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# Peridotite enclaves hosted by Mesoarchaean TTG-suite orthogneisses in the Fiskefjord region of southern West Greenland

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ABSTRACT

This study presents bulk-rock major, trace, and platinum-group element data, as well as mineral chemistry for peridotites which form large enclaves (up to 500 × 1000 m) within Mesoarchaean orthogneisses of the Akia terrane in the Fiskefjord region, southern West Greenland. The largest peridotite body, known as Seqi, contains highly fosteritic olivine with a median Mg# of 92.6 and hosts extensive layers of chromitite, which can be traced for tens of metres with thicknesses of up to 30 cm. Thinner (<100 m thick), but extensive (up to 2000 m long) peridotite sheets are associated with coarse norite and orthopyroxenite with distinct cumulate textures in the Amikoq complex, located a few tens of kilometres south of Seqi. Intercalated amphibolites of tholeiitic basaltic composition show complementary geochemical evolution to the peridotites, consistent with igneous crystal fractionation trends. The U-shaped trace element patterns of the peridotites may either reflect the parental melt composition from which these olivine-rich rocks were derived, or alternatively this feature may be the result of melt-rock interaction. Overall, we interpret the Fiskefjord region peridotites to have formed as ultramafic cumulates derived from Archaean high-Mg, low Ca/Al magmas, although their geodynamic setting remains to be established.


## 1. Introduction

Peridotites are found sporadically as large enclaves within Mesoarchaean amphibolite- to granulite-facies orthogneisses in the Akia terrane of southern West Greenland, North Atlantic craton [39]. These peridotites consist mainly of chromite-rich dunite and minor harzburgite. They commonly contain amphibole, but essentially no clinopyroxene is observed. Although the Seqi dunite body, which is the largest of the ultramafic enclaves at ca. 500 × 1000 m, has been mined for industrial grade olivine, the origin of these peridotites is yet unknown. These unusually large inclusions of coarse peridotites found within tonalite–trondhjemite–granodiorite (TTG)-suite orthogneisses, are not a common feature of other Archaean cratons. The only similar cases occur where layered mafic intrusions are present (e.g., Stillwater and Bushveld). However, all of the Fiskefjord peridotites are intruded by the TTGs and thus predate the continental crust-forming event of the Akia terrane at ca. 3000 Ma. Mafic amphibolites and norites are intercalated with the peridotites in the Amikoq complex (Fig. 1). The tholeiitic basaltic rocks and are similar to the amphibolites from other supracrustal belts in the North Atlantic craton. Although the field relations between these mafic and ultramafic rocks are not clear, they appear to be part of the same rock association, which includes the Qussuk and Bjørneøen supracrustal belts [39,40].

Two contrasting origins can be envisioned for the Fiskefjord region peridotites: Either they represent (1) residual mantle residues formed by large degrees of melt-extraction, or (2) alternatively they represent ultramafic cumulates formed by mainly olivine accumulation (+spinel ± orthopyroxene). If these peridotites were originally mantle residues then these mafic to ultramafic rock assemblages may represent remnants of ophiolitic crust that was obducted during accretionary processes. Accordingly, this would suggest that horizontal tectonics were in operation prior to 3000 Ma. This is currently a much debated topic and the apparent absence of mantle rocks associated with Archaean supracrustal belts is a critical point in the arguments for and against Archaean subduction zone processes (see Discussion of [12,120,121]).

On the other hand, if these peridotites rather formed during fractional crystallisation and cumulate processes, this could have

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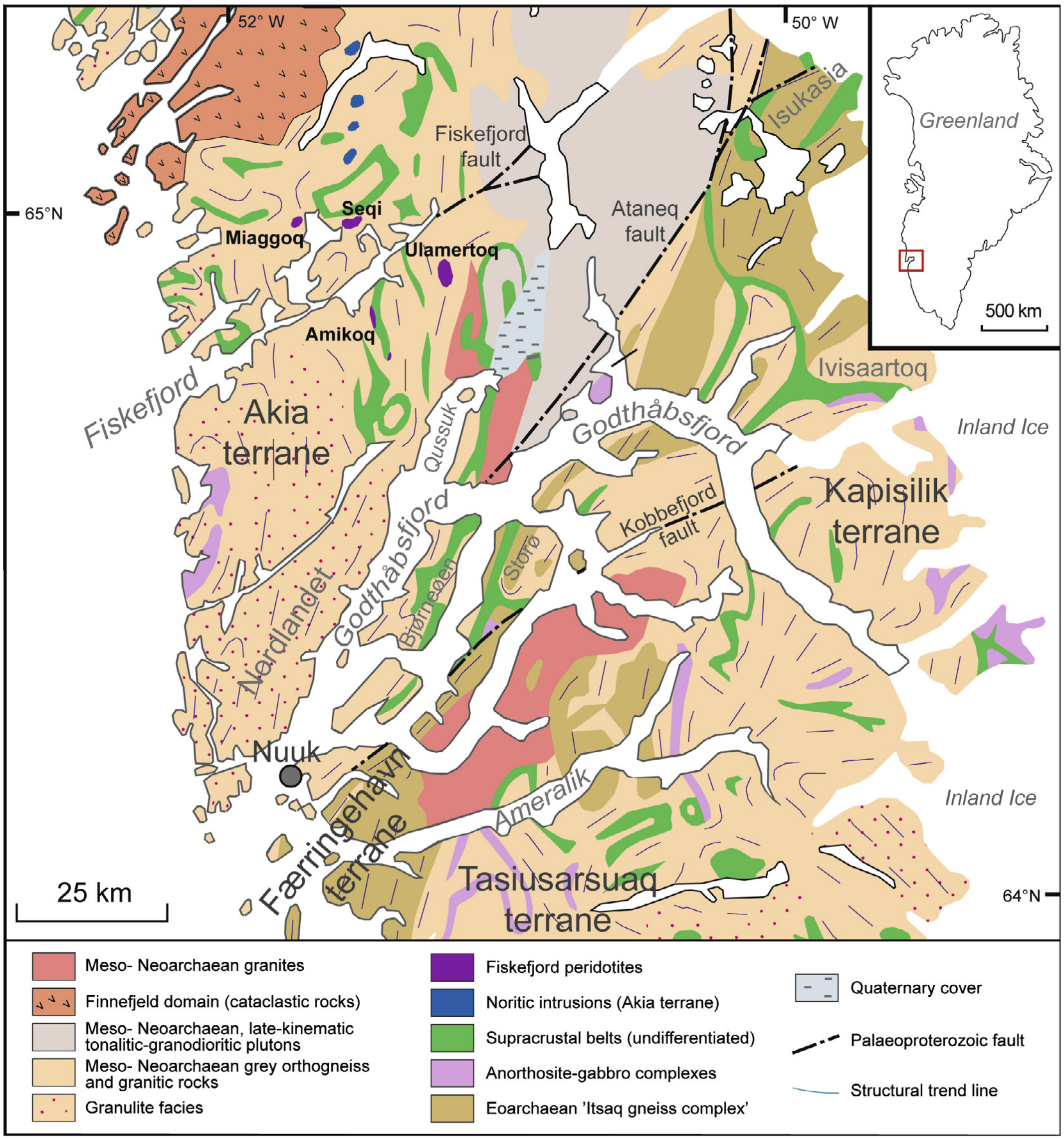


**Fig. 1.** Geological map of the Nuuk and Fiskefjord regions in southern West Greenland. The peridotite locaties of the Seqi Olivine Mine and the Amikoq complex, from which the studied samples have been collected, are shown in purple. Two additional large peridotite bodies (Miaggoq and Ulamertoq) are present, but no samples are currently available from these localities. The map in based on work by the Geological Survey of Denmark and Greenland (GEUS).

important economic implications, given that Ni and platinum-group element (PGE) mineralisation is typically hosted by ultramafic cumulates e.g., [82,77]. In either case, these peridotites and the associated norites, orthopyroxenites, and mafic supracrustal rocks, which are also found as related belts and slivers within these TTG-suite orthogneisses, may yield important new insights into the crustal evolution of the North Atlantic craton. In this contribution bulk-rock and mineral geochemical data for the peridotites are presented with the aim of elucidating the petrogenesis of the ultramafic components of the Akia terrane.

## 2. Regional geology

Fiskefjord is located in the northern part of the Nuuk region and cuts through Mesoarchaean orthogneisses of the Akia terrane. The present study describes peridotites found along the Fiskefjord, as well as at the Seqi and the Amikoq localities to the north and south, respectively (Fig. 1). At the Amikoq locality, the peridotites crop out together with intercalated norites and orthopyroxenites, which based on their close association, appear to be co-genetic [39]. This inference is supported by the observation of a similar intimate association of these particular lithologies at the Miaggoq and Ulamertoq localities. However, no data is presently available from these two peridotite bodies.

The Nuuk region consists of several discrete crustal terranes, with the oldest being the over 3600 Ma Itsaq gneiss complex [87], that were ultimately amalgamated during the Neoarchaean [34,86]. A recent study by Dziggel et al. [29] interpreted this region as comprising paired metamorphic belts, implying that the amalgamation occurred in an accretionary setting. Peridotites are also reported within the Itsaq gneiss complex, but these are not as extensive as those of the Akia terrane and appear to be directly associated with anorthosite and gabbro. Thus, the peridotites of the Nuuk and Akia terranes appear to be of different origins [14,36,98,97]. A recent overview of the igneous and metamorphic history of the Akia terrane can be found in Garde et al. [43]. Below we outline the main geological features that are relevant for understanding the Fiskefjord region peridotites.

The regional TTG-suite orthogneisses of the Akia terrane, which host the Seqi-Amikoq association of peridotites and supracrustal rocks, have been dated by U-Pb in zircon at ca. 3050–3000 Ma [39,40]. Subordinate dioritic gneisses have magmatic ages of about 3200 Ma, and represent local pre-existing crust [39]. The amphibolite-facies supracrustal rocks that are present within the Akia orthogneisses have been dated directly at ca. 3071 Ma using magmatic zircon extracted from a volcano-sedimentary schist found within the mafic to andesitic Qussuk–Bjørneøen volcanic sequence [40]. Aluminous schists present in the Qussuk sequence have been proposed to represent metamorphosed hydrothermally altered basalt [41]. Such lithologies are also present within the Amikoq complex [2], and are also found in the Storø supracrustal belt about 10 km southeast of the Qussuk peninsula [104,110]. Leucocratic fragmental amphibolites of the Qussuk sequence have been proposed to represent analogues of modern andesites, and are inferred to have formed in an arc-related setting [40]. Andesites are also found in the Ivisaartoq supracrustal belt about 50 km east of Qussuk [94], and similar andesites are even relatively common (comprising ca. 50% of the volcanics) within the Mesoarchaean Tasiusarsuaq terrane of SW Greenland [106,108]. All of the above is consistent with the operation of Mesoarchaean subduction zones in this region, as also concluded by Windley and Garde [118] in a recent review of the geology of the North Atlantic craton.

The Akia terrane experienced granulite-facies metamorphism with local retrogression to sillimanite-grade amphibolite-facies at 2995–2975 Ma. Re-crystallisation of zircon, synkinematic intrusion of granite sheets, and isoclinal folding of the older diorites and early amphibolites was associated with this event [39,40,42]. A U-Pb age of 2990 ± 13 Ma was obtained on zircon from the Amikoq complex by Nilsson et al. [85], but this age likely reflects mineral growth associated with regional metamorphism.

The magmatic age of the peridotites of the Seqi-Amikoq association is likely close to that of the supracrustal rocks, with which they are intercalated. The age of 3071 Ma for the above-mentioned volcano-sedimentary schists in the Qussuk–Bjørneøen sequence, appears to be the maximum age, because norites and orthopyroxenites associated with the peridotites of the Amikoq complex are apparently intrusive into the folded mafic supracrustal amphibolites [2,50]. This would constrain the age of the Amikoq complex rather tightly at 3071–3050 Ma, depending on the exact age of the locally intruding regional TTG-suite orthogneisses. However, further field work is needed in order to establish the detailed relations between the supracrustal amphibolites and the norite–peridotite association with greater confidence. Despite the fact that the largest peridotite body of the Fiskefjord region (known as Seqi) has recently been mined by the Swedish company Minelco, no scientific studies currently exist on these peridotites or the associated norite and orthopyroxenite suite. A few internal company reports have been released, which mainly deal with the technical aspects of mining [23,24,76,26], and environmental issues [3,102]. However, none of this work considered the petrogenesis of the peridotites or the associated rocks. Garde [39] published data for a few peridotite samples from the Akia terrane, but focusing on the hosting TTG-suite orthogneisses. The unpublished M.Sc. thesis of Tine Kristensen [70] currently represents the only detailed petrological work on the peridotites of the Amikoq complex.

## 3. Samples and petrography

The peridotites examined in this study were collected along the shore of Fiskefjord, within the Seqi olivine mine, and from the Amikoq complex (Fig. 1). GPS-positions of the samples are listed in Supplementary Tables S1 and S3. In the following, a description of these peridotites and their main petrographic features are presented. To simplify the classification in this study, two main groups of rocks are distinguished, namely (1) dunites from the Seqi Olivine Mine and (2) various types of peridotites found along Fiskefjord and in the Amikoq complex. Throughout this study, the latter two areas are collectively referred to as the 'Fiskefjord peridotites', whereas the term 'Fiskefjord region peridotites' is used for all of these rocks including the Seqi dunites.

The peridotites from the Seqi Olivine Mine are dominated by dunites, whereas the Fiskefjord peridotites comprise both dunites and amphibole-bearing harzburgites. The latter are commonly associated with norites, and minor orthopyroxenite layers are also present. However, the focus of the present study is exclusively on the geochemistry of the peridotites, and we rely on previously published data for the norites, orthopyroxenites and the associated supracrustal rocks [39,40,70].

The dunites of the Seqi Olivine Mine (Fig. 2a) consist of olivine with locally abundant intergranular chromite (Fig. 2b). The grain size varies from medium to coarse and Dahl [26] identified several distinct dunite 'facies' within the mine, such as 'homogenous', 'layered' and 'porphyroblastic' dunites, which some examples shown in Appendix A. Most dunites have granoblastic textures with equilibrated 120° triple junctions between olivine grains (Fig. 3a and b). Talc is present as a minor component and is sometimes visible along olivine rims. Chromitite layers up to 30 cm thick are observed along the north-eastern margin of Seqi and can be traced for tens of metres (Fig. 2c). These chromitites commonly show rhythmic alternation between delicate chromite- and olivine-rich laminae, which can be trace for several metres. Some of these chromitite layers are tightly folded and display complex buckling (Fig. 2d). We present additional field photographs from the Seqi Olivine Mine in Appendix A.

The peridotites found along Fiskefjord and in the Amikoq complex commonly have thin extensive layers of chromitite (Fig. 3c and d) and are generally orthopyroxene (opx) rich (Fig. 3e and f). These harzburgites have textures that range from proto- to equigranular cf. [79], and are much more diverse mineralogically than the Seqi dunites. Opx is mostly poikilitic and amphibole is abundant in some parts of the peridotite layers (Fig. 3g and h). Amphibole is also observed as cm-thick layers and irregular aggregates within the Fiskefjord peridotites, but it is not obvious if these are igneous or metamorphic features, as these rocks presently display amphibolite-facies mineral assemblages. Plagioclase is only rarely observed in the peridotites, even when these are in direct contact with norites. Talc is present as individual crystalline grains in some samples. Chlorite, serpentine and coarse talc are commonly present in peridotites that are associated with crosscutting granitoid sheets and late faults at all of the peridotite localities.

## 4. Methods

A brief summary of the analytical procedures employed in this study is presented below. For a more detailed description, the reader is referred to the Appendix B. Bulk-rock major and trace element data was acquired for ten of the most refractory peridotites by inductively coupled plasma (ICP) methods from Acme Labs, Vancouver (see Table S1). The trace element abundances for these samples were re-analysed at Lamont–Doherty Earth Observatory (LDEO) to obtain better precision due to the low incompatible trace element concentrations (Table S2). The remaining samples in our data set were measured for their bulk-rock major element compositions by X-ray fluorescence (XRF) at the Geological Survey of Denmark and Greenland (GEUS) [72]. Trace element data for these samples were also obtained at GEUS by solution ICP-MS using the fused borate discs from the XRF analysis (Table S3).

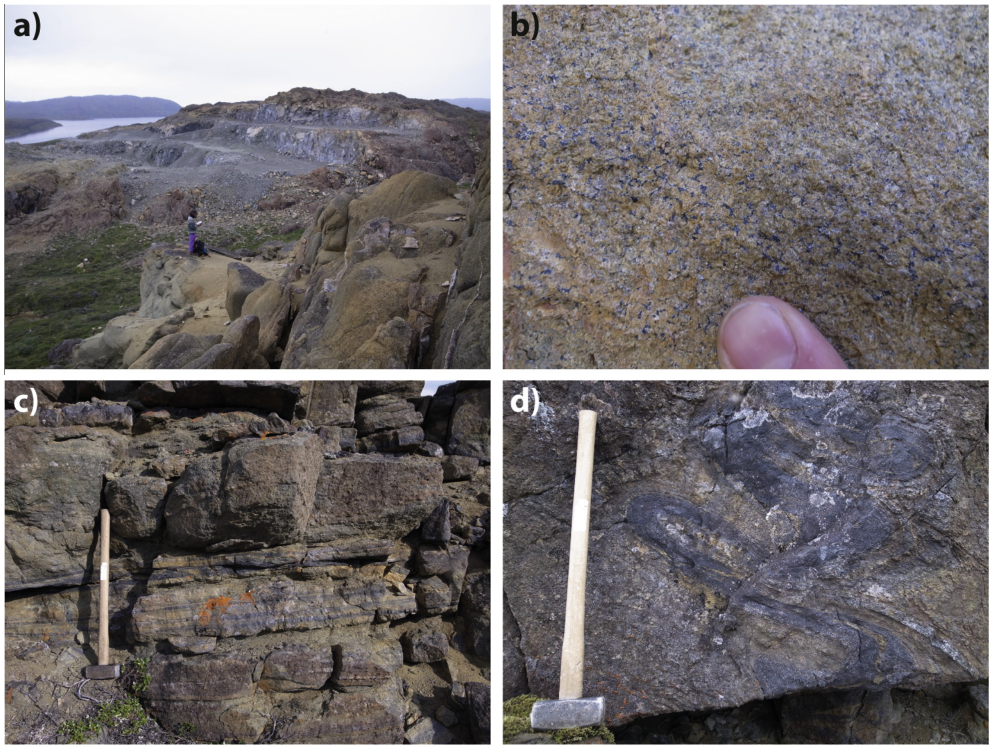


**Fig. 2.** Field photos from the Seqi Olivine Mine. (a) Overview of Seqi looking west. Person for scale. (b) Close-up of dunite with abundant intergranular chromite. Finger for scale. (c) Horizontally layered chromitite layers in dunite at the north-eastern margin of Seqi. The individual layers can be traced for tens of metres. Hammer is 65 cm tall. (d) Tightly folded and buckled chromitite band from the north-eastern margin of Seqi. In places ductile rupture of such layers is also observed. Hammer for scale is 65 cm tall. We present additional field photographs from the Seqi Olivine Mine in Appendix A.

Platinum-group element data (Table S4) were obtained at Université du Québec à Chicoutimi (UQAC) by NiS-FA followed by MC-ICP-MS measurement. See Appendix B for a summary or Savard et al. [100] for a full description of the analytical protocol.

Electron microprobe analysis of minerals (representative data available in Table S5) was conducted on a Cameca SX-100 at the American Museum of Natural History (AMNH), New York, and on a JEOL JXA 8200 at the Geological Institute, Copenhagen (GIC). Peak counting times at AMNH were 40 s for Si, Mn, Ti, Al, Ca, Fe, Cr, Mg, Ni, Zn, 10 s for Na and 20 s on the background. At GIC peak counting times were 20 s for all elements, except for Cr and Ni, which were measured for 40 s, and background times were 20 s. A voltage of 15 kV and a beam current of 20 nA (1 μm diameter) was used at both AMNH and GIC. Several common mineral standards were measured at each session to verify the accuracy of the analyses.

All of the data obtained for this study are provided as Supplementary material (Tables S1–S5). The freeware program GCDkit of Janošek et al. [59] was used to plot the geochemical-diagrams for this paper.

## 5. Results

### 5.1. Major and trace element data

The Seqi dunites ($n = 10$) have MgO ranging from 48.6 to 53.2 wt.%, $SiO_2$ from 40.8 to 41.9 wt.%, FeOt from 5.29 to 8.75 wt.%, and $Al_2O_3$ from 0.20 to 1.10 wt.% (Fig. 4). The bulk-rock Mg# of the dunites (assuming $Fe^{2+}$ is 100% of total Fe due to the olivine-rich nature of these rocks) ranges from 90.8 to 94.7 with a median value of 92.3. They have $CaO/Al_2O_3$ ratios less than 1.21 and $Al_2O_3/TiO_2$ ratios with a median value of 48.5. The dunites generally have negative Eu-anomalies with Eu/Eu* from 0.36 to 1.02. Their rare earth element (REE) patterns are U-shaped with negative LREE slopes ($La_N/Sm_N$ from 1.05 to 3.15) and positive HREE slopes (Fig. 5a). All of the dunites have large positive Pb-anomalies and one sample (Seqi-1) has an anomalously positive Zr and Hf peak.

The Fiskefjord peridotites ($n = 19$) have MgO ranging from 33.1 to 46.0 wt.%, $SiO_2$ from 37.0 to 50.8 wt.%, FeOt from 6.18 to 19.3 wt.%, and $Al_2O_3$ from 1.24 to 5.16 wt.% (Fig. 4). The bulk-rock Mg# of the peridotites ranges from 77.4 to 92.4 with a median value of 83.8. They have $CaO/Al_2O_3$ ratios less than 1.50 and $Al_2O_3/TiO_2$ ratios with a median value of 64.5. The peridotites generally have negative Eu-anomalies with Eu/Eu* from 0.44 to 1.3 (only three samples have positive Eu/Eu*). Their REE patterns are U-shaped with negative LREE slopes ($La_N/Sm_N$ from 0.94 to 4.5) and positive HREE slopes (Fig. 5b). The peridotites also have a strongly positive Pb-anomaly, in addition to common positive Ti, Zr, and Hf anomalies.

### 5.2. Platinum-group element data

Platinum-group element (PGE) data was obtained for five Seqi dunites and five Fiskefjord peridotites. There are no systematic patterns for their PGEs, which are rather variable (Fig. 6). Broadly speaking, the chondrite-normalised PGE patterns are not very different between the two groups, except that Pd-concentrations are below the detection limit of 0.47 ppb in all of the Seqi dunites, but higher for the Fiskefjord peridotites. The Os contents range from 1.79 to 9.21 ppb for the dunites and from 0.75 to 9.34 ppb for the peridotites. Ru forms a tight range from 4.87 to 8.81 ppb for our samples. Interestingly, samples with measurable Rh concentrations have distinctly negative Rh-anomalies except for one sample (482032).

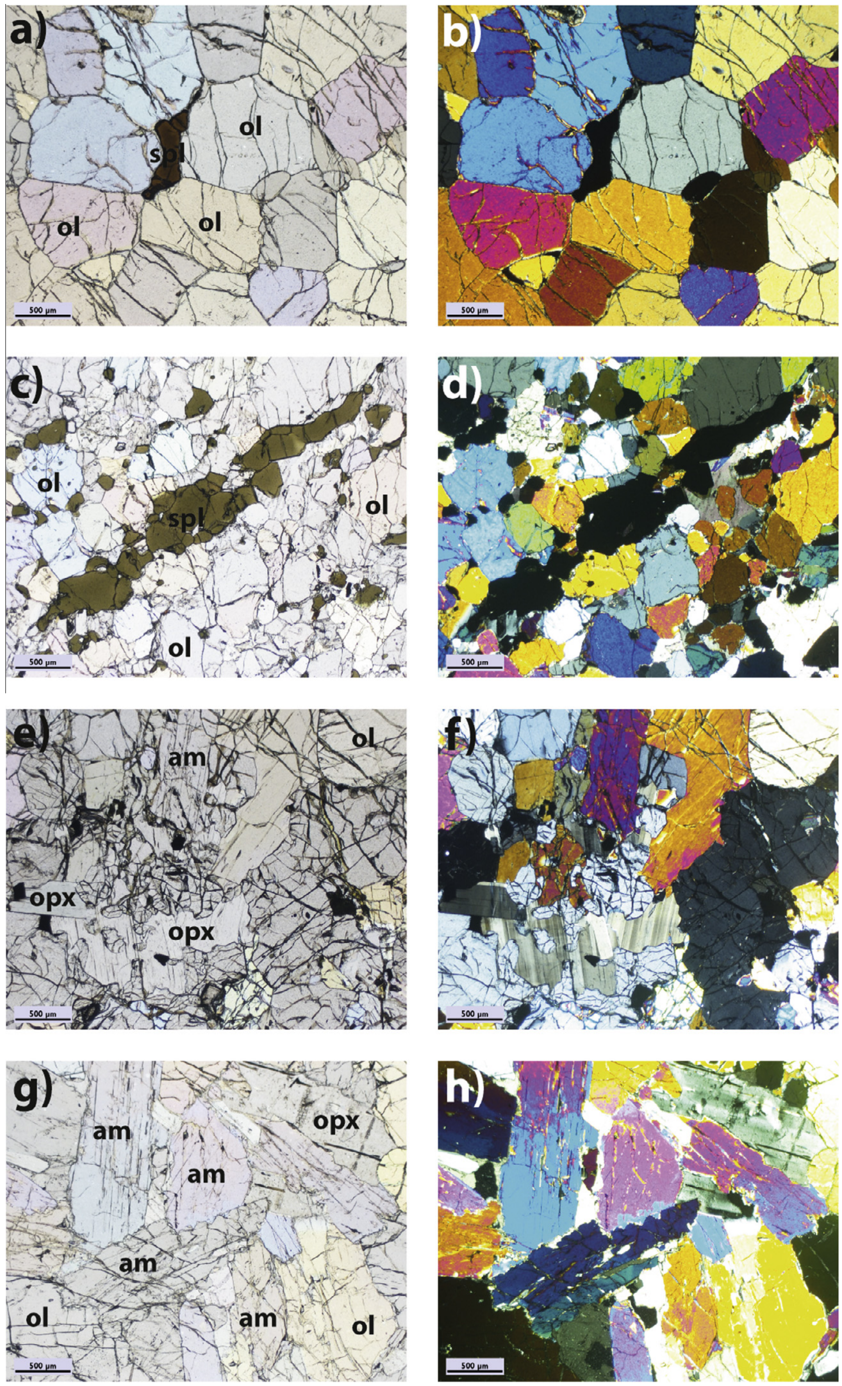


**Fig. 3.** Microphotographs showing the mineral textures of the Fiskefjord peridotites. (a) Granoblastic dunite from Seqi in plane polarised light (sample Seqi-2). Note the 120-degree angles between the individual olivine grains. (b) Sample Seqi-2 with crossed polarizers. (c) Peridotite from Fiskefjord with chromite layer under plane polarised light (sample 482065). (d) Sample 482065 with crossed polarizers. (e) Fiskefjord amphibole-bearing harzburgite under plane polarised light (sample 482006). (f) Sample 482006 with crossed polarizers. (g) Fiskefjord amphibole-bearing harzburgite under plane polarised light (sample 482041). (h) Sample 482041 with crossed polarizers.

### *5.3. Electron microprobe mineral data*

The olivine compositions of the Seqi dunites form a tight cluster in terms of their fosterite contents as is seen in Fig. 7a. Fosterite calculated as (Mg# = 100 × molar Mg/(Mg + $Fe^{2+}$)) range from 91.1 to 93.7, with a median value of 92.6 ($n$ = 469). The NiO contents of the olivine range from 0.32 to 0.52, with a median value of 0.43 wt.% (3369 ppm). The Fiskefjord peridotites show a broader range of olivine compositions with fosterite ranging from 83.2 to 92.4, with a median values of 89.2 ($n$ = 356). Overall, the NiO contents of the olivine in the Fiskefjord peridotites range from 0.23 to 0.59, with a median value of 0.41 wt.% (3236 ppm). NiO is positively correlated with fosterite content. Individual olivine grains are essentially unzoned, although some have slighter elevated Mg# at their rims when they are found adjacent to chromite or magnetite as a result of subsolidus exchange.

The spinel data were first filtered by excluding analyses with Si + Na > 0.05 counts per formula unit (cpfu), given that these

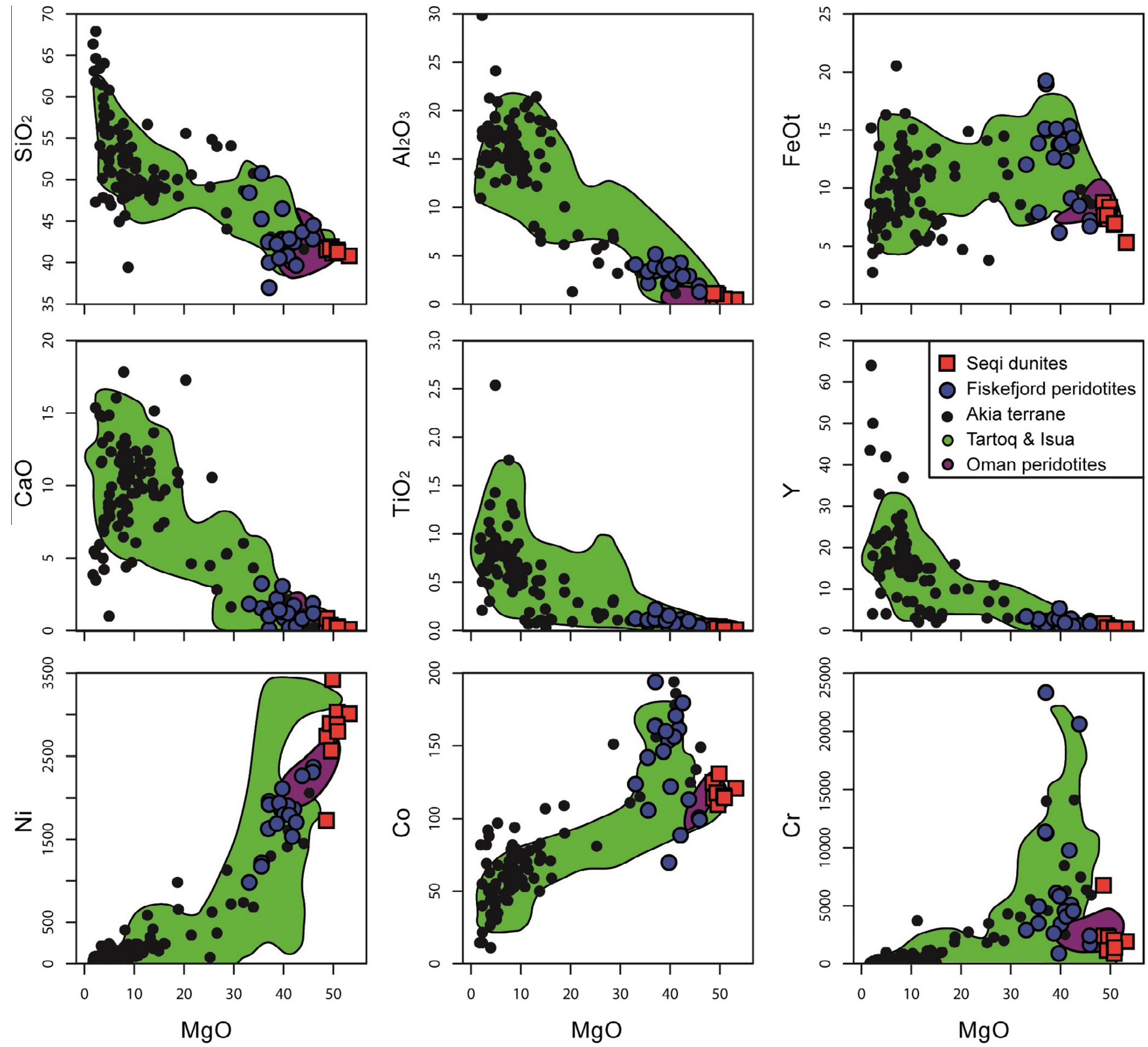


**Fig. 4.** Major and trace element variation plotted as a function of MgO. Major elements are given in wt.% and trace elements in ppm. The dunites from Seqi are shown as red squares and the various Fiskefjord peridotites are shown as blue circles. Data for undifferentiated mafic to ultramafic rocks from the Akia terrane (black dots) are from Garde [39], Garde [40] and Kristensen [70]. The green field in the background outlines data from the Meso- and Eoarchaean Tartoq and Isua assemblages [112,111] and references therein. Note that the geochemical variation of the Akia association shows similar trends. The purple field represents examples of mantle peridotites from the Oman ophiolite for reference [45,48].

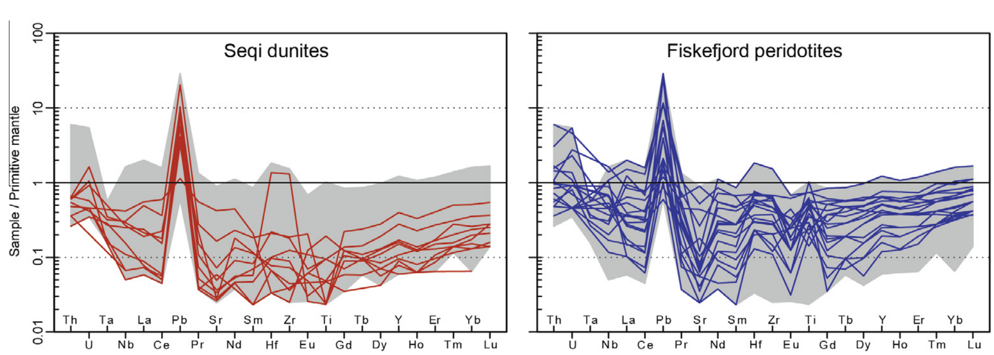


**Fig. 5.** Primitive mantle-normalised multi element diagram showing the depleted patterns for the the Seqi dunites and the Fiskefjord peridotites. Note the consistent positive Pb-anomalies, which may have been derived from the adjacent orthogneisses. The obvious positive Hf, Zr, and Ti anomalies for the Fiskefjord peridotites, may be related to accessory ilmenite or a similar phase (see main text). The grey field shows the total range of the data. PM-values are from Palme and O'Neill [91].

two elements are incompatible in the spinel structure and therefore likely reflect inclusion-rich grains. Additionally, a criterium of Fe-total >1 cpfu was used to exclude metamorphic magnetite. A metamorphic origin of these grains is supported by their elevated Mn, Zn and Ti and by their low Mg and Al contents, which is typical for disturbed spinel cf. [25]. This cut-off value happens to

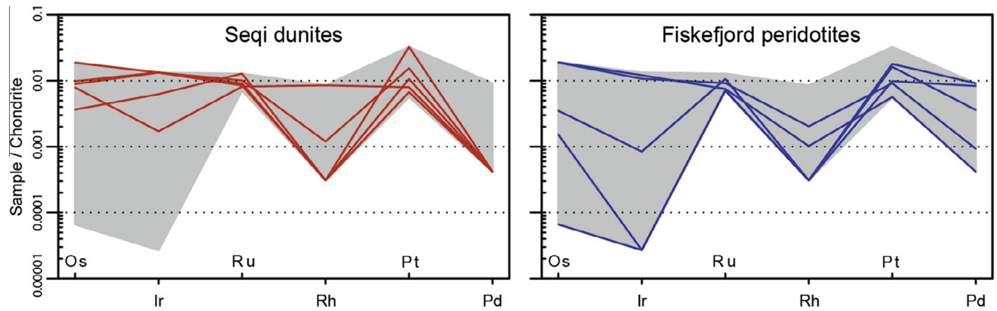


**Fig. 6.** Platinum-group element patterns normalised to chondrite [33]. The Rh-depletion may be corresponding to Rh-rich mineralisation found within norites of the Amikoq complex (see Section 6.2). The grey field shows the total range of the data. Please note where an element was found to be below the detection limit (DL), its presence at half of that value is assumed in order to plot coherent patterns. The respective DLs can be found in Table S4.

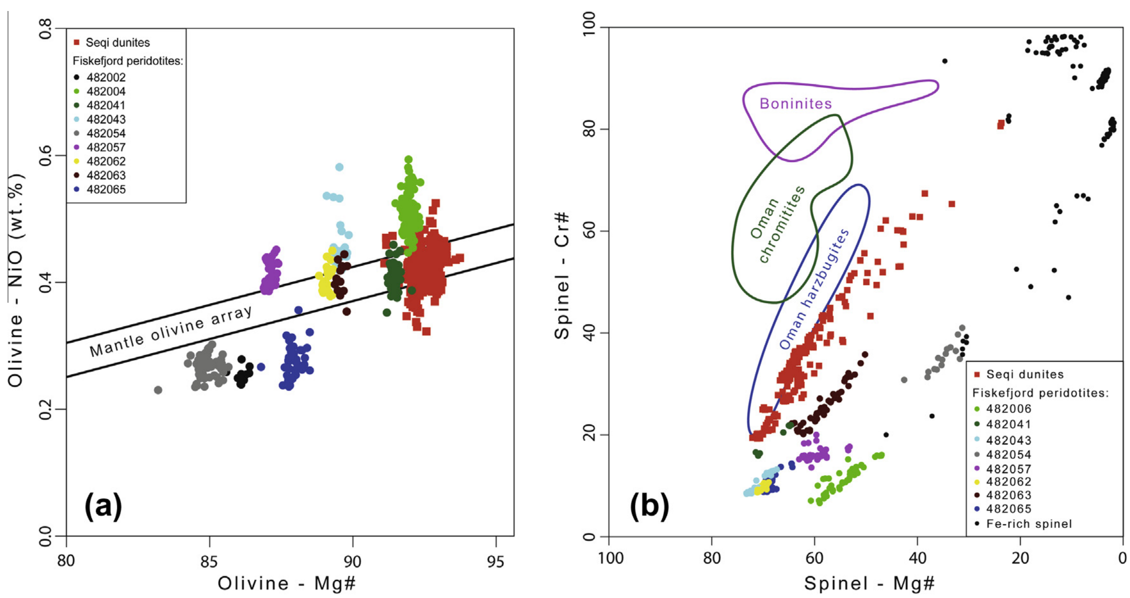


**Fig. 7.** Olivine and chromite compositions of the Fiskefjord region peridotites. (a) NiO (wt.%) in olivine versus their fosterite contents (Mg#). Note the tight range for the Seqi dunites with a median Mg# of 92.6. The mantle array is from Takahashi et al. [114]. (b) Cr# in spinel vs. Mg# in spinel showing a distinct trend for the Seqi dunites relative to the rest of the Fiskefjord samples, each of which has been marked with a different colour. The fields of Oman harzburgites and chromitites are from Rollinson [96] and the boninite field is from Ishikawa et al. [57]. Please note that the two legends do not use the same colour coding for the different sample numbers.

coincide with an $Fe^{3+}$# < ca. 15, which is similar to values reported to potentially discriminate between metamorphic and primary igneous compositions [52,16]. This effectively filters out $Fe^{3+}$-rich spinel (magnetite) that may have formed during metamorphism of the peridotites. We plot these filtered spinel data in the diagram of Fig. 7b, but also show the high-Fe analyses (black dots). $Fe^{3+}$# is calculated (assuming stoichiometry) according to the following formula: $Fe^{3+}\# = 100 \times$ molar $Fe^{3+}/(Fe^{3+} + Al + Cr)$. The Cr# of the spinel is calculated as $Cr\# = 100 \times$ molar $Cr/(Cr + Al)$. Spinel is generally zoned with higher Cr# and lower Mg# rims and vice versa for their cores; however the opposite case was observed for sample Seqi-2. The chromite in the Seqi dunites fall on a trend that is distinct from those of the Fiskefjord peridotites (Fig. 7b). The Cr# of the Seqi dunites ranges from 19.3 to 81.3, whereas the Fiskefjord peridotites have Cr# ranging from 6.6 to 41.0. Their Mg#s range from 23.9 to 72.1 and 31.3 to 73.3, respectively. Temperatures based on Fe–Mg exchange of olivine-spinel mineral pairs were calculated according Ballhaus et al. [5] and ranges of 502–545 °C (sample 482032) and 535–541 °C (sample Seqi-2) were found. Fig. 8 shows a plot of the above-mentioned olivine-spinel pairs from the Seqi Olivine Mine relative to the olivine-spinel mantle array (OSMA) of Arai [1]. Sample 482065 contains abundant ilmenite, but also has magnesian chromite (Fig. 7).

The pyroxene in the Fiskefjord peridotites are nearly pure enstatite, with a median component of $En_{88.0}$, $Fs_{11.5}$, and $Wo_{0.55}$. $Na_2O$ is below 0.04 wt.%, $TiO_2$ is less than 1.6 wt.%, the median $Al_2O_3$ contents is 2.5 wt.% and the median $Cr_2O_3$ contents is 1.5 wt.%. The pyroxene has Mg# ranging from 82.1 to 92.8 (median of 88.2).

Only two samples from Seqi (Seqi-1 and 482033) contain amphibole. The former contains mainly magnesio-hornblende, whereas the latter contains tremolite. Several of the Fiskefjord peridotites contain amphibole, and are dominated by magnesio-hornblende with some tremolite, while sample 482057 is the only sample to contain significant amounts of pargasite. The amphibole have MgO contents of 17.2 to 24.3 wt.% and Mg# > 83.7 (median 88.5). They have highly variable $Al_2O_3$ ranging from 0.09 to 13.2 wt.%, but constant CaO of 11.1 to 13.6 wt.%. Their median $TiO_2$ contents is 0.66 wt.% and their median $Cr_2O_3$ is 0.5 wt.%.

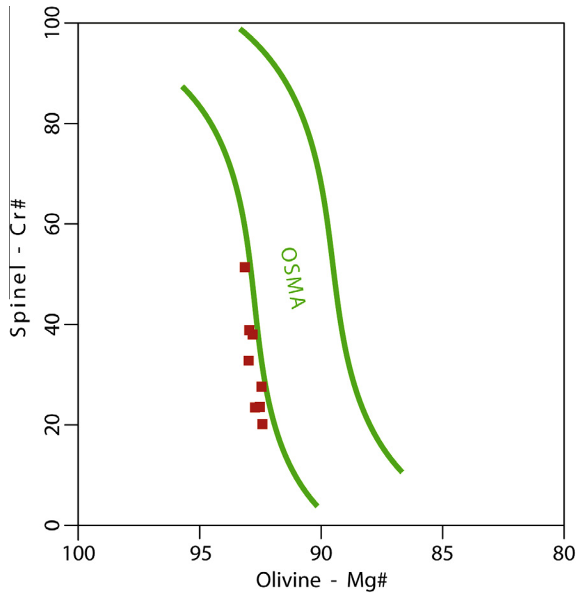


**Fig. 8.** Plot of olivine–chromite pairs from the Seqi Olivine Mine (red squares) showing some variation in spinel Cr# at essentially constant olivine Mg#. Olivine-spinel mantle array (OSMA) from Arai [1].

## 6. Discussion

### 6.1. Major and trace element variation

In most bivariate plots, the Fiskefjord region peridotites form an array extending from about 50 wt.% MgO towards the regional mafic rocks of the Akia terrane (Fig. 4). The Seqi dunites are generally more refractory than the Fiskefjord peridotites in terms of their major element compositions, and their incompatible trace element contents are also significantly lower (Fig. 5). Such refractory compositions are consistent with the very large proportion of modal olivine in the rocks, which is not capable of hosting incompatible trace elements. The elevated high-field strength element (HFSE) content that is seen as positive anomalies in several of the peridotites likely reflects an accessory mineral that has yet to be identified, because these elements are not compatible in either olivine or chromite (cf. GERM database; [55]).

The rocks of the Akia terrane have experienced a complex metamorphic history, with potential early hydrothermal alteration followed by granulite-facies metamorphism and then retrogression to amphibolite-facies conditions. Given that the incompatible trace element abundances for these ultramafic rocks are rather low, and generally below the values for primitive mantle, one has to be careful not to over-interpret their geochemical features, as these compositions would be susceptible to subsequent modification during alteration and metasomatism. Both groups of ultramafic rocks have relatively depleted trace element compositions, but have slightly enriched LREE, Th, U, and Nb, which give them U-shaped trace element pattern. This could either be the result of overprinting by a melt-component (inter-cumulus liquid?), or it could reflect the composition of the magma from which these peridotites may have been derived. Those particular elements (except for U) are unlikely to have been transported by metamorphic fluids as they are generally immobile [75]. In contrast, the strongly positive Pb-anomalies and U could easily have been added from the surrounding TTG orthogneisses, either during their intrusion at ca. 3050 Ma or during the regional metamorphic event at ca. 2975 Ma. The preferential addition of Th over Nb could perhaps be indicative of the involvement of supercritical fluids rather than a melt-component, because the latter would not be expected to fractionate these incompatible elements significantly [63].

We have tested a simplified inversion model of the trace element compositions of the Seqi dunites (cf., [10]). Because these rocks are absolutely dominated by olivine (>95% modal contents), the composition of the melt from which they crystallised could potentially be calculated by applying appropriate partition coefficients, under the assumption that no high-D accessory minerals or interstitial melt was originally present in these rocks. However, these assumptions are not supported by the modelling, because the results yield REE abundances up to two orders of magnitude higher than those observed for the associated mafic supracrustal rocks of the Akia terrane. This suggests a significant proportion of trapped interstitial liquid. However, given the complicated history of these dunites, it is virtually impossible to make any meaningful interpretation of this discrepancy, other than acknowledging that they were likely affected by significant early metasomatism and/or modified by trapped interstitial liquids.

It is interesting to note that there appears to be a peak in the Cr-contents of the Fiskefjord peridotites at about 40 wt.% MgO (Fig. 4). Cr is to some extent positively correlated with the $Al_2O_3$, FeOt, $TiO_2$, and V contents of the peridotites, which is consistent with their presence in chromite. The positive HFSE-anomalies (Hf, Zr, and Ti), which are also observed for the Seqi dunites are particularly obvious for the Fiskefjord peridotites (Fig. 5). These cannot be explained by the higher modal chromite contents in these compared to the Seqi dunites, because these elements are generally incompatible in chromite [55], as also mentioned above. The HFSE may therefore be hosted by a yet unidentified accessory phase, although it should be noted that ilmenite is present in some of the samples and that this mineral may in fact represent a suitable host for these particular elements.

Several thin, parallel chromitite layers can be traced for tens of metres, and some layers appear to have been strongly folded and even buckled prior to complete solidification of their olivine host rock (Fig. 2c and d). This deformation would likely have taken place under very hot conditions, because dunite behaves in a competent manner during the regional metamorphism. We consider this type of tight folding to be potential evidence of syn-magmatic deformation, because they do not follow the regional structural patterns. This would be consistent with a cumulate origin for these peridotites.

The geochemical variation seen for the Fiskefjord region peridotites and the regional Akia data is similar to what was reported recently for the ca. 3200 Ma Tartoq Group and the >3700 Ma Isua supracrustal belt (Fig. 4), which are also located in the North Atlantic craton of SW Greenland [112,111]. These studies concluded that olivine-dominated fractional crystallisation was able to explain the evolution of those tholeiitic and boninitic magmas. It was suggested that the observed compositions of those serpentinites are due to their formation as products of crystal fractionation coupled with melt-rock interaction. A similar major element variation is observed for the Akia regional data combined with the data for the Fiskefjord region peridotites reported in the present study (Fig. 4). This supports a strong control by fractional crystallisation processes on the geochemical variation for the mafic to ultramafic enclaves found within the orthogneisses in this region. A cumulate model for the Fiskefjord region peridotites is explored further in Section 6.4.

### 6.2. Platinum-group element patterns

The PGE distribution in ultramafic rocks can be used as a petrogenetic tool to distinguish between mantle, magma and cumulate rocks [53,54,8]. Nevertheless, the PGE patterns of the

Fiskefjord rocks are not easily interpreted in this way. A few of these peridotites have flat to slightly negative slopes for the IPGEs at around 0.01 times chondrite, which is common for mantle rocks. However, they all have negative Rh-anomalies in combination with mantle-like Pt contents. One sample (Seqi-2) has a positive slope, which is typical of magmas or their derivative cumulates, and this sample also has the unusual depletion in Rh. The remaining three samples have negative Ir-anomalies, which is typical of cumulates. Neither Pd nor Rh form alloys, whereas IPGEs are compatible in olivine and Ru in chromite [18,80]. Thus, the PGE patterns of the Fiskefjord region peridotites are overall compatible with a cumulate origin controlled by the accumulation of olivine plus chromite and perhaps associated alloys or platinum-group element minerals.

The consistently negative Rh-anomalies in the peridotites (Fig. 6) is interesting because Rh-rich mineralisation (up to 187 ppb) is reported to be hosted by norites (feldspatic pyroxenites) in the Amikoq complex [50]). Thus, it appears that at least some of the PGEs may have been distributed according to local fractional crystallisation processes, which led to the differentiation of peridotites, norites and orthopyroxenites in the Fiskefjord region. Unfortunately, currently no PGE data is available for the chromitite layers hosted by the Seqi dunites, but it is not unlikely that these could also host PGE mineralisation (e.g., [30,65,69,20]. Interestingly, the dunites all have Pd contents below the detection limit, which may thus be concentrated elsewhere in the magmatic system perhaps as a result of sulfide saturation (cf., [74]. However, sulfides are not common in these rocks and fractional crystallisation processes involving silicates, oxides and perhaps platinum-group minerals appear to have controlled the PGE distribution. Alternatively, the low Pd contents may reflect loss of sulfide during the peak granulite-facies metamorphism.

Chromitites found within mantle rocks are mostly of the podiform type, although layered examples are also found, but their petrogenesis is still debated. Podiform chromitites in the mantle are believed by some to have formed by redox changes or by replacive processes [90,4,46], whereas stratiform chromitites are thought to form by fractional crystallisation processes typically involving some wall-rock assimilation [103]. The latter would be consistent with the observation that the chromitites of the Seqi body appears to be constrained to the present north-eastern margin at the contact to the TTG-gneisses. The chromitites also occur as distinct horizons that may display early folding or perhaps even slumping and rupture during magmatic conditions. However, there are no accepted diagnostic differences between mantle and cumulate chromitites, and thus even the above field observations are non-unique.

### *6.3. Mineral compositions*

It cannot be ruled out that the Fiskefjord region peridotites may have experienced significant serpentinisation at some early stage in their complex history and later olivine-growth during peak granulite-facies metamorphism. This would obviously affect the significance of the observed spinel and olivine compositions. The Seqi olivine form a very tight range of Mg#, but have rather variable NiO concentrations (Fig. 7a). It is worth noting that mantle xenoliths in the North Atlantic craton have refractory olivine compositions, which in some cases average 92.8 [15,16]. This value is surprisingly similar to the median value of 92.6 that is reported here for the Seqi dunites. Such highly magnesian olivine compositions could either reflect derivation from some form of high-Mg mantle-derived magma, very large degrees of melt extraction from a mantle residue, or alternatively subsolidus/metamorphic overprinting. However, as pointed out above, the Fiskefjord region peridotites likely represent cumulates rather than mantle residues, because of their close association with noritic cumulates and due to their major element systematics (see Section 6.1). They could have formed via crystal fractionation of high-Mg magmas like komatiites, but such rocks are not known from the Fiskefjord or Nuuk regions, or even elsewhere in the North Atlantic craton. Mantle plume-related volcanism has so far not been documented in the Archaean rock record of this region, as OIB-type volcanics are not present [39,113]. A dry magma origin is not supported by the late crystallisation of plagioclase and the presence of amphibole/clinopyroxene in the Fiskefjord rock association, as we will discuss in more detail in Section 6.4 below.

All of the Fiskefjord region peridotites have spinel compositions which are distinctly different from the mantle harzburgite array e.g., [27,96], and none of the spinel analyses plot anywhere near the field of boninites. Fig. 7b shows that the spinel compositions of the Seqi dunites plot outside of the mantle field, but are within the range of spinel from tholeiitic basaltic magmas (not shown), based on the global data of Barnes and Roeder [7]. The spinel of the Fiskefjord peridotites also plot outside of the mantle field, but these are generally not as Cr-rich as spinel from basaltic rocks. This appears to be consistent with a cumulate origin for these peridotites. However, metamorphic spinel also show similar trends, which extend towards the Fe–Cr-rich corner [7]. In particular, the high-Fe analyses, which also have elevated $Fe^{3+}$# (>15) are typically interpreted to represent overprinted spinel, which is observed even in fresh peridotites e.g., [52,89,44]. This could indeed be due to low temperature Fe–Mg exchange between olivine, spinel and perhaps low-T metamorphic phases, such as chlorite, talc or serpentine. The relatively low temperatures recorded by Fe–Mg exchange between olivine and spinel (see Section 5.3) clearly indicates subsolidus metamorphic equilibration. This is supported by the trends that are seen in Fig. 7b, which are typical of amphibolite-facies metamorphic disturbance of chromite in metaperidotites [31,88,7,99,9]. Therefore, it does not appear likely that the highly fosteritic olivine compositions are a primary igneous feature, but it may rather reflect the interplay between the olivine-rich refractory bulk-rock composition of their host rocks and metamorphic and subsolidus re-equilibration.

Applying the relations of Roeder and Emslie [95] for olivine-liquid equilibria would require highly magnesian magmas with FeOt/MgO ratios as low as 0.36, in order to produce the most fosteritic olivine observed among the Seqi dunites (up to $Fo_{93.7}$). As mentioned above, ultramafic volcanic rocks, such as komatiites, are not observed in the Akia terrane according to Garde [39]. Additionally, Fe–Mg has notoriously fast diffusivity in olivine [38]. Therefore it seems more likely that the highly fosteritic olivine are the result of metamorphic Fe–Mg exchange between olivine and spinel. This is consistent with the obvious trends of Fe-enrichment that are seen for the spinel in Fig. 7b. Similar ferrichromite formation is even observed in fresh peridotites, such as those of the Thetford Mines Ophiolite Complex [89].

The origins of amphibole in the Fiskefjord peridotites is not well constrained by the available data, as they could represent either metamorphic or primary igneous minerals. Similar compositions are known from the Mesoarchaean Fiskenæsset Anorthosite complex, which is also found in SW Greenland. Huang et al. [56] concluded that the magnesio-hornblende found in Fiskenæsset peridotites was of primary igneous origin, and not metamorphic, based on their trace element compositions. They inferred that amphibole had crystallised after olivine and pyroxene, but before plagioclase. This crystallisation order is also possible for the Fiskefjord region association of peridotites and norites. However, trace element data are currently unavailable for the amphibole in these peridotites and thus their origin cannot be constrained further. It should be noted that late faults within the Seqi Olivine

Mine are typically lined with bright green amphibole (see Appendix A), so at least some amphibole is likely to be secondary/metamorphic in origin. Therefore, it is possible that some amphibole formed by metamorphic reactions between fluid, opx and chromite, or alternatively these may represent retrograde metamorphic hydration of primary clinopyroxene (cpx).

### 6.4. Petrogenesis of the Fiskefjord region peridotites

As stated above, we lean towards a cumulate rather than a mantle origin for the Fiskefjord region peridotites based on several lines of evidence presented in this study. First of all, the arrays seen in the major element data, which are spreading out from about 50 wt.% MgO (Fig. 4) is not typical of mantle residues, but is consistent with fractional crystallisation (olivine + opx) in addition to melt-rock interaction. The elevated FeOt content (up to 19 wt.%) of these peridotites is also not typical of mantle rocks, not even for melt-modified dunites cf. Hanghøj et al. [48]. However, elevated Fe is rather common for ultramafic cumulates [83,61,73,115,58]. A cumulate origin may be supported by the field observations of ductile deformation of laterally extensive, parallel layers of chromitites within the dunites, although some mantle sections also display such layered chromitites. The association of the peridotites with norites that have clearly interstitial plagioclase, and orthopyroxenite sheets with distinct orthocumulus textures [39,70], is also consistent with a cumulate origin for this entire rock assemblage. Thus, the Fiskefjord region peridotites likely formed as a result of crystal fractionation in a shallow magma chamber or alternatively in a melt conduit. Differentiation of a high-Mg magma, could potentially also have generated the mafic to andesitic volcanic rocks of the Akia terrane.

A cumulate origin for the dunitic to noritic rocks of the Fiskefjord region is further supported by the geochemical variation seen from the previously published regional data (Fig. 4). As mentioned in Section 6.1, these trends are similar to those found by Szilas et al. [112], Szilas et al. [111] for the ca. 3200 Ma Tartoq Group and the >3700 Ma Isua supracrustal belt. The above studies concluded that olivine-dominated fractional crystallisation could explain the major element variation ($SiO_2$, MgO and FeOt) of both tholeiitic and boninitic magma series. The observed compositions of the Tartoq–Isua ultramafic rocks are consistent with their formation as products of crystal fractionation coupled with melt-rock interaction (interstitial liquids). An even better match between the lava series and the ultramafic cumulates of the Tartoq and Isua data, would be obtained if opx was crystallising at the same time as olivine. However, the above-mentioned ultramafic rocks were completely serpentinised, so that there is no evidence for opx other than from normative calculations. In contrast, the Fiskefjord region peridotites contain robust evidence for the crystallisation of opx in the form of harzburgites and norites.

The pyroxenites of the Akia terrane from Garde [39] have MgO contents around 20 wt.%. Similar bulk-rock compositions were reported by Szilas et al. [107], suggesting that such pyroxene-dominated cumulate compositions may be common in the Archaean supracrustal belts of SW Greenland. Cumulate harzburgite and norite is known from Archaean and Proterozoic mafic–ultramafic intrusions, such as the Stillwater and Bushveld complexes (e.g., [62,21]. However, neither the parental melt composition or the processes that resulted in the early crystallisation of opx, followed by plagioclase rather than clinopyroxene (cpx), are well understood (e.g., [6,119,37,78,84,92,51]. It should be noted that modern examples of boninites show evidence for early crystallisation of opx [71,22,17], and that experimental studies have also confirmed the early crystallisation of opx from boninitic magmas [116,117]. The U-shaped trace element patterns of the Fiskefjord ultramafic rocks do resemble those of modern boninites, and thus it is possible that the trace element patterns may reflect their parental magma composition due to trapped liquids. The current understanding of boninites indicates that they are the products of hydrous melting of previously depleted mantle ([13,11,68]. A similar model could potentially be invoked for the petrogenesis of the Fiskefjord rocks, because hydrous conditions are suggested by the late crystallisation of plagioclase, which furthermore indicates shallow conditions for the fractionation of the parental magma [101,32,47]. Although there is currently no data available for the norites of the Amikoq complex we note that most of the peridotites in the present study have negative Eu-anomalies, which supports a co-magmatic relationship between these lithologies, although $Eu^{2+}$ is susceptible to disturbance.

Hydrous conditions would be further supported if the amphibole in the harzburgites was a primary igneous mineral; however this has yet to be determined by in situ LA-ICP-MS trace element data. If on the other hand the amphibole represent hydrated clinopyroxene (cpx), then this may still support hydrous conditions, given that cpx-bearing cumulates are also common in arc-related setting [58]. It should, however, be noted that in detail there is a discrepancy between the geochemical composition of the Akia terrane supracrustal rocks (basalts to andesites) and the Isua boninites. This is evident by the higher $TiO_2$ contents of Akia terrane supracrustal rocks for any given MgO, in combination with flat to slightly enriched incompatible trace element patterns. A closer resemblance for the basaltic range of the Akia supracrustal rocks is observed when comparing them with Mesoarchaean tholeiitic basalts of the Tartoq Group in SW Greenland [105,109]. The $Al_2O_3/TiO_2$ ratios of the Fiskefjord region peridotites are intermediate between the Tartoq and Isua serpentinites. Nevertheless, the Akia terrane supracrustal rocks are similar to the Isua boninites in one important respect, namely their relatively low $CaO/Al_2O_3$ ratios. This could potentially explain why opx, rather than cpx may have been crystallising from these magmas.

The presence of andesites in the Qussuk supracrustal belt is perhaps also evidence for magmas in which early crystallisation of opx could be expected, given the silicic compositions of such melts. These andesites have been invoked as evidence that the Akia igneous rocks formed in a subduction zone setting [40]. Based on geochemical modelling, Mesoarchaean subduction-related magmatic processes were also suggested by Szilas et al. [106], Szilas et al. [108] to explain andesites from the Tasiusarsuaq terrane, and subduction zone processes have even been proposed for Eoarchaean rocks in the Nuuk region of SW Greenland based on geochemical arguments and the presence of boninites [93,60,35]. There is also abundant independent support for convergent tectonics in SW Greenland during the Archaean as seen from structural and metamorphic evidence [19,81,49,118,66,67,29,64,28]. Thus, the Fiskefjord region peridotites could potentially have formed in a hydrous arc-related setting. Nonetheless, further field work is needed in order to establish the details of the relationship between these peridotites and the associated mafic to andesitic supracrustal rocks. Future petrological and geochemical research is also required specifically on the norites and orthopyroxenites, as well as the amphibole-bearing harzburgite, in order to fully understand the petrogenesis for the Fiskefjord region peridotites.

## 7. Conclusions

The main features of the Mesoarchaean peridotites from the Fiskefjord region of the Akia terrane described in this study can be summarised as follows:

- Field observations include laterally extensive, parallel chromitite layers in the Seqi dunite body, which may be tightly folded (Fig. 2), interstitial plagioclase in associated norites, and orthocumulus textures in orthopyroxenites of the Amikoq complex.

- Olivine Mg# ranges from 91.1 to 93.7, with a median value of 92.6 ($n = 469$) for the Seqi dunites, whereas the Fiskefjord peridotites have ranges from 83.2 to 92.4, with a median value of 89.2 ($n = 356$).
- Spinel in the Seqi dunites have compositions that are distinct from those of the Fiskefjord peridotites with primary Cr# ranging from 19.3 to 81.3 and 6.6 to 41.0, respectively. Spinel Mg# range from 23.9 to 72.1 and 31.3 to 73.3, respectively.
- Pyroxene compositions in the peridotites are highly magnesian (median Mg# of 88.2) with a median enstatite component of $En_{88}$. Amphibole is also very magnesian with Mg# > 83.7 and consists mainly of magnesio-hornblende.
- The platinum-group element patterns of the Fiskefjord region peridotites are variable, but some have fractionated IPGEs consistent with a cumulate origin. They mostly have negative Rh-anomalies, which may represent the source for Rh mineralisation, which has been documented in the associated norites of the Amikoq complex.
- Bulk-rock geochemical trends of the peridotites in combination with previously published data for the intercalated norites, pyroxenites and amphibolites, are consistent with the interpretation that these mafic–ultramafic rocks may be related by fractional crystallisation processes.

Given the above mineralogical and geochemical characteristics, in combination with the field observations, it is concluded that the Mesoarchaean peridotites of the Fiskefjord region likely formed as cumulates related to fractional crystallisation of high-Mg, low CaO/$Al_2O_3$ magmas, with late crystallisation of plagioclase. However, the measured spinel and olivine grains are unlikely to preserve their primary magmatic compositions, because they appear to be recording Fe–Mg exchange during subsolidus/metamorphic overprinting. The geodynamic environment in which these peridotites formed has yet to be established.

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## Appendices. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.grj.2015.03.003.

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