Mantle-derived dunite and lherzolite nodules from Ubekendt Ejland, west Greenland Tertiary province

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ABSTRACT. Scattered dunite and lherzolite nodules occur in one of the youngest basanitoid lavas on Ubekendt Ejland. They have protogranular to porphyroclastic textures. The dunites are composed of olivine ($Fo_{93.2-91.9b}$), enstatite ($En_{93.4-92.8}$) low in Al_2O_3 and CaO, and Cr-spinel (61–13% Cr_2O_3 and 3–55% Al_2O_3). A solitary lherzolite module has olivine ($Fo_{94.7-94.1}$), enstatite ($En_{94.7-94.2}$), Cr-rich spinel, Ti-phlogopite (11% TiO_2), and hyalophane. Petrographic evidence suggests that the two latter minerals have not been introduced by magmatic injection from the host in spite of the refractory nature of the coexisting phases, and metasomatic processes prior to the last deformation are therefore indicated. Partial melting of such mantle material would presumably produce small amounts of alkaline liquids even at very high temperatures. Another lherzolite nodule from a lamprophyre dyke has minerals with lower Mg/(Mg + Fe) ratios which, together with its preserved igneous textures, suggest a high-pressure precipitate. The lowest well-established equilibrium temperatures of 700–830 °C for both dunites and lherzolites indicate a pressure regime of 12–17 kbar, according to the oceanic geotherm, whereas unrealistically high pressure (20–5 kbar) are suggested using the continental shield geotherm.

MANTLE-DERIVED nodules from the North Atlantic province are extremely scarce, and until now only harzburgite nodules have been recorded from a lamprophyre dyke of Lower Tertiary age in east Greenland (Brooks and Rucklidge, 1973). In the west Greenland Tertiary province (Clarke and Pedersen, 1976) scattered nodules of serpentinite, dunite with harzburgitic affinities, and a solitary lherzolite, 1–5 cm in diameter, have been obtained from one of the uppermost alkaline lavas on Ubekendt Ejland (fig. 1) (Larsen, 1977). A single lherzolite inclusion, 3 cm in size, has also been found in one of the late lamprophyre dykes (Larsen, 1981).

These ultramafic nodules are at present the only available mantle material in the province—a mantle

which a priori might be strongly depleted due to the formation of vast volumes of olivine-rich tholeiites preceding the alkaline magmatic activity. The present study is part of a general description of the megacrysts and ultramafic inclusions of Ubekendt Ejland (Larsen, 1981).

Petrography of the host rocks

The dunite–lherzolite-bearing lava is a basanitoid which also carries gabbro inclusions (Larsen, 1977).
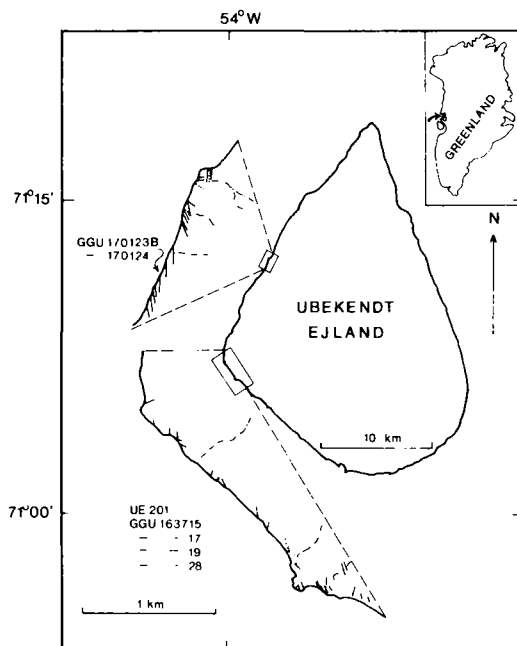

FIG. 1. Ubekendt Ejland with two expanded areas to show the sample localities. Heavy lines, coast line; thin lines, lamphrophyre dykes; dotted lines, carbonate zones; stippled doouble dotted lines, drainage. White: mainly basaltic lava flows.

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It contains 8 % olivine phenocrysts, Fo_{86-85}, and scattered clinopyroxene phenocrysts, besides anhedral olivine–spinel xenocrysts which are believed to be derived from the ultramafic nodules. The groundmass is very fine-grained, being composed of clinopyroxene, pyroxene, plagioclase, titanomagnetite, brown amphibole, and/or biotite, feldspathoids and green sheet silicates possibly replacing olivine and interstitial glass.

The lherzolite-bearing lamphrophyre dyke (170124) is an olivine monchiquite with camptonitic affinity (Larsen, 1981). This dyke also carries nodules of mica-pyroxenite, pyroxenite, wehrlite, and megacrysts of clinopyroxene, spinel, titanomagnetite, and apatite. The host rock contains microphenocrysts of olivine and clinopyroxene in a panidiomorphic groundmass with clinopyroxene, olivine, brown amphibole, and biotite set in a mesostasis of alkali feldspar(?) and analcime(?) besides plagioclase in the more coarse-grained areas. Ocelli and other types of inhomogeneities are similar to those described previously (Larsen, 1981).

Chemical analyses and norms of the host rocks are given in Table I.

Petrography of the nodules

The dunites are fine- to medium-grained (0.5–3 mm) and are composed of olivine together with small amounts of enstatite, Cr-spinel, serpentine (replacing olivine), chlorite, and carbonate (modes in Table II). The nodules are either massive (163715, 163728) with protogranular texture (terminology of Mercier and Nicolas, 1975) or foliated (163717) with an overprint of cataclastic texture shown by mosaic epigranular veins of enstatite. The large olivine crystals are strained. A few tiny enstatite inclusions in the olivine or vice versa occur. The spinel occurs as scattered grains (163728) or clusters between grain boundaries of the silicate minerals. The characteristic intergrowth with enstatite of the protogranular nodules described by Mercier and Nicolas (1975) is not observed. The spinel masses have nearly opaque centres of Cr-spinel and light brown rims of Cr-Al-spinel (163717). Relatively large carbonate crystals are bounded by olivine crystal surfaces in 163728 and may be primary. A tiny grain of chalcopyrite is also present in this nodule. Gas–liquid inclusions of CO_2 (J. Konnerup-Madsen, pers. comm.) occur as trains and isolated bubbles in 163717.

Lherzolite I (163719) is the only lherzolite nodule which has been recovered from the basanitic lava. Only 1 cm² of thin section could be produced from this nodule. It is composed of olivine, enstatite, Cr-diopside, Cr-spinel, and small amounts of hyalo-phane, phlogopite, and chlorite. The texture is porphyroclastic with larger strained olivine grains and strain-free neoblasts with polygonal grain boundaries. The Cr-diopside may be dusty due to tiny Cr-spinel grains. It has sieve texture and is intergrown with chloritic material (?altered glass), hyalophane and in some places phlogopite, being possibly at the point of breakdown. Cr-spinel is scarce and may be included in the olivine.

Lherzolite II (170124) is composed of altered olivine, Cr-diopside, enstatite, Cr-spinel and small amounts of plagioclase and phlogopite. The texture is granular to hypidiomorphic in some places where the pyroxenes are interstitial to the olivine. The olivine may contain spinel octahedra. Thus, some igneous textures appear to be preserved in this nodule. The plagioclase may, together with newly formed clinopyroxene, occupy irregular interstitial areas framed by tiny Cr-spinel octahedra. The nodule is mantled by a 1 mm thick rim of clino-pyroxenite, which may indicate that the interstitial areas mentioned above have formed by partial melting of the nodule. However, metasomatic introduction of this material cannot be excluded.

Mineralogy

Microprobe analyses of the minerals are given in Tables III–VII and the analytical procedures are described in Larsen (1981). All iron is reported as FeO.

The olivine (Table III) is homogeneous with a range of $Fo_{93.2-91.9}$ in the dunites, $Fo_{94.1-94.7}$ in lherzolite I, but is inferred to be much lower in lherzolite II from the Mg/(Mg + Fe) ratio of the coexisting pyroxenes. Compared with the olivine megacrysts (Larsen, 1981) and phenocrysts of the alkali basalts and picritic basalts the present olivine is distinguished by low CaO (0.00–0.03 %), TiO_2, and Cr_2O_3 contents and, except for lherzolite II, also by a higher Fo content.

The orthopyroxene (Table IV) of the dunites has a range of $En_{93.4-92.8}$ with very low contents of Al_2O_3 (<1 %) and CaO (<0.44 %) compared with orthopyroxenes of other mantle-derived nodules (fig. 2). The enstatite of the mosaic veins is, however, richer in these components (Table IV, 4). The enstatite of lherzolite I is richer in Mg ($En_{94.7-94.2}$) as is the coexisting olivine, but otherwise very similar to that of the harzburgite. The orthopyroxene of lherzolite II is relatively enriched in FeO, ($En_{87.1-85.4}$), CaO, and Al_2O_3.

The Cr-diopside (Table V) of lherzolite I has a $100 \times Mg/(Mg + Fe)$ value of 95.1 and is low in Al_2O_3 and TiO_2, and high in Cr_2O_3 and Na_2O. The Cr-diopside of lherzolite II has $100 Mg/(Mg + Fe)$ of 88.0–86.3 and higher contents of

Al_2O_3 and TiO_2. These diopsides belong to the lherzolite series of Kuno (1969) and are distinguished from the Cr-diopside megacrysts described previously (Larsen, 1981) by higher Al^{VI}/Al^{IV} ratios and higher Na content. On the basis of four cations, the sum of the oxygens exceeds six, similar to the Cr-diopside megacrysts (Larsen, 1981). This may be due to octahedral vacancy as Cr^{3+} enters the diopside structure in the same way as Al under high pressure (Wood and Henderson, 1978). Analytical uncertainty cannot be ruled out but is not indicated for the olivine and orthopyroxene analyses. Calculated end members, assuming that no Fe^{3+} is present, indicate that Na is included as the cosmochlore ($NaCrSi_2O_6$) and the jadeite molecules (Table IV).

The spinels (Table VI) show a range from nearly pure Mg–Fe chromites to chromian spinel with increasing ratios of Mg/(Mg + Fe). An extreme range is observed in one of the dunites with cores of Cr-spinel and rims of Al-spinel. The trend is quite different from that of the Cr-spinel in the

Table I. Chemical composition of host rocks

			Molecular norms		
	1	2		1	2
SiO_2	43.26	44.30	Or	13.5	2.6
TiO_2	1.43	2.28	Ab	–	17.7
Al_2O_3	14.50	14.11	An	23.7	24.9
Fe_2O_3	2.55	4.02	Lc	0.6	
FeO	5.82	7.10	Ne	13.0	5.2
MnO	0.16	0.19	Di	32.8	22.0
MgO	8.57	10.14	Ol	10.7	21.5
CaO	12.89	11.18	Mt	2.8	1.5
Na_2O	2.29	2.87	Il	2.1	3.2
K_2O	2.29	0.43	Ap	0.8	1.4
P_2O_5	0.38	0.65			
H_2O	2.41	3.44			
CO_2	2.70				
Totals	99.25	100.71			

1: Olivine monchiquite dyke with camptonitic affinity (GGU 170124) Larsen (in press)

2: Basanitoid lava (UE 201) Larsen (1977)

Table III. Microprobe analyses of olivines

	Dunites			Lherz.
GGU no.	163715	163717	163728	163719
No of anal.	2	3	1	1
SiO_2	41.6	41.8	40.8	40.9
TiO_2	n.f.	n.f.	n.f.	0.02
Al_2O_3	0.01	n.f.	0.02	n.f.
Cr_2O_3	0.03	0.01	0.01	0.03
FeO_{total}	7.80	7.11	7.40	5.83
MnO	0.20	0.11	0.10	0.14
MgO	49.9	51.6	50.7	53.0
NiO	–	–	0.24	0.33
CaO	0.04	0.02	0.00	0.03
Totals	99.6	100.7	99.3	100.3
Fo content	92.0	92.8	92.4	94.2
Fo range	91.9–92.6	92.8–93.2	92.3–92.4	94.1–94.7

Cation proportions for Σ Oxygen = 4

Si	1.013	1.004	0.997	0.985
Ti	–	–	–	–
Al	–	–	0.001	–
Cr	0.001	–	–	0.001
Fe	0.158	0.143	0.151	0.118
Mn	0.004	0.002	0.002	0.003
Mg	1.810	1.847	1.847	1.903
Ni	–	–	0.005	0.006
Ca	0.001	0.001	–	0.001

Lherz. = lherzolite

Table II. Modal composition of the ultramafic inclusions

	Ol	Opx	Cpx	Sp	Phl	Fsp	Sh	Cab	no. of counts
Dunites									
163715*	92	1	–	1	–	–	5	1	–
163717	77	1	–	3	–	–	16	3	1700
163728*	92	2	–	<1	–	–	5	<1	–
Lherzolites									
163719	80	7	5	.7	.7	.7	6	+	425
170123B*	–	10	15	2	+	+	73	+	–

* Visual estimates. Ol = olivine, Opx = orthopyroxene, Cpx = clinopyroxene, Sp = Cr-spinel, Phl = phlogopite, Fsp = felspar, Sh = sheet silicates, Cab = carbonate.

Table IV. Microprobe analyses of orthopyroxenes

	Dunites					Lherzolites		
GGU No.	163715	163717		m.v.	163728	163719	170123B	
No. of anal.	2	1	1	1	1	1	1	1
SiO_2	57.0	58.8	58.6	56.0	58.2	58.5	57.2	56.4
TiO_2	0.02	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	0.14
Al_2O_3	0.06	0.44	0.76	2.19	0.09	0.08	0.43	1.69
Cr_2O_3	0.03	0.07	0.17	0.09	0.05	0.06	0.06	0.21
FeO_{total}	4.66	4.52	4.62	4.75	4.85	4.16	8.50	8.10
MnO	0.14	0.13	0.10	0.12	0.14	0.11	0.25	0.22
MgO	37.3	35.9	35.7	36.6	37.2	38.2	32.3	31.8
CaO	n.f.	0.09	0.14	0.25	0.07	0.15	0.49	0.70
Na_2O	n.f.	n.f.	n.f.	0.01	n.f.	0.09	0.03	–
K_2O	n.f.	n.f.	0.01	0.02	n.f.	0.03	n.f.	–
Totals	99.2	100.0	100.1	100.0	100.6	101.4	99.3	99.4§
$\frac{100 \times Mg}{Mg+Fe}$	93.4	93.4	93.2	93.2	93.2	94.3	87.1	87.5

Cations as proportions of 4 and the equivalent sum of Oxygen

ΣO	5.955	6.022	6.021	5.949	5.974	5.956	6.018	6.024
Si	1.953	2.012	2.004	1.905	1.972	1.958	2.010	1.983
Al	0.002	0.018	0.031	0.088	0.004	0.003	0.018	0.070
Cr	0.001	0.002	0.005	0.003	0.001	0.002	0.002	0.006
Ti	0.001	–	–	–	–	–	–	0.004
Fe	0.134	0.129	0.132	0.135	0.137	0.116	0.250	0.238
Mn	0.004	0.004	0.003	0.003	0.004	0.003	0.007	0.007
Mg	1.905	1.832	1.820	1.856	1.879	1.906	1.692	1.667
Ca	–	0.003	0.005	0.009	0.003	0.005	0.018	0.026
Na	–	–	–	0.001	–	0.006	0.002	–
K	–	–	–	0.001	–	0.001	–	–
$\frac{1000 \times Ca}{Ca+Mg}$	–	1.63	2.74	4.83	1.59	2.62	10.5	15.54

T^oC

Ref. 1	–	815	860	905	815	850	1070	1150
Ref. 2	–	<900	<900	<900	<900	<900	940 / 920	1000 / 950
Ref. 3	<600	<600	<600	<600	~650	<600	<600	<600

§ Sum includes 0.18 per cent NiO, m.v. = Orthopyroxene from mosaic vein

Ref. 1: Boyd & Nixon (1973), ref. 2: Nehru (1976, at 10-20 kb respectively) and ref. 3: Dankwerth & Newton (1978).

Table V. Clinopyroxene from Lherzolites

Microprobe analyses					4 cations and Σ Oxygen				End members*			
GGU no.	163719	170123B	170123B			163719	170123B	170123B		163719	170123B	170123B
		c	m				c	m			c	m
No of anal.	2	1	1	Si	2.016	1.977	1.928	$CaTiAl_2O_6$	–	0.36	2.24
SiO_2	56.3	53.9	52.5	Ti	0.000	0.004	0.022	$CaCrAlSiO_6$	–	1.62	2.35
TiO_2	0.01	0.13	0.81	Al	0.029	0.123	0.174	$NaAlSi_2O_6$	2.87	7.32	7.41
Al_2O_3	0.68	2.84	4.03	Cr	0.050	0.016	0.024	$(NaCrSi_2O_6)$	4.98	–	–
Cr_2O_3	1.76	0.56	0.81	Fe^{3+}	–	–	–	$NaFe^{3+}Si_2O_6$	0.52	–	–
FeO_{total}	1.77	4.07	3.63	Fe^{2+}	0.053	0.125	0.112	$CaAl_2SiO_6$	–	1.31	1.61
MnO	0.08	0.16	0.20	MnO	0.002	0.005	0.006	$MgSiO_3$	52.0	43.2	41.1
MgO	19.5	15.8	15.02	Mg	1.041	0.864	0.821	$CaSiO_3$	36.3	39.0	38.8
CaO	18.9	20.7	21.3	Ca	0.725	0.813	0.838	$FeSiO_3$	2.51	6.49	5.89
Na_2O	1.21	1.03	1.04	Na	0.084	0.073	0.074	excess Si	0.79	0.67	0.63
K_2O	n.f.	n.f.	n.f.	K	–	–	–				
Totals	100.2	99.2	99.4	O	6.013	6.013	6.013	* Calculated in order given above			

$\frac{100 \times Mg}{Mg+Fe}$ 95.1 87.3 88.0 T^oC: 1175 960 925   Davis & Boyd (1966)

                                    1241 1033 985   Wood & Banno (1973, eq. 27)**

163719: Sieve textured Cr-diopside   1120 850 820   Mysen (1976, Fig. 3)
170123B,c: Cr-diopside core   – 1035 890   – (1976, Fig. 4)**
170123B,m: Cr-diopside margin   1323 1154 1074   Mori (1977, eq. 16)**

**) Coexisting orthopyroxene of Table IV column 6, 7 and 8

Table VI. Microprobe analyses of spinels

	Dunites						Lherzolites		
GGU no.	163715	163717				163728	163719	170123B	
	1	2	3	4	5	6	7	8	
No. of anal.	2	1	1	1	1	2	1	2	
SiO_2	–	0.02	0.04	0.05	0.27	0.04	0.25	0.05	
TiO_2	0.03	0.04	0.01	n.f.	0.02	0.02	1.15	0.18	
Al_2O_3	3.91	22.8	45.8	50.7	55.3	4.79	6.23	29.1	
Cr_2O_3	61.0	48.7	24.5	20.1	13.6	61.2	58.0	37.6	
FeO_{total}	20.4	13.0	9.13	8.16	7.78	20.8	21.2	19.1	
MnO	0.42	0.22	0.14	0.12	0.10	0.35	0.32	0.28	
MgO	12.2	15.5	19.5	21.0	22.1	11.6	9.77	13.9	
CaO	n.f.	n.f.	n.f.	0.01	n.f.	0.02	0.01	0.01	
NiO	–	–	–	–	–	0.10	–	0.10	
V_2O_5	–	–	–	–	–	0.21	–	0.09	
Totals	98.0	100.3	99.1	100.1	99.2	99.1	96.9*	100.4	
Fe_2O_3**	8.11	1.22	0.04	0.31	0.93	6.98	3.27	4.16	
FeO	13.11	11.90	9.09	7.91	6.98	14.52	18.21	15.43	
New sum	98.8	100.4	99.1	100.2	99.3	99.8	97.2	100.9	

Σ cations = 24 and Σ O = 32 with calculated Fe^{3+}

Si	–	0.005	0.009	0.011	0.056	0.011	0.069	0.012	
Ti	0.006	0.007	0.002	–	0.003	0.004	0.239	0.032	
Al	1.250	6.476	11.754	12.587	13.512	1.517	2.028	8.125	
Cr^{3+}	13.084	9.279	4.218	3.347	2.229	12.998	12.666	7.043	
Fe^{3+}	1.653	0.221	0.008	0.045	0.139	1.410	0.690	0.727	
Fe^{2+}	2.975	2.399	1.665	1.393	1.210	3.262	4.207	3.057	
Mn	0.097	0.045	0.026	0.021	0.018	0.080	0.075	0.056	
Mg	4.937	5.568	6.330	6.594	6.831	4.645	4.023	4.909	
Ca	–	–	–	0.002	–	0.006	0.003	0.003	
Ni	–	–	–	–	–	0.022	–	0.019	
V	–	–	–	–	–	0.045	–	0.017	
$\frac{100 \times Mg}{Mg+Fe^{2+}}$	51.6	68.0	79.2	82.6	83.5	58.7	45.1	61.6	
$\frac{100 \times Mg}{Mg+Fe_{total}}$	62.4	69.9	79.3	82.1	85.0	49.9	48.9	56.5	
$Cr/(Cr+Al+Fe^{3+})$	0.818	0.581	0.264	0.209	0.140	0.816	0.822	0.443	
$Al/(Cr+Al+Fe^{3+})$	0.078	0.405	0.736	0.788	0.851	0.095	0.134	0.511	
$Fe^{3+}/(Cr+Al+Fe^{3+})$	0.103	0.014	0.000	0.003	0.009	0.089	0.941	0.047	
T^oC***		731	822	914	1040	1038	859	550	

*Preliminary analysis, **Calculated from stoichiometry, ***After Roeder et al.(1978) using Fo from the olivines of Table III.

1: Opaque leaf-shaped Mg-chromite. 2: Deep brown Cr-spinel core of brown spinel masses. 3: Brown Cr-spinel, inner part of spinel masses. 4: Light brown Cr-spinel, outer part of spinel masses. 5: Greenish brown Cr-Al spinel, margin of spinel masses. 6: Opaque Mg-chromite. 7: Opaque Mg-chromite. 8: Light brown Cr-spinel.

Table VII. Microprobe analyses of different minerals

Mineral	Lherzolite 163719			163717
	Phl 1	Phl 2	Hyl	Se
No of anal.	1	1	2	1
SiO_2	37.9	38.2	61.5	43.8
TiO_2	11.6	10.0	–	0.03
Al_2O_3	12.1	12.9	20.1	0.02
Cr_2O_3	–	–	–	0.03
FeO_{total}	4.57	4.01	0.07	4.18
MnO	0.03	0.03	–	0.18
MgO	18.7	20.5	0.26	35.8
NiO	–	–	–	0.04
CaO	0.05	0.09	0.60	0.00
Na_2O	0.88	0.85	5.65	0.02
K_2O	10.35	10.43	6.54	0.01
BaO	0.14	–	3.13	–
SrO	n.f.	–	0.14	–
F	0.45	0.62	–	–
Cl	0.06	0.05	–	–
Totals	96.8	97.7	98.0	84.1
100xMg/(Mg+Fe)	87.9	90.1	–	93.8

Unit formulae				
	Phl 1		Phl 2	
Si	5.416		5.496	
Al	2.038	8.00	2.147	8.00
Ti^{iv}	0.546		0.357	
Ti^{vi}	0.701		0.705	
Fe	0.546	5.24	0.474	5.50
Mn	0.004		0.004	
Mg	3.984		4.317	
Ca	0.008		0.014	
Ba	0.008		–	
Na	0.244	2.15	0.233	2.11
K	1.887		1.879	
O	22		22	

Phl = phlogopite, Hyl = hyalophane, Se = serpentine

Note: The phlogopite analyses are preliminary and Al_2O_3 may be too low by 0.8% and K_2O may be too high.

Table VIII. Calculated temperatures T^oC

Method	Lherzolite I	Lherzolite II	Dunites	
Diopside solvus				
Davis & Boyd (1966)	1175	925–960	–	
Wood & Banno (1973, eq. 27)	1241	995–1033	–	
Mysen (1976, Fig. 3)	1125	820–850	–	
Mori (1977, eq. 16)	1323	1068–1081	–	
$D_{Opx-Cpx}^{Alvi/Cr}$ (Mysen, 1976, Fig. 4)		890–1035	–	
Al_{Opx} (Danckwerth & Newton, 1978)	<600	<600	<600–650	
Ca_{Opx} (Boyd & Nixon, 1973)	850	1070–1150	815–905*	
(Nehru, 1976, at 10–20 kb)	<900	950–1000	<900	
Spinel-olivine (Roeder et al. 1978)	550	–	731–914	(1040)**
(Fabriès, 1979)	700	–	830–940	

*Highest value from the mosaic enstatite. Note that all these pyroxenes may not be saturated with CaO. **Highest value from the spinel margin.

picrite basalts but agrees with the compositional field of other mantle-derived nodules (fig. 2). The most Cr-rich spinels are similar in composition to those found in inclusions in diamonds reviewed by Haggerty (1979), and their Cr contents correlate with the Fo content in the coexisting olivine, as observed in the previously described megacrysts.
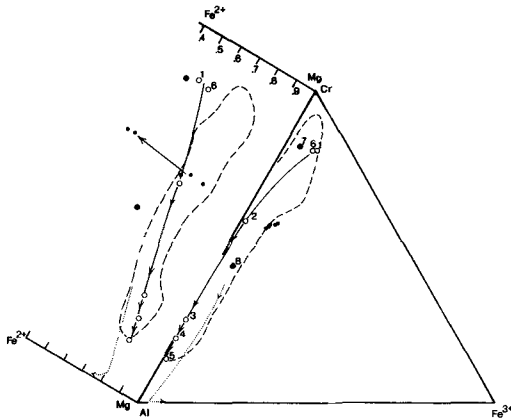

FIG. 2. Part of the spinel prism (unfolded). Open circles: spinel in dunites (zoning is indicated). Filled circles: spinel in lherzolites, dots: spinel in picrite basalts (unpublished data from Ubekendt Ejland, zoning is indicated). The stippled line delineates spinel from mantle inclusions in kimberlite after Smith and Dawson (1975), dotted line: spinel trend in megacrysts from Drever's block (Larsen, 1981).

The phlogopite (Table VII) contains 10.0–11.6% TiO_2 and has $100 Mg/(Mg + Fe)$ values of 90.1–87.9. Si and Al are insufficient to fill the tetrahedral sites, requiring most of the Fe to be present as Fe^{3+} to make up for the deficiency. This is not supported by pleochroism (Puustinen, 1973) and it is therefore likely that Ti^{4+} is present in the tetrahedral site in significant amounts. This conclusion is not affected by the preliminary nature of the microprobe analyses (Table VII). Ti-rich phlogopite without Ti^{IV} has been reported from a garnet lherzolite nodule, and was regarded as a primary constituent of the mantle (Dawson et al., 1970), whereas Carswell (1975) and Boettcher et al. (1979) suggested that Ti-rich phlogopites are of secondary origin. However, none of the secondary phlogopite analyses given by these authors are as rich in TiO_2 as those presented here. Dawson et al. (1970) draw attention to similar Ti-rich phlogopites of leucite-bearing ultrabasic lavas (jumillite) described by Carmichael (1967) and Prider (1939) and to these may be added phlogopite phenocrysts from a biotite mafurite (Edgar, 1979). These phlogopites also have a Si + Al deficiency in the tetrahedral site and the presence of Ti^{IV} is

supported in the analysis of Prider where Fe_2O_3 was reported.

The hyalophane (Table VII) has a composition of $Cn_{5.8}An_{3.4}Or_{36-9}Ab_{51.5}Sr$-fsp$_{-0.4-2.7}$, which is similar to the hyalophane megacrysts in the monchiquitic dykes of Ubekendt Ejland described by Larsen (1981) and to interstitial hyalophane in a phlogopite-bearing lherzolite plug of the Mordor complex (Langworthy and Black, 1978). The Ba-rich sanidine of the jumillites is much more potassic (Carmichael, 1967).

P–T estimates

Equilibrium temperatures according to different mineral thermometers are compared in Table VIII with individual estimates given in Tables IV–VI. The large range observed within each nodule presumably indicates lack of equilibrium due to different closing temperatures for the different minerals, or uncertainties in the calibration of the geothermometers. The diopside solvus thermometers give a range of 1125–1323 °C for lherzolite I and a range of 844–1154 °C for lherzolite II. Much lower temperatures are indicated from the Al_{opx}-, Ca_{opx}-, and spinel–olivine thermometers in lherzolite I whereas the two latter thermometers are within the range of the diopside solvus temperatures in lherzolite II. This suggests different geneses and/or source regions although the latter three thermometers are not well established. The Ca_{opx} method (Boyd and Nixon, 1973) is dependent on pressure in the spinel–lherzolites (Nehru, 1976; Mysen, 1976), and as the Al_{opx} method is not calibrated to the very low Al_2O_3 values of the present orthopyroxenes, the temperatures below 600 °C are questionable. The spinel–olivine thermometer of Roeder et al. (1979) has also recently been challenged by Engi and Evans (1980), especially in the low-T range, and according to the curves of Fabriès (1979), the T of 550 °C (Table VI, 7) would be raised to 700 °C. Assuming that the Al_{opx} method is inaccurate, equilibration temperatures of 731–1040 °C (830– 940 ° according to Fabriès, 1979) are indicated for both the Ca_{opx} and spinel–olivine methods in the dunites. The higher temperatures are obtained in the mosaic-veined orthopyroxene as well as the spinel margin (of 163717) and may suggest a temperature increase due to shearing of the mantle. The lower temperatures suggest a regional temperature regime of 700–830 °C.

Pressure estimates are only approximate in the spinel–lherzolite facies due to lack of good geobarometers. With equilibration of 700–830 °C, pressures of 20–25 kbar may be inferred according to the continental shield geotherm and between 10 and 15 kbar according to the oceanic geotherm

(Clarke and Ringwood, 1964). Experimental data indicate that spinel periodotite would only be stable between 8 and 17 kbar at these temperatures (Wyllie, 1971, p. 118), suggesting that the region was underlain by a relatively hot mantle of the oceanic type. (If the lowest equilibration T were as low as 550 °C, a slightly lower P regime would be indicated.) The clinopyroxenes plot in the high P field of the Al^{VI}-Al^{IV} diagram of Aoki and Kushiro (1968) with a relatively high Na content bound in the jadeite molecule or its chromian equivalent (cosmochlore), suggesting pressures above 10 kbar (Kushiro, 1969; Thompson, 1974). The high P indication of the cosmochlore component is inferred from the fact that Cr-diopsides from layered intrusions are low in Na (Wager and Brown, 1968). The geobarometer based on the Al_2O_3 content in the orthopyroxene coexisting with spinel is now known to be strongly T dependent (Danckwerth and Newton, 1978) as is the CaO content of the olivine (Finnerty and Boyd, 1978). Minimum estimates of 4 kbar at 800 °C and 6 kbar at 1150 °C are inferred from measurements of volume and critical temperatures of the CO_2 inclusions (J. Konnerup-Madsen, pers. comm.). The Ti-rich phlogopite would probably be stable to high P (Forbes and Flower, 1974), and Ryabchikov and Green (1978) reported phlogopites with up to 8.1 % TiO_2 formed at 30 kbar, 1200–1275 °C and $CO_2/(CO_2 + H_2O) =$ 0.25 from a biotite mafurite. Presumably the hyalophane, by analogy with sanidine, will be stable to high P (Wendlandt, 1977). In conclusion a P–T regime of 10–17 kbar and 700–830 °C is inferred although equilibrium between all phases was not achieved.

Discussion

The harzburgitic dunite inclusions are believed to represent depleted mantle material left behind after extraction of a basaltic liquid (O'Hara, 1968). Due to the low closing temperature estimates (uncertain as these are), the nodules cannot represent the residua after the formation of the picrite basalts or the alkali basalts in which they occur. They are therefore derived from levels above the magma generation.

The minerals of lherzolite II from the lamprophyre dyke are characterized by low 100 Mg/ (Mg + Fe) ratios (86–88), which are outside the range of normal mantle-derived nodules but similar to a nodule described by Wilkinson and Binns (1977). Furthermore, some igneous textures seem to be preserved suggesting that it may be a high-pressure olivine–spinel cumulate with intercumulus Cr-diopside and bronzite. In this connection it should be noted that a wehrlite with an identical Cr-

diopside and clear igneous texture occurs in the same dyke. With a temperature as low as 828 °C (Table VIII), it seems likely that the nodule originated from an earlier, pre-Tertiary, magmatic cycle (assuming that no re-equilibration took place during cooling of the lava).

Lherzolite I has 100 Mg/(Mg + Fe) values between 94.1 and 95.1 in the olivine and pyroxenes, which is comparable with the most depleted harzburgites of the South African kimberlite pipes (Boyd and Nixon, 1978). The presence of phlogopite and hyalophane is therefore unexpected. Even though they are associated with the sieve-textured clinopyroxene they could not have been formed by exsolution, or breakdown of this phase, owing to the inability of Ba and K to enter the pyroxene structure (Philpotts and Schnetzler, 1970; Shimizu, 1974). The phlogopite may have survived a former episode of partial melting as proposed by Forbes and Flower (1974). Alternatively, it could have formed together with hyalophane as a result of influx of alkalis and other incompatible elements. Textural evidence suggests that such an influx occurred prior to the last deformation as these minerals are associated with the clinopyroxene only. Together, they constitute an eutectic assemblage of the nodule; according to Wendlandt (1977), olivine-enstatite + sanidine + diopside + liquid coexist between 6 and 19 kbar in the system $KAlSiO_4 - Mg_2SiO_4 - SiO_2 - CaMgSi_2O_6 \pm CO_2$. With small amounts of water present, phlogopite would form before sanidine, at least at low pressure (Luth, 1967). Partial melting of the nodule would only be able to produce small amounts of potassic undersaturated liquids or would be able to contaminate slowly rising basic magmas by zone refining (Harris, 1957). In discussing the origin of the alkali basalts of Ubekendt Ejland (Larsen, 1977), it was argued that the high Ba/K ratio (0.28) of the most primitive type, i.e. the host lava, was not likely to be produced by partial melting of amphibole- or phlogopite-bearing lherzolites. However, the presence of hyalophane with Ba/K as high as 0.50 may solve this problem. The occurrence of phlogopite in the lherzolites supports the view that, in spite of the huge production of tholeiitic basalts, mantle material enriched in incompatible elements was present and could have been involved in the production of the alkaline rocks.

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REFERENCES

Aoki, K., and Kushiro, I. (1968) *Contrib. Mineral. Petrol.* **18**, 326–37.

Boettcher, A. L., O'Neil, J. R., Windom, K. E., Stewart, D. C., and Wilshire, H. G. (1979) In *Proc. Second Intern. Kimberlite Conf.* **2**, 173–82 (eds. Boyd, F. R., and Meyer, H. O. A.). Am. Geophys. Union, Washington.

Boyd, F. R., and Nixon, P. H. (1973) *Carnegie Inst. Washington Yearb.* **72**, 431–45.

—— —— (1978) *Geochim. Cosmochim. Acta,* **42**, 1367–82.

Brooks, C. K., and Rucklidge, J. C. (1973) *Contrib. Mineral. Petrol.* **42**, 197–212.

Carmichael, J. S. F. (1967) Ibid. **15**, 24–66.

Carswell, D. A. (1975) *Phys. Chem. Earth,* **9**, 417–29.

Clarke, D. B., and Pedersen, A. K. (1976) In *Geology of Greenland* (eds. Escher, A., and Watt, W. S.) 365–85. Geol. Surv. Greenland, Copenhagen.

Clarke, S. P. Jr., and Ringwood, A. E. (1964) *Rev. Geophys.* **2**, 35–88.

Danckwerth, P. A., and Newton, R. C. (1978) *Contrib. Mineral. Petrol.* **66**, 189–201.

Davis, B. T. C., and Boyd, F. R. (1966) *J. Geophys. Res.* **71**, 3567–76.

Dawson, J. B., Powell, D. G., and Reid, A. M. (1970) *J. Petrol.* **11**, 519–48.

Edgar, A. D. (1979) *Contrib. Mineral. Petrol.* **71**, 171–5.

Engi, M., and Evans, B. W. (1980) Ibid. **73**, 201–3.

Fabriès, J. (1979) Ibid. **69**, 329–36.

Finnerty, A. A., and Boyd, F. R. (1978) *Carnegie Inst. Washington Yearb.* **77**, 713–17.

Forbes, W. C., and Flower, M. F. J. (1974) *Earth. Planet. Sci. Lett.* **22**, 60–6.

Haggerty, S. E. (1979) In *Proc. Second Intern.* Kimberlite Conf. **2**, 183–96 (eds. Boyd, F. R., and Meyer, H. O. A.). Am. Geophys. Union, Washington.

Harris, P. G. (1957) *Geochim. Cosmochim. Acta,* **12**, 195–208.

Kuno, H. (1969) *Mem. Geol. Soc. Am.* **115**, 189–234.

Kushiro, I. (1969) *Mineral. Soc. Am. Spec. Pap.* **2**, 179–91.

Langworthy, A. P., and Black, L. P. (1978) *Contrib. Mineral. Petrol.* **67**, 51–62.

Larsen, J. G. (1977) *Meddels, Grønland* **200**, 1, 1–42.

—— (1981) *Lithos* **14**, 241–62.

Luth, W. C. (1967) *J. Petrol.* **8**, 372–416.

Mercier, J-C. C., and Nicolas, A. (1975) Ibid. **16**, 454–87.

Mori, T. (1977). *Contrib. Mineral. Petrol.* **59**, 261–79.

Mysen, B. O. (1976) *Am. Mineral.* **61**, 677–83.

Nehru, C. E. (1976) Ibid. 578–81.

O'Hara, M. J. (1968) *Earth Sci. Rev.* **4**, 69–133.

Philpotts, J. A., and Schnetzler, C. C. (1970) *Geochim. Cosmochim. Acta,* **34**, 307–22.

Prider, R. T. (1939) *Mineral. Mag.* **25**, 373–89.

Puustinen, K. (1973) *Bull. Geol. Soc. Finland,* **45**, 35–42.

Roeder, L. P., Cambell, J. H., and Jamieson, H. E. (1979) *Contrib. Mineral. Petrol.* **68**, 325–34.

Ryabchikov, I. D., and Green, D. H. (1978) In *Problems of Petrology of the Earth's Crust and Upper Mantle,* **403**, Nauka, Novisibirsk [*Tr. Inst. Geol. Geofiz. Akad.*]

Shimizu, N. (1974) *Geochim. Cosmochim. Acta,* **38**, 1789–98.

Smith, J. V., and Dawson, J. B. (1975) *Phys. Chem. Earth,* **9**, 309–22.

Thompson, R. N. (1974) *Mineral. Mag.* **39**, 768–87.

Wager, L. R., and Brown, G. M. (1968) *Layered Igneous Rocks.* Freeman & Co. San Francisco.

Wendlandt, R. F. (1977) *Carnegie Inst. Washington Yearb.* **76**, 435–41.

Wilkinson, J. F. G., and Binns, R. A. (1977) *Contrib. Mineral. Petrol.* **65**, 199–212.

Wood, B. J., and Henderson, C. M. B. (1978) *Am. Mineral.* **63**, 66–72.

—— and Banno, S. (1973) *Contrib. Mineral. Petrol.* **42**, 109–24.

Wyllie, P. J. (1971) *The Dynamic Earth.* Wiley, New York.