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CHEMICAL AND PHYSICAL CHARACTERISTICS OF DIAMOND CRYSTALS FROM GARNET LAKE, SARFARTOQ, WEST GREENLAND: AN ASSOCIATION WITH CARBONATITIC MAGMATISM

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Abstract

A shallow-dipping kimberlite – ultramafic lamprophyre sheet at Garnet Lake, Sarfartoq, West Greenland, contains diamond crystals in abundance. The crystals are most commonly colorless, and irregular or octahedral in shape. Nitrogen concentrations are unusually high, averaging 1100 ppm, compared to diamond crystals from elsewhere; the nitrogen is not strongly aggregated, however, averaging 26% IaB. This observation points to a short residence-time in the mantle, low temperature of mantle residence, or likely a combination of both conditions. Evidence of two populations is apparent in the relative abundance of different states of aggregation of the nitrogen in the stones. The common octahedral morphologies constrain the minimum temperature of formation for the majority of the crystals to 1375°C, assuming a 41 mWm^{-2} geotherm. Nitrogen concentrations and aggregation states only allow for very short residence-times, however, up to 1 Ma at this temperature. Hence a model of diamond formation quickly followed by ponding within a shallower, cooler mantle at a temperature of approximately 1252°C, supported by the tight clustering of associated mantle xenoliths, is preferred. Under these cooler conditions, the unusually high concentrations of nitrogen, combined with relatively low aggregation, give a calculated spread of diamond residence up to a maximum of 42.3 Ma. An emplacement age of 568 ± 11 Ma (2σ) obtained for the Garnet Lake kimberlite is based on the weighted average ^{207}Pb/^{206}Pb age for two perovskite fractions. This age is coincident with revised data on emplacement of the neighboring 565 Ma Sarfartoq carbonatite complex. Combined with diamond residence-time, the maximum likely age for diamond formation is *ca.* 610 Ma. Geographic and petrological similarities between kimberlitic hosts and the Sarfartoq carbonatite are apparent; in view of the close temporal similarity, we propose that CO_2-rich fertilization of mantle rocks giving rise to the formation of diamond has in this case assisted in the subsequent production of carbonatite magmatism and associated kimberlitic melts acting as transporting medium for the diamond.

Keywords: diamond, nitrogen, kimberlite, ultramafic lamprophyre, carbonatite, Garnet Lake, Sarfartoq, Greenland.

Sommaire

Un filon-couche de kimberlite – lamprophyre ultramafique à faible pendage à Garnet Lake, Sarfartoq, Groënland, contient une abondance de cristaux de diamant. Ces cristaux sont en général incolores, et de morphologie soit irrégulière, soit octaédrique. Les concentrations d'azote sont anormalement élevées, en moyenne 1100 ppm, par rapport aux cristaux de diamant d'ailleurs; en revanche, les atomes d'azote ne sont pas fortement agglomérés; en moyenne, il n'y a que 26% de type IaB. Ce fait indiquerait une courte période de résidence dans le manteau, une température de résidence relativement faible, ou plus probablement une combinaison des deux facteurs. Deux populations sont présentes en termes de l'abondance relative des états d'aggrégation des atomes d'azote. La morphologie octaédrique commune montrent que la température minimum de formation dans la majorité des cas était 1375°C, en supposant un profil géothermique de 41 mWm^{-2}. Les concentrations d'azote et le degré de leur aggrégation ne permettent qu'une brève période de résidence, toutefois, jusqu'à 1 Ma à cette température. Nous préférons donc un modèle de formation rapide du diamant, suivie d'une période de résidence à plus faible profondeur, où la température serait plus basse, 1252°C, reconstruction qui concorde avec le regroupement serré des xénolites mantelliques associés. Dans ces conditions de plus faible température, les teneurs anormales d'azote et le faible taux d'aggrégation des atomes d'azote permettent de calculer une période de résidence pouvant atteindre 42.3 Ma. Un âge de mise en place de la kimberlite de Garnet Lake, 568 ± 11 Ma (2σ), est fondé sur une moyenne pondérée des âges ^{207}Pb/^{206}Pb obtenus pour deux fractions de pérovskite. Cet âge coïncide avec les

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données nouvelles sur la mise en place du complexe carbonatitique avoisinant de Sarfartoq, 565 Ma. D'après cette reconstruction et la période de résidence du diamant, l'âge maximum probable de formation des cristaux de diamant serait d'environ 610 Ma. Les ressemblances géographiques et pétrologiques entre les hôtes kimberlitiques et la carbonatite de Sarfartoq sont claires; vue leur relation temporelle étroite, nous préconisons qu'une fertilisation en CO_2 du manteau menant à la formation du diamant a dans ce cas assisté à la production éventuelle d'un magmatisme carbonatitique et de venues kimberlitiques associées qui ont assuré le transfert du diamant vers la surface.

(Traduit par la Rédaction)

Mots-clés: diamant, azote, kimberlite, lamprophyre ultramafique, carbonatite, Garnet Lake, Sarfartoq, Groënland.

INTRODUCTION

Kimberlites and ultramafic lamprophyres are abundant in West Greenland (Larsen & Rex 1992, Jensen *et al*. 2004a, Larsen 2006). They principally occur as sheets on a cm-scale up to approximately 4 meters in thickness, which in some rare instances bulge to up to 8 meters over a few meters, and are confined to cratonic and craton-edge settings. The petrology of the kimberlites and associated rocks, evidence for a typical cratonic geotherm (Garrit *et al*. 1995, Hutchison 2005, 2008, Sand *et al*. 2008), and location as part of the ancient North American craton support the existence of conditions favorable for the occurrence of diamond in West Greenland. Conditions are in many ways analogous to the setting of diamond occurrences within the adjoining 2.7–4.0 Ga old Slave Province (*e.g*., Bowring *et al*. 1989, van Breemen *et al*. 1992, Davis *et al*. 2003). The characteristics of Greenlandic diamond have not so far been described in the scientific literature.

Here, we report on the emplacement age of the Garnet Lake intrusive sheet, in Western Greenland near the Arctic Circle, and the physical and chemical properties of diamond crystals recovered from samples in the 2004 and 2005 sampling seasons. Diamond crystals are described in terms of their color, clarity and morphology, in addition to surface features due to resorption and physical wear. Furthermore, a proportion of the largest crystals (representing 8% of the population) are described in terms of the abundance of nitrogen and the state of its aggregation, as determined by Fourier Transform InfraRed (FTIR) spectrometry. These data are used to model mantle temperatures and residence time of the diamond crystals within the mantle. By combining age of emplacement with residence time of diamond, calculations and applications of crystal-chemical constraints, a history of diamond formation in this region is subsequently presented in the context of craton evolution, mantle fertilization and regional magmatism.

BACKGROUND INFORMATION

Small numbers of diamond occurrences have been reported by industry from stream sediments, till and kimberlitic rocks from localities throughout West and Southwest Greenland since the 1970s. The first finds, three diamond crysts from *ca*. 86 kg of kimberlite from Pyramidefjeld, Southwest Greenland (at approximately 61°N, Fig. 1) were reported in 1972 by Renzy Mines. Further north, in the Maniitsoq region (65–66°N), diamond tests recovered a total of 170 stones from 1.98 tonnes of diamond-bearing rocks, including several macrocrystals from several occurrences (data up to 2006). Numerous additional barren samples have also been reported (Jensen *et al*. 2004a, b). The majority of recovered stones and the largest stones (up to 1.62 mm), however, were discovered close to the northern extent of the Sukkertoppen Icecap around 66°24'N latitude, bounding the Sarfartoq River valley. The surface expression of the boundary between the approximately 3 Ga Mesoarchean North Atlantic Craton (Garde *et al*. 2000) and Archean rocks affected by the 1.9–1.8 Ga Paleoproterozoic Nagssugtoqidian Orogen (Willigers *et al*. 2002, Connelly *et al*. 2006, and references therein) occurs in this region. Up until 2004, 536 stones had been recovered from 1.70 tonnes of diamond-bearing samples from 18 sites north of the Sukkertoppen Icecap. Diamond recovery from these locations has been reported in unpublished company filings; the relevant information from these documents is compiled in Jensen *et al*. (2004a, b).

GARNET LAKE

Garnet Lake, some 200 m wide, is located approximately 3 km north of the Sukkertoppen Icecap (Fig. 1). The location is approximately 19 km to the undeformed side of the undeformed Archean – Nagssugtoqidian boundary. The diamondiferous body at Garnet Lake is a sheet with a projected true thickness of up to 4.25 m, inclined at approximately 20° to the east and striking at 160° to grid north. This sheet is termed the Garnet Lake main sheet, as drilling results have delineated numerous smaller subparallel sheets that lie above and below the main sheet, connected by a network of feeder channels. The surface expression of one of these shallower sheets, termed the Silly kimberlite, owing to its spectacular abundance of peridotite xenoliths, is exposed to the south of a small lake approximately 600 meters northeast of Garnet Lake (Hutchison 2005). The thickness, morphology and orientation of the main sheet

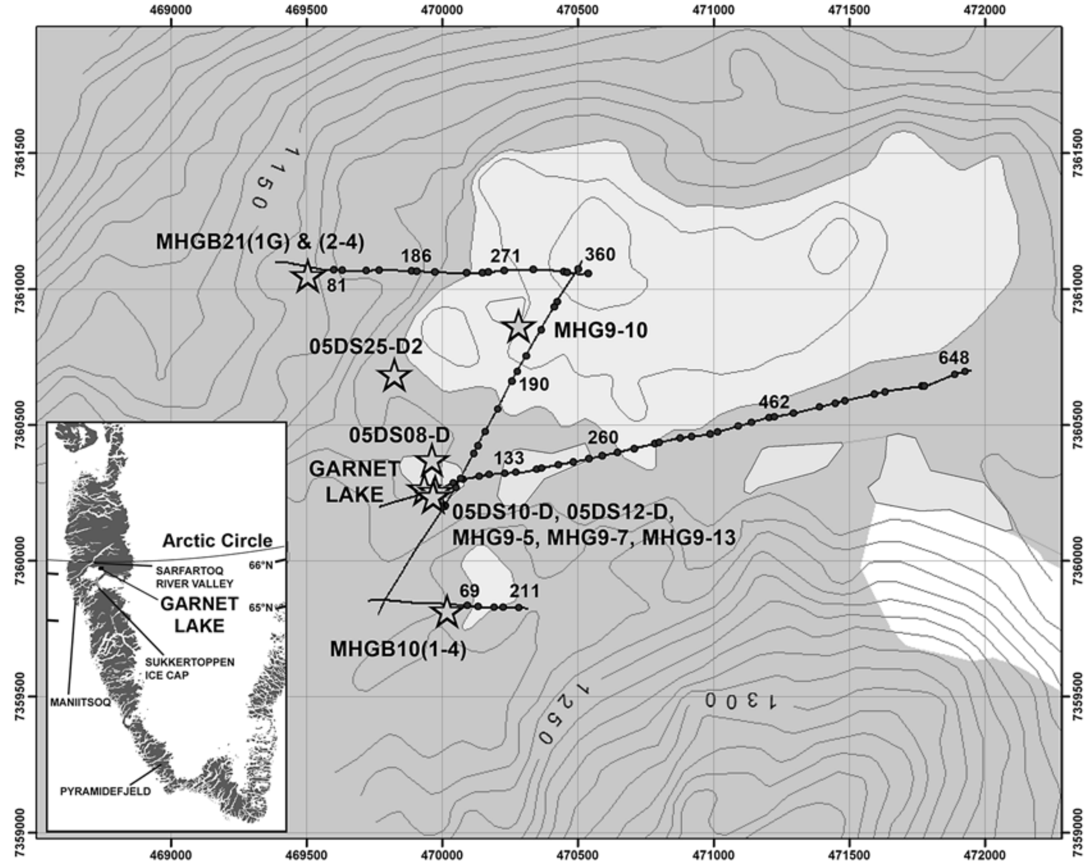

FIG. 1. Location of diamondiferous samples from Garnet Lake. Stars represent the locations of diamondiferous samples; solid lines are the traces of seismic lines delineating the Garnet Lake main sheet. Values shown are selected modeled depths in meters below ground surface to the main sheet; contour interval is in meters. The grid intervals are in meters on UTM Grid 22W. Garnet Lake is shown in the geographical context of West and South Greenland; additional locations described in the text are indicated.

and associated bodies have been delineated using a combination of seismic reflection and drill-core surveys. Evidence points to variations in strike and thickness throughout the body; in places, it appears to exhibit an anastomosing behavior.

The Garnet Lake diamond discovery is distinctive among diamond-bearing rocks in Greenland in that it has produced a large number of diamond crystals of significant size, including the largest Greenlandic stones recovered to date. Twenty-six macrocrystals (>0.5 mm) and 457 microcrystals have been recovered from 542.2 kg of drill core and surface samples up until 2006 from the Garnet Lake vicinity.

It is not the purpose of this study to present a characterization of the diamond carrier medium. A separate petrographic study indicates that components of kimberlite *sensu stricto* occur as separate units within the body largely consisting of kimberlite *sensu lato* (Hutchison 2008). Kimberlite *sensu stricto* is recorded from other localities in West Greenland (Nielsen & Sand 2008). The kimberlite *sensu lato* has numerous features consistent with an ultramafic lamprophyre and some transitional features, such as chromite transitional between Type-1 and Type-2 compositions of Mitchell (1995). This rock type also contains an apparent carbonatitic component, as revealed by the presence of the unusual carbonate of Sr, Ba, Ca olekminskite (Hutchison 2005). The kimberlite *sensu stricto*, although fulfilling the classical mineralogical and compositional criteria required for a kimberlite (Hutchison 2008), contains ilmenite with a Mg-depleted rim (6–7 wt% MgO). The physical relationship between the two rock types has not been fully constrained. This characteristic of zoned ilmenite with a rim more typical of an ultramafic lamprophyre suggests that a progression from kimberlite *sensu stricto* toward ultramafic lamprophyre has taken place.

The term "kimberlitic", although poorly constrained, is used in the following to refer to other rocks where a robust classification has not been carried out. It should be noted, however, that numerous authors who discuss diamond-hosting rocks from Greenland have used the term "kimberlite" as a blanket term referring to rocks containing some minerals characteristic of kimberlite. In some, although certainly not all such cases, the rocks in question may be more correctly termed orangeite (after Mitchell 1995), carbonatite–aillikite or ultramafic lamprophyres. The correct classification of diamond-bearing rocks from West Greenland is a contentious issue, with some authors (*e.g.*, Nielsen & Jensen 2005, Nielsen & Sand 2008) only recently describing examples of true Type-I kimberlites. In the more distant past, such rocks were not known from Greenland (*e.g.*, Mitchell *et al.* 1999). It is apparent that a robust petrological classification must be applied on a case by case basis.

DETERMINATION OF KIMBERLITE AGE: METHODOLOGY AND RESULTS

A small sample of kimberlite *sensu stricto* (05DS07–155b) from Garnet Lake was processed using standard crushing and mineral separation steps for U–Pb geochronology on perovskite. Isolating perovskite involved the use of a jaw crusher, disk mill, Wilfley table, Frantz Isodynamic separator and the heavy liquid methylene iodide. Stringent decontamination procedures were used at all steps in the process. The selected fractions of perovskite were cleaned, weighed and then dissolved in a 50:50 mixture of $HF:HNO_3$ together with a mixed $^{205}Pb–^{235}U$ tracer solution at 220°C for 4–5 days. Uranium and lead were purified using anion-exchange chromatography, and their isotopic compositions were measured on a VG354 thermal ionization mass spectrometer operating in single Daly detector peak-hopping mode. The U/Pb analytical results for these analyses are reported in Table 1 with corresponding one-sigma errors. The uranium decay constants used are as follows: ^{238}U: 1.55125×10^{-10} yr^{-1}, ^{235}U: 9.8585×10^{-10} yr^{-1} (Jaffey *et al.* 1971).

TABLE 1. LOCATIONS OF SAMPLES OF KIMBERLITE FROM WHICH DIAMOND CRYSTALS HAVE BEEN RECOVERED

Sample	Location	Easting	Northing	Depth range below ground (m)
05DS08-D	Gt. Lk. m.s.*	469963	7360374	34.6 - 39.2
05DS10-D	Gt. Lk. m.s.¥	469935	7360266	6.2 - 77.5
05DS12-D	Gt. Lk. m.s.	469975	7360257	6.1 - 10.4
05DS25-D2	Gt. Lk. m.s.*	469824	7360688	14.1 - 56.7
MHG9-13	Gt. Lk. m.s.	469969	7360241	0
MHG9-5	Gt. Lk. m.s.	469967	7360238	0
MHG9-7	Gt. Lk. m.s.	469967	7360238	0
MHGB10(1-4)	Gt. Lk. m.s.	470019	7359817	0
MHGB21(1G)	Gt. Lk. m.s.	469506	7361052	0
MHGB21(2-4)	Gt. Lk. m.s.	469506	7361052	0
MHG9-10	Silly kimberlite	470282	7360867	0

Locations of samples from drill holes are not those of the ground-penetration point; rather they represent the average point on the surface above the point at which the sample has been collected. Coordinates are in meters projected on UTM Grid 22W.
Gt. Lk. m.s.: Garnet Lake main sheet.
*: Sample also includes kimberlite from a shallower subparallel sheet of kimberlite.
¥: Sample also includes kimberlite from a deeper subparallel sheet of kimberlite.

Abundant, tiny, dark brown to black cubes of perovskite were recovered from this sample. Some grains exhibit visible zoning, with a thin light orange-brown rim. A few crystals have a slight amount of white alteration on the exterior surfaces. Two multi-grain perovskite fractions of dark cubes were selected for analysis. Both fractions have high uranium contents (360 and 409 ppm) and low Th/U (0.99 and 1.18) with respect to typical groundmass perovskite in kimberlite (usually 50–150 ppm and >10, respectively; *e.g.*, Heaman & Kjarsgaard 2000, Heaman *et al.* 2003). An unusual feature of the Garnet Lake perovskite is the modest amount of discordance (9–14%), as can be seen on Figure 2. These two fractions of perovskite have similar $^{207}Pb/^{206}Pb$ ages of 565 and 569 Ma, and the weighted average $^{207}Pb/^{206}Pb$ age, 568 ± 11 Ma (two sigma), is interpreted as the best estimate for the age of emplacement of the Garnet Lake kimberlite. This age corresponds to the Early Cambrian and toward the younger end of the age range (604–556 Ma), previously reported for West Greenland Neoproterozoic kimberlites (Heaman 2005).

DIAMOND SAMPLES AND METHODOLOGY

Two different kinds of samples were collected. The first type consists of combined drill-core samples which wholly or in part involve a portion of the Garnet Lake main sheet and, in some cases, also subparallel sheets. The second type consists of float, which by means of field observation of coincidence with outcrop and with surface projection models from seismic and drilling programs, can be considered to be frost-heaved from the Garnet Lake main sheet. The locations of sample sites from both types of sample are documented in Table 1 and shown in Figure 1. Also included in Figure 1 are modeled depths below ground surface to the main sheet, as determined seismically. These values give an indication of the morphology of the sheet. Sample sites cover a distance of approximately 1250 m along strike and 80 m down dip on the main sheet.

The majority of diamond crystals were recovered from samples that consist wholly of kimberlite from the Garnet Lake main sheet. A small number of crystals were recovered from samples where some kimberlite from subparallel sheets and feeder channels likely dilutes the proportion of stones attributable to the main sheet. Given the small number of these stones (16), caution should be exercised in drawing conclusions as to the significance of any deviation from characteristics observed in undiluted samples from the main sheet.

Diamond crysts were separated from their kimberlite hosts at the GeoAnalytical Laboratories of the Saskatchewan Research Council, Canada, following ISO/IEC 17025 standards. Samples were crushed, and the diamond crystals were released by a chemical technique involving caustic fusion in pressurised containers of NaOH followed by acid leaching. Stones were subsequently recovered down to 75 μm size by hand picking from residues. In order to remove the potential for contamination, all diamond crystals used in drilling were Type-Ib aggregated, synthetic, cubic, yellow crystals of known size; they are easily distinguished from the naturally occurring stones.

The recovered crystals were separated according to size fraction and subsequently described in terms of color, clarity, wear and surface features (Table 2). Where stones are frosted, they are usually described as colorless unless it is apparent that they also have a body opacity, in which case they are described as white. Some white stones are alternatively termed “cloudy” if the opaque color of the stone does not involve a surface texture. Hence use of the alternative term “frosty” inherently also implies a degree of surface etching. In addition to the clarity of stones as a whole, the presence of obvious mineral inclusions also is noted. Morphology follows the classifications schemes of Gurney *et al.* (2004) and Robinson *et al.* (1989), with reference to Robinson (1979) and Orlov (1977). Stones are classified as octahedral if they exhibit a majority octahedral component (resorption classes 3–6 of Robinson 1979). Hence the term “octahedral” also includes some stones with a cubic component of growth. Stones that have less than 50% of identifiable crystallographic morphology are termed “irregular”, and in terms of their degree of *survival*, they are also classified as “irregular/fractured” (Table 2). Where a clear fracture-surface can be identified, stones are described as broken, “(B)” in Table 2. These stones represent a subset (about a third) of those described as fractured or irregular (“Fr/Ir”) in Table 2. For the balance of those stones, whereas clear broken surfaces have not been identified, this may not always be apparent on highly irregular crysts. Hence the 20% of stones from the complete sample is likely a lower estimate. The remaining stones are irregular owing to resorption. It is not evident whether breakage has occurred during mineral separation or naturally; hence, this characteristic is not discussed further.

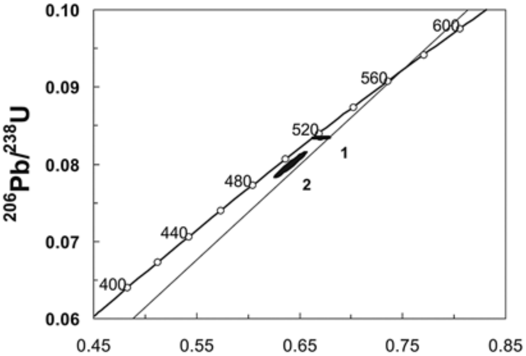

FIG. 2. U–Pb concordia plot for Garnet Lake sample 05DS07–155b. Solid black forms represent the scatter of data for analyses conducted on the two perovskite separates for this sample. The thick black line is the concordia line, and the thin black line reflects the 9–14% discordance shown by this sample.

Where stones were made available and were large enough (typically with maximum dimension greater than 200 μm), their infrared characteristics have been measured. Smaller stones were not measured owing to the significant risk of loss during handling with the equipment available. The FTIR measurements were conducted at the University of British Columbia (UBC) in Vancouver and the University of Alberta in Edmonton. The measurements at UBC were conducted using a Thermo-Nicolet 710 spectrometer with a Nic-Plan Infrared microscope attachment. The measurements at Edmonton were conducted using a Thermo-Nicolet Nexus 470 spectrometer fitted with a Continuum infrared microscope with a KBr beam splitter. Aperture sizes were chosen to be smaller than the size of the diamond crystals and in order to minimize scattered infrared light from other sources. Spectra were collected for 200 seconds over the range 4000 to 600 cm^{-1} (650 cm^{-1} for UBC measurements) at a resolution of 4 cm^{-1}. For most stones, more than one analysis was conducted. Nitrogen concentration and aggregation can vary within individual crystals (Boyd *et al.* 1987). Care should thus be exercised in the interpretation of data from such analyses where light passes through the whole stone. Although a true measurement of nitrogen variability would require measuring broken fragments of a stone, analyzing different paths of light through a single crystal allows for some degree of quality control and a rough assessment of the variability of nitrogen content and aggregation within each crystal analyzed. In the case of this study, multiple analyses on single crystals did not reveal large differences in data acquired. Deconvolution of the spectra involved baseline correction using commercially available software from Thermo Nicolet.

Equipment at both laboratories revealed a large absorption in the one-phonon region of most spectra, confirming the presence of unusually high levels of nitrogen. Nitrogen concentration and aggregation were calculated using constants from Boyd *et al.* (1994, 1995), and the results of calculations were cross-checked using two different spreadsheets to apply quality control.

TABLE 2. VISIBLE PHYSICAL FEATURES OF DIAMOND CRYSTALS FROM GARNET LAKE

			Color					Clarity				Shape						
Sample	Location	#	C/I	A	W	P	Y	Cl	Fr	Cy	(I)	O	D	C	Thh	Irg	Agg	(tw)
05DS12-D	Gt. Lk. m.s.	15	15	0	0	0	0	5	10	0	0	4	0	0	0	9	2	3
MHG9-5	Gt. Lk. m.s.	71	68	3	0	0	0	70	1	0	1	3	0	0	0	68	0	0
MHG9-7	Gt. Lk. m.s.	28	28	0	0	0	0	20	8	0	0	3	0	0	2	21	2	0
MHG9-13	Gt. Lk. m.s.	52	52	0	0	0	0	38	14	0	1	14	0	0	7	28	2	1
MHGB10(1-4)	Gt. Lk. m.s.	226	201	4	15	4	2	155	56	15	33	78	6	1	1	121	17	12
MHGB21(1G)	Gt. Lk. m.s.	1	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0
MHGB21(2-4)	Gt. Lk. m.s.	3	3	0	0	0	0	3	0	0	0	2	0	0	0	1	0	0
05DS08-D	Gt. Lk. m.s.*	6	6	0	0	0	0	2	4	0	1	1	2	0	0	3	0	1
05DS25-D2	Gt. Lk. m.s.*	4	1	1	2	0	0	2	0	2	1	3	0	0	0	1	0	0
05DS10-D	Gt. Lk. m.s.¥	6	6	0	0	0	0	1	5	0	0	1	1	0	0	4	0	0
Percentages	*diluted m.s.*	*16*	*81.3*	*6.3*	*12.5*	*0.0*	*0.0*	*31.3*	*56.3*	*12.5*	*12.5*	*31.3*	*18.8*	*0.0*	*0.0*	50.0	0.0	6.3
	pure m.s.	*396*	*92.9*	*1.8*	*3.8*	*1.0*	*0.5*	*73.7*	*22.5*	*3.8*	*8.8*	*26.3*	*1.5*	*0.3*	*2.5*	62.9	5.8	4.0
	ALL Gt. Lk.	*412*	*92.5*	*1.9*	*4.1*	*1.0*	*0.5*	*72.1*	*23.8*	*4.1*	*9.0*	*26.5*	*2.2*	*0.2*	*2.4*	62.4	5.6	4.1

		Survival			Surface features (resorption, etching)								
		Ub	Fr/Ir	(B)	Ser	Tr	Hk	Ps	Lam	Step	Rib	Shld	KA
05DS12-D	Gt. Lk. m.s.	4	11	1	3	2	2	2	2	0	5	0	0
MHG9-5	Gt. Lk. m.s.	2	69	6	5	0	2	2	13	0	0	0	0
MHG9-7	Gt. Lk. m.s.	6	22	0	4	2	0	0	2	3	4	0	0
MHG9-13	Gt. Lk. m.s.	16	36	6	6	2	1	1	7	1	7	1	0
MHGB10(1-4)	Gt. Lk. m.s.	71	154	61	49	14	18	19	20	68	68	32	1
MHGB21(1G)	Gt. Lk. m.s.	0	1	0	0	0	0	0	0	0	0	0	0
MHGB21(2-4)	Gt. Lk. m.s.	2	1	0	0	0	0	0	0	0	0	0	0
05DS08-D	Gt. Lk. m.s.*	2	4	1	2	2	2	0	0	0	1	0	0
05DS25-D2	Gt. Lk. m.s.*	2	2	2	2	1	0	1	0	1	1	0	0
05DS10-D	Gt. Lk. m.s.¥	1	5	1	2	0	1	0	1	0	3	0	0
Percentages	*diluted m.s.*	*31.3*	*68.8*	*25.0*	*37.5*	*18.8*	*18.8*	*6.3*	*6.3*	*6.3*	*31.3*	*0.0*	*0.0*
	pure m.s.	*25.5*	*74.2*	*18.7*	*16.9*	*5.1*	*5.8*	*6.1*	*11.1*	*18.2*	*21.2*	*8.3*	*0.3*
	ALL Gt. Lk.	*25.7*	*74.0*	*18.9*	*17.7*	*5.6*	*6.3*	*6.1*	*10.9*	*17.7*	*21.6*	*8.0*	*0.2*

#: number of diamond crystals; *: sample includes some kimberlite from shallower body than the main sheet; ¥: sample includes some kimberlite from deeper body than the main sheet; Gt. Lk.: Garnet Lake; m.s.: main sheet; MHG9-7 is a predominantly xenolith-free sample of kimberlite; MHG9-5 is xenolith-rich, and MHG9-13 is a mixed sample. C/I: colorless; A: amber; W: white; P: pink; Y: yellow; Cl: clear; Fr: frosted; Cy: cloudy; (I): inclusions; O: octahedral (<50% dodecahedral form); D: dodecahedral (>50% dodecahedral form); C: cubic; Thh: tetrahexahedral; Irg: irregular; Agg: aggregate; (tw): twinned; Ub: unbroken; Fr/Ir: fragment or irregular; (B): broken; Ser: serrate; Tr: trigons; Hk: hillocks; Ps: pits; Lam: lamellae; Step: stepped; Rib: ribbed; Shld: shield lamellae; KA: knob-like asperities.

Two crystals of diamond from the Silly kimberlite, which likely is a subparallel body lying above the Garnet Lake m.s., are described as being a colorless, clear and irregular stone, and a colorless, clear octahedral stone with serrate lamellae.

RESULTS

Visual characteristics

Descriptions of visually observable physical characteristics of the diamond crystals are presented in Table 2. A variety of different colors, clarities and crystal forms are apparent, suggesting that more than one population of diamond exists. The qualitative nature of these observations, however, only allows for the identification of small additional populations that deviate from the majority of stones in terms of color. Subsequent to diamond growth, crystals have survived the processes of entrainment within the carrier melt and its eruption and the effects of subsequent separation of the minerals to different degrees. Overwhelmingly however, most stones are clear, colorless and of an irregular or unclassified shape.

Of the non-colorless stones, the dominant color is opaque white (4% of all stones). Amber, pink and yellow stones are present but very rare. Cloudy stones are also found rarely. Mineral inclusions are apparent in 9% of the whole population. All inclusions observed are small, irregular and black. It is likely that most inclusions are graphite or sulfides. Destructive testing of the samples was not permitted; given the small size of the diamond crystals and the problems that refraction and conversion to graphite along the inclusion–host interface cause in the accurate visual identification of inclusions in diamond, further identification of inclusions was not possible.

Where crystal form can be determined, the stones are observed to be usually octahedra, all with minor degrees of dodecahedral forms (resorption classes 3–6 of Robinson 1979) and thus are classified as octahedral (Gurney *et al*. 2004). A minor cubic component is seen to occur to varying degrees; in such cases, stones might more strictly be called cubo-octahedra. In addition to irregular and octahedral crysts, some 23 aggregates are recorded (6% of the total population). Almost all aggregates are colorless and clear and are irregular intergrowths. There are no examples of opaque boart or ballas. Two colorless polycrystalline aggregates are recorded. A small number of stones (17) are twinned. Rare tetrahexahedral, dominantly dodecahedral (classes 1 and 2 of Robinson 1979) and a single cubic stone were recovered in total, accounting for less then 5% of stones. Of the total population, about 19% are clearly broken; following the argument described in the methodology, this is a likely underestimate, and some 26% have remained unbroken, which following the same argument likely also is an underestimate.

The dominant surface-features observed are ribs, followed by stepped features and serrate lamination, undefined lamination, shield lamellae, hillocks, pits and negative trigons. A single stone exhibits knob-like asperities. An example of an octahedral-dodecahedral stone showing prominent negative trigons is shown in Figure 3. Although various surface-features are observed, they are not common. No single surface-feature is apparent in more than a quarter of the stones described. Only 4% of the total number of crystals studied is described as frosted.

Comparing samples taken entirely from the Garnet Lake main sheet with samples where some dilution from neighboring sheets may have occurred, some differences appear. Data in Table 2 suggest that diamond crystals not from the main sheet are less likely to be colorless and clear, but perhaps also more likely to be octahedral than irregular. Given the small number of stones, the statistical significance of these differences is unclear. Sample MHGB10(1–4), however, accounts for over half of the crystals whose physical features are described. Although caution should also be applied to the statistical robustness of differences between the MHGB10(1–4) crystals and other Garnet Lake stones, it does appear that the MHGB10(1–4) diamond population has more white (6% compared to 1%), cloudy (7% compared to 1%), included (15% compared to 2%), stepped (30% compared to 3%) and ribbed (30% compared to 11%) crystals of diamond. These differences occur amongst the rarer categories; for the majority of the populations where the stones are clear, colorless octahedral or irregular stones, no strong differences are evident.

Size distribution of stones

The number of stones captured by various sizes of sieve during the separation process is shown in Table 3. Data from all samples involving the Garnet Lake main sheet are combined in order to present a statistically meaningful dataset. Projected values for the number of stones per 100 tonnes of sample are presented although the total weight of kimberlite crushed to yield the crystals described was 425.1 kg. Such a sample size cannot be considered representative of 100 tonnes of material; this is, however, the standard unit employed in comparison of diamond abundance between localities (*e.g*., Chapman & Boxer 2004). Data are displayed graphically in Figure 4 in terms of the log of the number of stones per 100 tonnes of sample against the log of sieve size in μm. The relationship of abundance to size presents a smooth curve.

Infrared characteristics

Diamond crystals with characteristic infrared absorption at 1282 cm^{-1} and little or no absorption at 1175 cm^{-1} are termed Type-IaA diamond; those with a characteristic absorption at 1175 cm^{-1} and little or no absorption at 1282 cm^{-1} are termed Type-IaB diamond (Davies 1976). Type-IaA spectra are attributable to

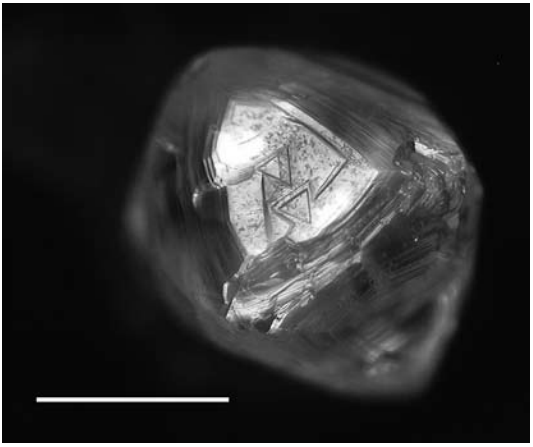

FIG. 3. Combination octahedral-dodecahedral diamond MHG9–13_1 showing negative trigon etching. Scale bar is approximately 1 mm.

pairs of nitrogen atoms occurring within the diamond structure (Davies 1976), and Type-IaB absorption is attributed to groups of four tetrahedrally arranged atoms of nitrogen surrounding a vacancy (Evans & Qi 1982). Type-IaA diamond aggregates further to form Type-IaB diamond following an Arrhenius law dependent on temperature and time. The mathematical constants describing this interdependence on time and temperature are described in Taylor *et al.* (1990), Mendelssohn & Milledge (1995) and McKenna (2001). From this mathematical 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 the development of Type-IaB centers is regular (Woods 1986).

Averaged values of the concentration of nitrogen occurring in different forms for each diamond are presented in Table 4. The crystals analyzed mostly have high concentrations of nitrogen (up to 2021 ppm, averaging 1102 ppm). Despite this amount, the aggregation to IaB diamond is not particularly high (up to 60.9% IaB and averaging 26.6% IaB) compared to worldwide populations (Kaminsky & Khachatryan 2001). Nitrogen-rich diamond does not require such high temperature or long residence time to achieve the same degree of aggregation as nitrogen-poor stones (Taylor & Milledge 1995). Furthermore, as the relationship between abundance of diamond and nitrogen concentration presented in Figure 5 shows, two populations of diamond seem to be present. The larger population exhibits a peak occurrence in the range of 10–20% IaB aggregation, and the smaller has a peak in the range 50–60% IaB. As it was only possible to measure the infrared characteristics of the larger stones, it is not clear how these populations extend into smaller sizes of stone. However, for stones where nitrogen data are available, there is no relationship evident between crystal size and nitrogen concentration or aggregation.

Measurements of total concentration of nitrogen in ppm against nitrogen aggregation as percentage of IaB are presented graphically in Figures 6 and 7 (after Taylor & Milledge 1995). In both figures, it is clear that there is a relatively small spread in the range of nitrogen concentration in comparison with a larger spread in nitrogen aggregation. An indication of the same twin peaks evident in Figure 5 can also be seen in the distribution of data on these two figures. There is no apparent difference in the characteristics of diamond from samples from the Garnet Lake main sheet and

TABLE 3. SIZE DISTRIBUTION OF DIAMOND CRYSTALS

Sieve size (μm)	+75	+106	+150	+212	+300	+425	+600	+850	+1180	+1700	Total
Number of crystals	104	101	74	64	33	23	6	5	2	0	412
Diamond crystals per 100 tonnes	24460	23760	17410	15060	7763	5410	1411	1176	470.5	0	

Samples used in this compilation consist of all of those that involve a proportion of the Garnet Lake main sheet, as described in Table 2. Stones assigned to a particular sieve-size are those captured by square mesh holes of the sieve size in micrometers. Calculations of stones per 100 tonnes use a total sample weight of 425.1 kg. The two stones from the Silly kimberlite, lying above the Garnet Lake sheet, fall on the +75 and +212 sieve fraction.

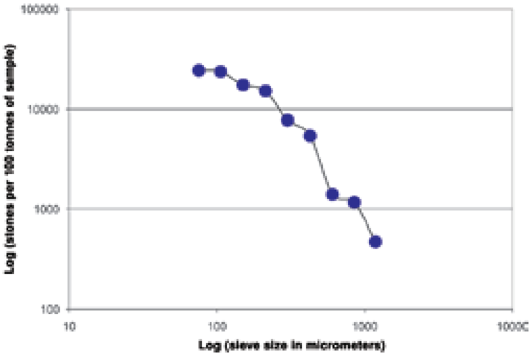

FIG. 4. Log–Log plot of projected number of diamond crystals per 100 tonnes against sieve size in micrometers.

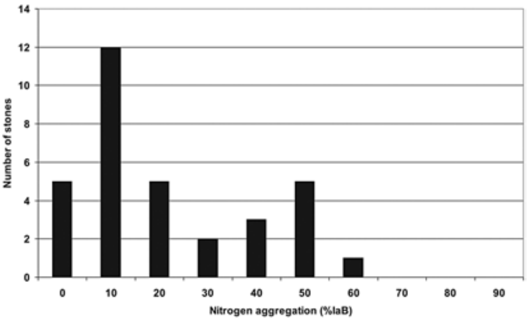

FIG. 5. Histogram of distribution of diamond crystals in terms of nitrogen aggregation.

TABLE 4. NITROGEN CONCENTRATION AND STATE AGGREGATION IN DIAMOND AS DETERMINED BY FTIR AND INFERRED TEMPERATURE AND RESIDENCE-TIME

Diamond	Location	#	Type	N(A)	N(B)	N(T)	% IaB	t (Ma)	T (°C)	Description	x	y	z
05DS12D1/2-1	Gt. Lk. m.s.	1	IaA	1156	193.2	1349	14.3	2.3	1236	C/I, Fr, Irg, Fr/Ir, Rib	0.28	0.24	0.20
05DS12D2/2-1	Gt. Lk. m.s.	3	IaA	1249	166.0	1415	11.8	1.7	1228	C/I, Fr, Irg, Fr/Ir	0.76	0.50	0.40
05DS12D2/2-2	Gt. Lk. m.s.	2	IaA	704.8	134.7	839.6	16.2	4.2	1253	C/I, Fr, Agg, (Tw), Ub, Ps, Hk	0.68	0.52	0.16
05DS12D2/2-3	Gt. Lk. m.s.	2	IaA	1653	301.6	1954	15.4	1.7	1228	C/I, Cl, Irg, Fr/Ir, Lam	0.56	0.44	0.20
05DS12D2/2-4	Gt. Lk. m.s.	1	IaA	781.4	60.9	842.3	7.2	1.7	1228	C/I, Fr, O, Ub, Ser, Rib, Ps, Hk	0.54	0.42	0.40
05DS12D2/2-5	Gt. Lk. m.s.	2	IaA	668.8	142.9	811.6	17.5	4.8	1257	C/I, Fr, O, Agg, Fr/Ir, Ser, Rib, Tr	0.52	0.40	0.40
05DS12D2/2-6	Gt. Lk. m.s.	2	IaA	695.4	193.6	889.0	21.8	5.7	1262	C/I, Cl, Irg, Fr/Ir	0.56	0.20	0.20
05DS12D2/2-7	Gt. Lk. m.s.	1	IaA	475.9	201.7	677.6	29.8	11.4	1283	C/I, Fr, O, (Tw), Ub	0.22	0.18	0.10
MHG9-5_1	Gt. Lk. m.s.	2	IaAB	433.1	419.9	853.1	49.2	20.8	1300	C/I, Cl, Irg, Fr/Ir, Lam	1.98	1.34	0.98
MHG9-5_2	Gt. Lk. m.s.	3	IaAB	406.9	488.1	895.1	54.5	24.5	1306	C/I, Cl, Irg, Fr/Ir, Lam	1.84	1.02	0.72
MHG9-5_3	Gt. Lk. m.s.	3	IaAB	236.2	284.6	520.8	54.6	42.3	1322	C/I. Cl, Irg, Fr/Ir, (B)	0.84	0.72	0.60
MHG9-5_4	Gt. Lk. m.s.	3	IaAB	507.7	497.1	1005	49.5	17.8	1296	C/I. Cl, Irg, Fr/Ir	0.60	0.54	0.26
MHG9-5_5	Gt. Lk. m.s.	3	IaAB	428.4	528.6	957.0	55.2	23.6	1304	C/I. Cl, Irg, Fr/Ir, Ser	0.50	0.44	0.40
MHG9-7_1	Gt. Lk. m.s.	2	IaA	889.9	90.9	980.8	9.3	1.9	1231	C/I, Cl, Agg, Fr/Ir, Ser, Step, Tr	1.56	1.40	1.16
MHG9-7_2	Gt. Lk. m.s.	3	IaA	979.8	104.1	1084	9.6	1.8	1229	C/I, Cl, O, Ub, Ser, Rib, Tr	1.00	0.98	0.90
MHG9-7_3	Gt. Lk. m.s.	3	IaAB	571.8	384.9	956.7	40.2	12.9	1286	C/I. Fr. Thh, Ub	0.60	0.48	0.40
MHG9-7_4	Gt. Lk. m.s.	2	IaAB	443.9	516.1	960.0	53.8	22.2	1302	C/I, Fr, Irg, Fr/Ir, Rib	0.50	0.44	0.34
MHG9-7_5	Gt. Lk. m.s.	3	IaA	713.4	182.1	895.4	20.3	5.2	1260	C/I. Cl, Irg, Fr/Ir, Ser, Step	0.48	0.36	0.32
MHG9-13_1	Gt. Lk. m.s.	3	IaAB	714.2	356.6	1071	33.3	8.5	1274	C/I, Cl, O, Ub, Tr, Shld	1.90	1.70	1.42
MHG9-13_2	Gt. Lk. m.s.	3	IaA	1232	61.6	1294	4.8	0.7	1204	C/I, Cl, Thh, Ub, Rib	0.98	0.96	0.90
MHG9-13_3	Gt. Lk. m.s.	3	IaA	988.6	127.2	1116	11.4	2.1	1234	C/I, Cl, O, Ub, Ser, Step	0.60	0.52	0.40
MHG9-13_4	Gt. Lk. m.s.	3	IaAB	458.3	574.8	1006	54.4	21.7	1302	C/I, Fr, Irg, Fr/Ir, Rib	0.76	0.60	0.20
MHG9-13_5	Gt. Lk. m.s.	3	IaA	875.1	225.5	1101	20.5	4.3	1254	C/I, Cl, Thh, (Tw), Ub, Hk	0.60	0.40	0.36
MHG9-13_6	Gt. Lk. m.s.	3	IaA	1019	193.3	1212	16.0	2.9	1243	C/I, Cl, Irg, Fr/Ir	0.56	0.52	0.20
MHG9-13_7	Gt. Lk. m.s.	3	IaAB	724.2	313.9	1038	30.2	7.6	1271	C/I, Cl, O, Fr/Ir, (B), Ser, Rib	0.40	0.40	0.36
MHG9-13_8	Gt. Lk. m.s.	3	IaAB	336.0	523.9	859.9	60.9	33.2	1315	C/I, Fr, Irg, Fr/Ir	0.46	0.34	0.18
MHG9-13 9	Gt. Lk. m.s.	3	IaA	1050	239.2	1289	18.6	3.2	1246	C/I, Cl, Irq, Fr/Ir, Lam	0.66	0.40	0.30
MHG9-13_10	Gt. Lk. m.s.	3	IaA	1175	238.5	1414	16.9	2.6	1240	C/I, Fr, Thh, Ub	0.40	0.40	0.20
05DS08D1/2-1	Gt. Lk. m.s.*	4	IaA	1055	98.8	1154	8.2	1.4	1223	C/I, Cl, (I), D, Fr/Ir, (B), Hk	0.56	0.52	0.46
05DS08D1/2-2	Gt. Lk. m.s.*	2	IaA	1195	449.6	1644	27.3	4.2	1253	C/I, Fr, D, Ub, Ser, Rib	0.30	0.28	0.20
05DS10D1/2-2	Gt. Lk. m.s.¥	2	IaA	1146	214.6	1360	15.6	2.5	1239	C/I, Cl, Irg, Fr/Ir, Rib	0.40	0.28	0.18
05DS10D1/2-3	Gt. Lk. m.s.¥	2	IaA	1648	372.8	2021	18.3	2.0	1233	C/I, Fr, D, Fr/Ir, (B), Ser, Rib, Hk	0.36	0.32	0.26
MHG9-10_1	Silly kimberlite	3	IaA	801.0	106.9	907.8	11.8	2.7	1241	C/I, Cl, O, Ub, Ser	0.34	0.28	0.24
						Stats.	*Max.*	*42.3*	*1322*				
							Min.	*0.7*	*1204*				

Description abbreviations are as shown in Table 2. Gt. Lk. m.s.: Garnet Lake main sheet; *: sample includes some kimberlite from shallower body than the main sheet; ¥: sample includes some kimberlite from deeper body than the main sheet; N(A): nitrogen ppm (atomic) of A centers; N(B): nitrogen ppm (atomic) of B centers; N(T): total nitrogen (ppm atomic); % IaB: percentage of nitrogen occurring as IaB aggregates; t (Ma): residence time in Ma calculated on the basis of 1252°C; T (°C): Temperature calculated assuming a residence time of 4 Ma; MHG9-7 is a predominantly xenolith-free sample of kimberlite; MHG9-5 is xenolith-rich, and MHG9-13 is a mixed sample; x, y, z: measured dimensions of stone (mm).

those from subparallel and feeder channel kimberlite that have been sampled, except that the diluted samples do not include diamond crystals from the more highly aggregated population. Given that these latter samples come from more than one kimberlite body, any absence in diversity is attributed to the small dataset involved. No systematic difference can therefore be attributed to the two sample types.

Inspection of FTIR spectra of stones shows that platelet formation is regular, as defined by Woods (1986). This observation thus allows for the calculation of temperatures and residence times using the standard methodology of Mendelssohn & Milledge (1995). Figure 6 includes isochrons calculated assuming temperatures of 1252°C and 1375°C, and Figure 7 includes isotherms assuming a residence time of 4 Ma. The significance of these curves is discussed in the following. These temperatures were chosen to reflect a likely minimum initial temperature of diamond formation based on diamond morphology (1375°C) and a known ambient equilibrium temperature experienced by neighboring rocks (1252°C). There is no implication that the diamond crystals initially crystallized from the same melt that produced the associated mantle-derived xenoliths, simply that the diamond crystals will have experienced the same ambient temperature at some point during their history.

DISCUSSION

Visual characteristics

The diamond crystals described are dominantly colorless, clear stones, either in irregular shapes or where crystal shape is apparent, as octahedra with a minor to moderate dodecahedral component. This is indicative of a single dominant population exhibiting the features of diamond crystals xenocrystic with respect to their magmatic hosts (Harris 1992). The large majority of diamond crystals from Garnet Lake have no features consistent with growth within the kimberlitic melt during ascent. Tetrahexahedral forms and dodecahedral forms represent points in a continuum of resorption (McCallum *et al.* 1994). Aggregate and twinned crystals can form under the same conditions as octahedra. These characteristics do not allow for further subdivision of the population in terms of growth conditions of diamond, therefore; rather, they indicate that the crystals sampled have experienced a variety of degrees of resorption. Surface-etch features, most commonly ribs, stepped features, serrate lamination and shield lamination, support the same conclusion. They are all examples of early-stage resorption (Robinson 1979). Given also that only 4% of the total number of diamond crystals studied are described as frosted, we can infer that the majority of diamond crystals from the Garnet Lake main sheet have apparently not undergone extensive degrees of late-stage chemical damage.

The very rare occurrences of yellow stones deserve some attention. Worldwide, yellow stones fall into two categories: so-called "cape yellow" stones that contain UV-active "N3" centers (Fritsch 1998), and so-called Ib diamond. Yellow Ib aggregated diamond has experienced either an extremely short residence-time in the mantle or unusually low temperatures, and usually a combination of both (Taylor *et al.* 1996). These types of diamond are generally considered to have formed contemporaneously with the production of the kimberlitic magma (Boyd *et al.* 1987). As the particular yellow crystals of diamond in question are too small for FTIR measurements, it is not clear to which category of yellow stones they belong. However, the morphology of one of these stones is cubic. Experiments demonstrate that diamond having a cubic morphology is formed under relatively low-temperature conditions (Litvin 1969), is almost always of Type Ib (where nitrogen is present in measurable quantities), and is considered to form within the kimberlitic melt (Boyd *et al.* 1987). The morphology and color of the albeit extremely rare yellow crystals of diamond of cubic morphology from Garnet Lake may by the same argument suggest that such crystals have formed contemporaneously with generation of the kimberlitic melt. These rare stones, which may have grown within the kimberlitic melt, exist alongside more common crystals of diamond that show evidence of surface resorption. This apparent contradiction is not uncommon (*e.g.*, Gurney *et al.* 2004) and likely arises owing to the interaction of pressure and varying chemical conditions (particularly oxygen fugacity) during diamond entrainment and emplacement within its magmatic host. It is notable that a variability of chemical conditions is consistent with the hybrid nature of the Garnet Lake rocks, as evidenced by petrography (Hutchison 2008). Kimberlite *sensu stricto* is observed as a component to the Garnet Lake main sheet (Hutchison 2005, 2008) and has a similar mineralogy to rocks described from further south, near Maniitsoq (Nielsen & Jensen 2005). The Garnet Lake kimberlite samples contain Mg-rich ilmenite (MgO up to 15 wt%), which suggest chemical conditions favorable to diamond growth (Jago 2004). A pulse of Type-I kimberlite (after Mitchell 1995) is incorporated into the Garnet Lake sheet carrying with it rare, newly crystallized diamond. We propose that the majority of diamond crystals have been in contact with a melt largely of ultramafic lamprophyre (UML) type which, given the rounding and etch features apparent for some diamond crystals, had a composition which was partially detrimental to the preservation of diamond, at least in the latter stages of its residence within the melt. Such UML mineralogy is seen in Garnet Lake samples (Hutchison 2005, 2008).

Size distribution of stones

The relationship of abundance to size presenting a smooth curve is typical of diamond distributions where there is no great abundance of a separate growth of phenocrysts of diamond. Populations with abundant phenocrysts have a sharp break in slope toward the shallow size-fractions (Chapman & Boxer 2004). This size distribution of Garnet Lake crysts is consistent with the observation of very few diamond crystals with characteristics consistent with late-stage growth within the carrier melt.

Infrared characteristics and diamond formation

As is apparent from Figures 6 and 7, the concentration and aggregation of nitrogen reflect either a range in age of formation under constant temperature, or a single diamond-forming event at a range of temperatures (and hence depths), or a combination of both. Nitrogen aggregation is strongly affected by both time and temperature, and so it is not possible to definitively say which factor has had greater influence without additional lines of evidence.

Estimates of pressure and temperature from a single xenolith of garnet lherzolite taken from the Garnet Lake main sheet give four-phase internally consistent values of 61.4 kbar, 1252°C to 66.7 kbar, 1327°C (Hutchison 2005), depending on the thermobarometers used (Ellis & Green 1979, Brey & Köhler 1990). Further thermobarometry calculations on additional Garnet Lake xenoliths (Hutchison & Frei 2008) cluster around the same range of pressure–temperature conditions, and points lie on a 41 mWm^{-2} geotherm. This is consistent with results from two-phase assemblages, where compositional data for kimberlite indicator minerals in till compiled in Jensen *et al.* (2004a) and from xenolith samples (Garrit *et al*. 1995, Sand *et al*. 2008) predominantly support a 40–41 mWm^{-2} geotherm with maximum temperatures of around 1270°C. The pressure–temperature points for the Garnet Lake xenolith lie well within the stability field of diamond (Kennedy & Kennedy 1976). However, both temperature values are too cold for the formation of octahedral and cubo-octahedral varieties of diamond. 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 the diamond. Studies of *non-touching* mineral inclusions in diamond crystals from South Africa, which have retained chemical compositions reflecting the pressure–temperature conditions of their original entrapment within their growing hosts, are consistent with high temperatures of initial growth of a similar order (Phillips *et al*. 2004). These authors demonstrated that the diamond crystals within their dataset crystallized on average at 1197°C, ranging up to 1320°C.

The relatively small degree of Type-IaB aggregation for such unusually high concentrations of nitrogen in the Garnet Lake suite necessarily require short residence-times, especially at high temperature of residence. Application of a value for formation at 1375°C gives a range in residence times for the diamond crystals of between 15,000 and 910,000 years (Fig. 6). On the basis of the prevailing mantle geotherm (Hutchison 2005), octahedral and cubo-octahedral morphologies do not allow the diamond crystals to have formed any cooler than this. Given that these residence times are so short, what is perhaps more likely is that the diamond crystals formed at the necessary relatively high temperature over a brief period of time and were subsequently entrained into reservoirs, perhaps metasomatic precursors of the nascent kimberlitic melt at shallower depths and subsequently cooler temperatures. Here, further growth of diamond had largely stopped but nitrogen continued to aggregate within the crystals at a relatively slower rate consistent with the cooler ambient conditions. Such a change from diamond formation at relatively high temperatures to the majority of residence and subsequent nitrogen aggregation at cooler temperatures is apparent from the differences between equilibrium temperature conditions between *touching* and *non-touching* inclusions in South African suite of diamond crystals (Phillips *et al*. 2004). Compared to growth at temperatures averaging 1197°C, Phillips *et al*. (2004) presented an average of 1050°C for *touching* inclusions. Mineral inclusions in physical contact with each other record chemical partitioning consistent with final re-equilibration under the ambient conditions before the temperature falls below closure temperatures of the minerals concerned. Given the necessity for a reasonable period of time to allow re-equilibration to occur, these will likely be the conditions experienced during entrainment within and subsequent emplacement of kimberlitic melt. The temperature–time experienced immediately before kimberlite emplacement would not contribute significantly to the nitrogen aggregation history of the diamond crystals. In the case of the study by Phillips *et al*. (2004), diamond crystals will likely have experienced temperature conditions somewhere between that recorded by *touching* inclusions and *non-touching* inclusions for much of their mantle residence. A similar scenario is likely to have occurred for the dominant population of Garnet Lake diamond crystals.

The question that subsequently arises is, what temperature are Garnet Lake crystals of diamond likely to have experienced for the large majority of their residence in the mantle? This question is important given the strong temperature-dependence of the relationship between nitrogen aggregation and time. However, it should be still be stressed that the nitrogen contents of Garnet Lake diamond crystals are particularly high for the relatively low degrees of nitrogen aggregation they exhibit. Hence compared to diamond populations from elsewhere, at any specific temperature, the Garnet Lake crystals display a considerably shorter residence-time than is common from other deposits.

In contrast to the significant range of pressures and temperatures recorded from mantle xenoliths from kimberlitic rocks throughout West Greenland (Sand *et al*. 2008), the recorded equilibrium conditions of *all* xenoliths studied from the Garnet Lake main sheet cluster strongly together around 1252°C (Hutchison & Frei 2008). There are no recorded xenoliths that record significantly cooler temperatures. Whereas the 1252°C temperature reflects the ambient temperature for the bulk of the mantle residence, in some cases the xenoliths studied show very minor re-equilibration on the rims of touching grains. This minor re-equilibration is taken to reflect the final re-equilibration during entrainment into a carrier melt and emplacement within the crust, as similarly exemplified by the South African diamond crystals (Phillips *et al*. 2004). We therefore contend that 1252°C is a reasonable temperature to use for the ambient temperature of xenolith residence in the mantle.

Finally, it is necessary to consider whether the diamond crystals have experienced the same temperature as the xenoliths used for temperature calculations. There are no recorded instances of diamond crysts being recovered from specific xenoliths from Garnet Lake. Furthermore, provision of the sample suite of diamond crystals has not allowed for diamond breakage and hence inclusion identification. Thus it is not possible to assign diamond crystals to a particular paragenesis on the basis of their inclusion characteristics. However, it is notable that at Garnet Lake, aside from olivine, the only visually identifiable mantle-derived indicator mineral in hand specimen is garnet. In heavy-mineral

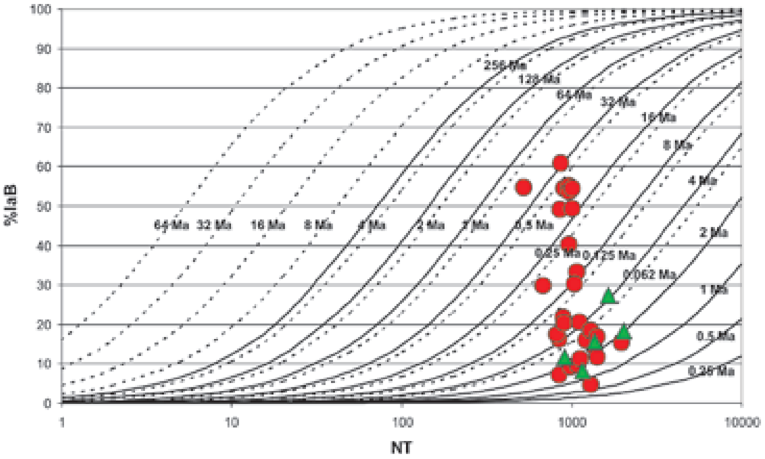

FIG. 6. Graph of nitrogen aggregation as percentage of type IaB against nitrogen concentration in ppm atomic, presented logarithmically with isochrons. Solid lines represent isochrons calculated on the basis of nitrogen aggregation assuming residence at 1252°C; dashed lines represent isochrons calculated on the basis of aggregation at 1375°C. Circles represent diamond crystals from samples of the Garnet Lake main sheet. Triangles represent diamond crystals from samples including associated subparallel sheets and feeder channels, including the Silly kimberlite.

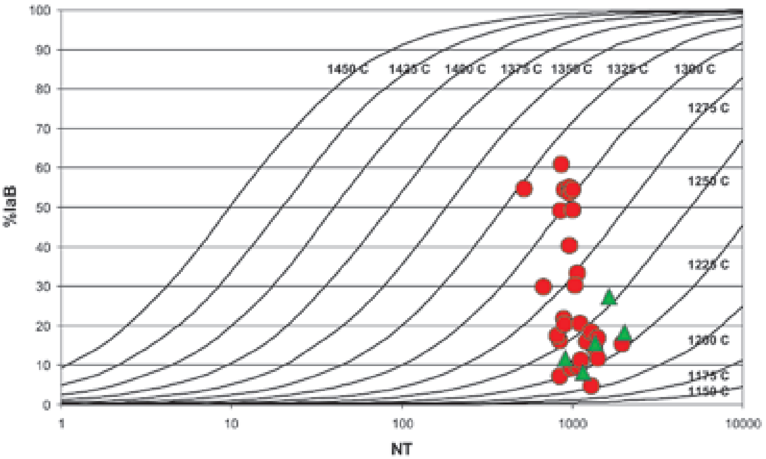

FIG. 7. Graph of nitrogen aggregation as percentage of type IaB against total concentration of nitrogen in ppm atomic, presented logarithmically and with isotherms after Taylor & Milledge (1995). Solid lines represent isotherms calculated on the basis of nitrogen aggregation assuming residence times of 4 Ma. Circles represent diamond crystals from samples of the Garnet Lake main sheet. Triangles represent diamond crystals from samples including associated subparallel sheets and feeder channels, including the Silly kimberlite.

separation and analysis, these disaggregated crystals of garnet have the same range of composition as seen in the xenoliths (Hutchison 2008). Furthermore, separates derived from eclogites are very rare compared to those derived from peridotites, and the vast majority of the rare xenoliths recovered from the Garnet Lake main sheet are peridotitic (Hutchison 2008). These are the same peridotite xenoliths as used in the determination of ambient mantle temperature. The strong dominance of a peridotitic component to mantle minerals at Garnet Lake, combined with the unusually high abundance of diamond crystals in the Garnet Lake main sheet compared to neighboring kimberlitic occurrences, lend credence to the assumption that temperatures recorded by peridotitic xenoliths do reflect the temperatures experienced by the associated crystals of diamond described.

As Figure 6 also shows, the "cooler" estimate of 1252°C obtained from measurements of the xenolith samples still necessitates quite short residence-times to account for the nitrogen characteristics measured. In this case, the maximum time allowed to develop the level of aggregation measured is 42.3 Ma. As xenoliths reveal a range in pressure–temperature conditions (after Jensen *et al.* 2004a), an alternative explanation can be considered, rather than the diamond crystals ponding at the same depth over a range of time intervals and requiring an episodic transport of diamond crystals from their initial location of growth to the site of ponding. The diamond crystals could have been moved from the site of their formation in a single event and ponded at a range of depths before the system was flushed at the time of kimberlite emplacement. The roots of kimberlite magmatism are not believed necessarily to lie as deep as the depths of diamond formation; rather, kimberlite forms from the accumulation of incipient melts traveling from greater depth (Dawson 1980) and triggered by heat from below. Such melts can transport diamond xenocrysts in addition to other mantle material. We propose that the diamond crystals formed initially in a melt consistent with a nascent kimberlite, which subsequently became intermixed to different degrees by a more UML-like component. This melt caused some resorption of the diamond and at the same time, if it was of a higher temperature than the ambient conditions and was stable, may have allowed for the further aggregation of nitrogen. Final exhumation appears in some cases to have involved a Type-I kimberlite component capable of growing new diamond in small quantities. An average residence-time from the initial depths of formation to final exhumation in kimberlite would be approximately 4 Ma. Isotherms on the basis of this time are included in Figure 7. A range in temperatures over which nitrogen would have aggregated under this scenario would therefore be 1204° to 1322°C. Calculated values for residence time assuming 1252°C and temperatures assuming 4 Ma residence time are included in Table 4. Assuming that the diamond crystals recovered were formed along the same 41 mWm^{-2} geotherm and using values of a range of temperature of formation from 1204° to 1322°C, these translate to a range of equivalent depths for diamond accumulation of 170.0 to 202.3 km (55.4 to 66.1 kbar).

It is likely that some combination of the two scenarios has come into play. This is made particularly clear by the fact that there are two identifiable populations of diamond present, according to nitrogen aggregation. Whatever residence time in the mantle is correct, whether a maximum of ~42 Ma or an average of 4 Ma with a range of depths, residence times are necessarily short compared to diamond xenocrysts from other localities. In some cases, the diamond can be over 1 Ga older than their kimberlite hosts (*e.g.*, Richardson *et al.* 1984, Pearson *et al.* 1999, Taylor & Anand 2004). On the other hand, examples of diamond with short residence-times are known elsewhere in the diamond record and are not unrealistic, particularly considering that some diamond crystals form within the kimberlitic melt itself (Arima *et al.* 1993). Although we certainly do not argue that the bulk of Garnet Lake diamond crystals are phenocrysts, the presence of rare yellow and cubic stones amongst the Garnet Lake sample (Table 2) suggests that some limited amount of diamond formation did occur contemporaneously with the erupting kimberlitic melt at Garnet Lake.

A residence time of 4 Ma places the average age of the diamond xenocrysts at *ca.* 572 Ma if one assumes an age of emplacement of 568 Ma for the kimberlite from U/Pb perovskite dating of the separates from sample 05DS07–155b taken 30 meters along strike on the main sheet from sample 05DS08–D. The principal igneous center in the vicinity of Garnet Lake is the Sarfartoq carbonatite complex; it lies 21 km northeast of Garnet Lake. With an average age of 565 Ma (Secher *et al.* 2008), it is contemporaneous within error with the emplacement of the Garnet Lake main sheet. Calculated ages of diamond formation show a continuum from ~42 Ma (assuming a dominant temperature of residence of 1252°C, Fig. 6), up to very close to the point of kimberlitic and carbonatitic magmatism.

As discussed previously, the petrology of the magmatic hosts to the Garnet Lake diamond crystals is complex and commonly shows a close similarity with components of carbonatitic magmatism (Hutchison 2005, 2008). On the scale of hand specimens, areas of kimberlite occasionally are entirely consistent with a classification as kimberlite *sensu stricto* (after Mitchell 1995), as indicated for example by an abundance of perovskite and a Ba-rich rim to phlogopite. There are transitional types, as evidenced mineralogically by the presence of a spinel phase of composition intermediate between Type 1 and Type 2. Other specimens would more correctly be termed ultramafic lamprophyre (after Mitchell 1995) owing to the presence of tetraferriphlogopite and monazite, or more generally as metasomatized lithospheric mantle-derived rocks (MLM, after Mitchell 2008). There certainly is occasional evidence in samples from the Garnet Lake main sheet for magma mixing; in most cases, however, a distinct petrological identification is more appropriate. Classification aside, the occasional presence of minerals such as olekminskite (Hutchison 2005) and the high abundance of carbonate provides evidence that the Garnet Lake main sheet further includes a carbonatitic-type component. In addition to this petrological similarity, there is a clear geographical association between kimberlite and carbonatite in the local area. The Sarfartoq carbonatite contains small occurrences of kimberlite of younger age (Larsen & Rex 1992). Further, the traces of many of the numerous kimberlitic rocks in the region appear to suggest a ring-like distribution of sheets centered on the Sarfartoq carbonatite (Larsen & Rex 1992, data compiled in Jensen *et al*. 2004a). The evidence for the age of the diamond in the Garnet Lake main sheet indicating that the crystals do not considerably predate their kimberlitic hosts strongly suggests therefore that not only kimberlite formation but also diamond growth have a connection with carbonatite formation. In experimental work, the association of diamond growth with carbonatite generation has been demonstrated (Shushkanova & Litvin 2008). Host-rock composition and the continuum of diamond ages to the point of carbonatite magmatism provides a natural example of this connection.

SUMMARY

Diamond crystals from the Garnet Lake sheet and associated kimberlitic rocks, Sarfartoq, West Greenland, yield evidence in terms of size distribution and nitrogen aggregation for two principal populations. Nitrogen concentration and aggregation state suggest diamond formation over a brief period at temperatures in excess of 1375°C, followed by entrainment within upwelling carbonate-rich melts to shallower depths, in the range 170.0 to 202.3 km, and subsequent cooler temperatures. While continued aggregation of nitrogen occurred, appropriate to the ambient temperatures, the chemical composition of the fluid or melt allowed at least a small degree of resorption. Mantle residence within the 170.0 to 202.3 km depth-range proceeded over no more than approximately 45 Ma, supporting maximum ages of approximately 610 Ma for the suite of diamond crystals sampled. Diamond formation and emplacement are likely associated with fertilization of the mantle lithosphere. Such fertilization led to the subsequent entrainment and emplacement of diamond crystals within subsequent kimberlitic hosts, in rare cases also allowing the precipitation of further diamond most likely with a kimberlite-related composition *sensu stricto*. Progression to bulk compositions more consistent with an ultramafic lamprophyre may have provided the conditions appropriate for the limited degree of final diamond resorption apparent in the surface features of some crysts. Closely associated with the described magmatic processes occurred the large-scale Sarfartoq carbonatitic magmatism.

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