

Depletion and enrichment processes in the lithospheric mantle beneath the Kola Peninsula (Russia): Evidence from spinel lherzolite and wehrlite xenoliths

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Abstract

A suite of spinel lherzolite and wehrlite xenoliths from a Devonian kimberlite dyke near Kandalaksha, Kola Peninsula, Russia, has been studied to determine the nature of the lithospheric mantle beneath the northern Baltic Shield. Olivine modal estimates and Fo content in the spinel lherzolite xenoliths reveal that the lithosphere beneath the Archaean–Proterozoic crust has some similarities to Phanerozoic lithospheric mantle elsewhere. Modal metasomatism is indicated by the presence of Ti-rich and Ti-poor phlogopite, pargasite, apatite and picroilmenite in the xenoliths. Wehrlite xenoliths are considered to represent localised high-pressure cumulates from mafic–ultramafic melts trapped within the mantle as veins or lenses. Equilibration temperatures range from 775 to 969 °C for the spinel lherzolite xenoliths and from 817 to 904 °C for the wehrlites.

Laser ablation ICP-MS data for incompatible trace elements in primary clinopyroxenes and metasomatic amphiboles from the spinel lherzolites show moderate levels of LREE enrichment. Replacement clinopyroxenes in the wehrlites are less enriched in LREE but richer in TiO₂. Fractional melt modelling for Y and Yb concentrations in clinopyroxenes from the spinel lherzolites indicates 7–8% partial melting of a primitive source. Such a volume of partial melt could be related to the 2.4–2.5 Ga intrusion of basaltic magmas (now metamorphosed to garnet granulites) in the lower crust of the northern Baltic Shield. The lithosphere beneath the Kola Peninsula has undergone several episodes of metasomatism. Both the spinel lherzolites and wehrlites were subjected to an incomplete carbonatitic metasomatic event, probably related to an early carbonatitic phase associated with the 360–380 Ma Devonian alkaline magmatism. This resulted in crystallisation of secondary clinopyroxene rims at the expense of primary orthopyroxenes, with development of secondary forsteritic olivine and apatite. Two separate metasomatic events resulted in the crystallisation of the Ti–Fe-rich amphibole, phlogopite and ilmenite in the wehrlites and the low Ti–Fe amphibole and phlogopite in the spinel lherzolites. Alternatively, a single metasomatic event with a chemically evolving melt may have produced the significant compositional differences seen in the amphibole and phlogopite between the spinel lherzolites and wehrlites. The calculated REE pattern of a melt in equilibrium with clinopyroxenes from a cpx-rich pocket is identical to that of the kimberlite host, indicating a close petrological relationship.

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1. Introduction

The occurrence of peridotite xenoliths entrained in mafic alkaline magmas, kimberlites and lamproites is of great importance because it enables direct investigations of the nature of the sub-continental lithospheric mantle. Studies of peridotite xenoliths from beneath the Kaapvaal craton, South Africa (Boyd et al., 1993), Siberian craton, Russia (Boyd et al., 1997), North American craton, Canada (Schmidberger and Francis, 1999) and the central Greenland craton (Bernstein et al., 1998) have revealed that the Archaean–Proterozoic sub-continental lithospheric mantle is usually more refractory than the Phanerozoic lithospheric mantle (Griffin et al., 1998). It has been suggested that the highly depleted nature of the ancient mantle results from a high degree of partial melting and extraction of komatiites and basalts during the Archaean/Proterozoic (Boyd and Mertzman, 1987; Griffin et al., 1998). However, these studies have mainly concentrated on garnet peridotite xenoliths in kimberlites, and only a few (e.g. Menzies et al., 1987; Bernstein et al., 1998; Grégoire et al., 2005) have investigated spinel-facies mantle xenoliths from beneath Archaean/Proterozoic crust. In Europe, studies have mainly concentrated on peridotite xenoliths derived from beneath Phanerozoic crust (see reviews by Menzies and Bodinier (1993) and Downes (2001)) whereas those from beneath Archaean–Proterozoic

crust are relatively rare (Menzies et al., 1987; Peltonen et al., 1999).

Within the Baltic Shield of northern Europe, peridotite xenolith localities have been found mainly in kimberlite pipes in Finland (Kukkonen and Peltonen, 1999; Peltonen et al., 1999) and Arkhangelsk (Sablukov et al., 2000; Beard unpubl. data). Until now information about the occurrence of mantle-derived peridotite xenoliths within the Kola Peninsula was limited to the discovery of three xenoliths in the Khibina complex (Arzamastsev and Dahlgren, 1994). In this paper, we present new data on a suite of spinel lherzolite and wehrlite xenoliths from Kola. They occur as small (5–25 mm) fragments embedded in a kimberlite dyke near the White Sea (Beard et al., 1998). Unfortunately, whole rock major and trace element geochemistry could not be obtained due to the very small size of the xenoliths. However, 12 spinel lherzolite and 4 wehrlite xenoliths were examined optically and analysed by electron microprobe. Trace elements and REE contents in clinopyroxenes and amphiboles were analysed in situ by laser ICP-MS. This suite presents an opportunity to investigate processes in the shallow sub-continental lithospheric mantle beneath the Archaean/Proterozoic crust of the Kola Peninsula. We show that the xenoliths from beneath the Kola craton are more similar to Phanerozoic mantle than to Archaean–Proterozoic mantle. Depletion was due to moderate degrees of

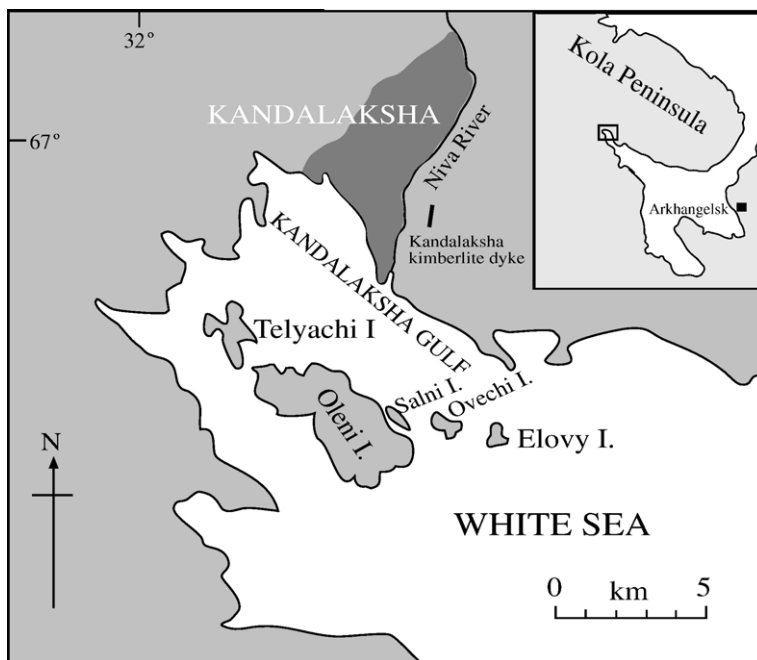


Fig. 1. Sketch map of the NW tip of the Kandalaksha Gulf, showing the location of the Kandalaksha monticellite kimberlite dyke. Inset: Kola Peninsula and Arkhangelsk.

partial melting and subsequently enrichment occurred by several metasomatic events.

2. Geological setting

The Baltic Shield is the largest area of exposed crystalline basement in the east European platform. In the northern part the Kola–Karelian orogen consists of several Archaean terranes, amalgamated by collisional tectonics during the early Proterozoic (Balagansky et al., 1998). Crustal formation took place between 2.9 and 2.5 Ga (Windley, 1992; Timmerman and Daly, 1995). The Kola Archaean terranes are bounded by Proterozoic mobile belts and well-preserved volcanic rift basins. A major period of basaltic magmatism occurred at 2.4 Ga (Amelin and Semenov, 1995; Amelin et al., 1996). The most recent magmatic activity occurred in Devonian times, when highly undersaturated alkaline magmas were intruded (Downes et al., 2005). The peridotite xenoliths of this study occur in a Devonian monticellite kimberlite dyke (Beard et al., 1998) intruded into 2.65–2.75 Ga Belomorian magmatized amphibolites (Claesson et al., 2000), near the town of Kandalaksha (Fig. 1).

3. Analytical methods

Major element mineral analyses were obtained using a Jeol 733 Superprobe with an Oxford Instrument ISIS energy dispersive system (EDS) at Birkbeck. Data was collected at 15 kV for 100 s count-time with a 2 μ m beam diameter and corrected using a SEMQuant (ZAF4) program. The microprobe was calibrated using Specpure[®] Co metal (99.99% Co) and profile standardisation material included natural silicates and oxides. The thin sections were prepared, polished, photographed and carbon-coated at Birkbeck. Compositions were determined from the average of three or more points on the same mineral phase. Olivine and pyroxene grains are unzoned, as shown by the homogeneous compositions determined across several representative grains. Total Fe is reported as FeO. Multiple analyses on a single mineral grain revealed a good reproducibility, with standard deviations (1 sigma) for the major oxides as follows SiO₂ (0.25), TiO₂ (0.08), Al₂O₃ (0.11), FeO (0.1), MnO (0.03), Cr₂O₃ (0.04), MgO (0.12), CaO (0.08), K₂O (0.05) and Na₂O (0.05).

The Kola peridotite xenoliths are too small for separation of clinopyroxene and amphibole, so they

Table 1

Petrographic summary of the Kandalaksha peridotite xenoliths including lithology, mineral assemblage, textures and calculated temperatures

Section no.	Xeno no.	Lithology	Mineral assemblage	Textures/ comments	Temperature (°C)			
					Brey and Köhler, 1990 (BKN)	Brey and Köhler, 1990 (Ca-opx)	Wells, 1977	Witt-Eickchen and Seck, 1991 (Ca-Al-opx)
Section 1	xen 1	Spinel lherzolite	ol, opx, cpx, sp, amph, phl, ap	Porphyroclastic		830		795
	xen 2	Spinel lherzolite	ol, opx, cpx, sp, phl	Porphyroclastic/ amphibole vein	830	916	870	803
	xen 3	Wehrlite	ol, cpx, phl, ilm	Equigranular/ cpx-rich pocket				
Section 2	xen 1	Spinel lherzolite	ol, opx, cpx, sp, amph	Porphyroclastic		790		
Section 3	xen 1	Spinel lherzolite	ol, opx, cpx, sp, amph, ap	Porphyroclastic	839	927	858	849
	xen 2	Spinel lherzolite	ol, opx, cpx, sp	Protogranular	937	821	969	
Section 4	xen1	Spinel lherzolite	ol, opx, cpx, sp, amph	Protogranular	957	914	935	863
Section 5	xen1	Wehrlite	ol, cpx, sp, (relict) opx, amph, phl, ilm, ap	Equigranular		904		895
Section 6	xen 1	Spinel lherzolite	ol, opx, cpx, amph, phl	Protogranular	929	905		868
Section 7	xen1	Wehrlite	ol, cpx, sp, (relict) opx	Equigranular		840		817
Section 9	xen 1	Spinel lherzolite	ol, opx, cpx, phl, ap	Porphyroclastic	932	790	912	
	xen 2	Spinel lherzolite	ol, opx, cpx, sp	Protogranular		842		
	xen 3	Wehrlite	ol, cpx, ilm	Equigranular				
Section 10	xen 1	Spinel lherzolite	ol, opx, cpx, sp, amph, ap	Porphyroclastic	775	818	842	
	xen 2	Spinel lherzolite	ol, opx, cpx, sp	Porphyroclastic	940	821	935	
	xen 3	Spinel lherzolite	ol, opx, cpx, amph	Protogranular				800

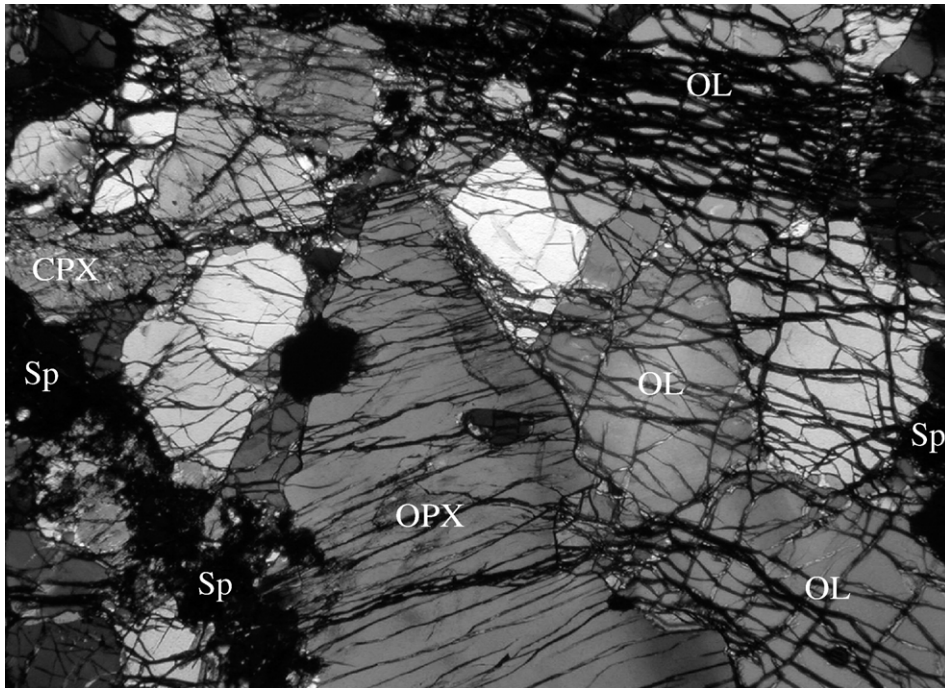


Plate 1. Photomicrograph of spinel lherzolite sample sec3xen1, consisting of olivine (ol), orthopyroxene porphyroclasts (opx), clinopyroxene (cpx) and spinel (sp). Crossed-polar. (field of view 8 mm).

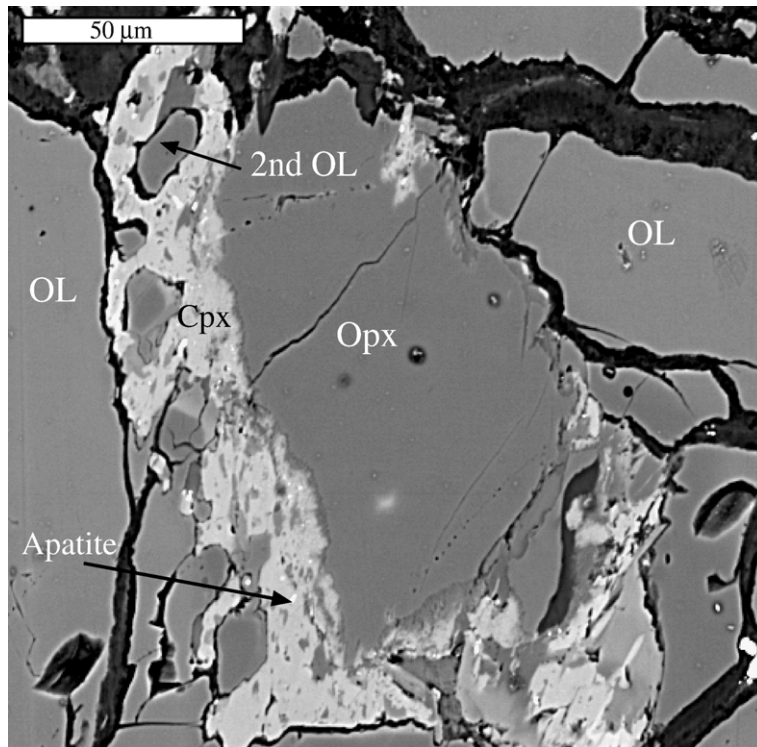


Plate 2. Backscattered electron micrograph of wehrlite sample sec5, showing the development of a clinopyroxene replacement rim at the expenses of orthopyroxene (opx). The clinopyroxene (cpx) is poikilitic with inclusions of secondary olivine (2nd OL), rare apatite and abundant fluid inclusions. Scale bar=50 μm .

were prepared as polished sections (80–100 μm thick) and carefully mapped using the backscattered electron imaging facilities on the electron microprobe, to locate suitable clinopyroxenes and amphiboles prior to LA-ICP-MS analysis. At least three spot analyses were taken for each intended LA-ICP-MS target site and the mean CaO wt.% content of three microprobe analyses was used for internal calibration during LA-ICP-MS analysis. The LA-ICP-MS system used in this study consisted of a CETAC LSX-100 frequency quadrupled Nd:YAG laser (266 nm) coupled to a Surrey Research ICP-MS Instrument, at the NERC ICPMS facility, using the analytical procedure described by Mason et al. (1999). Calcium (^{43}Ca) was determined on all samples and used as the internal calibration to correct for differences in ablation characteristics between samples and standards. The synthetic glass reference material NIST 612 was used as a calibration standard, with the average composition of Pearce et al. (1997) being used in this study. An assessment of accuracy of the LA-ICP-MS system has also been made using a diopside crystal (cpx108 — Beard, unpubl. data), which has previously been analysed by SIMS ion probe at Pavia, Italy (Vannucci, pers. comm.). It shows an excellent agreement with LA-ICP-MS results. Each individual xenolith is referred by the number of the thin section and the

number of the xenolith, e.g. sec1xen2, as some sections contain more than one xenolith.

4. Petrography

A summary of sample lithology and mineral assemblages is given in Table 1. The Kola xenoliths are fine- to medium-grained and are generally mantled by a serpentine alteration rind. They show no interaction with the host kimberlite. Only spinel-facies xenoliths are present; no garnet peridotites were found, unlike in the Arkhangelsk kimberlites (Sablukov et al., 2000). Due to their small volumes, no bulk rock analyses could be obtained and so the least-squares method used to calculate a modal mineralogy could not be employed. A visual estimate of the smaller xenoliths indicated an approximate modal composition of: 65–70% olivine; 15–20% orthopyroxene; 5–8% clinopyroxene; 3–5% spinel; 1–2% amphibole; 1% phlogopite. Thus the majority of the xenoliths are spinel lherzolites using the Streckeisen (1976) classification. However, some of the xenoliths have very low orthopyroxene contents (<5%). Their modal estimates are: 70–75% olivine; 15–20% clinopyroxene; <1–5% orthopyroxene; 3–5% spinel; 1–3% amphibole; 1–2% phlogopite, and therefore they are spinel wehrlites (Streckeisen, 1976). This was

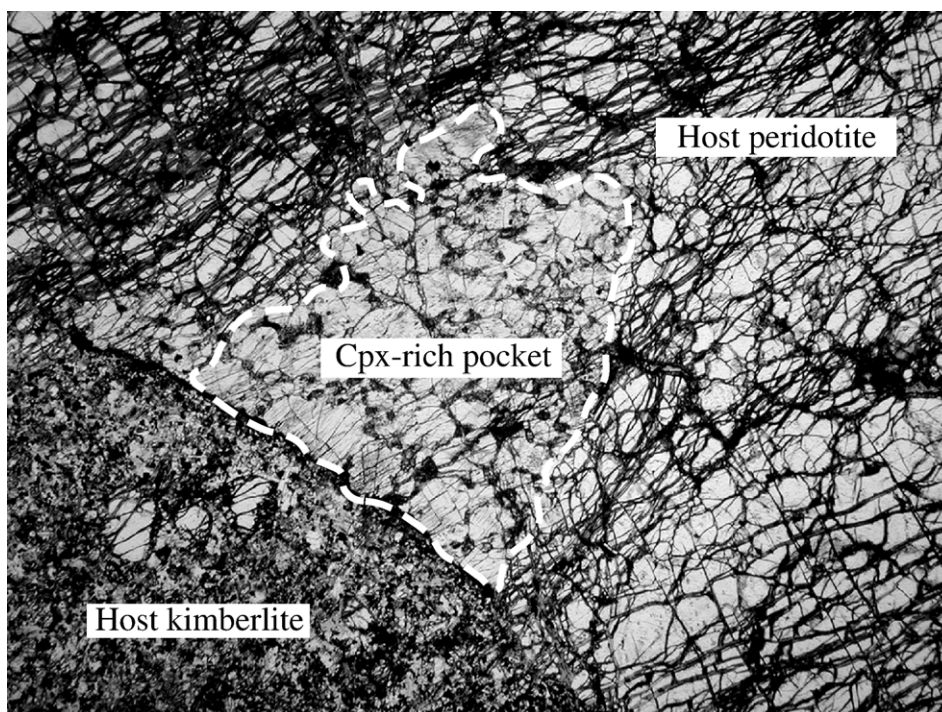


Plate 3. Photomicrograph of cpx-rich pocket (outline in white) in sample sec1xen3, consisting of diopside, Cr-spinel, perovskite, monticellite, pargasite and fluor-apatite. Crossed-polars. (field of view 8 mm).

Table 2

Electron microprobe data for major mineral phases in the Kola peridotite xenoliths

Spinel lherzolites														
Olivine														
	Sec1xen1	Sec1xen1 secondary	Sec1xen2	Sec1xen2 secondary	Sec2xen1	Sec3xen1	Sec3xen2	Sec4xen1	Sec6xen2	Sec9xen1	Sec9xen2	Sec10xen1	Sec10xen2	Sec10xen3
SiO ₂	40.89	40.73	40.70	40.81	41.03	41.03	41.28	40.98	40.75	40.50	40.48	40.27	40.71	40.88
FeO	9.55	6.88	9.03	8.37	9.24	9.51	8.82	9.16	9.22	8.67	8.92	8.97	7.94	8.28
MnO	0.08	0.28	0.15	0	0.11	0.05	0	0.00	0.12	0.12	0.14	0.14	0.12	0.13
MgO	49.05	51.28	49.59	49.67	49.54	48.81	49.58	49.31	49.11	49.74	49.65	50.12	50.26	50.79
CaO	0.00	0	0.00	0.35	0.00	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NiO	0.43	0.23	0.32	0.49	0.39	0.39	0.25	0.46	0.39	0.38	0.36	0.41	0.42	0.37
Total	100.00	99.4	99.79	99.69	100.31	99.78	99.93	99.92	99.58	99.40	99.54	99.91	99.43	100.43
Fo	90	93	91	92	91	90	91	91	90	91	91	91	92	92
Fa	10	7	9	8	9	10	9	9	10	9	9	9	8	8
Wehrlites							Sulphides							
Olivine							Spinel lherzolites				Wehrlites			
	Sec1xen3	Sec1xen3 secondary	Section 5	Sec7xen1	Sec9xen3		Sec1xen1	Sec1xen1		Sec1xen2	Section 5	Section 5		
							1	2		3	1	2		
SiO ₂	39.04	40.96	39.75	40.37	39.48	Fe	30.83	29.11		34.86	61.44	60.89		
FeO	15.93	6.03	15.10	12.94	15.90	Ni	34.97	36.54		30.23	1.08	0.98		
MnO	0.22	0	0.20	0.23	0.22	S	33.47	33.38		34.90	38	37.9		
MgO	44.32	52.59	44.59	46.39	44.01	Total	99.27	99.03		99.99	100.19	99.77		
CaO	0.00	0.31	0.00	0.05	0.00									
NiO	0.30	0	0.37	0.20	0.21									
Total	99.81	99.89	100.01	100.17	99.81									
Fo	83	94	84	86	83									
Fa	17	6	16	14	17									
Spinel lherzolites											Wehrlites			
Spinels											Spinels			
	Sec1xen1	Sec1xen2	Sec2xen1	Sec3xen1	Sec3xen2	Sec4xen1	Sec9xen2	Sec10xen1	Sec10xen2		Section 5	Sec7xen1		
SiO ₂	0.19	0.41	0.18	0.33	0.23	0.15	0.29	0.21	0.32	SiO ₂	0.33	0.34		
TiO ₂	0.02	0.91	0.00	0.15	0	0.00	0.00	0.00	0	TiO ₂	6.67	2.70		
Al ₂ O ₃	57.36	22.87	57.15	44.98	39.5	54.84	56.07	56.96	44.01	Al ₂ O ₃	9.33	8.10		
FeO	10.76	23.00	11.18	15.14	16.64	12.48	12.44	11.75	14.28	FeO	43.81	33.71		
MnO	0.00	0.00	0.00	0.14	0	0.07	0.00	0.00	0.1	MnO	0.31	0.12		
Cr ₂ O ₃	11.49	39.07	11.08	21.12	25.92	12.40	11.66	10.56	22.49	Cr ₂ O ₃	31.27	46.82		
MgO	19.97	13.04	20.25	17.89	16.89	20.05	19.46	19.81	18.16	MgO	8.16	7.74		
Total	99.78	99.29	99.84	99.74	99.18	99.98	99.91	99.27	99.36	Total	99.88	99.52		
mg#	0.77	0.58	0.77	0.78	0.72	0.74	0.75	0.77	0.74	mg#	0.34	0.36		
cr#	0.12	0.53	0.11	0.12	0.24	0.20	0.13	0.11	0.26	cr#	0.69	0.81		

Spinel lherzolites

Clinopyroxenes

	Sec1xen1	Sec1xen2	Sec2xen1	Sec3xen1	Sec3xen2	Sec4xen1	Sec6xen1	Sec9xen1	Sec9xen2	Sec10xen1	Sec10xen2	Sec10xen3
SiO ₂	53.51	52.45	53.40	52.96	52.85	52.66	53.50	53.96	53.98	53.63	53.45	52.3
TiO ₂	0.12	0.31	0.11	0.16	0.00	0.15	0.11	0.28	0	0.00	0	0.36
Al ₂ O ₃	4.37	3.31	4.25	4.71	4.43	4.77	2.09	2.91	4.58	5.16	3.88	2.69
FeO	1.84	3.19	2.15	2.83	2.31	2.60	2.49	2.34	2.43	2.06	2.31	1.83
MnO	0.00	0.11	0.00	0.10	0.00	0.13	0.06	0.00	0	0.00	0	0.05
Cr ₂ O ₃	0.76	0.83	0.80	0.84	0.99	0.91	1.20	0.55	0.76	0.73	1.14	1.91
MgO	15.97	16.40	15.86	15.55	16.56	15.87	17.05	16.26	15.44	14.77	16.13	16.92
CaO	22.40	21.70	22.26	21.40	21.48	21.52	22.18	22.80	22.1	22.54	22.25	22.54
Na ₂ O	1.19	1.18	1.30	1.51	1.13	1.16	0.86	0.78	1.07	1.43	1.33	0.91
Total	100.15	99.49	100.12	100.04	99.73	99.76	99.54	99.88	100.36	100.29	100.49	99.51
Mg#	0.94	0.90	0.93	0.91	0.94	0.92	0.93	0.92	0.92	0.93	0.92	0.94
Cr#	0.10	0.14	0.12	0.11	0.13	0.11	0.25	0.11	0.1	0.09	0.21	0.32
Wo	48.65	46.09	48.40	47.24	46.40	47.05	46.80	48.85	48.6	50.44	49.37	47.41
En	48.24	48.44	47.96	47.74	49.74	48.29	49.49	47.29	47.24	45.98	46.64	49.51
Fs	3.11	5.47	3.65	5.03	3.87	4.66	3.72	3.86	4.16	3.59	3.99	3.08

Spinel lherzolites

Orthopyroxenes

	Sec1xen1	Sec1xen2	Sec2xen1	Sec3xen1	Sec3xen2	Sec4xen1	Sec6xen1	Sec9xen1	Sec9xen2	Sec10xen1	Sec10xen2	Sec10xen3
SiO ₂	55.80	56.26	55.46	55.74	57.46	55.83	56.66	57.63	57.4	56.66	57.66	56.35
TiO ₂	0.00	0.16	0.00	0.00	0	0.00	0	0.00	0	0.00	0	0.06
Al ₂ O ₃	2.96	1.78	3.40	3.06	1.53	2.82	1.71	2.25	2.64	3.74	2.96	2.41
FeO	6.35	6.98	6.17	6.22	5.57	6.08	7.27	5.90	6.1	6.17	5.19	5.62
MnO	0.13	0.03	0.11	0.15	0	0.16	0.17	0.09	0	0.14	0	0.15
Cr ₂ O ₃	0.28	0.32	0.28	0.26	0.27	0.35	0.38	0.26	0.31	0.26	0.33	0.31
MgO	34.14	33.85	33.84	33.58	34.82	34.09	32.86	33.00	32.62	32.28	33.36	35.33
CaO	0.27	0.54	0.33	0.51	0.34	0.35	0.52	0.33	0.45	0.33	0.25	0.24
Na ₂ O	0.12	0.03	0.00	0.05	0	0.09	0.15	0.00	0	0.05	0.1	0
Total	100.05	99.95	99.58	99.55	99.99	99.76	99.72	99.46	99.52	99.62	99.85	100.47
Mg#	0.91	0.89	0.91	0.91	0.93	0.91	0.91	0.91	0.91	0.90	0.92	0.92
Cr#	0.06	0.12	0.05	0.06	0.16	0.08	0.05	0.06	0.07	0.04	0.07	0.08
Wo	0.50	1.01	0.63	0.99	0.63	0.67	0.92	0.64	0.89	0.65	0.49	0.45
En	89.92	88.67	90.01	89.49	91.18	90.08	89.97	90.34	89.7	89.53	91.53	91.2
Fs	9.58	10.32	9.36	9.53	8.18	9.25	9.41	9.02	9.41	9.82	7.98	8.35

(continued on next page)

Table 2 (continued)

Wehrlites					Wehrlites		
Clinopyroxenes					Orthopyroxenes		
	Sec1xen3	Section 5	Sec7xen1	Sec9xen3		Section 5	sec7xen1
SiO ₂	54.06	53.08	54.03	52.98	SiO ₂	57.58	56.47
TiO ₂	0.39	0.57	0.39	0.74	TiO ₂	0.19	0.12
Al ₂ O ₃	1.52	2.33	1.54	3.21	Al ₂ O ₃	0.83	0.51
FeO	3.87	4.36	4	4.57	FeO	8.25	8.46
MnO	0.04	0.14	0	0.00	MnO	0.17	0.19
Cr ₂ O ₃	1.04	1.17	1.45	0.95	Cr ₂ O ₃	0.45	0.32
MgO	16.02	15.52	16.49	14.77	MgO	31.64	33.32
CaO	21.97	21.06	20.81	21.73	CaO	0.52	0.33
Na ₂ O	1.26	1.50	1.18	1.02	Na ₂ O	0.2	0.07
Total	100.16	99.72	99.99	99.95	Total	99.83	99.75
Mg#	0.88	0.87	0.88	0.86	Mg#	0.87	0.87
Cr#	0.31	0.25	0.38	0.17	Cr#	0.27	0.30
Wo	46.45	45.63	48.84	47.40	Wo	1.01	0.62
En	47.11	46.77	44.52	44.83	En	86.12	86.79
Fs	6.44	7.60	6.64	7.78	Fs	12.87	12.59

Mg#=Mg/(Mg+Fe); Cr#=Cr/(Cr+Al).

confirmed by modal analysis of the two largest xenoliths using point-counting (over 1000 points), giving a spinel lherzolite composition of: 69.9% olivine; 17.6% orthopyroxene; 6.5% clinopyroxene; 3.4% spinel; 1.5% amphibole; 1% phlogopite for sample sec2xen1, and a wehrlite composition of: 75% olivine, 16.1% clinopyroxene; 0.7% orthopyroxene, 4.4% spinel; 2.8% amphibole; 1% phlogopite for sample sec5.

The scheme of [Mercier and Nicolas \(1975\)](#) was used to classify the textures of the xenoliths. The relatively unaltered medium-grained spinel lherzolites are transitional between protogranular and porphyroclastic. Olivine and orthopyroxene show undulose extinction with curvilinear grain boundaries, the orthopyroxene porphyroclasts in the larger xenoliths are up to 7–9 mm in diameter and the spinels are holly leaf-shaped ([Plate 1](#)). Clinopyroxenes are usually much smaller with rare, thin exsolution lamellae of orthopyroxene. The spinel wehrlite xenoliths are finer grained and have equigranular textures with rounded spinel typically situated at poorly developed triple junctions. Olivine displays weak undulose extinction with curvilinear grain boundaries. In the wehrlites, clinopyroxene occurs as extensive replacement rims at the expense of orthopyroxene ([Plate 2](#)). The clinopyroxene is poikilitic with numerous inclusions of subhedral olivine, rare apatite and abundant fluid inclusions resulting in a spongy appearance. In the lherzolites, replacement of orthopyroxene by secondary clinopyroxene also occurs but to a lesser extent. The wehrlite xenoliths have also undergone a higher degree of alteration with extensive development of serpentine along numerous cracks and grain boundaries. Sulphides are present as discrete grains between the silicate phases in all of the xenoliths. Modal metasomatism is indicated by the presence of amphibole, phlogopite, fluorapatite and picroilmenite (MgFeTiO_3) occurring as disseminated grains in both types of xenoliths. Amphibole also occurs as thin (10–20 μm) veins in some of the spinel lherzolite xenoliths.

One wehrlite xenolith (sec1xen3) contains a fine-grained pocket (6 mm²) consisting mostly of chromian diopside, with minor ferrichromite, perovskite, pargasite and rare fluorapatite ([Plate 3](#)). With the exception of the abundant chromian diopside, the mineral assemblage of the pocket is similar to that of the host kimberlite but the pocket shows a common boundary with its associated/enclosing wehrlite, indicating that it formed in the mantle prior to entrainment. It is not possible to determine whether this pocket was formed before or after any of the other metasomatic minerals discussed above.

5. The monticellite kimberlite host

The kimberlite host is fine-grained and contains abundant olivine microphenocrysts and rare spinel and olivine xenocrysts ([Beard et al., 1998](#)). The olivine microphenocrysts are partly to completely serpentinised but retain their euhedral habit and are zoned from Mg-rich core to Fe-rich rims, distinguishing them from the unzoned, cracked and partly serpentinised olivine xenocrysts which display undulose extinction. The groundmass is dominated by monticellite and poikilitic phlogopite. Other groundmass phases include abundant primary calcite, Ti-magnetite, chromite, perovskite, olivine and traces of apatite. The kimberlite yielded a K–Ar age of 365 ± 16 Ma ([Beard et al., 1998](#)), indicating that it is part of the 360–380 Ma Kola Alkaline Province ([Kramm et al., 1993](#)).

6. Mineral chemistry

Electron microprobe data for representative major mineral phases are given in [Table 2](#), data for the metasomatic mineral phases are given in [Table 3](#), and data for the mineral phases in the fine-grained cpx-rich pocket are given in [Table 4](#).

6.1. Olivines

Olivines from the spinel lherzolite xenoliths are unzoned and have a compositional range from Fo₉₀ to Fo₉₂. This is identical to the range from the Khibina spinel lherzolite xenoliths ([Arzamastsev and Dahlgren, 1994](#)) and from garnet peridotitic xenoliths from Finnish kimberlites ([Kukkonen and Peltonen, 1999](#); [Peltonen et al., 1999](#)), but is slightly lower than those from the Arkhangelsk kimberlites (Fo₉₂ to Fo₉₃) ([Sablukov et al., 2000](#)). However, the olivines in the Kola spinel lherzolites have a significantly lower Fo content than those reported from the Siberian, Kaapvaal and Greenland cratons ([Boyd et al., 1997](#); [Bernstein et al., 1998](#)). Secondary olivines also occur as small euhedral inclusions in secondary clinopyroxene mantles around orthopyroxene cores. They have higher Fo contents (Fo₉₂ to Fo₉₃) than the primary olivines in the same xenolith. In contrast, olivines from the wehrlite xenoliths have a significantly lower compositional range from Fo₈₃ to Fo₈₆, similar to olivines from phlogopite-bearing wehrlites from Germany ([Lloyd et al., 1991](#); [Zinngrebe and Foley, 1995](#)) and phlogopite-bearing peridotites from Kerguelen, Indian Ocean ([Grégoire et al., 2000](#)). As in the lherzolites, a second generation of olivines in the clinopyroxene mantles

Table 3

Electron microprobe data for the metasomatic mineral phases in the Kola peridotite xenoliths

Spinel lherzolites									Wehrlites			
Amphiboles									Amphiboles			
	Sec1xen1	Sec1xen2 vein	Sec2xen1	Sec3xen1	Sec4xen1	Sec6xen1	Sec10xen1	Sec10xen3		Sec1xen3	Section 5	Sec7xen1
SiO ₂	44.14	43.96	44.40	43.95	42.68	46.00	43.69	44.57	SiO ₂	46.40	44.16	46.63
TiO ₂	0.15	1.24	0.30	0.60	0.28	0.09	0.18	0.28	TiO ₂	1.15	2.45	1.42
Al ₂ O ₃	13.42	11.87	14.61	14.04	15.03	11.02	14.40	12.83	Al ₂ O ₃	8.93	10.86	9.13
FeO	2.97	4.27	3.72	4.11	3.75	3.91	3.68	3.03	FeO	5.65	5.87	5.89
MnO	0.00	0.00	0.00	0.06	0.00	0.08	0.07	0.06	MnO	0.00	0.00	0
Cr ₂ O ₃	1.13	1.65	1.18	1.38	1.09	1.06	1.12	1.48	Cr ₂ O ₃	1.42	1.40	2.1
MgO	19.05	17.86	18.74	17.83	17.71	19.64	18.93	19.49	MgO	18.33	16.99	19.76
CaO	11.65	11.20	11.53	11.12	11.50	10.78	11.58	11.98	CaO	10.95	10.80	9.33
Na ₂ O	3.45	3.41	3.27	3.76	3.55	3.30	3.54	3.64	Na ₂ O	4.18	3.01	3.74
K ₂ O	0.04	1.17	0.00	0.46	0.14	0.70	0.05	0.02	K ₂ O	0.70	1.53	0
Total	95.97	96.62	97.75	97.29	95.74	96.53	97.22	97.38	Total	97.69	97.04	98
Mg#	0.92	0.62	0.90	0.89	0.89	0.90	0.90	0.92	Mg#	0.85	0.84	0.86
Cr#	0.06	0.08	0.05	0.07	0.05	0.07	0.05	0.08	Cr#	0.10	0.09	0.13
Spinel lherzolites									Wehrlites			
Phlogopites									Phlogopites			
	Sec1xen1		Sec1xen2		Sec6xen1		Sec9xen1			Sec1xen3		Section 5
SiO ₂	37.51		38.45		37.01		38.55		SiO ₂	39.16		37.28
TiO ₂	0.96		0.98		0.93		0.16		TiO ₂	2.31		3.94
Al ₂ O ₃	18.00		16.46		19.25		16.64		Al ₂ O ₃	15.85		14.97
FeO	7.70		3.63		4.93		3.69		FeO	4.62		5.63
MnO	0.00		0.00		0		0		MnO	0		0.00
Cr ₂ O ₃	0.30		1.29		0.14		0.86		Cr ₂ O ₃	1.21		1.02
MgO	22.04		23.89		23.8		25.77		MgO	23.13		20.85
CaO	0.21		0.00		0.25		0.38		CaO	0.2		0.00
Na ₂ O	1.85		1.27		1.69		2.54		Na ₂ O	1.04		1.04
K ₂ O	7.68		8.49		7.44		6.11		K ₂ O	9.2		9.38
Total	96.23		94.45		95.44		94.7		Total	96.72		94.09
Mg#	0.84		0.92		0.90		0.92		Mg#	0.90		0.87
Cr#	0.01		0.05		0.01		0.03		Cr#	0.05		0.05
Oxides									Apatite			
	Sec10xen1c		Section 5		Section 5		Section 5			Sec1xen1		Sec3xen1
			1		2		Ti–mag rim					
SiO ₂	0.41		0.22		0.21		0.37		SiO ₂	0.55		0.2
TiO ₂	56.33		50.17		49.57		21.93		TiO ₂	0		0
Al ₂ O ₃	0.1		0.2		0.61		1.78		Al ₂ O ₃	0.11		0
FeO	25.12		39.92		35.07		59.4		FeO	0.4		0.23
MnO	0.38		0.12		0		0.19		MnO	0		0
Cr ₂ O ₃	0.51		0.42		3.76		6.65		Cr ₂ O ₃	0		0
MgO	16.26		8.38		9.94		7.7		MgO	0.56		0.57
CaO	0		0		0		0		CaO	54.06		52.28
Total	99.11		99.43		99.16		98.02		Na ₂ O	0		0.71
									P ₂ O ₅	42.44		43.09
									Cl	0.53		0.5
									Total	98.65		97.58

around relict orthopyroxene cores have significantly higher Fo contents (Fo₉₄) than the primary olivines in the same xenolith.

On a diagram showing Fo in olivine versus modal olivine content (Fig. 2), the spinel lherzolite plots on the “oceanic trend” in the Phanerozoic mantle field of

Table 4

Electron microprobe data for the mineral phases in the cpx-rich pocket

	Cpx	Cpx	Amph	Amph	Ferrichromite	Perovskite	Apatite
	1	2	1	2	1	1	1
SiO ₂	53.57	53.84	45.58	45.77	0.39	0.42	0.51
TiO ₂	0.26	0.38	1.15	0.91	5.3	57.8	0
Al ₂ O ₃	1.29	1.16	9.08	9.46	2.23	0.29	0
FeO	3.79	3.84	6.04	5.65	70.19	1.01	0.36
MnO	0.15	0.1	0	0	0.35	0	0
Cr ₂ O ₃	1.04	1.01	1.45	1.7	12.38	0.3	0
MgO	16.38	16.56	18.62	18.67	5.4	0.29	0.82
CaO	21.73	21.93	10.68	10.99	0.73	38.85	51.84
Na ₂ O	1.11	1.09	3.36	3.24	0	0.44	0.4
K ₂ O	0	0	0.8	0.94	0	0	0
P ₂ O ₅	0	0	0	0	0	0	39.75
SrO	0	0	0	0	0	0.33	0.1
Nb ₂ O ₅	0	0	0	0	0	0.3	0
Total	99.32	99.91	96.76	97.33	96.97	100.03	93.78
Mg#	0.89	0.88	0.84	0.85	0.26		
Cr#	0.35	0.37	0.09	0.1	0.79		
Wo	45.66	45.65					
En	47.88	47.96					
Fs	6.46	6.39					

Boyd (1989), close to the composition of a spinel lherzolite xenolith from Khibina (Arzamastsev, 1994). As only one Kola lherzolite xenolith was large enough to determine an accurate modal composition, an “error box” using the ranges of visually estimated

modal proportions and analysed olivine compositions in the spinel lherzolite xenoliths is also plotted. This suggests that the sub-Kola mantle is similar to Phanerozoic lithospheric mantle despite the fact that it underlies Archaean–Proterozoic crust. Garnet peridotites from the Finnish kimberlites (Peltonen et al., 1999) also plot within the Proterozoic mantle field and close to the “oceanic trend”. Interestingly, spinel lherzolite xenoliths from the Kaapvaal craton, South Africa (Grégoire et al., 2005) plot along the “oceanic trend”. While spinel harzburgites from Greenland (Bernstein et al., 1998) have significantly higher modal olivine and mostly plot outside the Archaean mantle field. The wehrlite xenoliths cannot be plotted on the same diagram due to the low Fo content in their olivine.

6.2. Spinel

Spinel from the Kola peridotite xenoliths range from aluminous spinels in the lherzolites to Ti-rich ferrichromites in the wehrlites (Table 2). Those from the majority of the lherzolites have a high Al₂O₃ content (40–58 wt.%), Mg# (0.72–0.80), and low TiO₂ (<0.15 wt.%) and Cr# (0.11–0.26), typical for spinels from spinel peridotites in alkali basalts (Arai, 1994) and similar to those in the Khibina spinel lherzolite (Arzamastsev and Dahlgren, 1994) and Arkhangelsk peridotites (Sablukov et al., 2000; Beard, unpubl. data). The exception is to this is

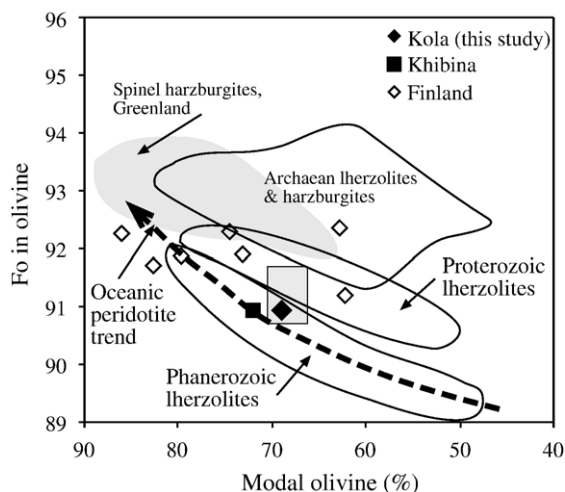


Fig. 2. Modal olivine (%) versus Fo in olivine for the Kola spinel lherzolite compared with fields for mantle-derived xenoliths from Archaean, Proterozoic and Phanerozoic terrains (fields modified after Boyd et al., 1993, 1997), garnet peridotites, Finland (Kukkonen and Peltonen, 1999), spinel harzburgite, Greenland (Bernstein et al., 1998) and spinel lherzolite, Khibina (Arzamastsev, 1994). An “error box” using the ranges of visually estimated modal proportions and olivine compositions in the Kola spinel lherzolite xenoliths is also plotted.

sample sec1xen2 (Table 2) with spinels with a variable and significantly lower Al_2O_3 content (23 wt.%), low Mg# (0.58), higher TiO_2 content (0.91 wt.%) and Cr# (0.53). On a diagram of Fo in olivine versus Cr# in spinel (Fig. 3), coexisting olivine–spinel pairs in the spinel lherzolites plot in the “olivine–spinel mantle array (OSMA)” as defined by Arai (1994). As the spinels coexist with aluminous orthopyroxenes, these xenoliths are typical spinel-facies peridotites (Haggerty, 1995; McDonough and Rudnick, 1998). Olivine–spinel pairs from Khibina and Arkhangelsk peridotite (Arzamastsev and Dahlgren, 1994; Sablukov et al., 2000) plot within the same field as those for the Kola peridotites (Fig. 3). The Ti-rich ferrichromites from the wehrlites have a significantly lower Al_2O_3 content (8–9 wt.%) and Mg# (0.34–0.36), but a much higher TiO_2 (2.7–6.7 wt.%), FeO (34–44 wt.%) and Cr# (0.69–0.81), similar to Ti-rich ferrichromites from phlogopite-bearing wehrlites from Germany (Lloyd et al., 1991)

and metasomatised peridotites from northern Tanzania (Rudnick et al., 1993). The ferrichromites in the cpx-rich pocket in sample sec1xen3 have slightly higher Cr# (0.79) and lower Al_2O_3 content (2.2 wt.%). On a diagram of Fo in olivine versus Cr# in spinel, olivine–spinel pairs in the wehrlites plot to the right of the OSMA (Fig. 3), suggesting that the wehrlites may represent cumulates as defined by Arai (1994). However, Fe and Ti enrichment as a result of upper mantle metasomatism would also effectively shift spinel compositions to the right of the OSMA (Haggerty, 1995).

6.3. Orthopyroxene

All orthopyroxenes from the Kola peridotite xenoliths are enstatites. Those from the spinel lherzolite xenoliths have a Mg# range from 0.89 to 0.93 and variable Al_2O_3 content (1.5–3.7 wt.%), similar to those from the Khibina spinel lherzolite xenolith (Arzamastsev and Dahlgren, 1994). In the wehrlite xenoliths, orthopyroxenes are rare, only occurring as ‘relict’ cores, and have a slightly lower Mg# (0.86–0.88) and a significantly lower Al_2O_3 content (0.4–0.7 wt.%). Orthopyroxenes from the Kola wehrlites have a slighter lower Mg# (Fig. 4) than those from those in garnet peridotite xenoliths from the Finnish (Peltonen et al., 1999) and Arkhangelsk kimberlites (Sablukov et al., 2000).

6.4. Clinopyroxene

Primary clinopyroxenes from the spinel lherzolite xenoliths are all chromian diopsides (Table 2), with a Mg# from 0.9 to 0.94, variable Al_2O_3 (2–5.2 wt.%) and low TiO_2 contents (<0.36 wt.%), similar to those from peridotite xenoliths from Arkhangelsk (Sablukov et al., 2000) and Khibina (Arzamastsev and Dahlgren, 1994). Secondary clinopyroxenes occurring as mantles around orthopyroxene cores are augites with higher MgO and significantly lower Al_2O_3 contents compared with the primary clinopyroxenes in the same xenolith, reflecting the original mineral chemistry of the host orthopyroxene. Clinopyroxenes from the wehrlites have a lower Mg# (0.86–0.88), and higher Na_2O (1–1.5 wt.%) and TiO_2 (0.4–0.74 wt.%) contents. Chromian diopsides in the cpx-rich pocket in sample sec1xen3 have a composition intermediate between to those in the wehrlites and the spinel lherzolites. Fig. 4 shows the significant difference in composition between these clinopyroxenes.

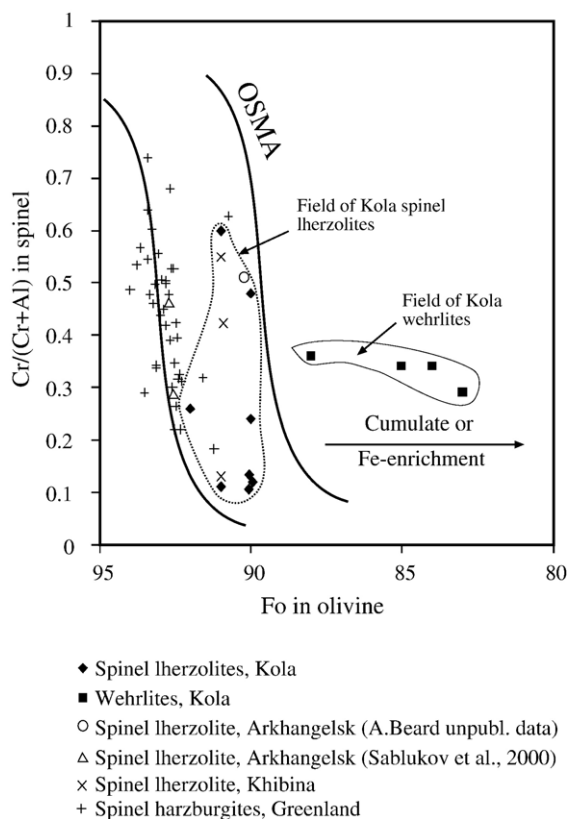


Fig. 3. Fo in olivine versus Cr/(Cr+Al) in spinel, showing the compositional variation in the spinel lherzolites and wehrlites compared to Khibina spinel lherzolite (Arzamastsev and Dahlgren, 1994), Arkhangelsk peridotites (Sablukov et al., 2000; A. Beard, unpubl. data) and Greenland spinel harzburgites (Bernstein et al., 1998). OSMA=olivine–spinel mantle array (Arai, 1994).

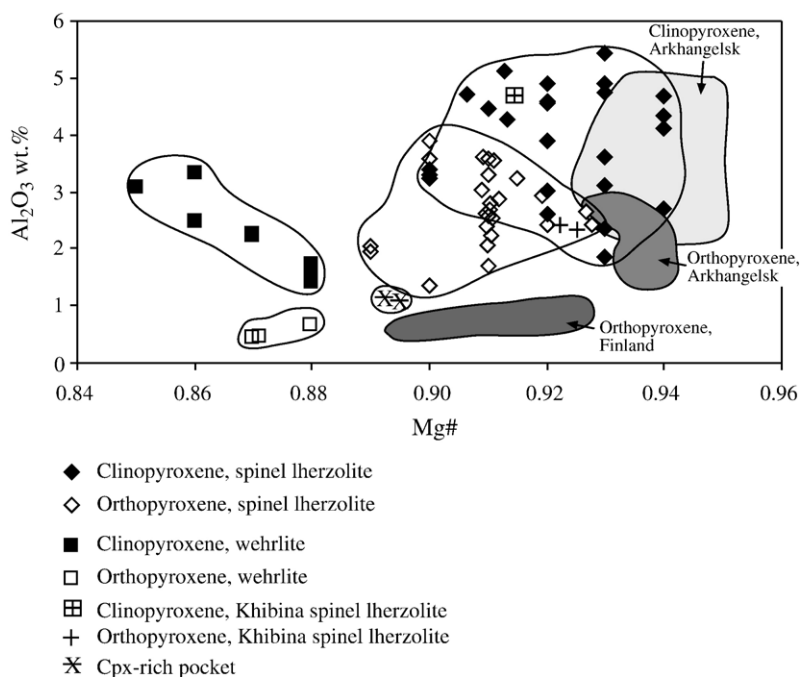


Fig. 4. Al_2O_3 wt.% versus Mg# in the pyroxenes, showing the compositional variation in the Kola spinel lherzolite and wehrlite xenoliths compared with pyroxenes from the Khibina spinel lherzolite (Arzamastsev and Dahlgren, 1994) and Arkhangelsk peridotites (Sablukov et al., 2000).

6.5. Amphibole

Disseminated amphibole within the spinel lherzolites ranges from pargasitic hornblende to pargasite with low TiO_2 (<1.2 wt.%) and FeO (3–4.3 wt.%) contents and high Mg#s (0.89–0.92) (Table 3). They closely resemble amphibole from peridotite xenoliths from Arkhangelsk (Sablukov et al., 2000) and Khibina (Arzamastsev and Dahlgren, 1994). However, those from the wehrlite xenoliths are magnesio-hastingsites with significantly higher amounts of TiO_2 (1.2–2.5 wt.%), FeO (ca 6.0 wt.%) and lower Mg#s (0.84–0.86). Amphibole veins in the spinel lherzolites are also magnesio-hastingsites, similar to the disseminated amphiboles in the wehrlite xenoliths, as are the amphiboles in the cpx-rich pocket. The significant difference in composition between these amphiboles is illustrated in Fig. 5.

6.6. Phlogopite

Phlogopites in the Kola peridotite xenoliths have high Mg#s (0.84–0.92). Those in the spinel lherzolites are aluminous (ca. 16–19 wt.% Al_2O_3) with low TiO_2 (0.1–0.9 wt.%), similar in composition to groundmass phlogopite in the host kimberlite. However, phlogopites in the wehrlite xenoliths have slightly lower Al_2O_3 (ca. 15 wt.%) and significantly higher TiO_2 (2.3–4 wt.%)

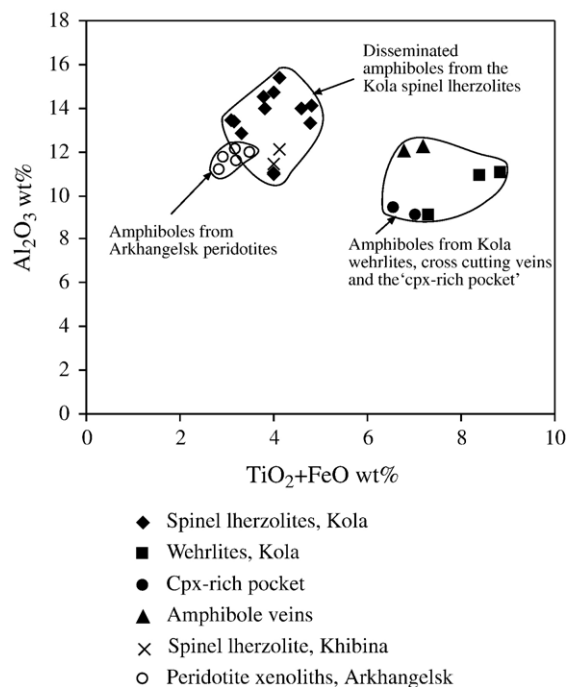


Fig. 5. Al_2O_3 wt.% versus $\text{TiO}_2 + \text{FeO}$ wt.% in amphibole, showing the compositional variation in the Kola spinel lherzolite and wehrlite xenoliths, in the cpx-rich pocket and in cross-cutting veins, compared with amphiboles from the Khibina spinel lherzolite (Arzamastsev and Dahlgren, 1994) and Arkhangelsk peridotites (Sablukov et al., 2000).

contents. Phlogopite also occurs in peridotite xenoliths from other localities in the Baltic Shield. Those in the Arkhangelsk xenoliths (Sablukov et al., 2000) have a low TiO_2 content similar to those in the Kola spinel lherzolites.

6.7. Ilmenite

Magnesian ilmenite (picroilmenite) occurs as small subhedral grains in the wehrlite xenoliths, with MgO and Cr_2O_3 contents of 8–16 and 0.5–3.7 wt.%, respectively (Table 3). They are very similar in composition to magnesian ilmenites in peridotite xenoliths from Arkhangelsk (Sablukov et al., 2000). They are a metasomatic variety closely resembling those from phlogopite-bearing peridotite xenoliths from Botswana (Stiefenhofer et al., 1997).

6.8. Apatite

Apatite is usually associated with secondary clinopyroxene, occurring as very small dark brown grains in the lherzolite and wehrlite xenoliths and in the cpx-rich pocket (Table 4). It has low MgO (ca. 0.5 wt.%), FeO (0.2–0.4 wt.%) and SiO_2 (0.2–0.55 wt.%) and moderate Cl contents (ca. 0.5 wt.%). The low microprobe totals indicate a possible high volatile (F, OH, CO_2) content. The apatites have a similar composition to apatite in spinel peridotites from Sikhote–Alin, Russia (Ionov et al., 1997) and western Victoria, Australia (O'Reilly and Griffin, 2000). Even though there are no other reported occurrences of apatite-bearing peridotite xenoliths in the Baltic Shield, the presence of anomalously P-enriched kimberlites on the White Sea coast (Beard et al., 1998) suggests that apatite is probably widespread in the lithospheric mantle beneath the Kola Peninsula.

6.9. Pyrrhotite (Fe_7S_8) and pentlandite ($\text{Fe,Ni}_9\text{S}_8$)

In the spinel lherzolite xenoliths, intergrowths of pentlandite–magnetite and pentlandite–pyrrhotite occur as small, moderately abundant disseminated grains; however, in the wehrlite xenoliths only very rare pyrrhotite occurs. The pentlandites have a high Ni content (30–37 wt.%) and have a similar composition to pentlandite in spinel lherzolite xenoliths from South Africa (Bishop et al., 1975).

6.10. Interpretation of mineral chemistry

The major primary mineral phases in the spinel lherzolite xenoliths fall within the compositional range

for spinel peridotites from sub-continental lithospheric mantle. The exception to this is sample sec1xen2 with spinels with higher Cr contents, more akin to a harzburgitic paragenesis. Positive correlations between the Al_2O_3 in coexisting spinel and orthopyroxene (Fig. 6a), and in coexisting clinopyroxene and orthopyroxene (Fig. 6b) indicate equilibrium between these phases. Depletion of Al_2O_3 in coexisting spinel and orthopyroxene, and in coexisting clinopyroxenes and orthopyroxenes, is also indicative of partial melt extraction. The wehrlite xenoliths have an unusual mineralogical association, with Fe-rich olivine (Fo_{83-87}) and Ti-ferrichromites more akin to cumulates, co-existing with very low Al_2O_3 orthopyroxene cores usually associated with a more refractory harzburgitic paragenesis. The presence of amphibole, phlogopite, magnesian ilmenite and apatite in the Kola peridotite xenoliths indicates that the lithosphere has undergone modal

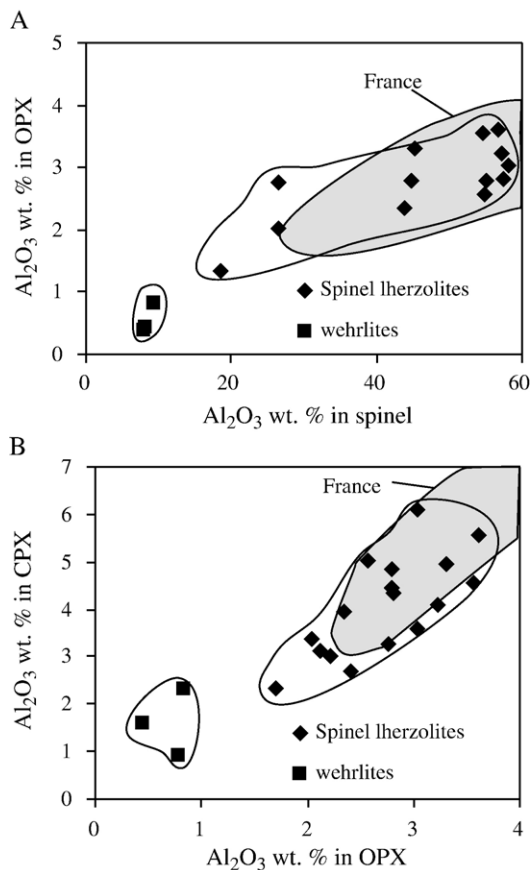


Fig. 6. (A) Al_2O_3 wt.% in spinel versus Al_2O_3 wt.% in orthopyroxene; (B) Al_2O_3 wt.% in orthopyroxene versus Al_2O_3 wt.% in clinopyroxene, showing the compositional variation in the Kola spinel lherzolites and wehrlites. Compositional field for spinel lherzolites, France (Zangana et al., 1999) shown for comparison.

metasomatism. The metasomatic amphibole and phlogopite in the wehrlites have significantly higher TiO_2 contents than amphibole and phlogopite in the spinel lherzolites (Table 3), suggesting more than one metasomatic events.

7. Temperature calculations

Equilibration temperatures (Table 1) for the spinel lherzolite xenoliths have been calculated using the two-pyroxene geothermometers of Wells (1977) (T_{Wells}) and Brey and Köhler (1990) (T_{BKN}), the Ca-in-orthopyroxene geothermometer of Brey and Köhler (1990) ($T_{\text{Ca-opx}}$) and the Ca/Al-in-orthopyroxene geothermometer of Witt-Eickschen and Seck (1991) ($T_{\text{Witt-Seck}}$). In the case of the two-pyroxene geothermometers of Wells (1977) (T_{Wells}) and Brey and Köhler (1990) (T_{BKN}) only clinopyroxene and orthopyroxene that appear to be equilibrium were used. The geothermometers all yielded similar temperature ranges for the spinel lherzolites: $T_{\text{Wells}} = 842\text{--}969\text{ }^\circ\text{C}$; $T_{\text{BKN}} = 775\text{--}957\text{ }^\circ\text{C}$; $T_{\text{Ca-opx}} = 790\text{--}927\text{ }^\circ\text{C}$ and $T_{\text{Witt-Seck}} = 795\text{--}868\text{ }^\circ\text{C}$. Similar temperature

ranges were obtained from the Khibina spinel lherzolite xenolith (Arzamastsev and Dahlgren, 1994) and from spinel lherzolite xenoliths from South Africa (Grégoire et al., 2005).

Due to the secondary nature of the clinopyroxenes in the wehrlites, only the Ca-in-orthopyroxene and Al-in-opx geothermometers were used (Table 1). Because of the rarity of relict orthopyroxene, temperatures could be obtained from only two wehrlites ($T_{\text{Ca-opx}} = 840\text{--}904\text{ }^\circ\text{C}$ and ($T_{\text{Witt-Seck}} = 817\text{--}895\text{ }^\circ\text{C}$). Pressures were not determined; however, spinel-facies peridotites indicate intermediate pressures (10–15 kb at $900\text{ }^\circ\text{C}$). The crust beneath the Kola Peninsula is 40–45 km thick (Ansorge et al., 1992) while the lithosphere thickness has been estimated at $>250\text{ km}$ (Artemieva, 2003).

8. LA-ICP-MS results

LA-ICP-MS data for in situ clinopyroxenes and amphiboles from the spinel lherzolites and wehrlites are given in Table 5. Trace element abundances in

Table 5

LA-ICP-MS analysis of clinopyroxenes and amphiboles from spinel lherzolite and wehrlite xenoliths (in ppm) (data obtained at NERC ICPMS facility)

	Clinopyroxenes from spinel lherzolites			Clinopyroxenes from wehrlite xenoliths		Clinopyroxenes from cpx-rich pocket			Amphiboles	
	Section 2	Section 3	Section 4	Section 5	Section 7	Section 1	Section 1	Section 1	Section 5	Sec3xen1
	Xen 2	Xen 1	xen 1		xen1	xen 3 cpx A	xen 3 cpx C	xen 3 cpx D	Wehrlite	Sp-lher
	n=8	n=8	n=4	n=12	n=6	n=4	n=4	n=4	n=3	n=3
Ni	N.A.	N.A.	N.A.	137.63	N.A.	N.A.	N.A.	N.A.	301.02	N.A.
Rb	0.15	0.13	0.31	0.09	0.32	1.06	0.04	0.25	4.03	5.18
Sr	361.96	246.70	290.27	130.12	107.34	198.38	103.15	106.02	231.02	398.44
Y	7.01	8.67	8.62	3.98	3.07	5.33	4.87	3.91	4.62	10.82
Zr	18.95	20.45	27.15	49.43	37.27	71.69	52.41	67.08	74.06	31.35
Nb	0.99	0.60	0.47	0.48	0.51	1.43	0.40	0.39	27.83	31.22
La	18.48	18.33	17.92	2.00	1.73	4.29	3.43	2.39	2.87	19.84
Ce	36.63	38.43	41.04	8.47	7.32	13.91	11.98	8.81	10.56	36.98
Pr	N.A.	N.A.	N.A.	N.A.	1.45	N.A.	N.A.	N.A.	N.A.	N.A.
Nd	11.83	12.53	14.36	7.80	8.19	10.29	9.05	7.18	9.38	14.82
Sm	1.43	1.59	1.78	1.89	2.41	2.23	2.07	1.61	2.16	2.11
Eu	0.41	0.47	0.54	0.58	0.61	0.71	0.63	0.47	0.57	0.56
Gd	1.02	1.10	1.40	1.38	1.43	1.58	1.53	1.12	1.67	1.63
Tb	0.17	0.20	0.25	0.20	0.18	0.24	0.22	0.17	0.26	0.26
Dy	0.99	1.10	1.29	0.93	1.01	1.21	1.13	0.83	1.07	1.51
Ho	N.A.	N.A.	N.A.	N.A.	0.16	N.A.	N.A.	N.A.	N.A.	N.A.
Er	0.70	0.85	0.72	0.36	0.52	0.43	0.46	0.29	0.41	1.21
Yb	0.66	0.84	0.90	0.25	0.42	0.33	0.29	0.21	0.25	1.15
Ta	N.A.	N.A.	N.A.	N.A.	0.16	N.A.	N.A.	N.A.	N.A.	N.A.
Th	1.95	1.61	1.28	0.04	0.16	0.27	0.30	0.16	0.02	1.45
U	0.34	0.30	0.20	0.01	0.15	0.06	0.06	0.03	0.01	0.24
La/Yb	18.54	14.83	13.27	5.51	2.74	8.78	7.89	7.60	7.65	11.50
La/Nd	1.56	1.47	1.25	0.26	0.21	0.80	0.72	0.63	0.58	2.56

clinopyroxenes from the spinel lherzolites, when normalised to primitive mantle (Fig. 7a), show enrichment in the incompatible elements with strong negative anomalies in Rb, Nb and Ti. The patterns are remarkably similar to those from clinopyroxenes from spinel lherzolite xenoliths from Ray Pic, France (Zangana et al., 1999) and from Gobernador Gregores, Argentina (Rivalenti et al., 2004). They are strongly LREE-enriched ($La_n/Yb_n=13–18$), having a steep LREE but a flat MREE–HREE pattern (Fig. 8a).

In contrast, clinopyroxenes from the wehrlite xenoliths have significantly lower incompatible trace element abundances than those in the lherzolites, producing a smooth ‘humped’ pattern with strong depletions in the most incompatible elements (Rb and Th) and the least incompatible elements (Y and HREE), and negative anomalies in Nb and Ti (Fig. 7b). The ‘humped’ trace element pattern is very similar to that of diopsides from a wehrlite from Mt. Vulture, Italy (Downes et al., 2002). Clinopyroxenes in the wehrlites are slightly depleted in La and Ce

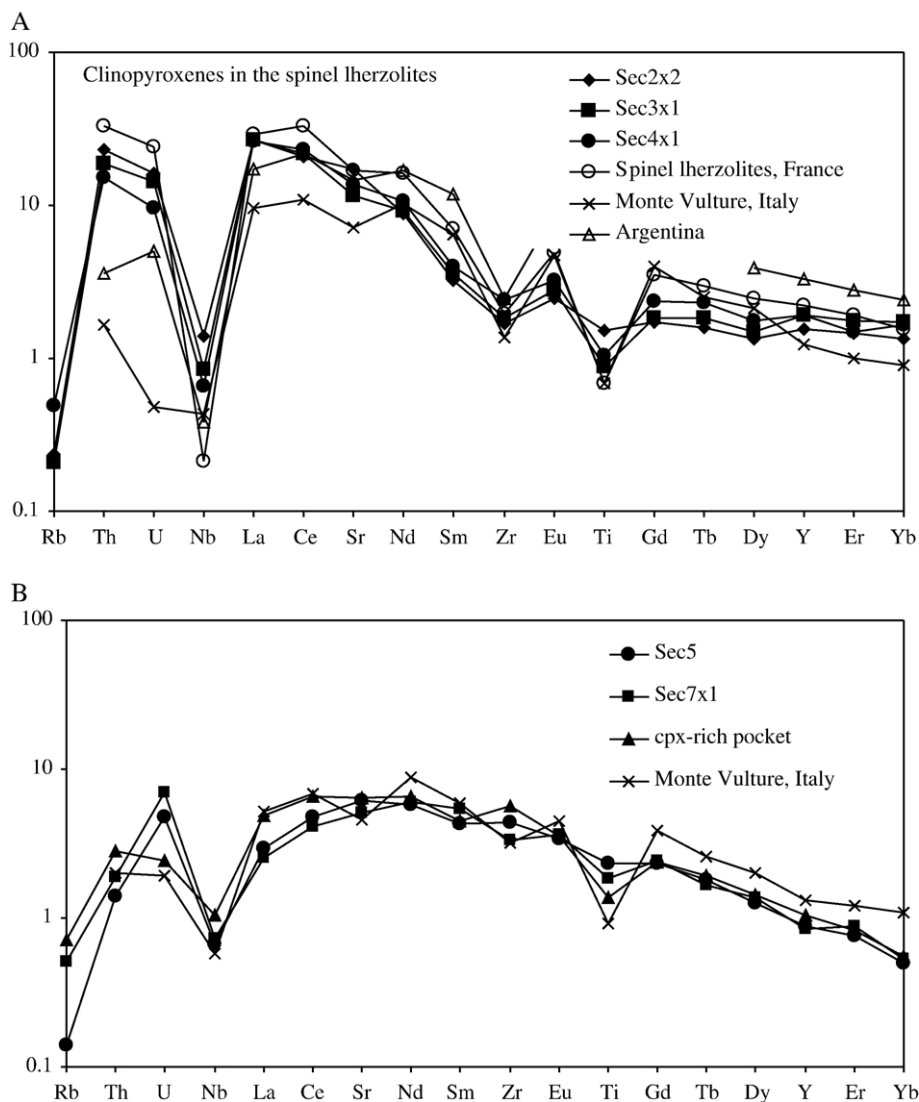


Fig. 7. Mantle-normalised trace element abundances in clinopyroxene from (A) the Kola spinel lherzolite xenoliths compared with clinopyroxenes from spinel lherzolite, France (Zangana et al., 1999), from Gobernador Gregores, Argentina (Rivalenti et al., 2004) and from Mt. Vulture, Italy (Downes et al., 2002); (B) the Kola wehrlite xenolith and the clinopyroxene-rich pocket compared with clinopyroxene from Mt. Vulture, Italy (Downes et al., 2002). Data normalised to primitive mantle (Sun and McDonough, 1989).

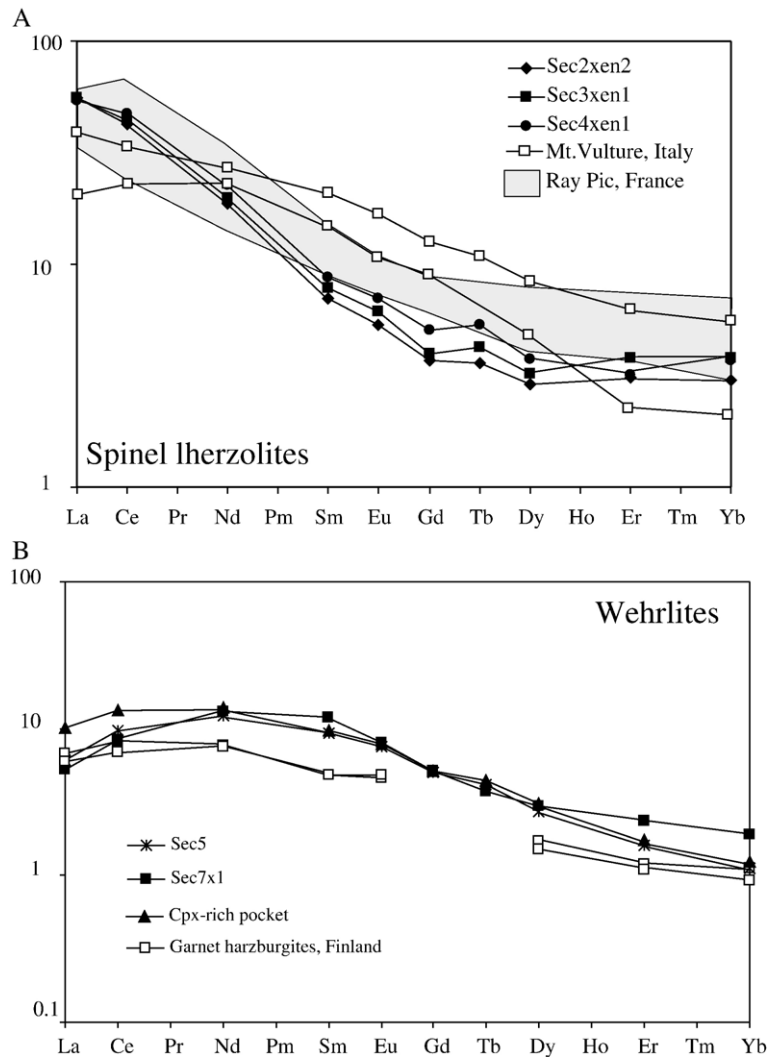


Fig. 8. Chondrite-normalised REE abundances in clinopyroxene from (A) the Kola spinel lherzolite xenoliths compared with clinopyroxenes REE compositional range (shaded area) in spinel lherzolite xenoliths from France (Vannucci et al., 1994; Zangana et al., 1999) and Mt. Vulture, Italy (Downes et al., 2002); (B) the Kola wehrlite xenoliths and the cpx-rich pocket compared with clinopyroxenes in garnet peridotitic xenoliths from the Finnish kimberlites (Peltonen et al., 1999). Normalisation coefficients from Nakamura (1974).

($La_n/Yb_n=3-5$) relative to Nd ($La_n/Nd_n<1$) and have low HREE abundances, with Yb below chondritic levels. The REE patterns are similar to those in garnet peridotitic xenoliths from the Finnish kimberlites considered to represent high-pressure cumulates (Peltonen et al., 1999) (Fig. 8b).

Clinopyroxenes from the spinel lherzolite xenoliths have Yb contents near chondritic levels while the wehrlites have Yb contents below chondritic levels. Overall, the Kola samples have slightly lower HREE abundances (Fig. 7c) than those in clinopyroxenes from spinel lherzolites in Phanerozoic regions (e.g. Vannucci et al., 1994; Zangana et al., 1999).

Clinopyroxenes with similar HREE contents near/below chondritic levels (Fig. 8b) have been reported from wehrlite xenoliths from Mt. Vulture, Italy (Downes et al., 2002) and from Gobernador Gregores, Argentina (Rivalenti et al., 2004). The negative anomalies in Rb and Nb have been previously reported in other mantle clinopyroxenes and are a common feature (Ionov and Hofmann, 1995), which is due to the exclusion of these elements from the crystal structure of clinopyroxene.

The cpx-rich pocket in sample sec1xen3 contains clinopyroxenes that also have a “humped” incompatible trace element pattern, similar to those from the

wehrlites but slightly more enriched in Rb and Th (Fig. 7b) with a less pronounced Nb anomaly. They have LREE-enrichment intermediate between those in clinopyroxenes from lherzolites and wehrlites ($La_n/Yb_n=8-9$) and are less depleted in La and Ce relative to Nd ($La_n/Nd_n=0.63-0.8$) with HREE contents below chondritic levels.

Mantle-normalised abundances in disseminated amphibole from the Kola lherzolites (Table 5; Fig. 9) show a moderate enrichment in incompatible trace elements and LREE ($La_n/Yb_n=8-11$) with a flat HREE pattern. The patterns are similar to those of disseminated amphiboles from spinel lherzolites from Siberia (Ionov et al., 1997) (Fig. 9). Amphiboles from a wehrlite xenolith have an overall lower incompatible trace content with strong negative anomalies for Th and U, a LREE-enrichment displaying a marked La and Ce depletion relative to Nd ($La_n/Nd_n=0.58$) and very low HREE abundances with Yb contents near chondritic levels (Fig. 9). The significant depletion in Th and U suggests that these elements were partitioned into apatite. The low HREE abundances may indicate that either the amphibole is replacing an original orthopyroxene in the wehrlites and/or the metasomatic melt/fluid was low in HREEs. The trace element abundances in the wehrlite amphiboles closely resemble vein amphiboles from a spinel lherzolite from Siberia (Ionov et al., 1997) (Fig. 9). Trace element patterns for amphibole from both types of xenoliths display positive Nb anomalies, a feature

reported from other mantle amphiboles (Ionov and Hofmann, 1995).

9. Discussion

9.1. Nature of the Kola lithosphere

The olivine modal estimates and their Fo contents in the spinel lherzolite reveal that the underlying lithosphere beneath the Archaean–Proterozoic crust of Kola has some similarities to that of Phanerozoic lithospheric mantle (Fig. 2). Studies on a suite of garnet peridotite xenoliths from Finland (Peltonen et al., 1999), which also plot close to the “oceanic trend” on Fig. 2, yielded Sr and Nd isotopic signatures similar to off-craton peridotites. Peltonen et al. (1999) proposed that the Finnish peridotites could either represent oceanic lithosphere tectonically subducted beneath the Archaean–Proterozoic crust of Eastern Finland or represent younger asthenosphere underplated to the base of the lithosphere.

9.2. Depletion of the sub-continental lithosphere of the Kola Peninsula

The high Mg# and low Al_2O_3 content of the primary mineral phases in the Kola spinel lherzolites record a depletion event related to removal of a partial melt. To estimate the amount of partial melting, the concentrations of incompatible elements in the clinopyroxenes were modelled for both batch and fractional melting of a

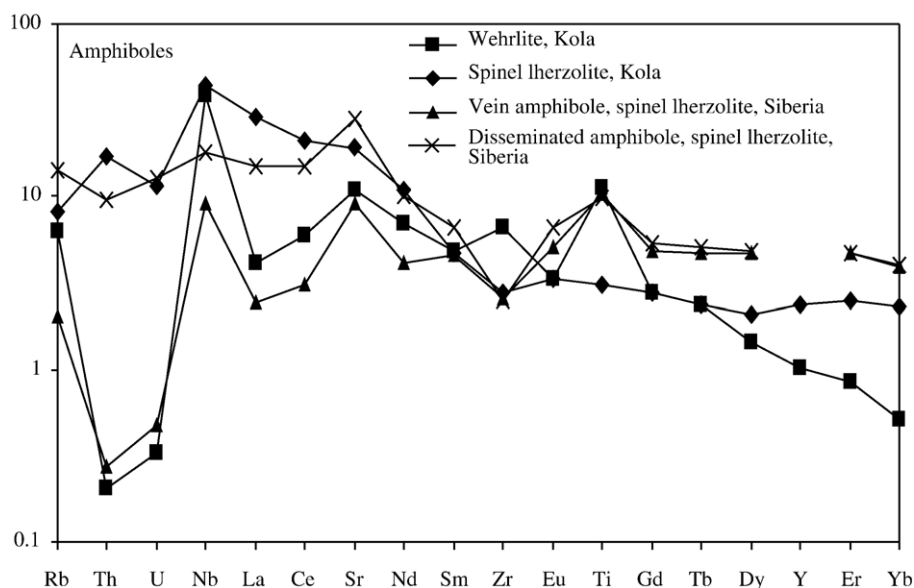


Fig. 9. Mantle-normalised trace element abundances in amphibole from the Kola spinel lherzolite and wehrlite xenoliths compared with disseminated and vein amphiboles from spinel lherzolite, Siberia (Ionov and Hofmann, 1995). Data normalised to primitive mantle (Sun and McDonough, 1989).

primitive mantle source. The batch and fractional melting equations of Norman (1998) were used. Both models assume that clinopyroxene is the only phase contributing to the bulk distribution coefficient in the residual solid. Results of this modelling suggest that the Y and Yb concentrations in clinopyroxenes from the Kola spinel lherzolites clearly follow melting trends. Fig. 10 shows that 7–8% fractional melting of a primitive source is required to produce the observed concentrations. The batch melting model (Fig. 10) yielded higher degrees of partial melting (15–25%) which are considered to be unrealistic. Y and Yb concentrations in clinopyroxenes in spinel lherzolite xenoliths from China (Chen et al., 2001), Arkhangelsk (Beard, unpubl. data), Mt. Vulture, Italy (Downes et al., 2002) and South Africa (Zhang et al., 2001) are also plotted on Fig. 10 for comparison. The degree of

melting required in the Kola spinel lherzolites xenoliths is significantly lower than those from harzburgite xenoliths from the Kaapvaal craton, South Africa.

The low HREE concentrations in the clinopyroxenes (Table 5) result in moderate estimates of partial melting and reveal a depleted lithosphere beneath the Kola Peninsula. The age of mantle depletion cannot be determined. However, the moderate volume of partial melts extracted could be related to the formation of basaltic magmas (metamorphosed to garnet granulites and eclogitic granulites) underplating the lower crust of the Baltic Shield (Kempton et al., 1995).

9.3. Nature of the metasomatism in the Kola lithosphere

The presence of phlogopite, amphibole, ilmenite and apatite in the Kola peridotites clearly record

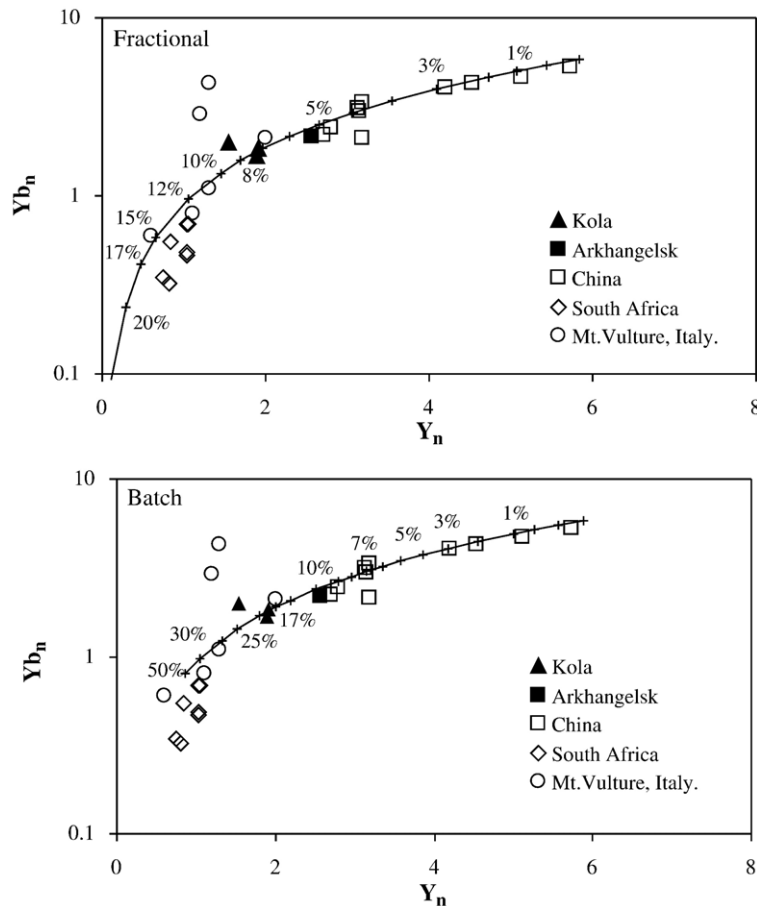


Fig. 10. A comparison of batch and fractional melting models with the Y and Yb contents of clinopyroxene from the Kola spinel lherzolite and wehrlites, assuming a primitive mantle source. Clinopyroxene from spinel lherzolite from China (Chen et al., 2001), Arkhangelsk (Beard, unpub. data), South Africa (Zhang et al., 2001) and Australia (Norman, 1998) are plotted for comparison. Y and Yb concentrations normalised to primitive mantle (Sun and McDonough, 1989). $D_{cpx} = 0.467$ for Y and 0.43 for Yb (Zack et al., 1997), and $X_{cpx} = 0.16$ were used for both models (Downes, 1997).

metasomatism in the mantle beneath the Kola Peninsula. However, the significant difference in Ti and Fe contents in the disseminated phlogopite and amphibole between the spinel lherzolite and wehrlite xenoliths, the replacement of clinopyroxene at the expense of primary orthopyroxene closely associated with the occurrence of secondary olivines and apatites, the occurrence of magnesio-hastingsitic amphibole veins in the spinel lherzolites and the cpx-rich pocket in wehrlite xenolith (sec1xen3) all indicate that several different metasomatic events have occurred. One of these events appears to have been associated with carbonatite metasomatism.

Experimental studies by Green and Wallace (1988) demonstrated that ephemeral carbonatite melts, generated within the pargasitic amphibole stability field at depths around 80–100 km, are extremely effective metasomatic agents. A carbonatite melt in equilibrium with an amphibole-bearing lherzolite should fractionate the LILE and P from the HFSE. The resulting melt should be rich in CaO, MgO, FeO and Na₂O with significant K₂O. It should be strongly enriched in LREE and LILE (e.g. Sr, Rb, Ba) but depleted in the HFSE (e.g. Ti, Zr, Hf) (Green and Wallace, 1988). As Ti has a low solubility in a carbonatite melt, it would be partitioned into residual pargasite, clinopyroxene and ilmenite. The carbonatite melt would react with the primary orthopyroxene, replacing it with a secondary diopside accompanied by forsteritic olivine and accessory apatite (Green and Wallace, 1988). This distinctive style of metasomatism has been suggested for peridotites from Australia (Yaxley et al., 1991, 1998; Norman, 1998), Tanzania (Rudnick et al., 1993), Spitsbergen (Ionov et al., 1993) and Algeria (Dautria et al., 1992). However, it has also been suggested that some of these petrological characteristics, which have attributed to carbonatitic metasomatism may be the consequence of a ne-normative silicate melt such as an alkali basalt (Peslier et al., 2002; Rivalenti et al., 2004).

The Kola peridotites record the effect of carbonatitic metasomatism, reflected in the spinel lherzolites by the formation of LREE-enriched clinopyroxene and apatite at the expense of primary orthopyroxene (Plate 2). The clinopyroxene rims are usually poikilitic/spongy with numerous inclusions of subhedral–euhedral olivine that are slightly more forsteritic (Fo_{92–93}) than the primary olivine (Fo₉₁). In the wehrlites a similar process has occurred with secondary subhedral–euhedral forsteritic olivine (Fo₉₄) and apatite occurring as numerous inclusions in poikilitic/spongy clinopyroxene. However, Green and Wallace (1988) also predicted that carbonatite metasomatism would cause a distinctive decoupling

of LILE from Ti. The amphibole, phlogopite and ilmenite in the peridotites have high Ti and Fe and therefore cannot be the result of the carbonatitic metasomatism, but indicate a separate Ti–Fe-rich metasomatic event. The amphibole and phlogopite in the wehrlites have significantly higher TiO₂ and FeO contents than those in the spinel lherzolites suggests that two separate metasomatic events occurred within the mantle.

Alternatively, the two separate metasomatic events that produced the Ti–Fe-rich amphibole and phlogopite in the wehrlites and the low-Ti–Fe amphibole and phlogopite in the spinel lherzolites may be genetically related and therefore could be considered as one event. Such metasomatic models have been suggested for xenoliths from Spitsbergen (Ionov et al., 2002) and Nushan, Eastern China (Xu and Bodinier, 2004). In these models, a primitive melt results in an initial metasomatism, this produces a chemically evolved resultant residual melt, enriched in incompatible elements, migrating upwards into the shallower mantle. This results in two phases of metasomatism that although spatially separated are in a sense genetically related and therefore could be considered to represent a single event. In the case of the Kola peridotites a metasomatic melt resulted in the crystallisation of Ti–Fe-rich amphibole, phlogopite, ilmenite and the cpx-rich pocket in the wehrlites. This produced a resultant residue melt lower in Ti and Fe but enriched in incompatible trace elements migrating into the spinel lherzolite crystallising the Ti–Fe-poor amphibole and phlogopite. The laser ablation ICP analysis revealed the amphiboles in the spinel lherzolites are enriched in the incompatible trace elements compared to those from the wehrlites (Fig. 9).

9.4. The wehrlites

The conversion of a clinopyroxene-poor peridotite to a wehrlite by a metasomatic agent has been reported in numerous locations worldwide (NE China, Xu et al., 1996; Canary Islands, Wulff-Pedersen et al., 1996; West Eifel, Germany, Zinngrebe and Foley, 1995; Patagonia, Goring and Kay, 2000). The low-Al orthopyroxenes in the Kola wehrlites strongly suggest the original rock was harzburgitic, before conversion by carbonatite metasomatism. Low-Al orthopyroxenes have also been reported in spinel peridotite xenoliths from the Grand Canyon, USA (Smith and Riter, 1997) and have been attributed to equilibration in a chlorite peridotite. Downes et al. (2004) also reported extremely low-Al orthopyroxenes in xenoliths of wehrlite cumulates from the Bearpaw Mountain, Montana, USA and suggested

that they were the product of aqueous fluids reacting with olivine. However, the complete bulk conversion of a harzburgite to a wehrlite in the sub-continental lithospheric mantle beneath the Kola seems unlikely due to the high volume of metasomatic agent required. Alternatively, wehrlites could represent high-pressure ultramafic cumulates (Frey and Prinz, 1978) derived from mafic–ultramafic melts trapped in the mantle, as suggested for similar rocks from Kerguelen (Mattioli et al., 1996) and Finland (Peltonen et al., 1999). Consequently, the Kola wehrlites more likely represent limited local high-pressure cumulates from mafic–ultramafic melts trapped in the mantle as veins or lenses within the spinel lherzolite and have undergone similar metasomatic processes.

9.5. The cpx-rich pocket

The cpx-rich pocket and its host wehrlitic xenolith have a common fractured margin indicating that the pocket had fully crystallised in the wehrlite before being entrained by the kimberlite host (Plate 3). The remarkably similar ‘humped’ trace element patterns in clinopyroxenes from the wehrlite xenoliths and the pocket, suggest that they were derived from a similar metasomatic agent. Furthermore, the calculated REE pattern of a melt in equilibrium with clinopyroxenes from the cpx-rich pocket is identical to that of the host kimberlite, except for a slightly lower LREE content (Fig. 11). This suggests that the pocket may possibly represent a kimberlite-like melt, which infiltrated and crystallised

in the sub-continental lithosphere. This percolating melt may have caused the metasomatic event responsible for crystallisation of Ti- and Fe-rich amphibole, phlogopites and ilmenite in the wehrlites. In contrast, a melt in equilibrium with the clinopyroxenes from spinel lherzolites displays a highly LREE and HREE-enriched and MREE-depleted REE pattern (Fig. 11).

10. Conclusions

The xenoliths we have studied represent a suite of mantle-derived rocks from beneath the Kola Peninsula, providing an opportunity to investigate processes in the sub-continental lithospheric mantle beneath the northern Baltic Shield. Olivine modal estimates and Fo content in the spinel lherzolite xenoliths reveal that the lithosphere beneath the Kola Peninsula Archaean–Proterozoic crust has some similarities to Phanerozoic lithospheric mantle. Estimates of equilibration temperature for the spinel lherzolites range from 775–969 °C, consistent with spinel-facies peridotites at an intermediate pressure (10–15 kbar). The wehrlites were intruded into the spinel lherzolite as high-pressure cumulates from mafic–ultramafic melt, forming veins or lenses.

LA-ICP-MS analysis of clinopyroxenes in the xenoliths reveal that the sub-continental lithosphere beneath the Baltic Shield has undergone a moderate degree of depletion with 7–8% partial melt extracted. This may be associated with the formation of basaltic magmas that underplated the lower crust at 2.4–2.5 Ga.

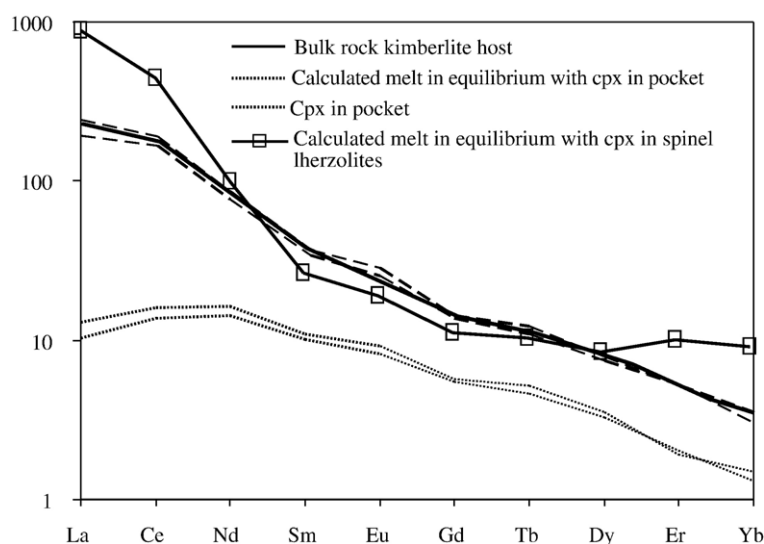


Fig. 11. Calculated REE content of a melt in equilibrium with clinopyroxene in the cpx-rich pocket compared to REE concentrations in the Kandalaksha kimberlite host. Kds (cpx/melt) from Zack et al. (1997). Normalisation coefficients from Nakamura (1974).

The depleted lithosphere was subsequently enriched during several metasomatic events.

The spinel lherzolites and wehrlites were subjected to an incomplete carbonatitic metasomatic event resulting in crystallisation of secondary clinopyroxene rims at the expenses of primary orthopyroxenes, with the development of secondary forsteritic olivine and apatite. The timing of this event is not clear, but it may be related to an early carbonatitic phase associated with the Devonian alkaline magmatism.

Two separate metasomatic events resulted in the crystallisation of the Ti–Fe-rich amphibole, phlogopite, ilmenite and the cpx-rich pocket in the wehrlites and the low Ti–Fe amphibole and phlogopite in the spinel lherzolites. Alternatively, a single metasomatic event with a chemically evolving melt produced the significant compositional differences seen in the amphibole and phlogopite between the spinel lherzolites and wehrlites.

The calculated REE pattern of a melt in equilibrium with clinopyroxenes from the cpx-rich pocket is identical to that of the kimberlite host, indicating a close petrological relationship.

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