

Irrespective of the genetic association between the two rock types, mineral assemblages and chemical characteristics of this second Garnet Lake rock type are considerably different from those of aillikite samples. Classification as 'kimberlite' is favoured over 'orangeite' and 'aillikite' given the abundance of ilmenite and perovskite, Ca-rich rims to primary olivine, and the absence of primary clinopyroxene and rarity of tetraferriphlogopite rims to phlogopite.

#### 3.3. The mantle component

In contrast to the diamond-poor, yet xenolith-rich Silly Kimberlite (Hutchison, 2005), the neighbouring Garnet Lake m.s. is characterised by a marked paucity of intact mantle xenoliths. Xenoliths, when they do occur in the main sheet (Fig. 1b), are typically harzburgites with other types as described below. However much more commonly, the visibly identifiable mantle material appears in the form of discrete red pyrope garnet xenocrysts (Hutchison, 2005) up to 5 mm and typically with black kelphytised rims (Fig. 1a). In addition to xenolith material, heavy mineral separation yields an abundance of mantle-association minerals including eclogitic and peridotitic garnet, picro-ilmenites, Crspinels, Cr-diopsides and olivine, i.e. so-called diamond indicator minerals (DIMs). Aside from recovered diamond crysts described herein and in Hutchison and Heaman (2008), recent bulk sampling has also revealed diamond macrocrysts visible within kimberlite hand samples (pers. comm. Hudson Resources Inc., 2008). Finally it is important to note that size, morphology and composition of olivine crysts in Garnet Lake area samples suggest that the majority of olivine crysts are in fact xenocrysts and are out of equilibrium with the final kimberlitic melt, consistent with the arguments of Nielsen and Sand (2008). This observation demonstrates that the Garnet Lake m.s., although poor in xenoliths, does still contain significant modal proportions of mantle material. Representative mantle mineral compositions are presented in Table 2 and compositional data appear in Figs. 3a-c, e, 4 and 5.

#### 3.3.1. Heavy mineral separates

Compositions of heavy mineral separates from Garnet Lake samples were introduced in Hutchison (2005). Garnet Lake m.s. garnets commonly lie within the G10D field of Grütter et al. (2004), although G9 garnets and eclogitic garnets are also common. Notably, some G4D garnets are very Na-rich (up to 0.28 wt.% Na<sub>2</sub>O). Garnet compositions are presented in  $Cr_2O_3$ –CaO compositional space in Fig. 4 in the context of the range of compositions for 8324 West Greenland mantle garnets from Jensen et al. (2004a). Picro-ilmenites can be strongly Mg-enriched (Fig. 3b), containing up to 14.4 wt.% MgO and are occasionally also  $Cr_2O_3$ -rich (up to 5.5 wt.%  $Cr_2O_3$ ). According to accepted compositions lie within the diamond stability field (Hutchison, 2005). Although present in some xenoliths, as described below, chromite is rare in Garnet

Lake m.s. mineral separates presumably due to their small size, occurring typically in reaction rims around garnets. Compositions of recovered grains are included with chromite xenocrysts and grains from xenolith thin sections in Fig. 3c. Rare phlogopite xenocrysts show a wide variation in composition (Fig. 3e).

Concentrations of trace elements have been determined for heavy mineral separates of garnet, olivine and Cr-diopside with results for rare earth elements (REE) in peridotitic garnets presented in Fig. 5. Garnet mineral separates exhibit a close correlation between REE concentrations and major element composition, particularly in terms of the variation in Ca, Cr, Ti and Mg#, which the Grütter et al. (2004) 'G' system aims to summarise (Fig. 5). The high-Ti metasomatised G11 garnets exhibit compositional trends rising to a relatively flat chondritenormalised trend from Sm to the heavy-REE and ranging from 4 to 10x chondrite. With a few outliers, most G10D harzburgitic garnets similarly exhibit rising concentrations from La and peaking at 4-7x chondrite at Sm. However G10D garnets also exhibit a depletion in midheavy REE concentrations recovering upwards again by Lu. Finally, whilst G9 lherzolitic garnets range over the compositions exhibited by the distinct G11 and G10D garnet fields, a number of samples, annotated in Fig. 5 present significantly depleted mid-REE compositional trends. These garnets (recovered from samples 05DS10-30, 05DS23-132 from the main sheet) have particularly low Ti (under 0.2 wt.% TiO<sub>2</sub>) and consistent with this are also depleted in other high field strength elements (Zr < 12 ppm and Hf < 0.4 ppm). Although Ta concentrations are higher than normal (>0.05 ppm) this may be a function of poor analytical uncertainty for this element. Lherzolitic garnets and in particular the G11 high-Ti metasomatised garnets are comparable in composition to those from Birim, Ghana (field shown in Fig. 5 after Stachel and Harris, 1997).

Whilst not shown here, the compositional range over all 'G' classes (Grütter et al., 2004) of Cr-poor garnets is small. Aside from some variability in La and Ce, trends rise smoothly from 0.3–2x chondrite for Pr to 2.5–10x chondrite for Eu rapidly becoming a flat trend through the heavy-REE to within the range of 6–22x chondrite for Lu. For individual major element compositional types, the ratio of light/heavy REE increases incrementally from pyroxenitic (G4 and G4D) garnets, through low-Cr megacrystal (G1) garnets to eclogitic G3D garnets.

#### 3.3.2. Mantle xenoliths

The dominance of harzburgites followed by garnet dunites and garnet lherzolites amongst the rare m.s. xenoliths is consistent with the composition and abundance of indicator minerals separated from crushed samples (Hutchison, 2005), although G10 garnets are more common in the disaggregated mantle material than in the complete xenoliths. A couple of equigranular picro-ilmenite-rich (50% by volume) xenoliths containing garnet and some minor orthopyroxene have also been identified. Garnets have eclogitic G4 and G4D compositions (after Grütter et al., 2004) occasionally with magnetite inclusions. Ilmenite contains up to 14.6 wt.% MgO whilst Ni is low (<0.2 wt.% NiO) and orthopyroxene has a range of Mg# between 0.88 and 0.93.

#### 3.3.3. Diamond recovery, characteristics and composition

As host rock classification is dependent on mineral chemical analysis rather than macroscopic features, it is not entirely clear how diamond abundance is attributable between the two distinct rock types present at Garnet Lake. This issue is compounded by the fact that the method by which diamonds are recovered differs from that for host rock phenocrysts, the former being almost completely destructive to minerals other than diamond. Notwithstanding this, diamond crysts have been recovered from rocks from which closely associated samples have been retained for host rock study and whilst it is clear that the numerical abundance of diamond crysts corresponds to the considerably more dominant aillikite rock, diamonds also appear to be contained within kimberlite samples. For example there is evidence for kimberlite (by Ca-rich rims to olivines up to 0.22 wt.% CaO) from the same locality as the principal diamond-



**Fig. 4.**  $Cr_2O_3/CaO$  plot of Garnet Lake m.s. garnet compositions with classification boundaries after Grütter et al. (2004). Large grey circles – Garnet Lake m.s. compositions; Small black diamonds – other Sarfartoq garnet compositions (Hutchison, 2005); Small dots :- compilation of all West Greenland garnet compositions (Jensen et al., 2004a). 'G' compositional fields follow Grütter et al. (2004) where the 'D' indicates that garnets falling within such fields, and depending on additional chemical criteria (Grütter et al., 2004) may or may not fall within the diamond stability field. The G1 field projects Cr-poor Ti-bearing garnets onto the portion of the G9 field which covers the  $Cr_2O_3$  compositional range greater than 1 wt.%. The abundance of G10 (and G10D) garnets is consistent with the high relative concentration of diamonds within Garnet Lake rocks and depth of origin described by mantle xenolith thermobarometric calculations.

bearing excavation pit at Garnet Lake. Furthermore, 6.6 kg of sample taken from around main sheet kimberlite sample 05DS25-203 (which has Carich olivines with rims containing up to 0.69 wt.% CaO) revealed 3 micro and 1 macro diamond crysts. However the abundance of diamonds may be lower in kimberlite than in aillikite. This is supported by the absence of diamond from 73.75 kg of samples collected from the vicinity of kimberlite samples MHG5-21, 10 km distant from Garnet Lake and the 20.2 kg of core 4.5 m either side of kimberlite sample 06DS05-64 lying above the m.s. Notwithstanding the association with rock-type, diamonds occur abundantly within Garnet Lake rocks (Hutchison, 2005, Hutchison and Heaman, 2008) and a number of crysts have been made available for description and compositional determination by infrared spectrometry.

Diamond crystals with characteristic infrared absorption at 1282 cm<sup>-1</sup> and little or no absorption at 1175 cm<sup>-1</sup> are termed Type-IaA and those with a characteristic absorption at 1175 cm<sup>-1</sup> and little or no absorption at 1282 cm<sup>-1</sup> are termed Type-IaB (Davies, 1976). Type-IaA spectra are attributable to pairs of nitrogen atoms occurring within the diamond structure (Davies, 1976) and Type-IaB absorption is attributed to groups of four tetrahedrally-arranged nitrogen atoms surrounding a vacancy (Evans and Qi, 1982). Type-IaA diamond transforms to Type-IaB diamond following an Arrhenius law dependent on temperature and time.

Hutchison and Heaman (2008) present a compilation of colour, morphology and preservation characteristics of 412 Garnet Lake diamond crysts (including 396 definitively from the main sheet). This compilation includes all of the additional diamonds for which FTIR data are presented in the current work with the exception of SGS prefixed diamonds. The range of visually observable characteristics of these 46 additional stones lie within the ranges reported in Hutchison and Heaman (2008). Typically Garnet Lake diamonds are colourless and irregular or octahedral in morphology and photographs of four representative crysts are shown in Fig. 6 demonstrating the range of crystallinity, resorption and transparency seen within the population.

Nitrogen concentrations for all 119 stones analysed to date by FTIR spectrometry (87 stones, Table 3 and Hutchison and Heaman, 2008) are high (e.g. Fig. 7 inset), and average 1035 ppm nitrogen, median 997 ppm. Yet nitrogen is not strongly aggregated (e.g. Fig. 7 inset) and averages of 33.7%, median 30.7%, IaB aggregated. Platelet development is regular. Calculated nitrogen concentration and aggregation for indivi-

dual diamonds, where multiple analyses have been obtained, gives one standard deviation uncertainty in total nitrogen concentration of  $\pm$ 7.9% for a sample size of 84 diamonds and  $\pm$ 15.8% uncertainty in %laB for a sample size of 79 diamonds. There is no correlation between aggregation and nitrogen concentration for measurements on individual crysts.

Data show an almost Gaussian distribution of diamond nitrogen concentration (Appendix A Fig. 2a) however two populations in terms of nitrogen aggregation are apparent with a sharp peak around 20% IaB superimposed on a broad Gaussian distribution peaking at around 50% IaB, described by the population as a whole (Appendix A Fig. 2b). No correlation is apparent between stone size and nitrogen concentration or aggregation.

# 4. Calculations

#### 4.1. Thermobarometry

Five garnet lherzolites were selected from core and hand samples from the Garnet Lake main sheet for thermobarometry. Garnet, olivine, clinopyroxene and orthopyroxene cores were selected for analysis using criteria based on proximity to each other and morphology, to maximise confidence in equilibration. Pressure and temperature estimates were calculated using an iterative approach combining the thermometer of McGregor (1974) and barometer of Brey and Köhler (1990). This combined geothermobarometer has been vigorously tested by Sand (2007) and determined to yield results most likely to be closest to true ambient conditions for similar West Greenland xenoliths. Results for Garnet Lake samples are shown in Fig. 8 in comparison with data from xenoliths hosted in West Greenland kimberlitic rocks of similar, likely Cambrian age from within a 150 km radius of Garnet Lake (Bizzarro and Stevenson, 2003; Sand et al., this issue) and from likely Jurassic mantle (Nielsen et al., 2008). In contrast to other West Greenland samples, which describe a range in depths along a mantle geotherm, Garnet Lake m.s. xenoliths exclusively are sourced in a small pressure/temperature window (Fig. 8). Average pressure/temperature data for Garnet Lake m.s. samples describe equilibrium conditions at 1258 °C and 6.20 GPa equivalent to a depth of 195 km and along a 41 mWm<sup>-2</sup> geotherm after Chapman and Pollack (1977).



**Fig. 5.** REE concentrations in peridotitic garnet mineral separates from Garnet Lake m.s., normalised to C1 chondrite composition (McDonough and Sun, 1995). Garnet 'G' numbers refer to the mineral classification scheme of Grütter et al. (2004). Pm<sup>\*</sup> – Prometheum does not occur naturally on Earth however is included in the figure to provide a linear scale of atomic number on the abscissa. Lherzolitic (G9) garnets cover the compositional range between flat mid-heavy REE concentrations of G11 metasomatised garnets and G10D harzburgitic diamonds exhibiting a smooth inflection to low concentrations from Gd to Tm. However in addition to this compositional range, some examples of G9 garnets are heavily depleted in mid-REE. Lherzolitic garnets and particularly the high-Ti metasomatised (G11) garnets correspond closely in composition with lherzolitic garnets (translucent hatched legend) from the Birim field (Stachel and Harris, 1997) and imply significant mantle fertilisation. It is speculated that in the case of Garnet Lake, mantle fertilisation may have acted as a precursor to diamond formation.



**Fig. 6.** Representative diamond crysts recovered from the Garnet Lake main sheet and showing the typical ranges of morphology and clarity from transparent, well preserved primary crystal morphology to translucent, irregular stones subjected to resorption and late-stage brittle fracture. (a) Colourless, clear, diamond octahedron 05DS25\_1. Surface features evident include a stepped / ribbed texture with serrate laminae and finely etched negative trigons (triangular depressions); (b) 0.070 carat irregular diamond cryst MHGB10\_22. Inspection of the colour of this cryst shows a subtle amber cast; (c) Colourless, clear, diamond dodecahedron 06DS04\_1. The surface is partially resorbed and occasional small hillocks are observed (not shown); (d) 2.392 carat diamond SGS\_DMS\_1. This cryst has an off-white translucent colouration and a dodecahedral morphology indicating a loss on resorption of 25%. There is evidence of some twinning and the stone is fractured and included with numerous graphite inclusions. This diamond was too large and thick to obtain an infra-red spectrum and hence does not appear in Table 3.

Fig. 8 further demonstrates that at a maximum of 6.29 GPa, 1274 °C, the Garnet Lake xenoliths recovered from the main diamondiferous sheet were sourced from well within the diamond stability field, coincident with a relatively cool,  $40-41 \text{ mWm}^{-2}$  geotherm and are some of the deepest measured mantle rocks in West Greenland at up to



**Fig. 7.** Calculated %IaB aggregation against nitrogen concentration in the context of isochrons based on residence temperature of 1258 °C. Black circles – this work; Grey circles – data from Hutchison and Heaman (2008). Error bars reflect measured analytical range for crysts where multiple measurements were taken, otherwise the population  $1\sigma$  errors of  $\pm$ 7.9% for total nitrogen and  $\pm$ 15.8% for %IaB are applied. The scatter of data represent the residence time of Garnet Lake diamond relative to emplacement. The majority of diamonds experienced only short (5 Ma) residence at modelled temperatures before emplacement below nitrogen closure temperatures. Hutchison and Heaman (2008) provide a fuller discussion of the application, assumptions and shortcomings of nitrogen measurements for residence time and temperature calculations using a smaller dataset of Garnet Lake diamonds: Inset. FTIR spectra of representing 1415 ppm atomic nitrogen) and relatively low laB aggregation (representing 11.7% Type laB centres).

199 km. With regard to source depth, Garnet Lake diamond potential should be excellent. The only marginally deeper xenoliths are from one sample from Bizzarro and Stevenson (2003) sourced close to Garnet Lake and two samples from Sand et al. (this issue) from Majuagaa ~150 km south.

Garnet Lake xenolith samples provide a robust method by which to calculate depths of origin however regional studies often rely on mineral separates where equilibrium is assumed. Using REE partition coefficients (Fujimaki et al., 1984) melt associated with lherzolitic



**Fig. 8.** Pressure / temperature data for western Greenland mantle xenoliths. Large black diamonds — Garnet Lake main sheet; Open symbols — West Greenland (circles: Maniitsoq area, Sand et al. (this issue), diamonds: Garnet Lake area, Sand et al. (this issue); squares: Garnet Lake area, Bizzarro and Stevenson (2003)); Small solid symbols — S.W. Greenland (grey circles: Pyramidefjeld, Nielsen et al. (2008), black squares: Midternæs, Nielsen et al. (2008)); Diamond / graphite phase boundary after Kennedy and Kennedy (1976); 40 and 42 (labelled) and 41 mWm<sup>-2</sup> geotherms after Chapman and Pollack (1977). Data demonstrate that Garnet Lake xenoliths equilibrated at pressures equivalent to approximately 200 km, providing a minimum thickness to the lithosphere at the time sampled and are some of the deepest rocks sampled from this part of West Greenland.

garnets from Garnet Lake matches the melt calculated from clinopyroxenes. This method applied to regional studies would provide an additional cross-check of the equilibrium assumption.

#### 4.2. Diamond formation

The mathematical constants describing the interdependence of time and temperature in relation to aggregation from IaA to IaB centres in diamond are described in Taylor et al. (1990) and Mendelssohn and Milledge (1995). From this relationship, isochrons and isotherms can be constructed in nitrogen aggregation/concentration space as a means of constraining the conditions of diamond growth and mantle residence. The applicability of published Arrhenius constants depends on the assumption that nitrogen platelet formation, which accompanies development of Type IaB centres, is regular (Woods, 1986), which is the case for Garnet Lake diamonds.

The combination of nitrogen-abundant yet poorly aggregated nitrogen clusters apparent in Garnet Lake diamonds is uncommon worldwide and necessitates either a short mantle residence time, cool mantle residence temperature or more likely a combination of both. The question remains as to what temperature to apply as a reasonable dominant residence temperature in order to calculate mantle residence times.

Clausing (1997) found an almost temperature-independent boundary between low temperature pure cube growth and higher-temperature cubo-octahedral growth at approximately 1375 °C. Given the rarity of diamond having a cubic morphology in the sample set, a value of 1375 °C can be considered to be at least a reasonable first principles estimate of the minimum temperature of formation of Garnet Lake diamond crysts. Studies of non-touching mineral inclusions in diamonds from South Africa, which have retained chemical compositions reflecting the pressure/temperature conditions of their original entrapment within their growing diamonds hosts are consistent with similar order high temperatures of initial growth (Phillips et al., 2004) averaging 1197 °C and ranging up to 1320 °C. However such a high formation temperature, following Taylor et al.'s (1990) methodology gives very short residence times for Garnet Lake diamonds. As there is little precedence in the literature for such extremely short residence times for diamond octahedra, it is considered more likely that Garnet Lake diamond crystals would have experienced most of their mantle residence subsequent to diamond formation under the cooler temperature conditions reflected by associated mantle xenoliths. Phillips et al. (2004) also provide examples of touching grains reflecting relatively cooler equilibrium temperatures compared to initial diamond crystallisation. At Garnet Lake, 1258 °C is taken as a reasonable lower temperature limit for residence in the mantle before emplacement in the crust based on the tight cluster of xenolith equilibrium conditions around this temperature and absence of examples of cooler mantle material.

Nitrogen concentration and %IaB aggregation for the full dataset currently available (including data presented in Hutchison and Heaman (2008)) are plotted in Fig. 7. Error bars reflect the variation in measured parameters where multiple measurements were made for each cryst, otherwise the population standard errors as described previously are applied. Fig. 7 also shows isochrons calculated for a mantle residence temperature of 1258 °C following the methodology also described previously. For a temperature of 1258 °C, application of the population standard uncertainties in nitrogen concentration (7.9%) and aggregation (15.8%) impose a residence time uncertainty of approximately  $\pm 31\%$ . The range of Garnet Lake data show that 46% of diamonds are calculated to have formed within the 5 m.y. immediately before kimberlite emplacement (Table 3, Fig. 7). This residence time is short but is not unprecedented compared to diamonds from some other localities (Richardson, 1986, Dobrzhinetskaya et al., 2007). The broad peak in nitrogen aggregation around 50% IaB, assuming the same residence temperature, supports an additional diamond forming event concentrated 15–25 m.y. before emplacement. Finally, and with the exception of a single outlier, the lower nitrogen concentration and more aggregated diamonds suggest that at this same temperature the oldest diamonds started to form approx. 56 m.y. (ranging within uncertainty between 37 and 86 m.y.) before emplacement.

# 5. Discussion

# 5.1. Genesis

The idea of an association between carbonatitic melt and kimberlitic melt from natural samples is not new (e.g. Ferguson and Currie, 1971; Dawson, 1980). For Greenlandic rocks, Nielsen and Sand (2008) argue that the carbonate-rich Majuagaa kimberlite, with the removal of olivine (based on Ni mass balance) and ilmenite, presents a bulk composition consistent with a melt of silicocarbonatite composition derived from very low degrees of partial melting of CO<sub>2</sub>-lherzolite. A similar conclusion may be invoked for Garnet Lake. Furthermore, the presence and REE characteristics of lherzolite xenocrysts recovered from Garnet Lake heavy mineral separates also support an early event of mantle fertilisation likely contributing directly to the formation of diamond. The association of Garnet Lake rocks with carbonatite is strong, particularly for the aillikites. Whilst a dominance of calcite over dolomite is common for kimberlites (Mitchell, 1995) as seen in Garnet Lake kimberlites, the particular abundance of dolomite over calcite in some aillikite samples from Garnet Lake presents analogies with rocks from Aillik Bay (Tappe et al., 2006). Whilst the Aillik Bay aillikites do not have the same relative abundance of dolomite (in this case an abundance of Sr-calcite), the mela-aillikites do, and field relations show intimate associations of these rock types with dolomite and dolomite-calcite carbonatite. The presence of olekminskite adds to the compelling arguments towards some genetic association between Garnet Lake and carbonatite rock types. Such an association is supported experimentally by Shushkanova and Litvin (2008).

The presence of two petrological components at Garnet Lake may suggest two different mantle sources. However, the observed compositional variation of spinels in kimberlites between locations and from cores to rims suggests that kimberlites sampled east of the main sheet are less evolved whereas main sheet kimberlites show an evolution from initial crystallisation of true kimberlite spinel compositions towards a later, more orangeitic or aillikite component. A further sheet above the main sheet is more orangeite/aillikite in spinel character and hence is interpreted as later still in terms of melt evolution. Compositional gradations therefore suggest that the original Garnet Lake vicinity melts were true kimberlite melts with subsequent evolution to a more aillikite-style component. This same evolutionary trend of kimberlite (T1) to orangeite (T2) is seen for spinels for Garnet Lake aillikites where the trend from cores to rims becomes more significantly Fe-rich in character. Furthermore, the occasional examples of chromite cores with T1 spinel rims is further consistent with a kimberlite precursor towards aillikite. For kimberlites to the south of Garnet Lake at Majuagaa, the primary olivine compositional trend, for calculated Majuagaa bulk composition, implies initial crystallisation at 8 GPa (Nielsen and Sand, 2008). The relative displacement of Garnet Lake initial melt composition olivines (Fig. 3a) to lower forsterite content and following the melting phase relations established for olivine (Jeanloz and Thompson, 1983) suggests either that Garnet Lake bulk compositions are more Fe-rich or else have formed at higher pressure, and hence deeper than at Majuagaa. The latter interpretation is consistent with the greater diamond content observed at Garnet Lake in comparison with rocks to the south (Jensen et al., 2004b) however is at odds with the interpretation from xenoliths that Majuagaa xenoliths are sourced at similar depths to Garnet Lake samples (Sand et al., this issue). The relationship between diamond concentration and melt composition is not entirely clear. However the indications that the less abundant kimberlite, whilst in some cases definitively diamond-bearing, may be less diamond-enriched than the

later aillikite melts, suggests a complex interplay of melt composition with either diamond formation or survival or both. It may be that the distinction between Majuagaa diamond paucity and Garnet Lake diamond abundance is driven by melt composition. Such a supposition makes sense particularly if variability in the  $H_2O/CO_2$  ratio is a controlling factor on both diamond formation and survival as favoured for similar rocks (Nielsen and Sand, 2008). Despite the distinctive rock types apparent at Garnet Lake, compositional variations are relatively smooth and suggest an evolution of melt composition. As contact relationships suggest multiply intruded events, it is proposed that evolution, rather than occurring in-situ, proceeded within a deeper magmatic source, likely an evolving magma chamber at depth. Relative abundance of diamond may hence be ascribed also to the residence time in this relatively low pressure (relative to initial melt and diamond formation in the mantle) and thus diamond-phobic rest-stop.

#### 5.2. Mantle conditions and diamond formation

Following the arguments of Stachel and Harris (1997), the similarity between Garnet Lake G11 high-Ti metasomatised garnet rare earth element compositions to those from Birim, Ghana reflect a fully refertilised garnet lherzolite component in the mantle. In this case, rather than metasomatism being detrimental to diamond growth, the process of mantle fertilisation may have been conducive, given the abundance of diamond crysts within Garnet Lake rocks.

The age of the Garnet Lake kimberlite is  $568 \pm 11$  Ma (Hutchison and Heaman, 2008) which is contemporaneous with revised age determinations of the emplacement of the Sarfartoq carbonatite complex lying 21 km distant (Secher et al., this issue). Garnet Lake kimberlites and aillikites also have a geochemical affinity with carbonatite and field observations suggest a style of emplacement where the Garnet Lake m.s. appears to comprise part of a complex of intrusions centred at the location of the carbonatite itself. Combining emplacement age with diamond residence times gives a peak diamond formation age at 583-593 Ma and a commencement of diamond formation around 624 Ma (605-644 Ma within analytical uncertainty). Given the significant error that temperature assumptions apply to these ages, they cannot be considered to be absolute, however data demonstrate diamond formation increased and hence the chemical conditions necessary for formation of diamond developed to a point where carbonatite and associated kimberlite and aillikite magmatism occurred. In experimental work the association of diamond growth with carbonatite generation has also been demonstrated (Shushkanova and Litvin, 2008). Host rock composition and the continuum of diamond ages to the point of carbonatite magmatism evident at Sarfartog provides a natural example of this connection. Although it is not suggested that the diamonds formed within kimberlite/ aillikite, it is proposed that mantle re-fertilisation as evidenced in the mantle garnets, may have triggered diamond growth as well as carbonatite and associated kimberlite and ultra-mafic lamprophyre formation. These melts concurrently acted as carriers for the diamonds and other mantle material into the crust.

Given the close temporal, geographic and chemical association between the diamondiferous Garnet Lake rocks and the Sarfartoq carbonatite complex, it is reasonable to ask whether the carbonatite itself has a potential for diamond recovery. Perhaps the closest analogue to Garnet Lake are the diamondiferous Benfontein sills which were originally classified as 'carbonatitic' (Dawson and Hawthorne, 1973). Here, and as for Garnet Lake, samples with >50% carbonate are mechanically segregated and hence not true magmatic carbonatites. Similar types of rocks have recently been reported from Antarctica (Belyatsky et al., 2008). Nonetheless, there is considerable evidence for a continuum between some carbonate kimberlites and true carbonatite (e.g. Gaspar and Wyllie, 1984). Extensive literature review has revealed no reports of diamonds recovered from true carbonatite. Such absence may be a sampling issue, however in contrast to kimberlites, the oxygen fugacity of carbonatite melt may be too oxidised for diamond survival at low pressure. Comparison of Oka carbonatite oxygen fugacity calculations (Friel and Ulmer, 1974) with modelled diamond stability (Ballhaus, 1993) suggests that any diamonds which had been entrained into the melt at higher pressure would be burnt at low pressure. Whilst diamond recovery at Garnet Lake may provide a reasonable argument for diamond testing of carbonatite, the recovery is likely to be low.

# 6. Summary and conclusions

The Garnet Lake diamondiferous main sheet has a temporal, geographic and chemical association with carbonate melt and the nearby Sarfartoq carbonatite complex. Multiple melt composition is evident within the sheet and it is proposed that Garnet Lake represents the end result of an evolving system from mantle fertilisation and diamond formation, initial kimberlite melt generation evolving towards aillikite and associated with carbonatite.

The Garnet Lake m.s. is one of the deepest sourced kimberlitic bodies known from West Greenland and provides mantle material from well within the diamond stability field. Associated mineral compositions reflect this deep source and are consistent with the relatively large abundance of diamonds recovered from Garnet Lake. Thermobarometry demonstrates that the mantle lithosphere below Garnet Lake at the time of sampling in the late Neoproterozoic was relatively cool, with a  $41\,\mathrm{mWm^{-2}}$  mantle geotherm and deep, having a minimum depth of approx. 200 km. The mantle was typically harzburgitic with a minor eclogitic component. Diamond formation appears to have been triggered by mantle metasomatism at the base of the lithosphere evidenced also by associated lherzolitic garnet compositions. The pace of diamond growth increased over the ~56 m.y. period leading up to the eventual emplacement of carbonatite, and associated kimberlite and ultramafic lamprophyre (aillikite) melts which transported the diamonds and other mantle material towards the surface.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.lithos.2009.05.034.

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