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Osmium isotopes in the Wiedemann Fjord mantle xenoliths: A unique record of cratonic mantle formation by melt depletion in the Archaean

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[1] **Abstract:** The Wiedemann Fjord mantle xenoliths from Tertiary basanitic dykes in east Greenland contain extremely depleted spinel harzburgites. The harzburgites are unusual because of their highly forsteritic olivine and low modal orthopyroxene, consistent with an origin as residues of up to 40% melting. Also present are lherzolites with olivine contents as low as 50% and with up to 25% clinopyroxene, and there is a continuous range of compositions between the most depleted harzburgites and the lherzolites. Osmium isotopic data show that the depleted harzburgites were formed by melt depletion in the Archaean. In contrast to most other Archaean xenoliths (e.g., from the Kaapvaal and Siberian cratons) the composition of the Wiedemann Fjord harzburgites is consistent with depletion by polybaric melting. The lherzolites have less refractory mineral compositions than the harzburgites (lower bulk Mg # and Cr #, higher aluminum contents in orthopyroxene (opx)) and also have more radiogenic Os isotopic compositions. The data suggest that the Wiedemann Fjord xenoliths formed as restites from high degrees of melting in the Archaean and that some of the restites were partly refertilized by metasomatism involving addition of pyroxene and reequilibration of mineral and isotopic compositions.

Keywords: Mantle xenoliths; Os isotopes; mantle depletion; mantle enrichment; Archaean.

Index terms: Chemical evolution; composition of the mantle; geochronology; isotopic composition.

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1. Introduction

[2] Mantle xenoliths from Archaean cratons generally have higher forsterite (Fo = 100 × Mg/(Mg + Fe)) contents in olivine (often >91% Fo), and higher Cr # (Cr/(Cr + Al)) in spinels than mantle xenoliths from Proterozoic and Phanerozoic crustal terrains [e.g., *Boyd*, 1987, 1989; *Menzies*, 1990]. These characteristics have been explained in terms of extensive melt extraction from the mantle [e.g., *Jordan*, 1979; *Boyd*, 1989; *Menzies*, 1990], and the genesis of such refractory mantle material has been linked to the extraction of komatiites [*Boyd and Mertzman*, 1987; *Boyd*, 1989; *Walker et al.*, 1989; *Bernstein et al.*, 1998]. Most high Mg # xenoliths from Archaean cratons (e.g., Kaapvaal and Siberian cratons) have high modal orthopyroxene (>20% [e.g., *Boyd*, 1989]). No melting experiments have produced liquid compositions that would leave an orthopyroxene-rich residue similar to these high Mg # peridotites [e.g., *Walter*, 1998; *Herzberg*, 1995], and models for their origin include metamorphic differentiation of high pressure residues [e.g., *Boyd*, 1989; *Herzberg*, 1993], mixtures of residual peridotites and high-pressure igneous cumulates [e.g., *Herzberg*, 1993, 1995; *Herzberg and O'Hara*, 1998], and addition of SiO_2 to orthopyroxene-poor peridotites by melt-rock reaction [*Kelemen et al.*, 1998].

[3] Unmetasomatized, residual peridotites residing in the cratonic upper mantle should preserve long-term Re/Os depletion and therefore have low $^{187}Os/^{188}Os$. Furthermore, $^{187}Os/^{188}Os$ should correlate with modal composition and with major and trace element concentrations in minerals that are indicative of melt depletion. Few mantle peridotite xenoliths fulfill these criteria, which has led to the widely held belief that few, if any, unmetasomatized residues are preserved in the cratonic upper mantle. The Wiedemann Fjord mantle xenoliths were first discovered by *Brooks and Rucklidge* [1973] and investigated in terms of modal and mineral compositions by *Bernstein et al.* [1998]. They occur in a suite of ~40-myr-old basanitic dykes crosscutting Tertiary flood basalts of the East Greenland volcanic rifted margin at around 68°30′N, 28°W. The flood basalts are more than 6 km thick and were erupted between 58 and 47 Ma, with the main phase of volcanism occurring around 55 Ma. To the south the basalts rest on Precambrian basement and to the north on basement affected by the Caledonian orogeny [*Bernstein et al.*, 1998].

[4] The xenoliths are almost exclusively spinel harzburgites with highly forsteritic olivine (average Fo 92.7%), although a few lherzolites with lower forsterite contents are present. The high forsterite contents, together with high modal olivine contents and moderate Cr/Al ratios in spinel, places the Wiedemann Fjord harzburgites in an unusual and important compositional field (Figure 1). *Bernstein et al.* [1998] showed that the major element composition of the harzburgites is consistent with an origin as residues from ~40% mantle melting. It was also demonstrated that simple decompression melting initiated at pressures around 5 GPa and ending at pressures at 2 GPa or less, produces liquids similar to Munro-type komatiite, leaving a residue resembling the Wiedemann Fjord harzburgites.

[5] This study examines the Os isotopic compositions of the Wiedemann Fjord xenoliths in

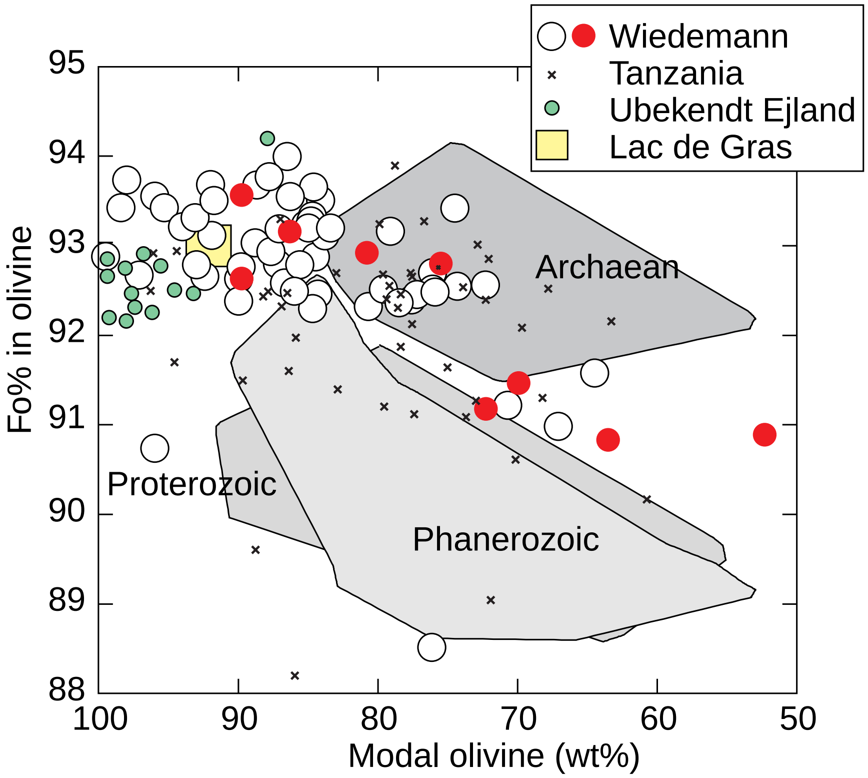


Figure 1. Forsterite (Fo) in olivine versus the modal olivine contents for the Wiedemann Fjord xenoliths. Revised from *Bernstein et al.* [1998] to include samples analyzed for osmium isotopic composition (solid circles). Thin sections for two samples are not available, and hence modal compositions cannot be determined by point counting. From modal analyses of crushed samples the two samples are estimated to be the most olivine rich of the samples analyzed. Note that most Wiedemann Fjord xenoliths have olivine contents higher than 85%. Fields for xenoliths hosted in regions of Archaean, Proterozoic, and Phanerozoic crust, are from *Menzies* [1990]. Recently, relatively olivine-rich (orthopyroxene-poor) peridotite xenoliths have also been described from the Slave craton (Lac de Gras [*Boyd and Canil*, 1997]), the Tanzania craton [*Rudnick et al.*, 1994; *Lee and Rudnick*, 1999], and from Ubekendt Ejland in west Greenland [*Bernstein and Brooks*, 1999].

order to place constraints on their genesis and to obtain an estimate of their age. The data are consistent with the hypothesis that the Wiedemann xenoliths formed as restites from high degrees of melting and that the depletion is of Archaean age.

2. Samples and Analytical Procedure

[6] The Wiedemann Fjord xenoliths are typically discoidal, with an average size of 1–2 cm in the maximum dimension. Although 90 xenoliths were included in the study of *Bernstein et al.* [1998], only a few samples from the suite are large enough for isotope study.

[7] Mineral separates from nine mantle xenoliths, five harzburgites and four lherzolites, were analyzed along with the host dyke (powdered whole rock) for the xenoliths (Tables 1 and 2). Olivine and spinel aliquots are handpicked separates (only clear olivines without visible inclusions were picked), olivine + pyro-

Table 1. Modal Compositions, Mineral Compositions, and Calculated Whole Rock Compositions of Wiedemann Fjord Xenoliths[a]

Sample	Lithology	Mode				% Fo	Cr #	Al_2O_3 in	*T*, °C	*T*, °C
		olivine	opx	cpx	spinel	olivine	spinel	opx	Ca-opx	Cr-Al
Nep 1	harzburgite	90*				93.6	45.34	1.65	831	830
Nep 2	lherzolite	52.2	20.7	25.2	1.9	90.9	11.43	5.94	980	947
Nep 3	harzburgite	86.1	12	0	1.9	93.2	41.39	1.86	825	866
Nep 4	lherzolite	63.6	25.8	9	1.6	90.8	15.64	3.90	979	941
Nep 5	harzburgite	90*				92.6	n.a	1.67	850	865
Nep 6	harzburgite	80.9	17.1	0.8	1.2	92.9	31.97	2.37	853	846
Nep 8	lherzolite	70	19.3	7.5	3.2	91.5	15.76	3.57	889	893
4–40	lherzolite	72.4	10.2	15.8	1.6	91.2	24.67	2.67	863	882
2–10	harzburgite	75.5	22.7	0.5	1.3	92.8	41.80	1.88	849	851
Whole Rock	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Sum	Mg #
Nep 2	45.55	0.11	3.38	6.59	0.05	36.01	5.10	0.50	97.99	90.7
Nep 3	42.06	0.02	0.83	6.46	0.12	47.77	0.08	0.02	98.34	93.0
Nep 4	44.76	0.05	2.33	7.39	0.04	40.99	2.06	0.22	98.52	90.8
Nep 6	43.62	0.01	0.91	6.67	0.18	48.32	0.30	0.02	100.80	92.8
Nep 8	43.48	0.06	2.72	7.45	0.08	43.74	1.72	0.14	100.26	91.3
4–40	43.95	0.07	1.87	7.40	0.14	42.83	3.32	0.27	100.69	91.2
2–10	44.45	0.03	0.90	6.47	0.10	46.89	0.22	0.03	99.95	92.8

[a] Asterisk indicates that modal data for Nep 1 and Nep 5 are not available. From the handpicking they are estimated to be the most olivine-rich of the samples, i.e., ~90% olivine. Temperatures were calculated after *Brey and Köhler* [1990] (Ca in orthopyroxene) and *Witt-Eickschen and Seck* [1991] (Al-Cr exchange between spinel and orthopyroxene). Mineral compositions were determined by electrone microprobe analyses at University of Copenhagen as described by *Bernstein et al.* [1998].

xene aliquots are total silicate fractions after removal of spinel and thus contain olivine, orthopyroxene, and clinopyroxene (in some samples) as well as possible accessory phases. These fractions were cleaned for obviously altered grains but not for cloudy grains.

[8] Samples labeled FF (flux fusion) in Table 2 were prepared for Os isotopic analysis by Ni-S fire assay preconcentration, using sodium tetraborate flux. Os separation was by distillation and Chelex bead chemistry, and analysis of Os isotopic composition was performed by negative thermal ion mass spectrometry (NTIMS) at the Woods Hole Oceanographic Institution [*Ravizza et al.*, 1996]. The Os blank is 1.4 pg/g of flux and has an $^{187}Os/^{188}Os$ ratio of 0.266. For the Wiedemann samples, ~2.6 and 6 g of flux was used for spinel and silicate fractions respectively, and all samples prepared for analysis by flux fusion were blank corrected.

[9] Remaining samples (labeled CT in Table 2) were analyzed using the carius tube technique [*Shirey and Walker*, 1995]. Samples were digested in an inverse aqua regia in sealed glass tubes (carius tubes) for >72 hours at 200°C. Subsequently, samples were distilled twice to extract the osmium and analyzed by NTIMS at University of Copenhagen. The Os blank for the caries tube technique is 2.8 pg/g sample, and for the sample size of the xenoliths it ranges from 0.06 to 1.4 pg. Samples run by the carius tube technique have not been blank corrected.

[10] A subset of the samples digested in carius tubes were analyzed for Re concentrations using isotope dilution. After Os distillation, Re was extracted from the remaining sample

Table 2. Re and Os Measurements for Wiedemann Fjord Xenoliths and Host Dyke[a]

Sample	Phase		Os, ppt	Re, ppt	^{187}Re/^{188}Os	^{187}Os/^{188}Os	2 S.E.	^{187}Os/^{188}Os Initial	TRD (Ma)
Nep 1	spinel	CT	27839			0.1114	0.00019		2290
Nep 1	spinel	FF	14970			0.1114	0.00098		2288
Nep 1	olivine and px	FF	500			0.1111	0.00062		2338
Nep 1	olivine and px	FF	195			0.1011	0.00154		3764
Nep 2	olivine	CT	12	105	39.80	0.1176	0.00099	0.0907	1394
Nep 2	olivine and px*	FF	1380			0.1252	0.00043		275
Nep 2	spinel*	FF	31040			0.1260	0.00078		149
Nep 3	olivine	CT	8			0.1088	0.00166		2673
Nep 3	olivine and px*	FF	690			0.1106	0.00038		2410
Nep 3	spinel	CT	29589			0.1089	0.00028		2658
Nep 3	spinel*	FF	105210			0.1070	0.00054		2927
Nep 4	olivine	CT	155			0.1243	0.00464		398
Nep 4	olivine and px*	FF	1150			0.1241	0.00045		436
Nep 4	spinel	CT	9279			0.1232	0.00069		568
Nep 4	spinel*	FF	10140			0.1228	0.00091		633
Nep 5	olivine	CT	12	148	59.40	0.1112	0.00151	0.0711	2330
Nep 5	whole rock*	FF	1550			0.1087	0.00065		2678
Nep 5	spinel*	FF	1390			0.1055	0.00333		3133
Nep 6	olivine	CT	304	109	1.70	0.1092	0.00084	0.1081	2597
Nep 6	spinel	CT	398	1283	15.29	0.1162	0.00061	0.1059	1597
Nep 8	spinel	CT	33382	4689	0.67	0.1233	0.00029	0.1229	550
4–40	olivine	CT	156	68	2.08	0.1191	0.00041	0.1177	1163
4–40	spinel	CT	5298	1985	1.78	0.1153	0.00057	0.1141	1722
2–10	olivine	CT	164	355	10.28	0.1067	0.00328	0.0997	2963
2–10	spinel	CT	17824	2427	0.65	0.1112	0.00064	0.1107	2318
429285	whole rock	CT	318	1229	18.32	0.1352	0.00088	0.1228	

[a] Re-depletion ages calculated from present-day ^{187}Os/^{188}Os ratios with respect to chondritic evolution, including ^{187}Re/^{188}Os = 0.40186 and ^{187}Os/^{188}Os = 0.127 [*Shirey and Walker*, 1998]. Asterisks indicate that the sample has been leached in cold 6 N HCl for 1 hour. Samples labeled FF (flux fusion) were prepared for Os isotopic analysis using Ni-S fire assay and analyzed at Woods Hole Oceanographic Institution [*Ravizza et al.*, 1996]. Samples labeled CT (carius tube) were prepared for an analysis using the carius tube technique [*Shirey and Walker*, 1995] and were analyzed at University of Copenhagen.

solution by liquid extraction. The samples were analyzed at the inductively coupled plasma–mass spectrometer (ICP-MS) facility at the Woods Hole Oceanographic Institution. The Re blank is 15–50 pg, and all samples have been blank corrected using a blank of 40 pg. Re concentrations were not measured on aliquots run by flux fusion because of the high Re blank in the fluxes. Additional analyses of Re concentrations are not possible because of the small sample sizes.

3. Results

[11] The modal composition, forsterite contents of olivine, spinel Cr #, and equilibration tem-

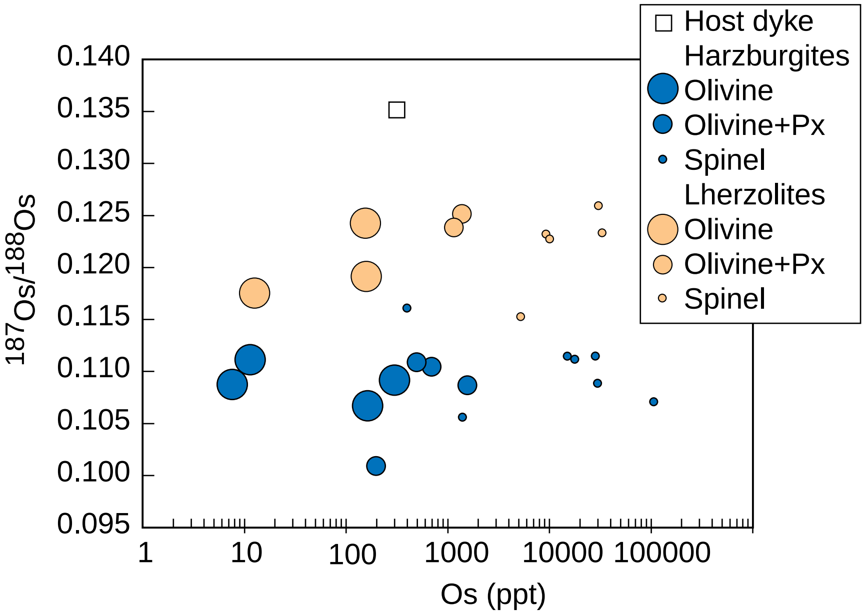


Figure 2. The ^{187}Os/^{188}Os ratio versus Os concentration for the Wiedemann Fjord samples and host dyke.

peratures are given in Table 1, and isotopic compositions are given in Table 2. The Os concentration in olivine separates varies from 8 to 304 ppt. In olivine + pyroxene fractions the concentrations are generally slightly higher, 195–1380 ppt, and for spinels they are higher yet, 398–105,210 ppt (Figure 2). Four samples (different aliquots of the same mineral fraction) were run twice, using different combinations of leaching and digestion method. In none of the four samples do the two separate analyses give the same Os concentration (Table 2). The variation observed in the duplicate analyses does not, however, vary in a systematic way. That is, leaching versus nonleaching, and flux fusion versus caries tube digestion, do not consistently yield higher or lower concentrations of Os.

[12] Re concentrations in the xenoliths range from 68 to 355 ppt in the olivine fractions and from 1283 to 4689 ppt in the spinel fractions. As for Os, there is no systematic difference in concentrations between lherzolites and harzburgites. The ^{187}Os/^{188}Os ratio varies from 0.1011 to 0.1260 for the xenoliths (Figures 2 and 3). These values are similar to those reported for xenoliths from the Siberian, Kaapvaal, Wyoming, and Tanzania cratons (Figure 3), although the Wiedemann Fjord xenoliths are at the unradiogenic end of the data range and extend to lower values. The present-day ^{187}Os/^{188}Os ratio of the host dyke is 0.1352, which is similar to Icelandic basalts and picrites [*van der Zander et al.*, 2000; *Smit et al.*, 2000] and to Tertiary picrites from west Greenland [*Schaefer et al.*, 2000]. The Os and Re concentrations in the host dyke are 318 and 1229 ppt, respectively.

[13] Different mineral fractions from individual xenoliths vary in isotopic composition but not in a consistent fashion; e.g., in some samples the spinel fraction is more radiogenic than the silicates, and in other samples spinel is less radiogenic (Table 2). Spinel fractions from three samples were analyzed by both flux fusion and carius tube, and although some of the aliquots were leached (see Table 2), the

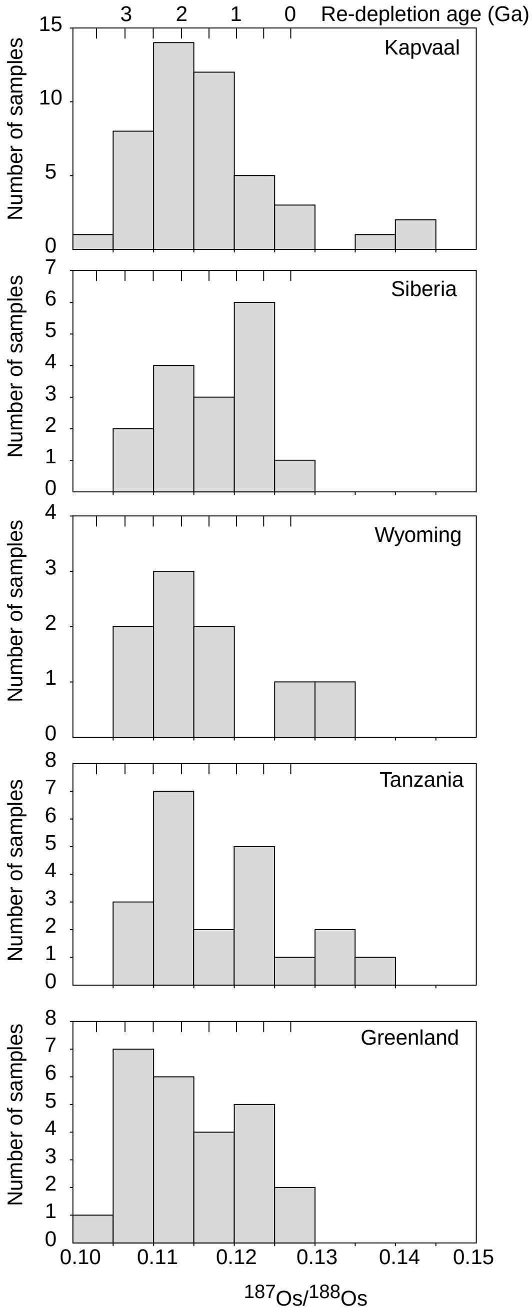


Figure 3. Histograms of $^{187}Os/^{188}Os$ for xenoliths from Wiedemann Fjord: Kaapvaal, Siberia, Wyoming, and Tanzania. Data from *Olive et al.* [1997], *Pearson et al.* [1995a, 1995b], *Carlson and Irving* [1994], *Walker et al.* [1989], and *Chesley et al.* [1999]. Note that data for the Wiedemann Fjord xenoliths represent 25 analyses of different mineral fractions from 9 individual xenoliths.

results in terms of isotopic compositions are identical within analytical error.

4. Discussion

4.1. *Distribution of Os and Re*

[14] With the exception of one sample (Nep 6, see Table 2), Os concentrations in spinels are at least an order of magnitude higher than in the olivine and olivine + pyroxene fractions. Spinel thus appears to contain a significant fraction of the Os inventory in individual xenoliths. For example, compared to lherzolite from Kilbourne Hole, the Os concentration in olivine is relatively low, whereas the Os concentration in spinel is extremely high [*Hart and Ravizza*, 1996]. The most plausible explanation for this is that the Os primarily resides in sulphides preferentially included in spinel. This also explains the uneven distribution of Os within the same mineral fractions and why separates of clear olivine (i.e., inclusion free) generally yield lower concentrations than separates containing olivine and pyroxene of a more mixed appearance. These expressions of the so-called “nugget effect” are in accordance with previous studies indicating that most of the Os in peridotites is resides in sulphide phases [e.g., *Morgan*, 1986; *Hart and Ravizza*, 1996; *Handler et al.*, 1999; *Burton et al.*, 1999] because of the siderophile and chalcophile nature of Os.

[15] The Re concentration in spinel is also an order of magnitude higher than in the clear olivine fractions, and it is most likely hosted in sulphide inclusions along with the Os, although it is plausible that some is contained in the spinel lattice if Re behaves similarly to Al [*Reisberg and Lorand*, 1995].

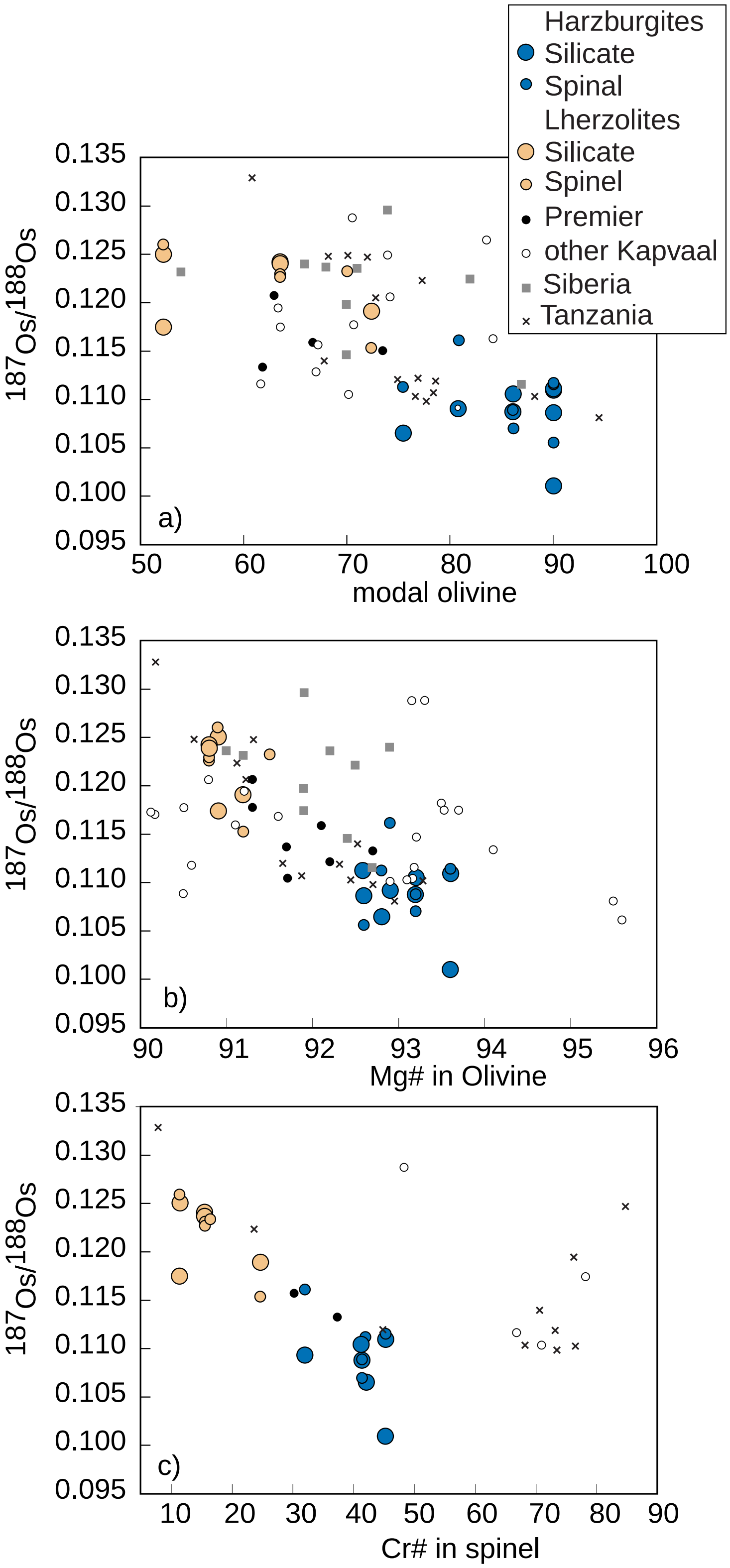
[16] Os concentrations in both olivine and spinel are more variable than Re concentrations, and consequently $^{187}Re/^{188}Os$ ratios show a

wide range from 0.65 to 59.40. Re/Os ratios are superchondritic (greater than 0.402 [*Shirey and Walker*, 1998]) for all samples analyzed for Re. This is not unusual for cratonic peridotites [e.g., *Walker et al.*, 1989; *Carlson and Irving*, 1994; *Chesley et al.*, 1999; *Pearson et al.*, 1998], although $^{187}Re/^{188}Os$ ratios above 10 are rare. Given the small sample size (350–500 mg) and relatively low Re concentrations in olivine, the Re blank may contribute as much as 35% of the measured Re in the olivine samples. The spinels, on the other hand, have significantly higher Re concentrations, and although the sample size is small (23–70 mg) the Re blank constitutes less than 2% of the total measured Re. With the exception of Nep 6, spinel has lower Re/Os ratios than olivine. *Burton et al.* [1999] estimates that ∼35% of the Re in a Kilbourne Hole lherzolite is hosted in the silicate portion proper and that the remaining 65% is located in sulphides (both interstitial and included). The high Re/Os ratios in Wiedemann samples support the idea that while Os almost entirely resides in sulphides, a significant fraction of the Re resides in "primary" silicates and spinel. In this view, preparation of mineral separates may have removed a large proportion of low Re/Os sulphide, leaving a relatively high Re/Os fraction for analysis. Alternatively, elevated Re/Os ratios could indicate that metasomatism may have affected the harzburgites; i.e., Re enrichment may have occurred during and after entrapment and transport to the surface.

4.2. Isotopic Composition

[17] Age information from Os isotopic composition is usually obtained through model ages or Re-depletion ages. The model age (T_{MA}) is the time of separation from mantle evolving in accordance with chondritic evolution. It is used for both mantle and crustal samples and is calculated assuming that the Re/Os ratio of the sample is representative of its long-term history [e.g., *Shirey and Walker*, 1998]. Many cratonic mantle samples give negative, or unrealistically high model ages (i.e., >5 Gy), either because Re has been added by host melt infiltration or by earlier metasomatism [e.g., *Walker et al.*, 1989; *Pearson et al.*, 1995b] or because the samples have suffered late stage Os loss [*Handler et al.*, 1999]. *Walker et al.* [1989] addressed this problem by calculating model ages for mantle xenoliths with the inherent assumption that all Re was removed during a melting event and that the present-day Re content was added by infiltration of the host magma, the so-called Re-depletion age (T_{RD}). The isotopic composition at time of eruption or emplacement (T_{EA}) is thus calculated from present-day Re/Os ratios, and a model age assuming a Re/Os ratio of zero is calculated from this composition. T_{RD} is a minimum model age, provided that the mantle followed chondritic evolution until the point of melt (and Re) extraction.

[18] All Wiedemann Fjord xenoliths with available Re concentrations have negative model ages, T_{MA}. Together with similar Re concentrations in harzburgites and lherzolites this is taken as evidence for late Re addition or Os loss. For the six xenoliths with available Re concentrations, Re-depletion ages can be calculated from the Os isotopic composition at the time of dyke intrusion, assuming that all Re was added to the xenolith during emplacement. Four xenoliths give ages from 619 to 3955 myr. Two olivine separates give ages older than that of the Earth, 5203 and 7849 myr respectively. The unrealistically high ages are a consequence of the high Re/Os ratios recorded in some of the Wiedemann Fjord samples, and they may indicate that Re addition or Os loss is younger than the intrusion of the dyke. In fact, Os loss may have taken place during sample preparation. A low Re/Os fraction of the samples may have been present in the whole rock xenolith, perhaps on grain boundaries, and removed


Harzburgites
Silicate
Spinal
Lherzolites
Silicate
Spinel
Premier
other Kapvaal
Siberia
Tanzania
$^{187}Os/^{188}Os$
0.135
0.130
0.125
0.120
0.115
0.110
0.105
0.100
0.095
a)
50
60
70
80
90
100
modal olivine
b)
90
91
92
93
94
95
96
Mg# in Olivine
c)
10
20
30
40
50
60
70
80
90
Cr# in spinel

during mineral separation. Both of the olivine separates that give ages above 5000 myr have relatively low Re concentrations (105 and 148 ppt). Given the small sample size and the relatively high and variable Re blank, the corresponding T_{RD} for these samples are highly uncertain.

[19] Because of the uncertainty in Re/Os and because Re concentration data are only available on a subset of the Wiedemann Fjord samples, we discuss the age information given by the Os isotopic composition in terms of Re-depletion ages calculated from the present-day Os isotopic composition. The Re-depletion ages calculated in this manner will be somewhat younger but still represent minimum ages for depletion provided that the parental mantle prior to depletion had a chondritic $^{187}Os/^{188}Os$ ratio.

[20] Re depletion ages calculated from present-day isotopic compositions, T_{RD}, range from 149 to 3764 myr (Table 2, Figure 3). Os isotopic composition (and T_{RD}) correlate with degree of depletion of the peridotites, e.g., modal olivine, forsterite contents in olivine and Cr # in spinel (Figure 4). Consequently, harzburgites are consistently less radiogenic than lherzolites, yielding Re-depletion ages of 1597 to 3764 myr. Thus the low $^{187}Os/^{188}Os$ ratios obtained for the harzburgites suggest that they are residues of melt depletion in the Archaean [*Walker et al.*, 1989; *Shirey and Walker*, 1998]. This is in accordance with the modal compositions, the major element mineral compositions and the low pyroxene-spinel equilibration temperatures (~850°C) in the Wiedemann Fjord harzburgites (see Figure 5, Table 1, and *Bernstein et al.* [1998]). Even though the harzburgites preserve a refractory composition, it is evident from the elevated Re/Os ratios that some metasomatism occurred even in the most depleted of the harzburgites, perhaps during or after transport of the xenoliths in the host dyke.

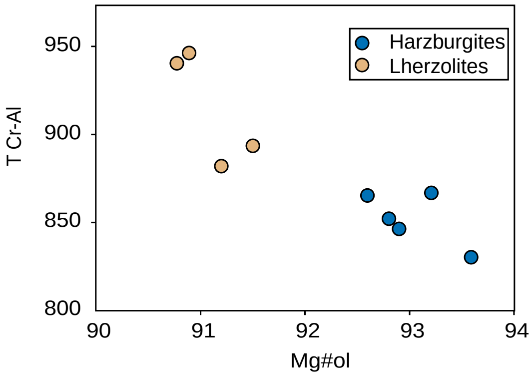


Figure 5. Calculated equilibration temperatures in degrees Celsius for the Wiedemann xenoliths. Temperature calculations are based on Al-Cr exchange between orthopyroxene and spinel [after *Witt-Eickschen and Seck*, 1991]. Note that temperature correlates with forsterite content in olivine.

4.3. Origin of Compositional Differences Between Harzburgite and lherzolite

[21] There is a range of compositions between the depleted harzburgites and the lherzolites in terms of Os isotopic compositions and modal and mineral compositions (Tables 1 and 2, Figure 4). Because of the correlation of $^{187}Os/^{188}Os$ with degree of depletion, the lower Re-depletion ages of the lherzolites cannot be explained by a younger depletion event alone

Figure 4. Relationships between Os isotopic composition and selected indices of depletion for the Wiedemann Fjord xenoliths; (a) modal olivine, (b) forsterite content in olivine (Fo = molar Mg/(Mg + Fe) × 100), and (c) Cr # (molar Cr/(Cr + Al) × 100) in spinel. Also shown are data from Kaapvaal, Siberia, and Tanzania. With the exception of the Premier xenoliths, Os isotopic compositions for xenoliths from Kaapvaal and Siberia do not correlate with indices of depletion. Os isotopic compositions for xenoliths from Tanzania correlate with forsterite content in olivine and modal olivine, but not with Cr # in spinel. Data from *Olive et al.* [1997], *Pearson et al.* [1995a, 1995b], *Walker et al.* [1989], *Lee and Rudnick* [1999], *Chesley et al.* [1999], and F. R. Boyd (unpublished data, 2000).

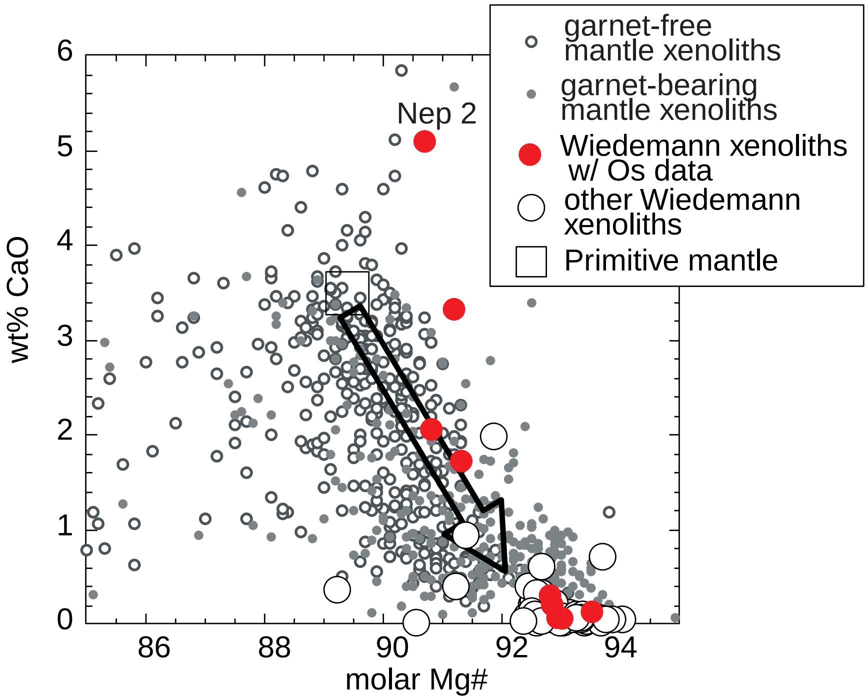


Figure 6. Whole rock CaO against Mg # for Wiedemann xenoliths and mantle xenoliths worldwide. Data from *Bernstein et al.* [1998] and *McDonough and Frey* [1989]. Primitive mantle from *Sun and McDonough* [1989]. Arrow illustrates trend of progressive depletion by melting of primitive mantle.

but must instead be a result of differences in degree of depletion. Two explanations for origin of the less refractory lherzolites are thus plausible: Either they are residues from lesser degrees of depletion than the harzburgites or they are refertilized harzburgites, i.e., depleted restites subjected to later metasomatism involving addition of pyroxene and reequilibration of mineral and isotopic compositions. The lherzolites give equilibration temperatures of up to 980°C (Table 1, Figure 5). The higher equilibration temperatures relative to the harzburgites may suggest that the lherzolites equilibrated at greater depths along the same geothermal gradient as the harzburgites, i.e., that they represent a deeper and therefore less refractory portion of the lithospheric mantle. Alternatively, the higher equilibrium temperatures for the lherzolites may be the result of relatively recent equilibration with higher temperature melts, for example, during the Tertiary North Atlantic igneous activity that brought the mantle nodules to the surface.

[22] The Wiedemann harzburgites may be regarded as residues of ~40% melting [*Bernstein et al.*, 1998], close to the point of exhaustion of orthopyroxene, opx-out. Cpx-out is at 20 to 25% melting at pressures less than ~50 kbar [e.g., *Herzberg*, 1995; *Walter*, 1998]. Assuming a melt production rate of 1%/kbar, which is a good average value for lherzolite but probably much higher than melt production from harzburgite after cpx-out [e.g., *Asimow et al.*, 1997], a 15–20% difference in the degree of decompression melting would require at least a 15–20 kbar difference in final pressure of decompression. For a minimum pressure of 10–15 kbar for the harzburgites [*Bernstein et al.*, 1998], an additional 15–20 kbar should put the lherzolites

into the pressure range where garnet is stable. The Wiedemann lherzolites appear to be true, spinel-facies peridotites, based on the high Al contents in opx and low Cr # in spinel [e.g., *Boyd et al.*, 1999; *Arai*, 1994], so a model relating the harzburgites and lherzolites as residues of different degrees of decompression melting must involve later decompression of the lherzolites and metamorphic breakdown of residual garnet. This is possible but seems implausible in the absence of additional evidence.

[23] In addition, the major element composition of the lherzolites is inconsistent with a residual origin. One sample (Nep 2) has higher bulk CaO, lower bulk MgO, and a modal composition more cpx-rich than primitive mantle [e.g., *McDonough and Rudnick*, 1998]. In addition, at a given Mg # the most enriched Wiedemann lherzolites have CaO contents that are higher than mantle xenoliths worldwide and higher than residues of melting of primitive mantle (Figure 6). We thus favor the hypothesis that the lherzolites are originally depleted residues that were subsequently modified by modal metasomatism and reequilibration of major mineral phases. Ongoing analysis of trace element abundances and Nd isotopic compositions in pyroxenes may help to further resolve this issue.

5. Conclusion

[24] The Re-depletion ages for xenoliths from the Kaapvaal, Tanzania, Siberia, and Wyoming cratons span approximately the same range as the Wiedemann Fjord samples, and the longevity of the cratonic lithospheric mantle from these cratons has previously been inferred using Re-depletion ages [e.g., *Walker et al.*, 1989; *Olive et al.*, 1997; *Chesley et al.*, 1999; *Pearson et al.*, 1995a, 1995b; *Carlson and Irving*, 1994]. For some of these samples the Re-Os systematics are thus robust enough to preserve the signature of an early depletion event, even if the samples have somehow been modified by metasomatism. The early Archaean Re-depletion ages reported here corroborate the hypothesis that the Wiedemann Fjord harzburgites are restites from high degrees of melt extraction, possibly linked to the generation of Munro-type komatiites [*Bernstein et al.*, 1998]. The Wiedemann Fjord harzburgites are unusual because, in contrast to most other Archaean xenoliths, they preserve refractory modal compositions and mineral chemistry. The harzburgites can thus be regarded as representing an almost entirely unmetasomatized sample of Archaean depleted mantle.

[25] The Wiedemann Fjord lherzolites are interpreted as representing originally depleted restites, which have been modified by modal metasomatism and reequilibration of major mineral phases at a later stage. Given the relatively high temperatures recorded by the lherzolites, we infer that this later modification was Phanerozoic and possibly linked to the Tertiary magmatism associated with rifting and passage of the Iceland mantle plume beneath the east Greenland continental margin.

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