Conditions of origin of kimberlites in West Greenland: new evidence from the Sarfartoq and Sukkertoppen regions

Lotte Melchior Larsen and Jørn Rønsbo

Minerals in a garnet lherzolite nodule from Sarfartoq and macrocrysts in a kimberlite from the Sukkertoppen region have been analysed by microprobe. Temperatures calculated for the Sarfartoq nodule lie in the range 1110–1137°C, and pressures are estimated at greater than 50 kbar. The calculated temperature for the Sukkertoppen macrocrysts is 1309°C. Temperatures recalculated from existing data for kimberlites in the Holsteinsborg region and in SW Greenland lie in the range 1034–1078°C (40–50 kbar). The temperature variations may reflect the setting of the kimberlites in Archaean and Proterozoic terrains. Assuming a common geotherm of 40mW/m^2 all the kimberlites in West Greenland originated within the diamond stability field.

L. M. L., Geological Survey of Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.
J. R., Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.

Kimberlites occur as dykes and sheets in several areas in West Greenland, as reviewed by Larsen (1991) and Larsen & Rex (1992). The regions of Holsteinsborg (Sisimiut), Sarfartoq and Sukkertoppen (Maniitsoq) contain three coeval kimberlite fields within a *c.* 600 Ma old kimberlite province, and in SW Greenland *c.* 200 Ma old kimberlites occur at Pyramidefjeld, Midternæs and Nigerlikasik (Fig. 1). Kimberlites generated at greater than *c.* 150 km depth may carry diamonds, and the conditions of origin of these rocks are therefore of economic-geological interest. This paper presents new microprobe data on minerals from a garnet lherzolite nodule from Sarfartoq and garnet macrocrysts in a kimberlite dyke from the Sukkertoppen region, from which temperatures can be calculated and pressures estimated.

Analytical methods

The microprobe analyses were carried out on a Jeol 733/Superprobe at the Geological Institute, University of Copenhagen, using wavelength dispersive methods. Major and minor elements were analysed at 15 kV, 15 nA, with a standard set of simple minerals and oxides and full ZAF correction. Ni in garnets was analysed at 20 kV, 500 nA, and standardised against analysed olivine with 0.34% NiO, with ensuing ZAF correction. In each garnet grain 20 points were each counted for 20 seconds on the peak and 20 seconds on the backgrounds. Under these conditions the lower limit of detection for Ni is *c.* 10 ppm. A control analysis of separated homogeneous clinopyroxene macrocryst material from the Batbjerg intrusion, East Greenland, with 212 ppm Ni according to XRF analysis, gave a microprobe Ni value of 216 ± 9 ppm.

Results

Analytical results are presented in Tables 1 and 2. The garnet lherzolite nodule from Sarfartoq, sample 265438, has a coarse-grained granular texture (Fig. 2a). Besides olivine (predominant), greenish clinopyroxene, orthopyroxene and garnet it contains ilmenite in anhedral, often rounded grains with exsolution lamellae of chromite. The garnets have broken down along the margins to fine-grained kelyphitic rims with scattered small grains of brown spinel and reddish-brown phlogopite. Olivine, orthopyroxene and clinopyroxene are compositionally very uniform, and hence average analyses are presented in Table 1. The garnet grains show minor but significant inter-grain differences and thus individual analyses are given in Table 1. The orthopyroxene is an enstatite with low contents of Al_2O_3 and CaO; most orthopyroxenes from lherzolites have higher Al_2O_3 contents but similar low contents are found in orthopyroxenes from Holsteinsborg (Scott, 1981) and

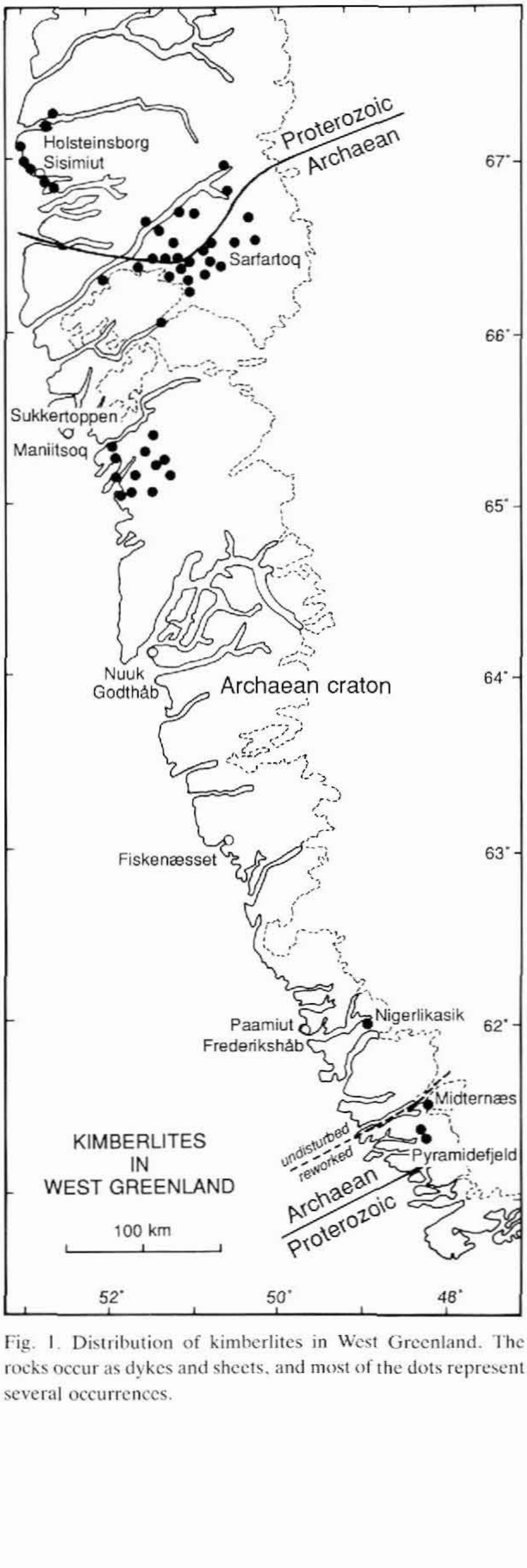

Fig. 1. Distribution of kimberlites in West Greenland. The rocks occur as dykes and sheets, and most of the dots represent several occurrences.

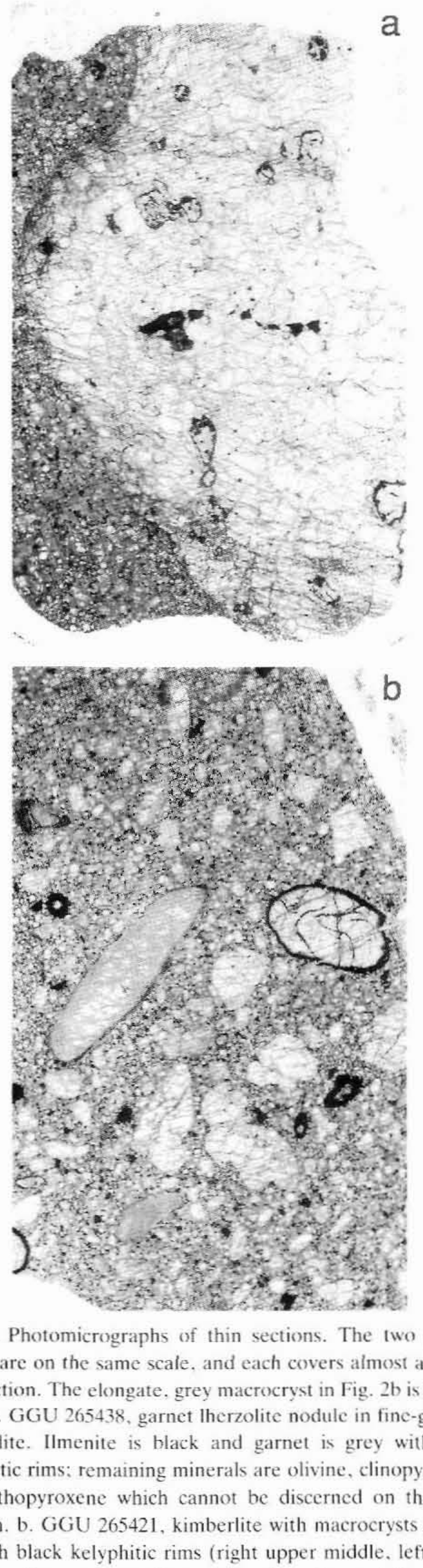

Fig. 2. Photomicrographs of thin sections. The two photographs are on the same scale, and each covers almost a whole thin section. The elongate, grey macrocryst in Fig. 2b is 13 mm long. a. GGU 265438, garnet lherzolite nodule in fine-grained kimberlite. Ilmenite is black and garnet is grey with dark kelyphitic rims; remaining minerals are olivine, clinopyroxene and orthopyroxene which cannot be discerned on the photograph. b. GGU 265421, kimberlite with macrocrysts of garnet with black kelyphitic rims (right upper middle, left lower corner), clinopyroxene (large grey elongate crystal), olivine (several light fractured crystals), and a few small ilmenites (left lower middle).

Table 1. Microprobe analyses of minerals from a garnet lherzolite nodule from Sarfartoq, West Greenland

	ol	opx	cpx	gt1	gt2	sp	phl	ilm	lam
SiO_2	40.44	57.05	54.42	40.80	39.38		36.72		
TiO_2	0.05	0.20	0.34	0.79	1.06	2.32	5.12	53.32	9.17
Al_2O_3	0.03	0.69	1.90	18.42	15.30	36.60	16.40	0.43	13.49
Cr_2O_3	0.02	0.23	1.06	5.23	8.37	24.01	1.17	2.60	35.46
Fe_2O_3		0.95	2.88	2.37	3.05	5.75		2.95	5.00
FeO	10.41	5.38	0.86	6.99	6.26	13.83	5.38	27.86	24.86
MnO	0.14	0.15	0.13	0.43	0.49	0.22	0.06	0.36	0.43
NiO	0.26	0.09	0.06	0.04	0.01	0.26	0.01	0.26	0.23
MgO	48.65	34.31	17.41	19.02	17.74	16.61	19.56	10.93	10.94
CaO	0.06	0.70	19.48	5.97	7.08		0.05		
Na_2O		0.16	1.80	0.09	0.11		0.83		
K_2O							9.14		
	100.06	99.82	100.34	100.17	98.89	99.60	94.44	98.71	99.57
Cations per formula unit									
Si	0.993	1.971	1.959	5.923	5.884		5.317		
Ti	0.001	0.005	0.009	0.086	0.119	0.150	0.558	3.775	0.673
Al	0.001	0.028	0.081	3.151	2.695	3.701	2.800	0.048	1.552
Cr	0.000	0.006	0.030	0.600	0.989	1.628	0.134	0.193	2.735
Fe^{3+}		0.025	0.078	0.259	0.343	0.371		0.209	0.367
Fe^{2+}	0.214	0.155	0.026	0.848	0.786	0.992	0.652	2.193	2.028
Mn	0.003	0.004	0.004	0.053	0.062	0.016	0.007	0.029	0.036
Ni	0.005	0.003	0.002	0.005	0.001	0.018	0.001	0.020	0.018
Mg	1.781	1.766	0.934	4.117	3.953	2.124	4.221	1.533	1.591
Ca	0.002	0.026	0.751	0.929	1.134		0.008		
Na		0.011	0.126	0.025	0.032		0.233		
K							1.689		
mg no	89.3	90.8	90.0	78.8	77.8	60.9	86.6	39.0	39.9
Ca	0.0	1.3	42.0	15.1	18.2				
Mg	89.3	89.6	52.2	66.9	63.6				
Fe^{tot}	10.7	9.1	5.8	18.0	18.2				

Sample GGU 265438, coarse garnet lherzolite, location 66°21.1′N, 51°21.8′W
ol: olivine, average of 5 analyses
opx: orthopyroxene, average of 7 analyses
cpx: green chrome diopside, average of 6 analyses
gt1 and gt2: analyses of two different garnet grains
sp: small spinel grain in rim on garnet
phl: small phlogopite grain in rim on garnet
ilm: large ilmenite crystal
lam: chromite exsolution lamella in ilmenite
Fe_2O_3 and Fe^{3+} calculated by assuming stoichiometry.
Formula recalculation bases: olivine 3 cations, pyroxenes 4 cations and 6 oxygens, garnet 16 cations and 24 oxygens, spinel and chromite 9 cations and 12 oxygens, phlogopite 22 oxygens, ilmenite 8 cations and 12 oxygens.
mg no: atomic $100Mg/(Mg+Fe^{tot})$.

the Matsoku Pipe, Lesotho (Cox *et al.*, 1973). The clinopyroxene is a chrome-diopside typical for lherzolites. The ilmenites are magnesian, with 11–13% MgO and 3–7% Cr_2O_3.

The kimberlite from the Sukkertoppen area, sample 265421, contains frequent garnet macrocrysts 1–7 mm in size (Fig. 2b). They are well rounded and shielded from the kimberlite host by fine-grained kelyphitic rims. Other macrocrysts include corroded and altered clinopyroxene, and ilmenite. The garnet macrocrysts are chrome-pyropes (Table 2) belonging to group 9 of Dawson & Stephens (1975), lherzolitic garnets. They have lower Cr, Ca and Fe, and higher Mg than the garnets in the Sarfartoq nodule and are most similar to the garnets of the Cr-poor megacryst suite of Eggler *et al.* (1979). The clinopyroxene macrocryst is likewise most similar

Table 2. Microprobe analyses of macrocrysts from a kimberlite dyke in the Sukkertoppen region, West Greenland

	gt1	gt2	cpx	ilm
SiO_2	41.81	41.54	54.60	
TiO_2	0.46	0.94	0.27	48.10
Al_2O_3	19.60	18.54	1.63	0.36
Cr_2O_3	4.47	4.41	0.20	0.26
Fe_2O_3	1.40	1.40	2.41	11.88
FeO	5.16	7.18	1.39	26.85
MnO	0.26	0.31	0.08	0.28
NiO	0.01	0.02	0.05	0.01
MgO	21.50	19.95	17.51	9.04
CaO	4.98	5.49	21.23	
Na_2O	0.05	0.08	1.21	
	99.71	99.87	100.58	96.78
Cations per formula unit				
Si	5.979	6.003	1.965	
Ti	0.049	0.102	0.007	3.533
Al	3.303	3.157	0.069	0.041
Cr	0.505	0.504	0.006	0.020
Fe^{3+}	0.150	0.152	0.065	0.873
Fe^{2+}	0.617	0.868	0.042	2.193
Mn	0.031	0.038	0.002	0.023
Ni	0.001	0.002	0.001	0.001
Mg	4.584	4.298	0.939	1.316
Ca	0.763	0.850	0.819	
Na	0.014	0.022	0.084	
mg no	85.7	80.8	89.8	30.0
Ca	12.5	13.8	43.9	
Mg	75.0	69.7	50.4	
Fe^{tot}	12.5	16.5	5.7	

Sample GGU 265421, kimberlite, location 65°18′N, 52°16′W
gt1 and gt2: two different garnet macrocrysts
cpx: clinopyroxene macrocryst, average of 3 analyses
ilm: ilmenite macrocryst
Fe_2O_3 and Fe^{3+} calculated by assuming stoichiometry.
Formula recalculation bases: garnet 16 cations and 24 oxygens, pyroxene 4 cations and 6 oxygens, ilmenite 8 cations and 12 oxygens.
mg no: atomic $100Mg/(Mg+Fe^{tot})$.

to the Cr-poor megacryst suite of Eggler *et al.* (1979) and is a calcic diopside with Ca/(Ca + Mg) = 0.46, rather different from the chrome-diopside in the lherzolite nodule. The ilmenite contains *c.* 9% MgO and 0.2% Cr_2O_3, distinctly different from the ilmenite in the lherzolite nodule.

The results of the Ni analyses are discussed below.

Thermometry and barometry

The garnet lherzolite nodule contains the minerals necessary for the application of the 'classical' opx-cpx thermometer and Al-in-opx barometer, and the minerals appear to be homogeneous and in equilibrium (ignoring the pressure-release break-down of the garnet margins). The latest formulation of this thermometer and barometer is that of Brey & Köhler (1990) which is used in the following.

The Al-in-opx barometer is dependent on the amount of Al in the M1 site in orthopyroxene in equilibrium with garnet, and on the composition of the orthopyroxene and the garnet. The dependence on Al(M1) in the orthopyroxene is critical because Al(M1) occurs in the denominator for a significant part of the barometer algorithm, so that the calculated pressure tends to infinity when Al(M1) approaches 0. The orthopyroxene in garnet lherzolite nodule 265438 has Al(M1) = 0 (Table 1) and the pressure cannot be calculated. However, Al(M1) is dependent on the quality of the whole analysis, especially the SiO_2 determination; a low SiO_2 value could result in too low calculated Al(M1). We see no indications that our SiO_2 determinations are too low (Tables 1 and 2) and conclude that most or all Al in the orthopyroxene is in the T site. All Al in the orthopyroxene equals 0.028 cations per formula unit, and we consider 0.010 cations to be the possible maximum for Al in the M1 site. This corresponds to a calculated pressure of 52 kbar, and we thus estimate that the garnet lherzolite nodule came from a pressure of at least 50 kbar.

The cpx-opx thermometer is dependent on the distribution of Fe and Mg between coexisting clino- and orthopyroxene. The calculated temperature is slightly pressure-dependent, with dT/dP = 1.5–2°/kbar. For P = 50 kbar the calculated temperature for the garnet lherzolite nodule is 1116°C when the Fe^{2+} calculated by assuming mineral stoichiometry is used, and 1131°C when total iron as Fe^{2+} is used.

Brey & Köhler (1990) also give two other thermometer equations. One is dependent on the amount of Ca in the orthopyroxene, and for P = 50 kbar T = 1137° ± 20°C (the uncertainty caused by the analytical spread, 0.65–0.75% CaO), and with a fairly high dT/dP of 5°/kbar. The other thermometer is based on the distribution of Na between ortho- and clinopyroxene and for P = 50 kbar T = 1205° ± 90°C (the uncertainty caused by the analytical spread, 0.11–0.22% Na_2O in the orthopyroxene), and with dT/dP = 2.4°/kbar. This rather uncertain value is not included in Table 3.

The Ni-in-garnet thermometer

This thermometer has been established by Griffin *et al.* (1989), specifically for chrome-pyrope garnets from peridotite nodules. It is calibrated in the temperature range 600–1500°C and with Ni contents in the garnets between *c.* 5 and 150 ppm. For 8 analysed garnet grains in the Sarfartoq lherzolite nodule we get an average Ni content of 53 ± 7 ppm (1σ), corresponding to a temperature of 1110 ± 48°C. For 5 analysed garnet macrocrysts in the Sukkertoppen kimberlite we get an average Ni content of 86 ± 7 ppm, corresponding to a temperature of 1309 ± 41°C.

As a control, garnets from Roberts Victor mine were also analysed. We obtained an average Ni content of 41 ± 7 ppm, corresponding to a temperature of 1022 ± 53°C. This is close to the median of the Ni-in-garnet temperatures obtained for Roberts Victor garnets by Griffin *et al.* (1990).

Table 3. Summary of estimated pressure and temperature conditions for West Greenland kimberlites and their mantle xenoliths

	Pressure kbar	Temp. °C $T_{cpx\text{-}opx}$	$T_{Ca,opx}$	$T_{Ni,gt}$
Holsteinsborg	>40[1]	1059 (40 kb)	991	-
	50-55[2]	1078 (50 kb)	1035	
Sarfartoq	>50[3]	1116 (Fe^{2+})[3]	1137[3]	1110[3]
	50-55[2]	1131 (Fe^{tot})[3]		
Sukkertoppen	55-60[2]	-	-	1309[3]
SW Greenland	*c.* 55[2]	1034 (40 kb)	-	-
		1052 (50 kb)		

$T_{cpx\text{-}opx}$ and $T_{Ca,opx}$ calculated after Brey & Köhler (1990)
1. From Scott (1981)
2. From Larsen & Rex (1992)
3. Analytical data from this work. The Sarfartoq temperatures are calculated for a pressure of 50 kb.

Comparison with other data

For comparative purposes we have recalculated the few existing usable mineral composition data from Greenland with the Brey & Köhler (1990) algorithms. The analytical data are, however, of uneven quality and the results should be used with caution.

Scott (1977, 1981) gave analyses of minerals from a garnet lherzolite nodule from the Holsteinsborg region. As for Sarfartoq, the orthopyroxene does not contain any Al in the M1 site, and the pressure cannot be calculated. Scott (1981) estimated pressures above 40 kbar. The recalculated opx-cpx temperatures are 1059°C for 40 kbar and 1078°C for 50 kbar.

Emeleus & Andrews (1975) analysed orthopyroxene and clinopyroxene in a garnet peridotite nodule from Nigerlikasik in SW Greenland. The orthopyroxene contains 1.49% Al_2O_3, twice the amount in the Sarfartoq–Holsteinsborg orthopyroxenes, but because there are no data on the garnet composition pressures cannot be calculated. The calculated opx-cpx temperatures are 1034°C for 40 kbar and 1052°C for 50 kbar.

Goff (1973) gave analyses of clino- and orthopyroxenes from Søndre Isortoq in the Sukkertoppen region, but there are no pairs from the same inclusion and thus no evidence for equilibrium between any mineral pair.

Larsen & Rex (1992) estimated depths of origin of kimberlite magmas from bulk rock geochemistry (mg numbers) and experimental data by Eggler (1989). The Sukkertoppen kimberlites seem to reflect the highest pressures (55–60 kbar), followed by the SW Greenland kimberlites at slightly lower pressures, whereas the Sarfartoq and Holsteinsborg kimberlites indicate 50–55 kbar pressures.

Discussion

Estimated pressures and temperatures for the West Greenland kimberlites are summarised in Table 3. The pressure estimates are only approximate, and a geotherm for Greenland cannot be constructed. Pollack & Chapman (1977) suggested a geotherm of 40 mW/m^2 for old continental shield areas, and this is shown in Fig. 2 with the new temperature data ($T_{Ni,gt}$) for Sarfartoq and Sukkertoppen projected onto it. *If* this geotherm can be used for all the kimberlites in West Greenland, those in Holsteinsborg, Sarfartoq and SW Greenland all formed in a relatively narrow interval of 1030–1130°C, 47–52 kbar, 145–165 km depth, whereas those in the Sukkertoppen region formed significantly deeper, at *c.* 1300°C, 70 kbar, 220 km depth. This may reflect the setting of the Sukkertoppen kimberlites in the middle of the Archaean craton and the other kimberlites at the margins of the craton (Sarfartoq and SW Greenland) and just outside it (Holsteinsborg).

All the West Greenland kimberlites formed within the diamond stability field (Fig. 3). A few microdiamonds have been found in kimberlite rock samples in SW Greenland and in large stream sediment samples at the mouth of the river that drains the Sarfartoq area (reviewed by Larsen, 1991, and Larsen & Rex, 1992). Griffin *et al.* (1990) found that African kimberlites with

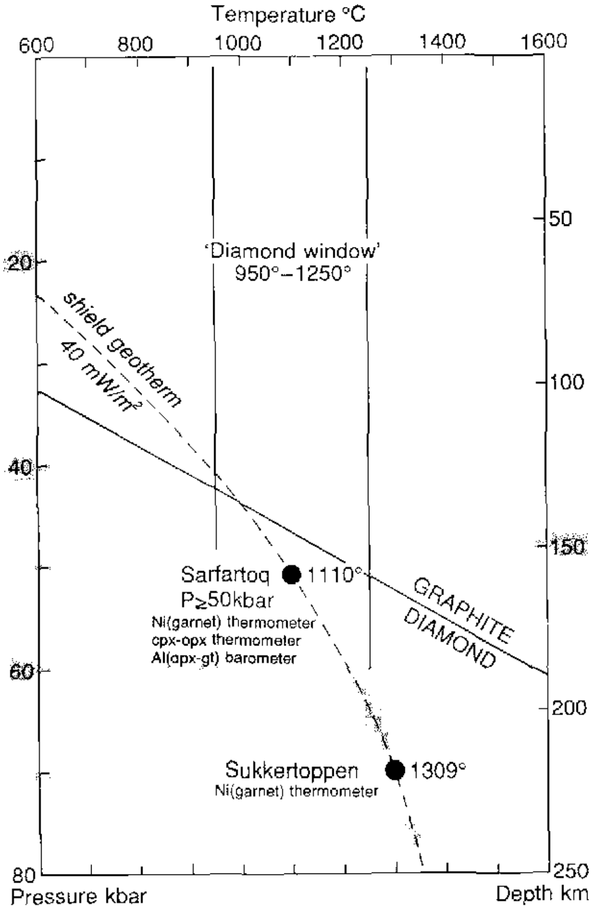

Fig. 3. Conditions of origin of kimberlites from the Sarfartoq and Sukkertoppen regions. Temperatures indicated are $T_{Ni,gt}$ calculated after Griffin *et al.* (1989). The 40 mW/m² geotherm is from Pollack and Chapman (1977). the graphite-diamond stability curve is after Kennedy & Kennedy (1976), and the 'diamond window' is after Griffin *et al.* (1990).

economic contents of diamonds give Ni-in-garnet temperatures concentrated in the interval 950°–1250°C, the 'diamond window' (Fig. 3). Lower temperatures indicate levels above the diamond stability field, and higher temperatures seem to be detrimental to the preservation of the diamonds. This is perhaps the case for the kimberlites from the Sukkertoppen region which Larsen (1991) considered to have the best diamond potential. On the other hand the Sarfartoq, Holsteinsborg and SW Greenland kimberlites all lie well within the 'diamond window'.

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