Petrology and geochemistry of the plutonic rocks of the Halmahera ophiolite, eastern Indonesia, an analogue of modern oceanic forearcs

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Abstract: Ophiolitic rocks form the basement of the eastern part of the island of Halmahera in eastern Indonesia. The ophiolite is tectonically dismembered but all the elements of a complete ophiolite are present with the uncertain exception of a sheeted dyke complex. The ophiolite was formed in a supra-subduction zone setting before the Late Cretaceous and is interpreted to represent the forearc of a Mesozoic arc whose remnants are now found within and close to the margins of the Philippine Sea Plate. The plutonic rocks of the ophiolite include peridotites interpreted as a 'mantle sequence' and cumulates interpreted as the deeper parts of an ophiolitic crustal sequence. The mantle sequence includes subordinate lherzolites of relatively enriched chemistry which represent upper mantle previously depleted by the extraction of MORB. A high degree of melting of the lherzolites under hydrous conditions left a mantle residue of depleted harzburgites, which are more refractory than the harzburgites of Troodos and Oman. Abundant cumulates which crystallized from the magma include peridotites and gabbroic rocks rich in orthopyroxene. The chemistry and mineralogy of the cumulates indicate open-system crystallization from a high Si, Mg, low Ti, LREE-depleted magma. Highly calcic plagioclase characteristic of island-arc plutons and found in the cumulate sequence of the Troodos ophiolite is not found in the Halmahera cumulates. The Halmahera ophiolite is interpreted as the onland analogue of the present-day Mariana forearc. Rocks dredged from the Mariana Trench, which like Halmahera is also situated at the margin of the Philippine Sea Plate, are remarkably similar to those of the Halmahera ophiolite.

This paper gives an account of the petrology and geochemistry of the plutonic rocks forming part of the ophiolite complex of Halmahera, eastern Indonesia. It updates a preliminary report of the petrology of these rocks (Ballantyne & Hall 1990) and complements a petrological and chemical study of the volcanic rocks of the ophiolite complex (Ballantyne 1991*a*, *b*).

The island of Halmahera (Fig. 1) is situated to the northwest of New Guinea in a tectonically complex area close to the southern boundary of the Philippine Sea Plate (Hall 1987). This is the region of convergence between the Philippine Sea Plate, the complex Eurasian Plate and the Australian Plate (Fig. 2). The basement of the eastern part of Halmahera (Fig. 3) consists of a dismembered ophiolite, intruded by arc plutonic rocks (Ballantyne 1990) and intercalated with Cretaceous to Eocene volcaniclastic and sedimentary rocks (Hall *et al.* 1988). Mapping in 1975–1976 (Sukamto *et al.* 1981; Soeria Atmadja 1981) led to the suggestion that the eastern Halmahera ophiolitic province was formed in a subduction zone environment and the work of two recent Anglo-Indonesian expeditions (in 1984 and 1987) has supported and extended this conclusion (Hall *et al.* 1988; Ballantyne & Hall 1990; Hall *et al.* 1991).

Structural dismemberment is such that an intact ophiolitic stratigraphy cannot be seen although lithologies representing all parts of a complete ophiolite suite (Coleman 1977; Moores 1982) are present in east Halmahera, with the possible exception of a sheeted complex. A small area of 'diabase' dykes associated with pillow lavas was reported in central Halmahera by Burgath *et al.* (1983), although no sheeted complex was found on the more extensive traverses made in other parts of the island by the later expeditions (Hall *et al.* 1988; R. Hall. pers. comm. 1991). The higher parts of the ophiolite plutonic sequence (Moores 1982) on Halmahera are massive dolerites with intergranular and ophitic textures which have suffered a pervasive hydrothermal alteration and, as a result, mineralogical data on the primary igneous assemblages are sparse. Intermediate to acid plutonic rocks are relatively uncommon in eastern Halmahera; diorites and trondhjemites have a trace element chemistry which indicates that they are not co-genetic with the ophiolite and reflect at least three post-ophiolitic, arc-related phases of igneous activity (Ballantyne 1990). The majority of plutonic

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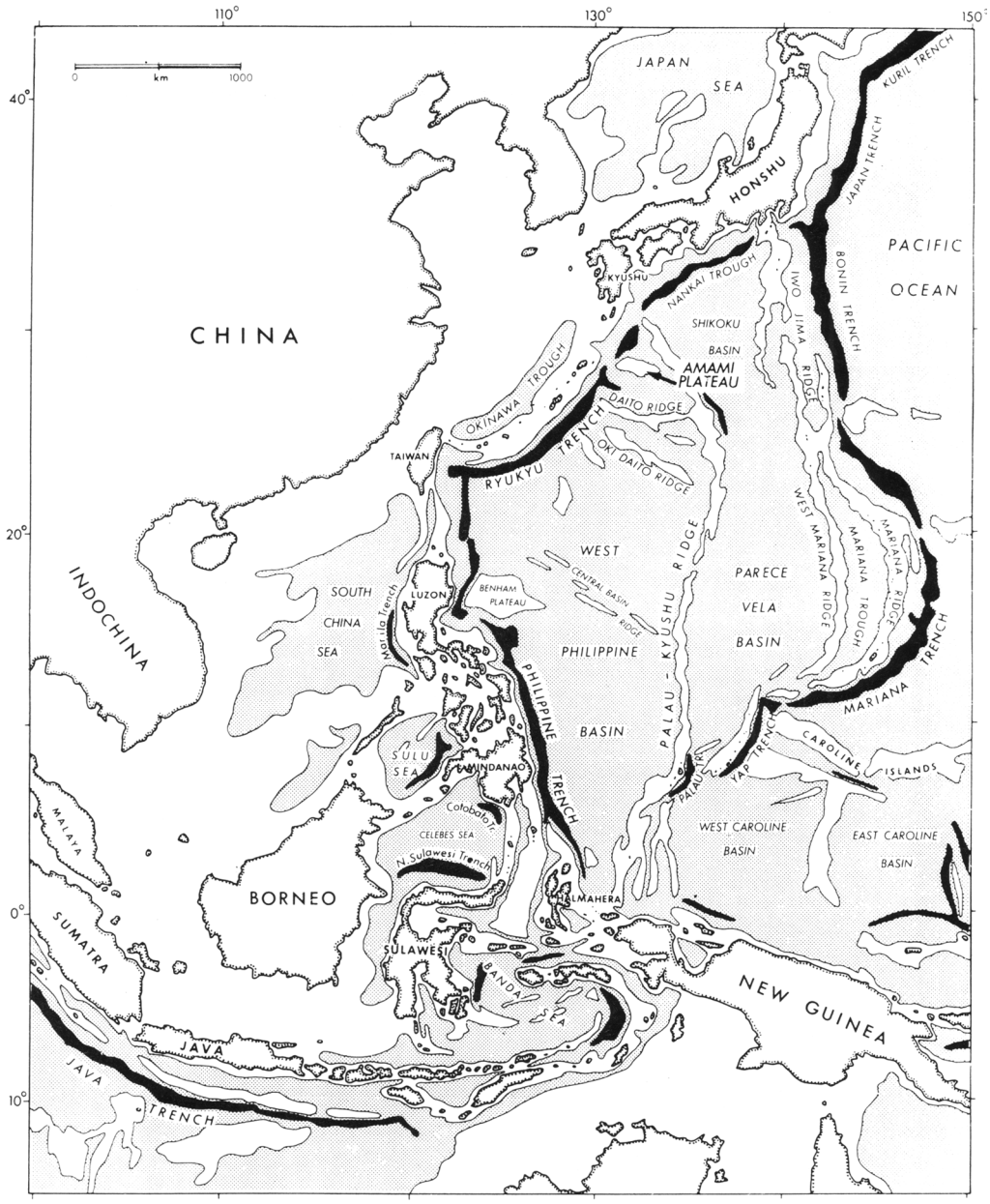

Fig. 1. Location of Halmahera (modified from Hall & Nichols 1990).

rocks in the Halmahera ophiolite are largely unaltered peridotites and cumulates; these are the subject of this account.

Analytical methods

Mineral analyses were made at University College London on a Cambridge Instruments Microscan V electron microprobe using a Link Analytical Systems 860 energy dispersive system; correction procedures were carried out using a full ZAF correction program supplied by Link. Natural silicates and pure metals were used as standards. Complete mineral analyses are available in Ballantyne (1990).

For whole rocks SiO_2 was determined by the method of Shapiro & Brannock (1962) and the re-

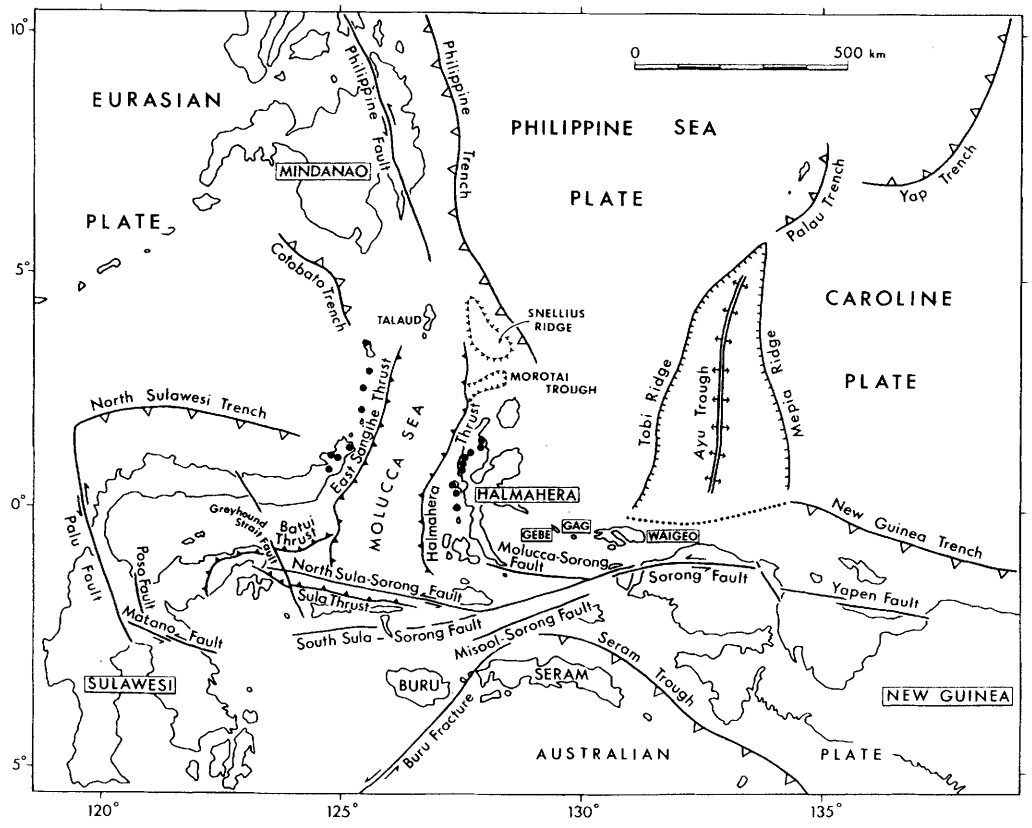

Fig. 2. Principal tectonic elements in the region of eastern Indonesia around Halmahera (from Hall & Nichols 1990).

Holloway and Bedford New College (RHBNC), University of London (Walsh 1980). Sample preparation involved dissolution in perchloric and hydrofluoric acids, except for the spinel-bearing peridotites for which this method led to erroneous results (underestimation of Mg and overestimation of Si); these rocks were fused with $LiBO_2$ and analysed for all major elements using the ICP 'MAJORS' program. Conventional gravimetric methods were used to obtain CO_2, H_2O and Fe^{2+}/Fe^{3+}.

The trace elements quoted in the Tables 2, 3 and 4 were analysed using a Philips PW1400 XRF and pressed powder pellets at RHBNC and are reported on a volatile-free basis normalised to 100% totals for major elements. Hyphens indicate concentrations below the XRF detection limits. Approximate errors (2σ counting statistics) are ±1 ppm for most elements, ±0.2 ppm for Nb, ±0.4 ppm for Rb and Y, ±1.5 ppm for La and Ce, ±2 ppm for Cu and Zn, ±3 ppm for Ba, ±6 ppm for Cr and ±50 ppm for Cl.

Clinopyroxene REE contents were determined by isotope dilution using a VG534 five-collector mass spectrometer in the Radiogenic Isotope Laboratory at RHBNC using methods described by Thirlwall (1982) modified for a multi-collector system.

Mantle-sequence peridotites

Mantle-sequence tectonized peridotites usually form the lower part of the igneous stratigraphy of a complete ophiolite and are widely interpreted as a residue after the extraction of magma generated by upper mantle partial melting. Such peridotites crop out extensively in eastern Halmahera. They are predominantly harzburgites with rare occurrences of lherzolite, but serpentinization can be so extensive that spinel is the only preserved primary phase. Some harzburgites (e.g. H6) contain up to 3–4% modal clinopyroxene as grains up to 0.5 mm across but most are devoid of clinopyroxene. Lherzolites, containing between 10% (HA81) and 20% (HA52) modal clinopyroxene, are restricted geographically to a narrow region (Ballantyne 1990), but field relations are obscure. Lherzolite samples display mosaic-porphyroclastic textures (Harte 1977) and vary from completely fresh to 60% serpentinized. Selected aspects of the primary mineral chemis-

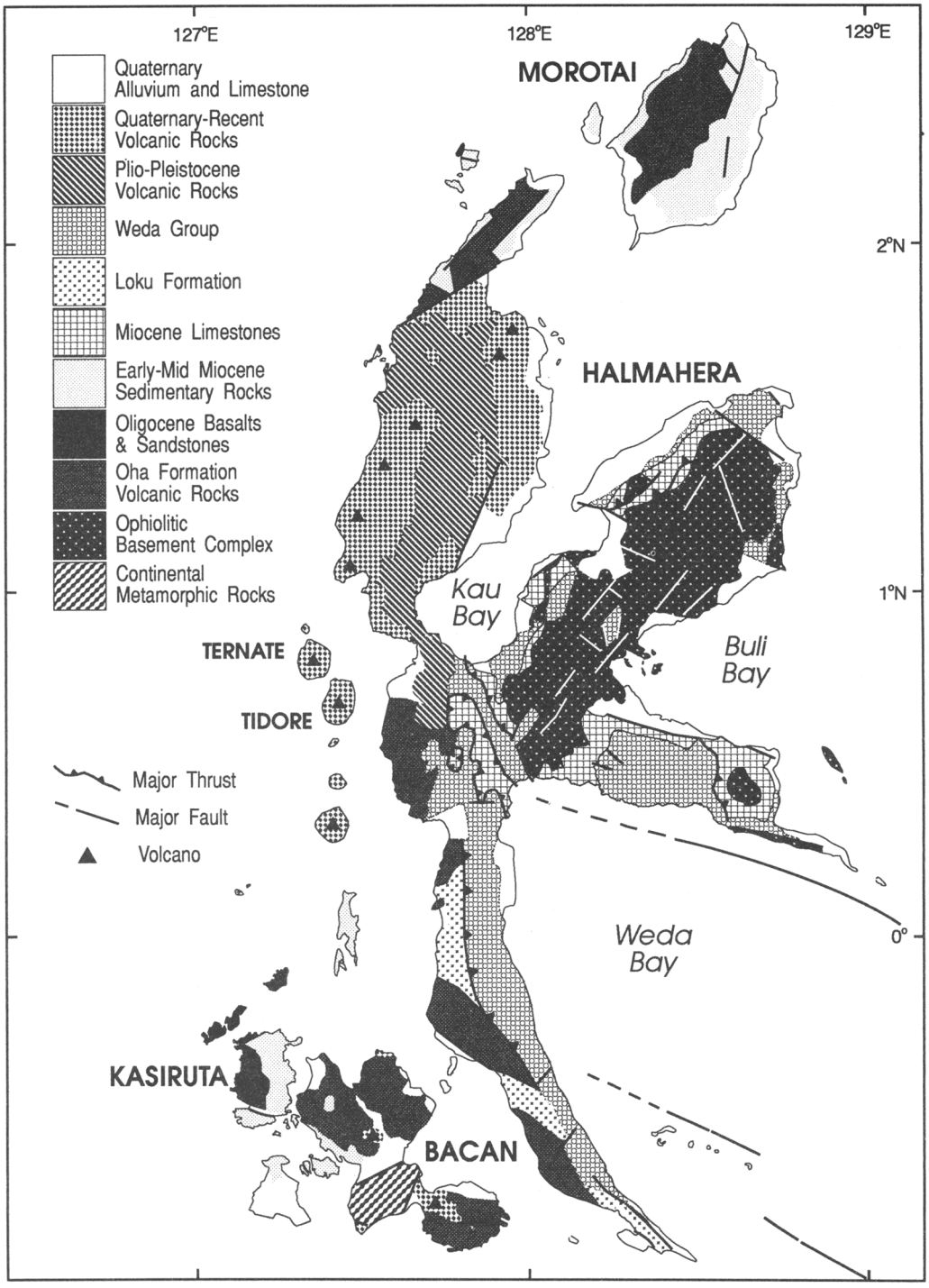

Fig. 3. Simplified geological map of Halmahera (modified after Hall & Nichols 1990).

try of the Halmahera mantle sequence rocks are summarized in Table 1.

Mineralogy and petrography of primary phases

Olivine. Olivines are unzoned and show a limited compositional range (Fig. 4), typical of ophiolitic mantle sequences. Harzburgite olivines are more magnesian and nickeliferous than those from the lherzolites (Table 1). Across all the mantle sequence peridotites. MnO shows weak negative correlations with Fo and NiO, reflecting the parallel substitutions of Mn for Fe and Ni for Mg in the olivine lattice.

Spinel. Accessory, disseminated Cr-bearing spinel is ubiquitous in the Halmahera mantle sequence peridotites, varying in colour from orange-brown through deep red-brown to black. Spinels usually show a bimodal grain size distribution in individual rocks, occurring as small crystals in clusters or strings parallel or slightly oblique (10–20°) to the tectonite foliation and as large (up to 3 mm), 'holly leaf', disrupted grains (Harte 1977), often with tension gashes ('pull-apart' fractures). Exsolution of vermicular spinel from orthopyroxene (often occurring at olivine/orthopyroxene grain boundaries) occurs more commonly in lherzolites than harzburgites. Orthopyroxene grains adjacent to exsolved vermicular spinels are poorer in Al_2O_3 than those elsewhere in the rock and with higher mg# and the exsolved spinels have lower cr# [cr# = (Cr/Cr + Al) × 100] than others in the rock. Such a chemical pattern suggests a reaction involving aluminous orthopyroxene, such as:

$$Mg_2SiO_4 + MgAlAlSiO_6 = MgAl_2O_4 + Mg_2Si_2O_6$$

as proposed by Menzies (1975) to account for the chemistry of aluminous exsolved spinels in harzburgites from the Othris ophiolite in central Greece.

The Halmahera mantle sequence spinels display wide compositional variation relative to their associated silicate minerals. Al-rich spinel is orange-brown in colour and restricted to lherzolites, whereas Cr-rich spinel is darker brown, red-brown and black and found in harzburgites (Table 1). Both harzburgite and lherzolite spinels are characterized by low TiO_2 contents, reaching a maximum of 0.30 wt% although usually below 0.10 wt%. Limited evidence suggests a chemical zoning in large spinels of the Cr-rich type, with Cr_2O_3 and FeO decreasing from core to rim and Al_2O_3 and MgO increasing, similar to that in spinels described by Ozawa (1986) from the Miyamori ultramafic complex in north-eastern Japan.

Evidence that spinel cr# is affected by host rock alteration is found only in harzburgite H6 where 'ferritchromit' spinel of very high cr# (88–93) and Fe^{3+} is associated with calcic amphiboles, similar to those described by Engin & Aucott (1971). The calcic amphiboles are associated with other minerals, such as hydrogrossular and prehnite, typical of calcium metasomatism related to serpentinization (Coleman 1967; Moody 1979; Rice 1983). Small, altered spinel grains in serpentinized harzburgite are black and 'ragged' in appearance and contain significant Fe^{3+} (on recalculation assuming 12 cations), whereas other grains in the same rocks are deep red in colour, contain little or no Fe^{3+} and have similar cr# to the altered examples. This suggests that spinel alteration on serpentinization is restricted to the Fe^{2+} to Fe^{3+} reaction and that primary Cr/Al ratios are maintained. For example, in the serpentinized harzburgite HR244, an Fe^{3+}-rich (43.4 wt%) phase, presumably a product of highly oxidizing conditions during serpentinization, forms a mantle around a primary, unoxidized spinel core of very similar cr# (core cr# = 61.2, oxidized rim cr# = 61.7).

Clinopyroxene. Clinopyroxene is rare as discrete grains in the harzburgites, but is common as narrow exsolution lamellae within orthopyroxene crystals. Individual grains are usually clustered around the boundaries of larger orthopyroxene grains, probably due to sub-solidus granule exsolution (Lindsley & Anderson 1983); such grains do not contain exsolution lamellae of Ca-poor pyroxene, but narrow exsolution lamellae are present in clinopyroxene situated further from orthopyroxene grain boundaries. Harzburgite clinopyroxenes are chromian diopsides of mean composition $En_{48.5}Fs_{2.8}Wo_{48.7}$ (Fig. 4) with higher mg# and Cr_2O_3 than coexisting orthopyroxene and with approximately equal Al_2O_3. Lherzolite clinopyroxenes have a mean composition of $En_{47.5}Fs_{4.5}Wo_{48.0}$ (Fig. 4) and porphyroclasts contain narrow exsolution lamellae of Ca-poor pyroxene. They are more aluminous than coexisting orthopyroxenes, with higher Cr_2O_3, and TiO_2 ranging from 0.16 to 0.32 wt% (Table 1). Na_2O varies between 0.56 and 0.84 wt% in clinopyroxene in the lherzolites HA52 and HA54, but reaches a maximum level of only 0.17 wt% in HA81. Na_2O does not vary systematically with either Al_2O_3 or Cr_2O_3 (cf. Johan & Augé 1986). V was detected during microprobe analysis of clinopyroxene porphyroclasts in HA54.

Table 1. *Selected aspects of the mineral chemistry of the Halmahera mantle sequence and crustal sequence primary phases*

Mantle sequence: mineralogy

Lherzolites

Olivines	Fo	NiO	MnO
n	9	9	8
min	90.1	0.28	0.05
max	91.0	0.51	0.19
mean	90.4	0.38	0.11
s	0.26	0.08	0.05

Spinels	cr#
n	15
min	14.6
max	24.3
mean	17.2
s	2.96

Cpx	mg#	Al_2O_3	Cr_2O_3	MnO
n	11	11	11	5
min	90.6	4.89	0.95	0.05
max	92.6	6.36	1.51	0.08
mean	91.4	5.61	1.27	0.06
s	0.59	0.47	0.16	0.01

Opx	mg#	Al_2O_3	Cr_2O_3	MnO	CaO
n	14	14	14	12	14
min	90.1	2.72	0.36	0.08	0.57
max	90.9	5.55	1.01	0.27	2.19
mean	90.5	4.07	0.68	0.16	1.24
s	0.24	0.89	0.17	0.05	0.55

Harzburgites

Olivines	Fo	NiO	MnO
n	29	29	27
min	90.9	0.23	0.05
max	92.1	0.54	0.22
mean	91.6	0.42	0.13
s	0.32	0.07	0.05

Spinels	cr#
n	55
min	45.4
max	75.8
mean	61.6
s	7.68

Cpx	mg#	Al_2O_3	Cr_2O_3
n	5	5	5
min	93.9	0.63	0.68
max	95.5	2.18	1.18
mean	94.7	1.65	0.93
s	0.61	0.54	0.21

Opx	mg#	Al_2O_3	Cr_2O_3	MnO	CaO
n	32	32	32	27	32
min	90.7	0.41	0.19	0.04	0.39
max	92.8	2.31	0.93	0.24	1.68
mean	91.9	1.04	0.55	0.12	0.95
s	0.59	0.49	0.14	0.06	0.36

Crustal sequence: mineralogy

Olivine-rich cumulates

Olivines	Fo	NiO	MnO
n	40	39	40
min	85.3	0.06	0.08
max	89.8	0.43	0.31
mean	87.3	0.24	0.20
s	1.23	0.08	0.06

Spinels	cr#
n	20
min	18.7
max	57.4
mean	40.6
s	10.94

Cpx	mg#	Al_2O_3	Cr_2O_3	MnO
n	41	41	41	22
min	86.9	0.89	0.3	0.05
max	93.5	4.01	1.54	0.21
mean	90.2	2.3	1.0	0.1
s	1.51	0.72	0.38	0.05

Opx	mg#	Al_2O_3	Cr_2O_3	MnO	CaO
n	20	20	18	20	20
min	85.8	0.73	0.14	0.15	0.32
max	90.1	2.56	0.75	0.34	3.9
mean	87.8	1.3	0.4	0.2	1.0
s	1.11	0.44	0.15	0.05	0.72

Olivine-poor cumulates

Cpx	mg#	Al_2O_3	Cr_2O_3	MnO
n	59	59	47	58
min	65.1	0.13	0.05	0.05
max	90.6	4.41	1.31	0.36
mean	80.1	1.8	0.4	0.2
s	6.50	0.68	0.34	0.08

Opx	mg#	Al_2O_3	Cr_2O_3	MnO	CaO
n	32	32	16	32	32
min	56.7	0.09	0.06	0.22	0.33
max	87.5	2.01	0.55	0.59	2.64
mean	76.5	0.8	0.2	0.3	1.2
s	8.28	0.44	0.14	0.11	0.47

n = number of samples; s = standard deviation.
For trace elements samples with concentrations below microprobe detection limits are excluded.

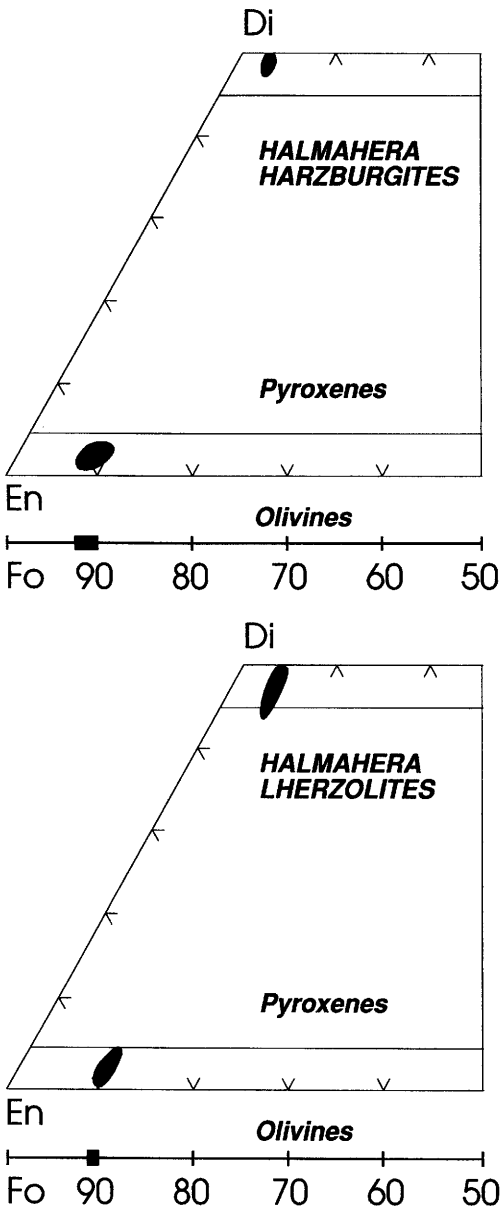

Fig. 4. Compositional variation of olivines and pyroxenes in Halmahera harzburgites and lherzolites.

Orthopyroxene. Halmahera mantle-sequence pyroxenes are unzoned in terms of their major constituents and, like the olivines, show limited compositional variation (Figs. 4). Harzburgite orthopyroxenes may contain small exsolution 'blebs' and thin lamellae of Ca-rich pyroxene along the (100) crystallographic planes, but such exsolution is rare in lherzolite orthopyroxenes, which contain significantly higher CaO (Table 1). CaO contents are very variable in all orthopyroxenes, which could reflect submicroscopic clinopyroxene exsolution lamellae, resulting in large variations in Wo and, correspondingly, En components, but the range in magnesium number [mg# = (Mg/Mg + Fe^{2+}) × 100] is more limited (Table 1). Harzburgite orthopyroxenes are the most magnesian, whereas Al_2O_3, Cr_2O_3 and MnO (correlating with FeO) are higher in lherzolite orthopyroxenes (Table 1). Al_2O_3 may vary in orthopyroxenes from individual lherzolite samples by up to 2 wt%; similar variation was not observed in the harzburgite orthopyroxenes, although there is a significant variation in orthopyroxene Al_2O_3 between rocks. Positive correlation between Cr_2O_3 and Al_2O_3 suggests that charge balance is maintained by a $CaCrAlSiO_6$-type substitution (Deer *et al.* 1978).

Whole-rock chemistry

Analyses of four harzburgites and three lherzolites are presented in Table 2. Locally, very high degrees of serpentinization occur along the imbricate, high-angle fault zones common in eastern Halmahera and the analyzed rocks have undergone varying degrees of serpentinization, and therefore both fresh (<5% serpentinized) and altered rocks have been analyzed. Abundances of magmaphile major elements such as Al, Ca, Ti, Na and K, and incompatible trace elements, such as Zr and Nb, are very low, whereas Cr, held in spinel and pyroxene, and Ni, held in olivine, are very high, up to maxima of 3380 and 2690 ppm respectively. Zn correlates with Cr, which supports microprobe evidence that it is accommodated in the spinel lattice.

Comparison of the chemistry of the harzburgites and lherzolites reveals that the lherzolites are appreciably enriched in CaO and Al_2O_3, in accordance with their clinopyroxene and aluminous spinel contents, and have lower bulk mg#, corresponding to the less magnesian nature of their constituent silicate phases (Table 1). Certain minor elements are also relatively enriched in the lherzolites, e.g. Sc, V, Cu and Ga (Table 2). Sc and V are probably held in clinopyroxene (Ross *et al.* 1954; Borisenko 1967) and Cu and Ga in spinel (McKay & Mitchell 1988). Higher concentrations of CaO, Al_2O_3, Sr, Sc, V and Ga in harzburgite H6 (Table 2) correlate with the presence of 3–4 modal % clinopyroxene and minor Ca-metasomatism.

The amount of H_2O^+ listed in the peridotite analyses is proportional to the degree of ser-

pentinization of the rocks (Table 2). The positive correlation of H_2O and CO_2 in Table 2 suggests that the serpentinising fluid had a CO_2 component. The amount of serpentinization and H_2O^+ are proportional to the Cl concentration, from which it is inferred that serpentinization occurred through the input of Cl-bearing, marine-derived water into the peridotites. Cl was detected commonly during microprobe analysis of the serpentine minerals.

Cumulates

Rocks with cumulate textures are particularly well represented in the material collected from Halmahera, although no contacts with overlying dolerites or underlying mantle sequence rocks are exposed. Orthopyroxene is an important (typically 20–25 modal %) and early crystallizing phase in the Halmahera cumulate rocks, and olivine is notable for its relative scarcity in the gabbroic rocks, which always contain two pyroxenes. Hornblende is a subordinate phase in some cumulates. Varying proportions of the cumulus and postcumulus minerals give rise to the following cumulate types (Streckeisen 1974): dunite, olivine clinopyroxenite, wehrlite, olivine gabbronorite, troctolite and gabbronorite. The rocks commonly exhibit an igneous lamination defined by the sub-parallel orientation of tabular cumulus plagioclase and, to a lesser extent, subhedral, prismatic pyroxene, but the rhythmic

Table 2. *Whole-rock geochemistry of Halmahera mantle-sequence peridotites*

	Harzburgites				Lherzolites			Undepleted upper mantle
	HP72	HA70	HR317	H6	HA81	HA52	HA54	
wt% oxide								
SiO_2	45.77	42.86	44.42	40.64	38.54	44.56	42.62	44.20
TiO_2	0.01	0.02	<0.01	0.06	0.03	0.06	0.04	0.10
Al_2O_3	0.30	0.52	0.50	0.90	1.61	2.42	2.05	2.70
Fe_2O_3	7.33	7.00	8.26	8.78	7.47	8.43	8.27	1.10
FeO								7.30
MnO	0.11	0.12	0.12	0.11	0.10	0.12	0.11	0.15
MgO	45.41	41.93	45.03	42.29	36.37	40.47	39.87	41.30
CaO	0.28	0.42	0.42	1.08	1.45	2.20	1.99	2.40
Na_2O	0.01	0.01	<0.01	0.05	<0.01	0.03	0.05	0.25
P_2O_5	0.05	0.05	0.05	0.06	0.05	0.06	0.04	0.02
H_2O^-	0.39	0.68	0.22	0.21	1.76	0.22	0.35	
H_2O^+	0.90	5.84	0.93	5.19	11.07	1.05	4.05	
CO_2	0.03	0.42	0.13	0.76	1.04	0.35	0.50	
Total	100.59	99.87	100.08	100.13	99.49	99.97	99.94	99.52
mg#	92.5	92.3	91.6	90.6	90.7	90.6	90.6	
Al_2O_3 + CaO	0.58	1.01	0.94	2.11	3.57	4.70	4.25	5.10
%serp	<5	37	<5	28	58	<5	17	
Trace elements (ppm)								
Cl		430		250	600	50	340	
Sc	6	6	8	12	13	15	13	
V	16	28	19	48	56	61	61	
Cr	2800	2760	2920	3380	2930	2770	2780	2050
Ni	2690	2340	2640	2530	2320	2330	2320	1570
Cu			4	2	14	23	21	
Zn	47	42	46	60	50	53	50	
Ga	1			1	2	2	2	
Sr	2.1	1.1	2.6	11.5	1.2	1.1	1.3	
Zr	0.1	0.2	0.2	1.6	0.1	0.4		
Nb	0.2		0.3		0.2		0.1	
Y	0.3	0.4		1.4	0.6	2.3	2.1	

All Fe as Fe_2O_3. K_2O below 0.01 wt% in all analyses; Rb, Th, La, Ce and Nd all below XRF detection limits.
mg# = 100 × Mg/(Mg + Fe), where Mg = MgO/40 and Fe = (Fe_2O_3 × 0.9)/72.
Al_2O_3 + CaO parameter recalculated to 100% volatile-free. %serp is the volume of rock serpentinized.
Blanks in the Halmahera sample analyses indicate concentrations below XRF detection limits.
Undepleted upper mantle composition from Harris *et al.* (1967).

grain-size and modal lamination (Irvine 1982) often reported from this level in intact ophiolites is not common.

Cumulate dunites are rare and invariably serpentinized, but can be recognized by the polygonal arrangement of trails of small Fe oxide grains with 120° triple junctions, preserving the boundaries of former olivine crystals.

Olivine-rich cumulates include wehrlites, olivine gabbronorites and troctolites which are coarse-grained and inequigranular orthocumulates, usually containing olivine + spinel as their cumulus assemblage with up to 70 modal % olivine. The early-formed olivine is sub-rounded and enclosed poikilitically by postcumulus orthopyroxene and clinopyroxene grains up to 10 mm across, usually with undulose extinction and bent cleavage planes. Olivine + plagioclase is rare as a cumulus assemblage although plagioclase is a ubiquitous, anhedral, postcumulus phase. Clinopyroxene is markedly more abundant than orthopyroxene in the olivine-rich rocks. Orthopyroxene occurs usually as large grains with included, equant chadacrysts of clinopyroxene.

Olivine-free gabbronorites are the most abundant cumulate rock type in Halmahera. The gabbronorites are usually completely unaltered. Cumulus plagioclase forms up to 60 modal % and the modal abundance of orthopyroxene is virtually equal to that of clinopyroxene, although the grain size of the former is invariably larger. Hornblende occurs only rarely as a cumulus phase of low modal abundance. The gabbronorites are characterized by a prominent igneous lamination and hypidiomorphic to allotriomorphic granular textures, with grain sizes varying from 0.5 mm to approximately 3 mm. Sample HA7 is an unusual layered ferrogabbronorite containing approximately 8 modal% postcumulus Fe–Ti oxide.

Mineralogy and petrography of primary phases

Olivine. Olivine from the cumulates is less magnesian than any of those from the mantle sequence peridotites (Table 1). Fo contents range from 89.8 to 76.0 in the cumulus olivine and zoning is not observed. Olivine more Fe-rich than Fo_{85} is not found in rocks with more than 10 modal% of the mineral. MnO reaches a maximum of 0.37 wt%; its concentration varies from 0.05 to 0.31 wt% in olivines more magnesian than Fo_{85}, but is consistently above 0.20 wt% in more Fe-rich grains. NiO shows a similar pattern, correlating positively with Fo up to 0.29 wt% below Fo_{85} and then scattering between 0.06 and 0.43 wt% in more magnesian grains.

Spinel. Black, euhedral to sub-rounded spinel is always associated in a cumulus assemblage with olivine and never coexists with cumulus plagioclase. Grains reach a maximum size of around 0.3 mm and occur at olivine grain boundaries, or rarely are enclosed within postcumulus clinopyroxene; there is no apparent compositional difference between spinels in these two modes of occurrence, indicating a lack of subsolidus Cr-Al exchange between spinel and the host pyroxene.

Cumulus spinel compositions exhibit only a limited range in cr#, from 48.6 to 64.1. They have similar cr# to the harzburgite spinels (Fig. 5) but markedly lower mg#, suggesting either lower temperatures of formation (Fisk & Bence 1980) or sub-solidus Mg-Fe re-equilibration with olivine (e.g. Henry & Medaris 1980; Ahmed 1982; Ozawa 1983, 1986). TiO_2 ranges from 0.2 to 1.2 wt% and correlates positively with cr# and negatively with Fo contents of coexisting olivine i.e. spinel becomes generally more chromian and titaniferous as olivine becomes more Fe-rich. This may reflect increasing activity of Si, Fe (which would affect cr# through the Cr–Fe solid solution combination in the spinel molecule) and Ti in the magmatic liquid (Dick & Bullen 1984; Allan *et al.* 1988) due to the early fractionation of large volumes of magnesian olivine.

Clinopyroxene. Coexisting cumulus ortho- and clinopyroxene compositions are plotted on the pyroxene quadrilateral in Fig. 6. In terms of quadrilateral components, cumulus clinopyroxenes vary from $En_{48.0}$ $Fs_{3.3}Wo_{48.7}$ (mg# = 93.5, olivine clinopyroxenite H215) to $En_{35.7}Fs_{19.7}Wo_{44.6}$ (mg# = 65.1, HA7). In cumulus assemblages with coexisting pyroxenes, the clinopyroxene has markedly higher mg# than the orthopyroxene. Postcumulus clinopyroxenes, in which exsolution lamellae of Ca-poor pyroxene are more prominent than in cumulus grains, ranges in mg# from 92.2 to 87.7 (Fig. 6).

Cumulus clinopyroxenes in the Halmahera ophiolite are characterized by low TiO_2 contents averaging 0.27 wt% (Ballantyne 1991*b*). Cr_2O_3 and mg# display a strong positive correlation and Cr_2O_3 is typically less than 0.74 wt%, although in one gabbronorite (H64) clinopyroxene Cr_2O_3 is 1.1–1.2 wt% at mg# = 88.2–88.7. In contrast, Cr_2O_3 is very variable (0.3–1.5 wt%) and shows no coherent relationship to mg# in postcumulus grains. In cumulus

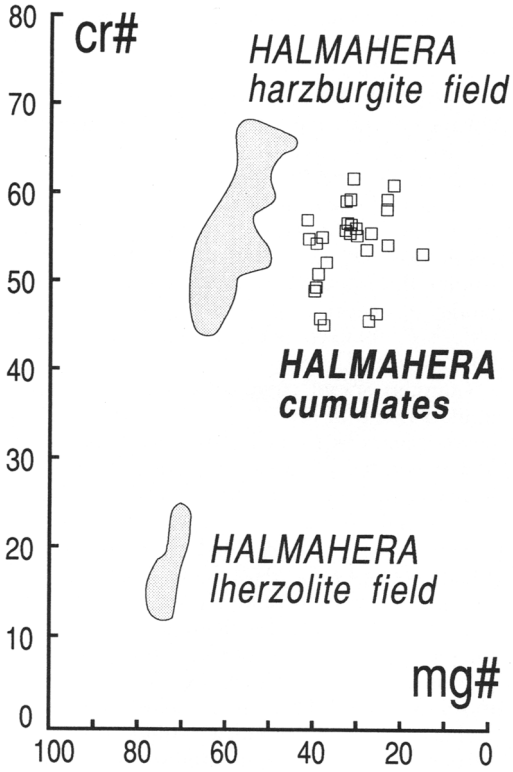

Fig. 5. Unoxidized cumulus spinels (n = 42) with field of unoxidised spinels from Halmahera mantle sequence harzburgites (see Fig. 10) for comparison.

clinopyroxenes there is a strong positive correlation between Al_2O_3 and Cr_2O_3, suggesting that charge balance is maintained by a $CaCrAlSiO_6$-type substitution (Deer *et al.* 1978). Al_2O_3 varies widely (0.8–4.4 wt%), but is approximately constant in clinopyroxenes within individual rocks, and correlates positively with mg#, suggesting increasing magmatic a_{SiO2} with differentiation. Na_2O is rarely above the microprobe detection level (approximately 0.15 wt%).

Zoning is rare in cumulus clinopyroxenes and observed only in more fractionated gabbronorite samples (e.g. H65 and H67). Rims of zoned grains are enriched by up to 6 mol.% Wo compared to the cores, accompanied by a minor core to rim increase in mg#, similar to reverse zoning reported in cumulus clinopyroxenes from the Oman ophiolite (Lippard *et al.* 1986). Al_2O_3 and MnO decrease consistently from core to rim in these zoned grains but TiO_2 shows no systematic variation. Such patterns appear to indicate that postcumulus crystal growth took place in these more fractionated rocks, probably through re-equilibration of the cumulus phases with interstitial pore liquid, leading to a slightly modified accumulate texture.

Applying the Kretz (1982) formulation of the temperature dependence of Mg/Fe distribution between coexisting ortho- and clinopyroxenes to microprobe data from the olivine-free gabbronorites H64, H65, H66 and H67 results in temperature estimates in the range 1180–1280°C. This is 200–300°C in excess of the estimated temperatures from Bushveld pyroxenes (Kretz 1982) and implies either a hotter magma or a lack of chemical equilibrium. The marked deviation on Fig. 6 from the 'primary solidus' (high-temperature crystallization) trend of Jaques (1981) indicates that the Halmahera pyroxenes have undergone re-equilibration at lower, sub-solidus, temperatures.

Orthopyroxene. Orthopyroxene always coexists with clinopyroxene. In olivine-rich cumulates orthopyroxene occurs as large, often postcumulus and poikilitic, grains of low abundance. In olivine-free gabbronorites there is typically 20–25% modal orthopyroxene. Whether orthopyroxene or clinopyroxene appears before clinopyroxene in the Halmahera rocks is difficult to ascertain; the two phases appear to have crystallised simultaneously. However, in olivine-free gabbronorites, petrographic evidence of the larger grain size of the orthopyroxene, although this may be an artefact of the annealing process, suggest the earlier formation of orthopyroxene.

Orthopyroxene mg# in cumulate rocks is always lower than in the mantle sequence harzburgites and lherzolites (Table 1); mg# in cumulus grains varies from 87.0 to 56.7 (Fig. 6), and up to 89.2 in postcumulus grains (Fig. 6). TiO_2 increases as mg# decreases, up to a maximum of 0.35 wt% (HA7), but concentrations above 0.2 wt% are rare. As in clinopyroxenes, Cr displays two different trends: in cumulus grains Cr_2O_3 is less than 0.33 wt% (except in H64 in which it reaches 0.55 wt%.) whereas in postcumulus grains it ranges up to 0.75 wt%. Both TiO_2 and Cr_2O_3 are depleted in cumulus orthopyroxene relative to coexisting clinopyroxene. Al_2O_3 varies widely (0.10–2.6 wt%), but has a small range within individual rocks and correlates positively with mg# and with Cr_2O_3. In contrast to TiO_2 and Cr_2O_3, MnO (range: 0.15–0.59 wt%) and NiO (up to 0.18 wt%) are partitioned preferentially into orthopyroxene. CaO correlates negatively with mg#, although with considerable scatter, and reaches a maximum concentration of 2.6 wt% (5.2 mol% Wo).

CaO is variable within individual rocks, reflecting either the presence of sub-microscopic

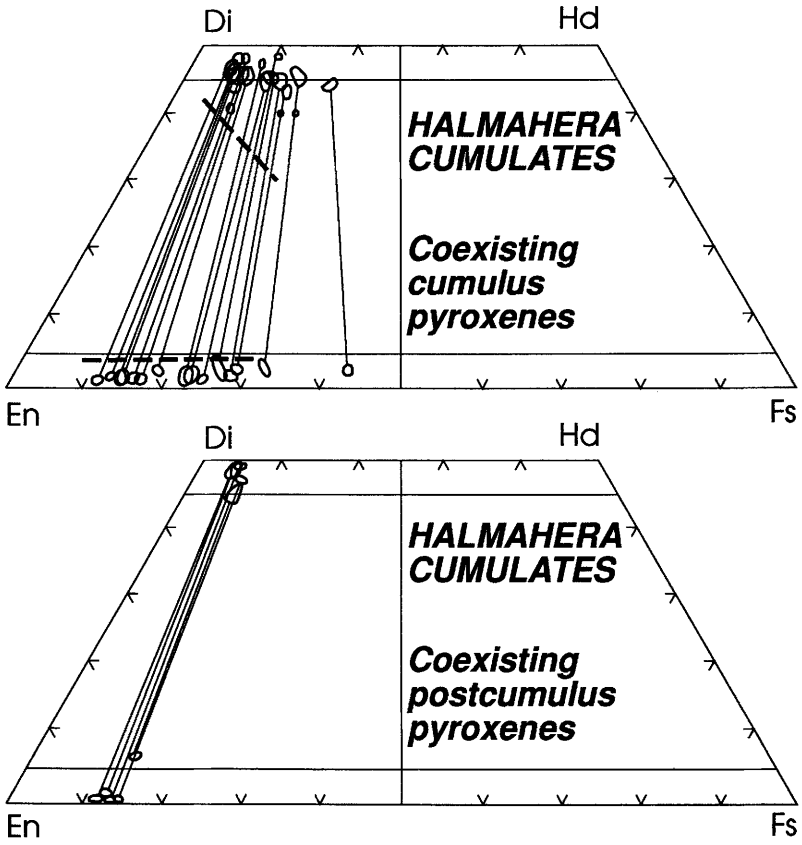

Fig. 6. Clino- and orthopyroxene cumulus assemblages (above) with tie-lines joining coexisting pairs and the solidus trends of Jaques (1981). Coexisting postcumulus assemblages below.

clinopyroxene exsolution lamellae or of varying degrees of sub-solidus re-equilibration (Jaques & Chappell 1980; Jaques 1981). Exsolution textures characteristic of inverted pigeonite were found in only one sample (HA7). No zoning was detected in orthopyroxenes from the cumulates.

Plagioclase. Plagioclase feldspar is an abundant, usually unaltered, cumulus phase in the layered gabbronorites. Polysynthetic twinning is ubiquitous in the gabbronorite plagioclase; the twin lamellae often vary in thickness and pinch out parallel to the rock lamination in the manner of the glide twinning described by Vance (1961), interpreted as of secondary origin and related to host rock deformation.

Early cumulus plagioclase occurs rarely with cumulus olivine in some troctolites and has a very limited compositional range ($An_{89.6-90.3}$). Plagioclase is usually a postcumulus phase in olivine-dominated rocks and invariably shows the effect of hydrothermal alteration (replacement by a fine-grained mixture of Ca–Al silicates) associated with serpentinization of the olivine. In these rocks plagioclase compositions range up to $An_{91.4}$, although data are less plentiful because of the alteration.

In hornblende-free gabbronorites compositions vary from $An_{59.6}$ to $An_{88.0}$ but in the few hornblende-bearing cumulates plagioclase is consistently more calcic, up to $An_{91.1}$. The possibility of hornblende preferentially incorporating magmatic Na is rejected because there is correlation of hornblende Na_2O and plagioclase Ab.

The maximum observed variation in plagioclase composition within a single rock was 8 mol.% An; this variation decreases with increasing An. No zoning was detected in any samples. K_2O is below the microprobe detection limit (0.1 wt%) in all analysed plagioclases in the cumulates, consistent with crystallization from a magma depleted in K.

Amphibole. Amphiboles occur as a cumulus phase in rocks characterized by calcic cumulus plagioclase. They are brown in colour and range in composition (Fig. 7) from actinolitic hornblende (HA87 and HA90) through edenitic (HA110) to hastingsitic hornblende (HA71) using IMA nomenclature (Leake 1978).

Amphibole compositions (Fig. 7) fall into two distinct groups. One group has high Al^{IV}/low Si, high TiO_2 and Na_2O (samples HA71 and HA110). The second group has low Al^{IV}/high Si, low TiO_2 and Na_2O (samples HA87 and HA90). The colour and pleochroic schemes are related to the Na_2O and TiO_2 contents: very pale green–brown and weakly pleochroic amphiboles in HA87 and HA90 have TiO_2 = 0.1–0.3 wt% and Na_2O = 0.5–0.9 wt% whereas darker brown and moderately pleochroic amphiboles in HA71 and HA110 have TiO_2 = 0.6–1.1 wt% and Na_2O = 2.1–2.5 wt%.

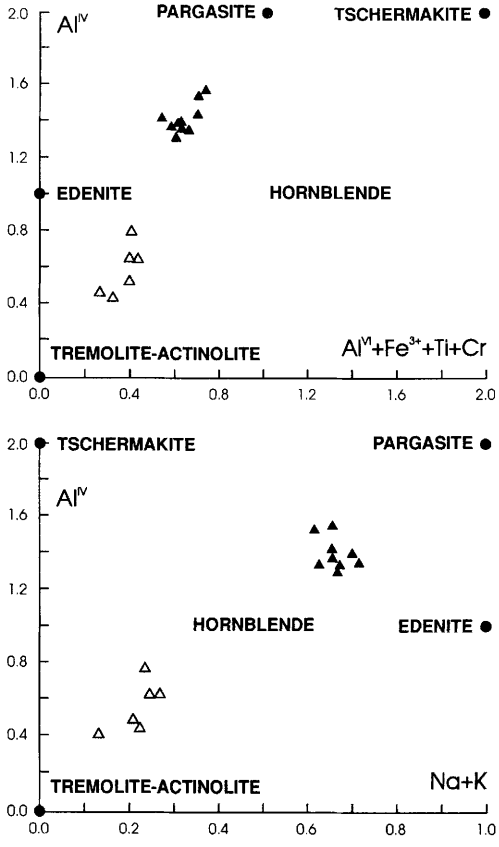

Fig. 7. Cumulus amphibole compositions: open symbols, high Si amphiboles (HA87, HA90); shaded symbols, low Si amphiboles (HA71, HA110).

There is no relation between cumulus amphibole occurrence and bulk alkali content. K is below 0.1 wt%, consistent with crystallization from a low-K magma, as suggested above. Cumulus hornblende always has lower mg# than coexisting pyroxenes, but Cr_2O_3 occurs at very similar levels in both amphibole and clinopyroxene, suggesting that they formed simultaneously as liquidus phases, as prior crystallisation of pyroxene would have depleted the melt in Cr (Conrad & Kay 1984). Compositional variations in amphibole are interpreted to reflect fluctuations in $a_{Al_2O_3}$ and a_{SiO_2}. Primary brown hornblende in the layered sequence of the Oman ophiolite (Lippard *et al.* 1986) is characterized by much higher TiO_2 (2–4.5 wt%) than those from Halmahera, reflecting the higher Ti content of the Oman magma compared to that of Halmahera.

Accessory phases. Cl-bearing apatite is present as tiny grains within cumulus plagioclase in a single gabbronorite (HR242). Magnetite is a common by-product of the serpentinization of olivine, but is present as a primary phase (associated with ilmenite) only in the most fractionated gabbronorite samples. It occurs as tiny anhedral grains concentrated along pyroxene/plagioclase boundaries (H67, H140) and as large, anhedral grains (HA7) in textures suggesting late crystal growth interstitial to the cumulus phases.

The paucity of early crystallizing, high temperature, primary Fe-Ti oxides indicates that the Halmahera magma had a low initial fO_2 (Helz 1973).

Whole-rock chemistry

Whole-rock major and trace element analyses of olivine-bearing and olivine-free cumulate rocks are presented in Tables 3 and 4. With the exception of two rocks discussed further below (ferrogabbronorite HA7 and microgabbronorite H107), these rocks may be considered as a single group in which the major and trace element chemical variation is mineralogically controlled.

The wide major element ranges, particularly of Al, Fe, Mg and Ca, reflect the cumulus mineralogy. For example, troctolites with cumulus spinel and olivine gabbronorites (H62, H159) contain up to 30 wt% MgO, troctolites with cumulus plagioclase (H59, HP66) have high Al_2O_3 (23–25 wt%) and olivine-free gabbronorites (e.g. H64, H65, H66, HR242) have high Al_2O_3 (17–20 wt%) and CaO (14–16 wt%). All the cumulates are extremely low in K_2O and P_2O_5.

Table 3. *Whole-rock geochemistry and mineralogy of olivine-bearing cumulate rocks*

	H215	H159	H59	HP66	H62	H158	H150	HA90
wt% oxide								
SiO_2	50.43	39.80	42.81	40.91	42.01	48.15	45.90	48.84
TiO_2	0.08	0.04	0.03	0.04	0.06	0.10	0.10	0.17
Al_2O_3	1.47	8.82	24.52	23.37	8.21	14.86	15.17	18.38
Fe_2O_3	3.82	7.14	2.97	3.36	8.44	4.64	4.28	4.35
MnO	0.07	0.11	0.05	0.06	0.14	0.10	0.09	0.09
MgO	22.56	29.20	10.59	11.98	25.23	13.51	11.82	9.66
CaO	16.46	5.11	12.05	13.12	7.35	15.43	17.35	16.80
Na_2O	0.09	0.58	1.31	0.48	0.42	0.77	0.50	0.89
K_2O	0.01	0.01	<0.01	<0.01	0.01	0.02	0.02	0.04
P_2O_5	0.01	0.04	0.05	0.06	0.03	0.03	0.03	0.04
H_2O^-	0.13	0.34	0.38	0.52	0.39	0.12	0.21	0.22
H_2O^+	3.54	7.41	5.76	5.30	6.35	1.62	3.40	0.74
CO_2	0.26	0.52	0.61	0.15	0.84	<0.05	0.33	0.16
Total	98.93	99.12	100.75	99.35	99.48	99.35	99.20	100.38
mg#	92.2	89.1	87.7	87.7	85.7	85.3	84.7	81.6
Trace elements (ppm)								
Cl	60	1700	630	120	1100	350		
Sc	59	10	8	9	24	38	32	40
V	82	31	15	19	72	110	120	120
Cr	2230	1560	220	190	2720	1240	2001	60
Ni	328	1520	395	420	1130	255	307	129
Cu	5	14	9	13	31	48	51	73
Zn	21	47	18	27	50	33	29	21
Ga	1	5	11	10	4	7	7	11
Rb				0.3		0.1		0.2
Sr	10.8	17.4	58.2	50	21	30.1	42.8	119
Y	2.1	1	0.9	0.8	2	3.6	4	5.1
Zr	1.9	0.6	0.4	1	1.3	1	2.2	1.9
Nb	0.4			0.1	0.5	0.4		0.1
Ba	4	2	3		2	2	5	5
Pb	0.2				0.7	0.3	0.2	0.1
Th							0.1	0.1
La				0.3				
Ce	0.3				0.8			0.5
Nd	1.6		0.4	0.1	1.3	0.1	1	1.5
Mineralogy								
Cumulus phases								
Olivine	*	*	*	*	*	*	*	*
Spinel		*			*			
Orthopyroxene	*					*	*	*
Clinopyroxene						*	*	*
Plagioclase			*	*		*	*	*
Homblende								*
Postcumulus phases								
Orthopyroxene		*	*	*	*			
Clinopyroxene		*	*	*	*			
Plagioclase		*			*			

All iron as Fe_2O_3.

Trace element chemistry is also largely a reflection of mineralogy. Ni correlates positively with MgO and decreases markedly with decrease in the modal abundance of olivine. Cr is high in all rocks. The highest Cr content (>3000 ppm) is in a spinel- and olivine-free gabbronorite (H64) containing highly chromian clinopyroxene. Cr decreases from the olivine-rich cumulates (Cr present in the spinel) to the plagioclase-rich cumulates. H64 is the most

Table 4. *Whole-rock geochemistry and mineralogy of olivine-free cumulate rocks*

	H64	H14	H66	HA110	HR242	H107	H65	H67	HA7
wt% oxide									
SiO_2	49.90	48.67	50.33	48.44	48.61	48.52	50.28	49.20	45.02
TiO_2	0.08	0.16	0.09	0.14	0.13	0.10	0.12	0.20	1.47
Al_2O_3	17.20	15.38	18.13	17.41	19.47	20.14	19.42	17.03	11.08
Fe_2O_3	3.17	5.96	5.17	5.69	5.08	5.03	5.74	9.31	20.86
MnO	0.08	0.12	0.12	0.12	0.11	0.07	0.12	0.16	0.24
MgO	11.30	11.80	10.22	10.92	9.28	8.52	8.65	9.87	8.46
CaO	15.87	14.64	14.15	14.62	14.90	11.82	13.94	12.94	11.54
Na_2O	0.88	1.42	1.12	1.27	1.18	2.39	1.63	1.36	1.28
K_2O	0.02	0.02	0.03	0.01	<0.01	0.32	0.03	<0.01	<0.01
P_2O_5	0.03	0.03	0.06	0.07	0.06	0.03	0.06	0.08	0.06
H_2O^-	0.21	0.08	0.13	0.15	0.11	0.41	0.17	0.09	0.19
H_2O^+	0.62	1.74	0.42	1.09	0.43	2.38	0.26	0.12	0.61
CO_2	0.21	0.14	0.23	0.29	0.07	0.72	0.17	0.14	0.17
Total	99.57	100.16	100.20	100.22	99.43	100.45	100.59	100.50	100.98
mg#	87.7	79.8	79.8	79.3	78.5	77.2	75.1	68.0	44.8
Trace elements (ppm)									
Cl		110							
Sc	34.2	47	39.6	42	32.6	35.9	37.2	41.7	40
V	110	152	106	144	126	56	113	217	63.1
Cr	3040	663	75	581	460	77	87	108	868
Ni	212	162	111	172	119	85	90	138	332
Cu	28	94	261	122	92	7	202	315	115
Zn	17	32	29	57	33	16	30	60	263
Ga	8	9	11	10	11	17	13	12	114
Rb	0.2		0.6	1.1	0.4	4.3	0.7		16
Sr	45	62	68.5	686	52.5	218	69.3	53.5	
Y	3.1	5.7	3.4	5.7	4.6	2.3	4.2	4.6	55.4
Zr	0.7	1.8	1.8	0.1	1.5		1.4	0.9	14.7
Nb	0.3	0.3	0.8	0.4	0.3	0.4	0.4	0.1	10.4
Ba	4	1	8	134		19	8	4	0.2
Pb	0.7	0.5	1.1	1.9	0.8	0.8	0.8	0.8	1
Th			0.5	0.6	0.5		0.4		0.5
La	2.4						0.9		0.4
Ce		0.9					0.3	0.3	
Nd	0.5	1.2	1.3	0.7	0.8		0.4		
Mineralogy									
Cumulus phases									
Orthopyroxene	*	*	*	*	*	*	*	*	*
Clinopyroxene	*	*	*	*	*	*	*	*	*
Plagioclase	*	*	*	*	*	*	*	*	*
Hornblende				*					
Fe Oxide					*			*	
Postcumulus Phases									
Fe Oxide									*

primitive olivine-free gabbronorite in terms of mg# and its high Cr probably reflects the enrichment of Cr in the liquid after the crystallization of large volumes of olivine.

Sr increases generally with the modal abundance of plagioclase, but has high values in gabbronorites with primary hornblende (HA90 and HA110). HA110 has very high Sr (686 ppm) and Ba (134 ppm); both Sr and Ba substitute for Ca in the plagioclase structure (Drake & Weill 1975), but the data of Smith *et al.* (1983) suggest that Ba is partitioned preferentially into the amphibole and thus probably resides largely in the Na-rich hastingsitic hornblende.

Sc and V are accommodated in the clinopyroxene lattice and so are notably depleted in the clinopyroxene-poor troctolites H59 and

HP66. The olivine-free gabbronorite H67 contains Fe-Ti oxides and relatively high V and Zn.

All the cumulates are extremely low in the HFS elements Ti, Zr, Y and Nb. Zr is very low (<2.2 ppm) and is not enriched in either the olivine-rich rocks with intercumulus material or the more fractionated, adcumulate gabbronorites.

The ferrogabbronorite HA7 and microgabbronorite H107 are exceptions. The lower mg# and higher concentrations of TiO_2 (1.47 wt%), Zr (10.4 ppm) and Y (14.7 ppm) in HA7 indicate that this rock is more fractionated than the other cumulates. However, the end product of a magmatic series crystallizing olivine, spinel and pyroxenes would be depleted in Cr and Ni and thus the significant concentrations of these elements in HA7 (Table 4) suggest that it is not a final differentiate. High V and Zn reflect partitioning into Fe-Ti oxide (Deer *et al.* 1962). HA7 is strikingly similar to 'strongly differentiated', planar-laminated, orthopyroxene-rich gabbronorite found at the top of the layered gabbro sequence in the southeastern part of the Oman ophiolite (Juteau *et al.* 1988). Similar rocks have also been recovered from the Indian Ocean crust (Engel & Fisher 1975; Kempton *et al.* 1988). The rocks described by Juteau *et al.* (1988) are remarkable in that orthopyroxene is rare as a cumulus phase in Oman (Pallister & Hopson 1981). The occurrence of ferrogabbronorites in Oman is associated with dense tonalitic veining and magmatic brecciation and interpreted as due to axial spreading centre discontinuities, in particular the tips of cells of spreading along a segmented axis.

The microgabbronorite H107 is relatively enriched in K_2O (0.32 wt%), Na_2O, Rb, Ba and Sr. This rock contains veins of pegmatitic plagioclase (An_{70-73}), and is probably a segregated, residual liquid enriched in elements incompatible with respect to the fractionating cumulus phases.

Rare earth element chemistry

REE concentrations in clinopyroxenes separated from four cumulates of contrasting mineralogy (gabbronorites H66, H158, HA90; olivine clinopyroxenite H215) were determined by isotope dilution mass spectrometry (Table 5). Chondrite-normalized profiles (Fig. 8) illustrate the strong LREE, lesser HREE depletion and slight negative Eu anomalies of the clinopyroxenes in H158 and HA90. The crossing of the patterns of H66 and H215 between La and Ce cannot be explained by analytical error and suggest changes in the LREE composition of the parental liquid. Total REE abundances do not increase systematically with host rock mg#; H66 contains lower concentrations of the REE than expected. This indicates a decoupling of the REE from the compatible elements, as predicted by O'Hara (1977), during open system fractional crystallization in a periodically replenished magma chamber.

Jaques *et al.* (1983) calculated magma compositions in equilibrium with the cumulate rocks of the New Guinea Marum ophiolite to be LREE-depleted with 11–25 × chondritic abundances of the HREE. The parental magma was estimated to contain total REE concentrations of 6–9 × chondrite, similar to that estimated for the Papuan ophiolite (<10 × chondrite) by Jaques & Chappell (1980). For the Halmahera ophiolite, REE magma compositions in equilibrium with the cumulates, calculated using the clinopyroxene/melt REE distribution coefficients of Henderson (1984), are shown in Fig. 9. The liquids calculated to have been in equilibrium with the four rocks have LREE-depleted patterns ($Ce_N/Yb_N = 0.21-0.89$) with HREE abundances between 0.8 and 5 × chondrite. These REE abundances are lower than those calculated for the New Guinea ophiolites, but are nevertheless lower than even the most primitive MORB and are typical of island arc or boninitic magmas.

Discussion and interpretation

Mantle sequence

The chemistry of Halmahera spinels has petrogenetic significance because, during partial melting, the less magmaphilic cation Cr is strongly partitioned into the solid and Al into the melt (Jaques & Green 1980; Mercier *et al.* 1984; Dick & Bullen 1984). Therefore the chemical composition of a spinel provides a sensitive indication of the degree of partial melting recorded by the host peridotite. Despite common serpentinization of silicate minerals in peridotites, spinels normally retain their primary chemistry, at least in terms of the cr# (Ozawa 1986, 1988), and thus preserve information of petrogenetic significance.

The Halmahera mantle sequence spinels exhibit the reciprocal variation between cr# and mg# described from ophiolitic mantle sequence spinels (Fig. 10). The Cr-rich, harzburgite spinels cluster mostly outside the range of spinels from abyssal peridotites (Dick & Bullen 1984), indicating that their host rocks have undergone a higher degree of partial melt extraction than that required to generate a MORB

Table 5. *Isotope dilution REE determinations of cumulus clinopyroxenes (ppm)*

	Gabbronorite H66	Olivine gabbronorite H158	Olivine clinopyroxenite H215	Olivine–Hornblende gabbronorite HA90
La	0.056 (3)	0.0812 (7)	0.051 (2)	0.1186 (5)
Ce	0.194 (4)	0.274 (1)	0.2089 (4)	0.597 (1)
Nd	0.4355 (1)	0.503 (1)	0.386 (1)	1.2384 (2)
Sm	0.2811 (5)	0.2936 (1)	0.1875 (1)	0.68395 (8)
Eu	0.1186 (4)	0.1219 (3)	0.0743 (2)	0.2655 (3)
Gd		0.618 (1)	0.28 (3)	1.217 (2)
Dy	0.88 (2)	1.057 (1)	0.359 (2)	1.791 (4)
Er	0.756 (3)	0.761 (2)	0.206 (1)	1.12 (3)
Yb	0.697 (1)	0.748 (2)	0.173 (1)	1 (4)
Lu		0.1122 (1)	0.0248 (2)	0.141 (3)
Chondrite-normalized magmatic concentrations				
La	2.1	3.1	1.9	4.5
Ce	0.66	0.93	0.71	2
Nd	1.2	1.3	1	3.3
Sm	1.5	1.6	1	3.7
Eu	1.7	1.8	1.1	3.8
Gd		2.5	1.1	4.9
Dy	2.3	2.8	1	4.7
Er	3.4	3.4	0.9	5
Yb	3.2	3.4	0.8	4.5
Lu		4.1	0.9	5.2
Ce/Yb	0.21	0.27	0.89	0.44

Figure in brackets is the uncertainty in the last quoted digit, and estimated REE concentrations normalized to chondritic values of Nakamura (1974) in the magma from which the clinopyroxene crystallized.

Magma REE values calculated using the K_D values for clinopyroxene/liquid partitioning in basaltic and andesitic rocks of Henderson (1984) (La: 0.08; Ce: 0.34; Nd: 0.6; Sm: 0.9; Eu: 0.9; Gd: 0.9; Dy: 1.1; Er: 1.0; Yb: 1.0; Lu: 0.8).

Normalized data plotted in Figs 8 and 9.

magma. In contrast, the high-alumina lherzolitic spinels plot within the abyssal peridotite field and their host rocks are compatible with an origin beneath a mid-oceanic spreading ridge. The association of the two types of peridotite suggests a multi-stage melting history for the Halmahera ophiolite. Although field relations are not clear, indications are that the lherzolitic rocks are restricted to a narrow area within a main mass of harzburgite.

In the Miyamori ophiolite complex in north-eastern Japan (Ozawa 1987, 1988) there are kilometre-scale, isolated bodies of predominantly tectonite lherzolite (spinel cr# = 10–37) within depleted harzburgite (spinel cr# = 40–78). The lherzolite is interpreted as mantle previously depleted by the extraction of MORB. The association of lherzolite and harzburgite is explained by melting in the lherzolite mantle wedge above a subducting slab, promoted by the addition of a H_2O-rich fluid derived from the slab, leaving a residue of harzburgite. A similar mechanism could explain the occurrence of small lherzolitic bodies within the Halmahera harzburgite.

Another indication of the relative degree of partial melt depletion of mantle sequence peridotites is given by the sum of their bulk CaO and Al_2O_3 contents, which provides a measure of the amount of magmaphile material remaining within the residual mantle (Ishiwatari 1985; Bonatti & Michael 1989). The bulk CaO and Al_2O_3 parameter for the Halmahera peridotites is normalised to 100% on an H_2O- and CO_2-free basis in Table 2. Values for the clinopyroxene-bearing harzburgite H6 may be unreliable due to the effects of the Ca-metasomatism (Coleman 1967) and those for the serpentinized rocks HA70 and HA81 should also be treated with caution as, according to Moody (1979), serpentinization causes the relative loss of both CaO and Al_2O_3 which cannot be corrected for by the normalization procedure.

Comparison (Table 2) with the calculated undepleted upper mantle composition of Harris *et al.* (1967) shows that the Halmahera lherzol-

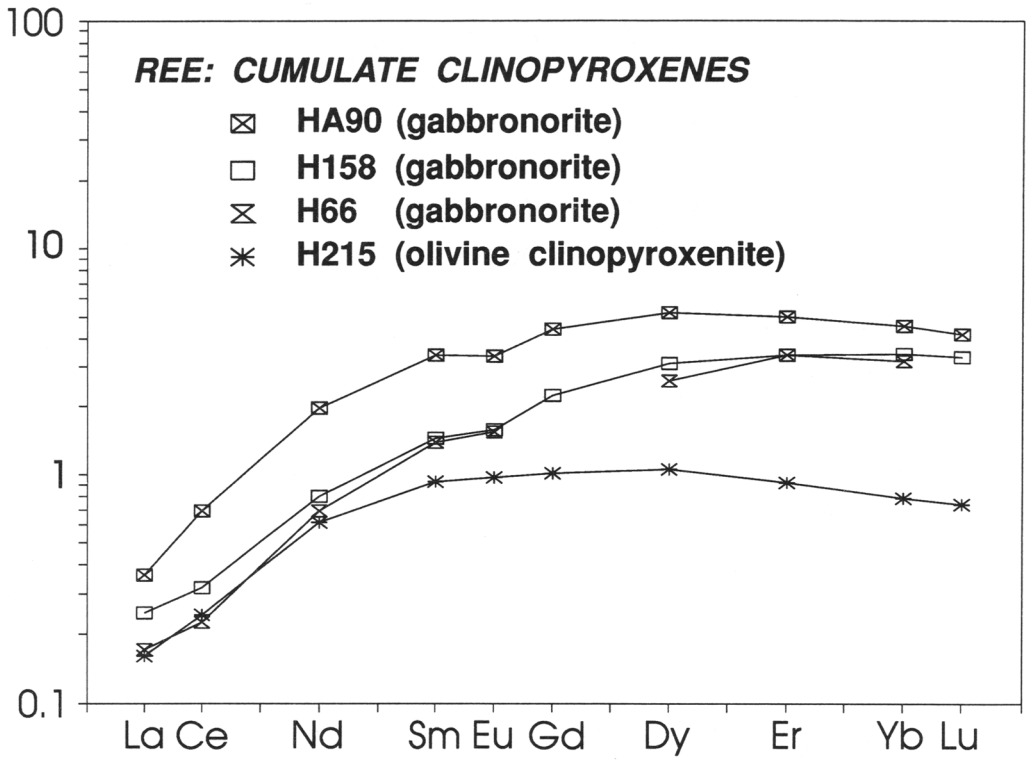

Fig. 8. Chondrite-normalized REE distributions in separated cumulus clinopyroxenes. Normalizing values from Nakamura (1974).

ites are relatively depleted in TiO_2, Al_2O_3 and CaO and enriched in Cr and Ni and hence do not represent pristine upper mantle material. However, their chemistry is consistent with melt extraction following a small degree of partial fusion. The systematic distinction in mineral chemistry between the Halmahera harzburgite and lherzolite is consistent with the whole-rock chemistry and with the conclusion that the two rock types reflect differing degrees of upper mantle partial melting; the more aluminous spinels and pyroxenes, less magnesian olivines and pyroxenes and less nickeliferous olivines in the lherzolites all correspond to the less refractory nature of their host rock. The degree of partial melt extraction recorded by a peridotite, as reflected by the co-variation between whole-rock CaO + Al_2O_3, orthopyroxene Al_2O_3, olivine Fo and spinel cr#, has been discussed for spinel peridotites from a range of ophiolitic complexes (Ishiwatari 1985) and various oceanic tectonic settings (Bonatti & Michael 1989). These parameters are listed in Table 6 for the Halmahera harzburgites and compared to published data from peridotites, including samples dredged from the forearc slopes of the Tonga and Mariana Trenches. The comparison shows that the Halmahera harzburgite represents an ophiolitic mantle sequence more depleted than those of Troodos and Oman and comparable, in terms of the mineralogical parameters at least, with those of the oceanic forearcs.

Comparison with experimental data on peridotite fusion (Jaques & Green 1980) shows that the bulk and mineral compositions of the Halmahera harzburgite (Ballantyne 1991**b**) can be generated by approximately 20% anhydrous melting of a starting material comparable with the Halmahera lherzolite (the Tinaquillo lherzolite). The experimental results of Jaques & Green (1980) suggest melting at 10 kbar (corresponding to 30 km depth) but Falloon *et al.* (1988) showed that for Halmahera harzburgite compositions pressures of approximately 15 kbar are required. Under hydrous conditions, for similar degrees of partial melting, melts are more siliceous and lower in CaO, MgO and FeO due to expansion of the olivine (Kushiro

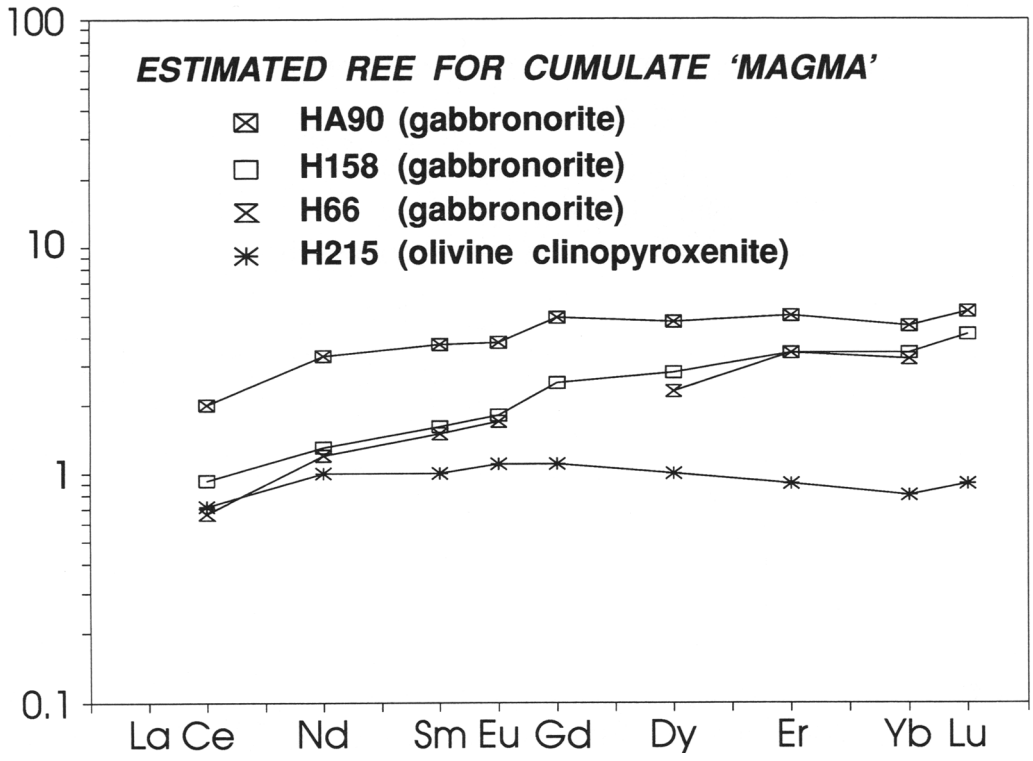

Fig. 9. Chondrite-normalised REE concentrations in the equilibrium magma from which the cumulate rocks crystallised. Normalizing values from Nakamura (1974).

1972) and diopside stability fields at the expense of orthopyroxene (Jaques & Green 1980).

Cumulates

The limited cryptic variation shown by the cumulus and postcumulus phases and whole-rock REE chemistry indicates that the Halmahera cumulates were derived by fractional crystallisation in an open magmatic system. The primary melt was saturated in Ni-bearing olivine and Cr-rich spinel, crystallization of which produced the olivine + spinel cumulates. The cumulate spinels have similar cr# to the harzburgite spinels; their markedly lower mg# is probably a consequence of sub-solidus Mg-Fe re-equilibration with olivine (e.g. Henry & Medaris 1980). Coexisting olivines have refractory compositions. The covariation of spinel Ti and cr# with olivine Fo in the cumulates indicate the early fractionation of large volumes of magnesian olivine (Dick & Bullen 1984; Allan *et al.* 1988).

Crystallization of olivine and spinel resulted in progressively increasing magmatic a_{SiO_2}, leading to the cessation of olivine precipitation and crystallization of orthopyroxene. A significant factor in the interpretation of ophiolitic cumulates is the relative order of appearance of plagioclase, orthopyroxene and clinopyroxene. Although there are rare exceptions such as troctolites containing cumulus olivine + plagioclase, in the Halmahera cumulates pyroxenes generally appear before plagioclase. Orthopyroxene and clinopyroxene appear to have crystallized simultaneously although there is weak textural evidence suggesting the earlier appearance of orthopyroxene in some rocks. Cotectic orthopyroxene + clinopyroxene + plagioclase cumulates are abundant whereas gabbros (*sensu stricto*) are rare in the Halmahera ophiolite.

Although data on cumulate sequences in ocean floor plutonic rocks are scarce, orthopyroxene is never a common phase and is extremely rare in the early stages of crystallization (Bloomer & Hawkins 1983). In contrast, the early appearance and volumetric importance of orthopyroxene in the Halmahera cumulates is

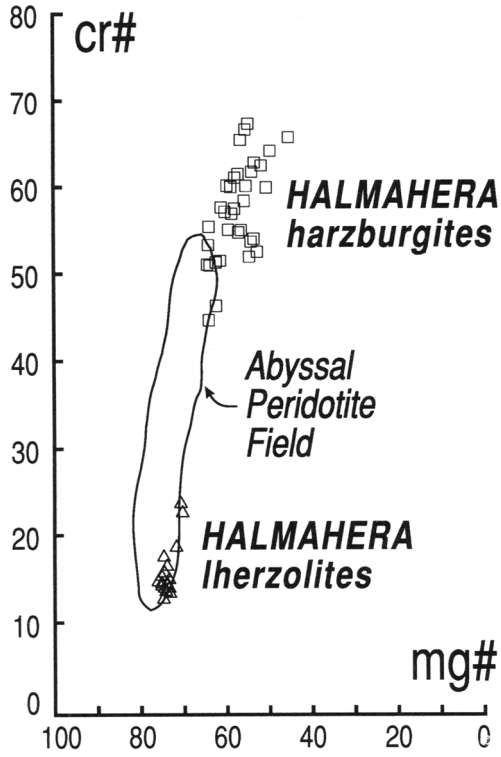

Fig. 10. Unoxidized Halmahera spinels compared with spinels from abyssal peridotites (Dick & Bullen 1984).

similar to cumulates from the Papuan (Jaques & Chappell 1980), Marum (Jaques 1981) and Troodos ophiolites (Thy 1987*a*, *b*). In the Marum ophiolite, clinopyroxene follows olivine and spinel (Jaques 1981), whereas orthopyroxene follows olivine and spinel in the Papuan ophiolite (Davies 1971). Sequences with each of olivine → plagioclase, olivine → clinopyroxene and olivine → orthopyroxene are found in some ophiolites, but the olivine → clinopyroxene type is dominant (e.g. the Oman ophiolite) (Ishiwatari 1985). Jaques & Green (1980) showed that the first phase crystallising after olivine in a cumulate sequence is determined by the degree of partial melting that took place in the lherzolite mantle source region. Olivine → plagioclase corresponds to low, olivine → clinopyroxene to medium and olivine → orthopyroxene to high degrees of partial melting. Ishiwatari (1985) showed also that high TiO_2 (0.6–0.8 wt%) is found in clinopyroxenes in plagioclase-type cumulate rocks, moderate (0.4 wt%) in those in clinopyroxene-type and very low (0.1 wt%) in those in orthopyroxene-type. The average value of TiO_2 (0.27 wt%) in clinopyroxenes from the Halmahera cumulates is consistent with the parental magma being generated by a moderate to high degree of partial melting, leaving a mantle residue represented by the Halmahera harzburgite.

Low fO_2 in the magma chamber is indicated by late crystallization and rarity of Fe-Ti oxides (Helz 1973). Low a_{H_2O} is implied by the generally anhydrous primary cumulus assemblage (e.g. Eggler 1972; Eggler & Burnham 1973) although the occurrence of hornblende in some Halmahera cumulates suggests that locally a_{H_2O} reached higher levels. In the few hornblende-bearing cumulates plagioclase is consistently more calcic than in the hornblende-free cumulates. High H_2O lowers the chemical potential of Ab relative to An in the melt (Johannes 1978) whilst having no effect on the olivine Fo–Fa equilibrium, so that magmas of high a_{H_2O} crystallize cumulates with highly calcic plagioclase for a given olivine Fo content. Such rocks are commonly found in arc settings (e.g. Stern 1979; Arculus & Wills 1980; Natland 1981; Smith *et al.* 1983). In contrast, MOR gabbros (e.g. Elthon 1987) contain plagioclase with lower An contents for a given olivine Fo. The Halmahera cumulates fall outside the arc field (Fig. 11) and the MOR field, although they plot closer to the field of cumulates from Oman (Browning 1984) with a tendency to slightly more calcic plagioclase at more fractionated compositions (Fig. 11). Cumulates from the Troodos ophiolite are characterised by much more calcic plagioclase (An_{86-99}) than the Halmahera rocks.

Cumulates dredged from the Mariana Trench (Bloomer & Hawkins 1983) contain up to 30 modal% orthopyroxene and plagioclase of very variable composition (An_{62} to An_{96}) typically less than An_{90}, except in rare anorthosites. Boninitic volcanic rocks of the Mariana forearc, which are postulated to be comagmatic with the cumulate gabbronorites, contain up to 3 wt% primary H_2O. Kushiro (1972) demonstrated that the orthopyroxene liquidus field widens considerably relative to that of olivine under hydrous conditions and that an MgO- and SiO_2-rich magma would result from a high degree of hydrous partial melting. The cumulates of Halmahera, Troodos and the Mariana Trench all indicate hydrous partial melting; the more calcic character of the Troodos plagioclase could be the result of a greater depth of crystallization (Bloomer & Hawkins 1983) or due to elevated P_{H_2O} (possibly up to 5 kbar) as interpreted by Thy (1987*a*).

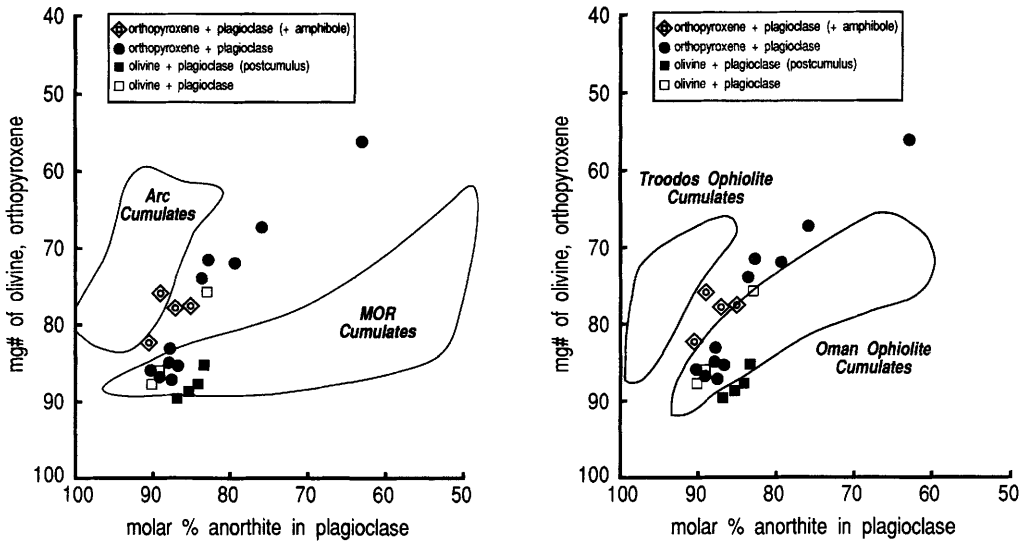

Fig. 11. Co-variation of plagioclase An content with coexisting cumulus olivine and orthopyroxene mg#. Fields of MOR cumulate rocks and arc cumulate rocks from Beard (1986); field of Oman ophiolite cumulate rocks from Browning (1984); field of Troodos ophiolite cumulate rocks from Thy (1987*a*, *b*). The Troodos field is the only one based on orthopyroxene; all others are based on olivine.

Modern analogues

A number of lines of evidence (Table 6; Ballantyne 1991*b*) suggest that the Mariana forearc, which like Halmahera is situated at the margin of the Philippine Sea Plate (Fig. 1), provides a modern analogue for the Halmahera ophiolite. Rocks representative of all sections of a complete ophiolite, with the exception of sheeted dykes (difficult to identify in dredged samples), have been recovered from the Mariana forearc (e.g. Bloomer 1981, 1983; Bloomer & Hawkins 1983, 1987; Johnson *et al.* 1987), which is dominated by normal faulting, reflecting its extensional nature (Hussong & Uyeda 1981), such that the gabbroic and ultramafic rocks are thought to be exposed in relatively small fault blocks (Bloomer 1983), analogous to the structure of eastern Halmahera. Similarly, rocks dredged from the 'Ogasawara Paleoland' (OPL), a submerged bathymetric high situated in the forearc 20 km west of the junction of the Ogasawara (Bonin) and Mariana Trenches, resemble those found in eastern Halmahera and include harzburgite (olivine Fo = 92, spinel cr# = 55–68), dunite and orthopyroxene-rich gabbro (Ishii 1985). The OPL is interpreted as a 'proto-ophiolite' reflecting near-trench mantle diapirism related to high degrees of partial melting through fluid input at the onset of subduction of old Pacific Ocean lithosphere beneath very young Philippine Sea lithosphere (Ishii 1985; Ishii *et al.* 1988). The evidence suggests that a terrane like the OPL could well be preserved as a remnant arc and, on uplift and obduction, would form an ophiolite closely comparable to the basement of eastern Halmahera.

Conclusions

The basement of east Halmahera consists of a dismembered ophiolite of pre-Late Cretaceous age imbricated with Cretaceous to Eocene volcanic and sedimentary rocks. Structural dismemberment means that the ophiolite stratigraphy cannot be seen, but components of each level of an intact ophiolite with the probable exception of sheeted dykes, are present. The ophiolite is polygenetic (Ballantyne 1990) and volcanic rocks include alkaline basalts similar to those of ocean island and seamounts, island arc tholeiites and boninitic volcanic rocks. Chemical and mineralogical evidence (Ballantyne 1991*b*) indicate that the boninitic volcanic rocks are comagmatic with cumulates of the plutonic sequence. Lherzolites of the plutonic mantle sequence represent an upper mantle previously depleted by extraction of MORB. Hydrous melting of this mantle in a supra-subduction

Table 6. *Selected analytical parameters of Halmahera, other ophiolitic, and ocean-floor peridotites discussed in text*

Peridotite type	Bulk rock Al_2O_3 + CaO	Olivine Fo	Opx Al_2O_3	Spinel cr#	Data sources(s)
Liguria lherzolite	5.22	90.1	4.11	25.8	Ernst & Piccardo (1979)
Oman harzburgite	2.05	91.3	1.60	56.6	Brown (1980); Pallister & Hopson (1981) Johan & Augé (1986); Lippard *et al.* (1986)
Troodos harzburgite	1.24			55.3	Menzies & Allen (1974); Greenbaum (1977) Ballantyne (1990)
Mariana Trench harzburgite	?5.98	91.6	1.29	55.2	Bloomer & Hawkins (1983)
Tonga Trench harzburgite	?0.25	91.6	1.29	57.3	Fisher & Engel (1969); Bloomer & Fisher (1987)
Halmahera harzburgite	1.16	91.6	1.04	61.6	Ballantyne (1990)
Papua harzburgite	0.08	92.7 92.3	<0.09 0.75	91.8	Jaques & Chappell (1980) England & Davies (1973)

Question marks indicate analytical results considered unreliable.
Bulk rock Al_2O_3 + CaO and orthopyroxene Al_2O_3 expressed as wt% and normalized to 100% totals volatile-free.

zone setting produced the magma from which the cumulate rocks and boninitic volcanic rocks crystallised, leaving harzburgites as the highly depleted residual material.

In comparison to other ophiolites, the Halmahera plutonic rocks are closely similar to those of the northern New Guinea ophiolites (Marum and Papua) and indicate high degrees of partial melting under hydrous conditions. Comparisons with spinel-bearing peridotites from ophiolites and various oceanic tectonic settings show that the Halmahera harzburgites are most similar to those of oceanic forearcs. The lack of highly calcic plagioclase precludes an origin for the ophiolite as typical island arc basement, like that of the West Mariana Ridge (Natland 1981). However, cumulates dredged from the inner slope of the Mariana Trench (Bloomer & Hawkins 1983) closely resemble those of the Halmahera ophiolite. The present-day Mariana forearc is a plausible modern analogue of the Halmahera ophiolite and its structure and the character of rocks dredged and drilled in the region are closely comparable to Halmahera. The Mariana forearc, like Halmahera, is today found at the margin of the Philippine Sea Plate and this connection may be more than merely fortuitous. However, more data are needed onland from other Philippine Sea Plate margin and western Pacific ophiolites and from the oceanic forearcs before such speculative connections can be assessed; in particular, the age of the oldest rocks in these terranes and their past positions in the Pacific are poorly understood.

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References

AHMED, Z. 1982. Porphyritic-nodular, nodular, and orbicular chrome ores from the Sakhakot–Qila complex Pakistan, and their chemical variations. *Mineralogical Magazine*, **45**, 167–178.

ALLAN, J. F., SACK, R. O. & BATIZA, R. 1988. Cr-rich spinels as petrogenetic indicators: MORB-type lavas from the Lamont seamount chain, eastern Pacific. *American Mineralogist*, **73**, 741–753.

ARCULUS, R. J. & WILLS, K. J. A. 1980. The petrology of plutonic blocks and inclusions from the Lesser Antilles island arc. *Journal of Petrology*, **21**, 743–799.

BALLANTYNE, P. D. 1990. *The Petrology of the Ophiolitic Rocks of Eastern Halmahera, Indonesia.*

PhD Thesis University of London.

—— 1991*a*. Implications of the geochemistry of ophiolitic volcanic rocks of eastern Halmahera, Indonesia. *Geodynamica*, in press.

—— 1991*b*. Petrological constraints upon the provenance and genesis of the East Halmahera ophiolite. *Journal of SE Asian Earth Sciences* (in press).

—— & HALL, R. 1990. The petrology of the Halmahera ophiolite, Indonesia: an early Tertiary forearc. *In*: *Troodos '87: Ophiolites and Oceanic Lithosphere Conference Proceedings*. in press.

BEARD, J. S. 1986. Characteristic mineralogy of arc-related cumulate gabbros: implications for the tectonic setting of gabbroic plutons and for andesite genesis. *Geology*, **14**, 848–851.

BLOOMER, S. H. 1981. Mariana fore-arc ophiolite, structure and petrology. *Eos*, **62**, 1086–1087.

—— 1983. Distribution and origin of rocks from the landward slopes of the Mariana Trench: implications for its structure and evolution. *Journal of Geophysical Research*, **88**, 7411–7428.

—— & FISHER, R. L. 1987. Petrology and geochemistry of igneous rocks from the Tonga Trench — a non-accreting plate boundary. *Journal of Geology*, **95**, 469–495.

—— & HAWKINS, J. W. 1983. Gabbroic and ultramafic rocks from the Mariana Trench: an island arc ophiolite. *In*: HAYES, D. E. (ed.) *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Part 2*. Geophysical Monographs Washington, **27**, 294–317.

—— & —— 1987. Petrology and geochemistry of boninite series volcanic rocks from the Mariana Trench. *Contributions to Mineralogy and Petrology*, **97**, 361–377.

BONATTI, E. & MICHAEL, P. J. 1989. Mantle peridotites from continental rifts to ocean basins to subduction zones. *Earth and Planetary Science Letters*, **91**, 297–311.

BORISENKO, L. F. 1967. Trace elements in pyroxenes and amphiboles from ultramafic rocks of the Urals. *Mineralogical Magazine*, **36**, 403–410.

BROWN, M. 1980. Textural and geochemical evidence for the origin of some chromite deposits in the Oman ophiolite. *In*: PANAYIOTOU, A. (ed.) *Ophiolites. Proceedings of the International Ophiolite Symposium Cyprus* 1979, Cyprus Geol. Survey Dept., 714–721.

BROWNING, P. 1984. Cryptic variation within the cumulate sequence of the Oman ophiolite: magma chamber depth and petrological implications. *In*: GASS, I. G., LIPPARD, S. J. & SHELTON, A. W. (eds) *Ophiolites and Oceanic Lithosphere*. Geological Society, London, Special Publication **14**, 71–82.

BURGATH, K., MOHR, M. & SIMANDJUNTAK, W. 1983. New discoveries of blueschist metamorphism and mineral occurrences in the Halmahera–Gag ophiolite belt, East Indonesia. *Bulletin of the Directorate of Mineral Resources, Indonesia*, **1**(13), 1–19.

COLEMAN, R. G. 1967. *Low temperature reaction zones and alpine ultramafic rocks of California, Oregon and Washington*. US Geological Survey Bulletin 1247.

—— 1977. *Ophiolites*. Springer-Verlag, Berlin-Heidelberg-New York.

CONRAD, W. K. & KAY, R. W. 1984. Ultramafic and mafic inclusions from Adak Island: crystallisation history, and implications for the nature of primary magmas and crustal evolution in the Aleutian Arc. *Journal of Petrology*, **25**, 88–125.

DAVIES, H. L. 1971. *Peridotite–gabbro–basalt complex in eastern Papua: an overthrust plate of oceanic mantle and crust*. Bulletin of the Australasian Bureau of Mineral Resources, Geology and Geophysics, **128**.

DEER, W. A., HOWIE, R. A. & ZUSSMAN, J. 1962. *Rock-forming Minerals. Vol. 5: Non-silicates*. Longmans, London.

—— & —— 1978. *Rock-forming Minerals. Vol. 2A: Single-chain Silicates*. Second Edition. Longmans, London.

DICK, H. J. B. & BULLEN, T. 1984. Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. *Contributions to Mineralogy & Petrology*, **86**, 54–76.

DRAKE, M. J. & WEILL, D. F. 1975. Partition of Sr, Ba, Ca, Y, Eu^{2+}, Eu^{3+}, and other REE between plagioclase feldspar and magmatic liquid: an experimental study. *Geochimica et Cosmochimica Acta*, **39**, 689–712.

EGGLER, D. H. 1972. Water-saturated and undersatured melting relations in a Paricutin andesite and an estimate of water content in the natural magma. *Contributions to Mineralogy and Petrology*, **34**, 261–271.

—— & BURNHAM, C. W. 1973. Crystallisation and fractionation trends in the system andesite-H_2O-CO_2-O_2 at pressures to 10 kb. *Geological Society of America Bulletin*, **84**, 2517–2532.

ELTHON, D. 1987. Petrology of gabbroic rocks from the Mid-Cayman Rise spreading center. *Journal of Geophysical Research*, **92**, 658–682.

ENGEL, C. G. & FISHER, R. L. 1975. Granitic to ultramafic rock complexes of the Indian Ocean ridge system, western Indian Ocean. *Geological Society & America Bulletin*, **86**, 1553–1578.

ENGIN, T. & AUCOTT, J. W. 1971. A microprobe study of chromites from the Andizlik–Zimparalik area, south-west Turkey. *Mineralogical Magazine*, **38**, 76–82.

ENGLAND, R. N. & DAVIES, H. L. 1973. Mineralogy of ultramafic cumulates and tectonites from eastern Papua. *Earth and Planetary Science Letters*, **17**, 416–425.

ERNST, W. G. & PICCARDO, G. B. 1979. Petrogenesis of some Ligurian peridotites — I. Mineral and bulk-rock chemistry. *Geochimica et Cosmochimica Acta*, **43**, 219–237.

FALLOON, T. J., GREEN, D. H., HATTON, C. J. & HARRIS, K. L. 1988. Anhydrous partial melting of fertile and depleted peridotite from 2 to 30 kb and application to basalt petrogenesis. *Journal of Petrology*, **29**, 1257–1282.

FISHER, R. L. & ENGEL, C. G. 1969. Ultramafic and

basaltic rocks dredged from the nearshore flank of the Tonga Trench. *Geological Society of America Bulletin*, **80**, 1373–1378.

FISK, M. R. & BENCE, A. E. 1980. Experimental crystallisation of chrome spinel in FAMOUS basalt 527–1–1. *Earth and Planetary Science Letters*, **48**, 111–123.

GREENBAUM, D. 1977. The chromitiferous rocks of the Troodos Ophiolite Complex, Cyprus. *Economic Geology*, **72**, 1175–1194.

HALL, R. 1987. Plate boundary evolution in the Halmahera region, Indonesia. *Tectonophysics*, **144**, 337–352.

—— & NICHOLS, G. J. 1990. Terrane amalgamation in the Philippine Sea margin. *Tectonophysics*, **181**, 207–222.

——, AUDLEY-CHARLES, M. G., BANNER, F. T., HIDAYAT, S. & TOBING, S. L. 1988. The basement rocks of the Halmahera region, east Indonesia: a Late Cretaceous–Early Tertiary forearc. *Journal of the Geological Society, London*, **145**, 65–84.

——, BALLANTYNE, P. D., HAKIM, A. S. & NICHOLS, G. J. 1991. Basement rocks of Halmahera, eastern Indonesia: implications for the early history of the Philippine Sea. *Proceedings of the 5th Circum-Pacific Conference, Hawaii 1990* (in press).

HARRIS, P. G., REAY, A. & WHITE, I. G. 1967. Chemical composition of the upper mantle. *Journal of Geophysical Research*, **72**, 6359–6369.

HARTE, B. 1977. Rock nomenclature with particular relation to deformation and recrystallisation textures in olivine-bearing xenoliths. *Journal of Geology*, **85**, 279–288.

HELZ, R. T. 1973. Phase relations of basalts in the melting range at P_{H_2O} = 5 kb as a function of oxygen fugacity. Part 1. Mafic phases. *Journal of Petrology*, **14**, 249–302.

HENDERSON, P. 1984. General geochemical properties and abundances of the rare earth elements. *In*: HENDERSON, P. (ed.) *Rare Earth Element Geochemistry*. Elsevier, Amsterdam-Oxford-New York-Tokyo, 1–32.

HENRY, D. J. & Medaris, L. G. Jr. 1980. Application of pyroxene and olivine-spinel geothermometers to spinel peridotites in southwestern Oregon. *American Journal of Science*, **280-A**, 211–231.

HUSSONG, D. M. & UYEDA, S. 1981. Tectonics in the Mariana Arc: results of recent studies, including DSDP Leg 60. *Oceanologica Acta, Proceedings 26th International Geological Congress, Geology of Continental Margins Symposium, Paris, July 7–17, 1980*, 203–212.

IRVINE, T. N. 1982. Terminology for layered intrusions. *Journal of Petrology*, **23**, 127–162.

ISHII, T. 1985. Dredged samples from the Ogasawara fore-arc seamount or 'Ogasawara Paleoland' – 'fore-arc ophiolite'. *In*: NASU, N. *et al.* (eds) *Formation of Active Ocean Margins*. Terrapub, Tokyo, 307–342.

——, ROBINSON, P. T., TOKUYAMA, H. & KOBAYASKI, K. 1988. Relations of fore-arc proto-ophiolites, mantle and serpentinite diapirs. *Geological Society of America Abstracts with Programs*, A158.

ISHIWATARI, A. 1985. Igneous petrogenesis of the Yakuno ophiolite (Japan) in the context of the diversity of ophiolites. *Contributions to Mineralogy and Petrology*, **89**, 155–167.

JAQUES, A. L. 1981. Petrology and petrogenesis of cumulate peridotites and gabbros from the Marum Ophiolite Complex, northern Papua New Guinea. *Journal of Petrology*, **22**, 1–40.

—— & CHAPPELL, B. W. 1980. Petrology and trace element geochemistry of the Papuan ultramafic belt. *Contributions to Mineralogy and Petrology*, **75**, 55–70.

—— & GREEN, D. H. 1980. Anhydrous melting of peridotite at 0–15 kb pressure and the genesis of tholeiitic basalts. *Contributions to Mineralogy and Petrology*, **73**, 287–310.

——, CHAPPELL, B. W. & TAYLOR, S. R. 1983. Geochemistry of cumulus peridotites and gabbros from the Marum ophiolite complex, northern Papua New Guinea. *Contributions to Mineralogy and Petrology*, **82**, 154–164.

JOHAN, Z. & AUGÉ, T. 1986. Ophiolitic mantle sequences and their evolution: mineral chemistry constraints. *In*: GALLAGHER, M. J., IXER, R. A., NEARY, C. R. & PRICHARD, H. M. (eds) *Metallogeny of Basic and Ultrabasic Rocks*. Institute of Mining and Mettalogy, London, 305–317.

JOHANNES, W. 1978. Melting of plagioclase in the system Ab-An-H_2O and Qz-Ab-An-H_2O at P_{H_2O} = 5 kbars, an equilibrium problem. *Contributions to Mineralogy and Petrology*, **66**, 295–303.

JOHNSON, L. E., FRYER, P. & ISHII, T. 1987. Mariana forearc basement adjacent to serpentinite diapirs. *Eos*, **68**, 1534.

JUTEAU, T., ERNEWEIN, M., REUBER, I., WHITECHURCH, H. & DAHL, R. 1988. Duality of magmatism in the plutonic sequence of the Sumail Nappe, Oman. *In*: BOUDIER, F. & NICOLAS, A. (eds) *The Ophiolites of Oman. Tectonophysics*, **151**, 107–135.

KEMPTON, P. D., HAWKESWORTH, C. J. & The Leg 118 Shipboard Party. 1988. The Nd, Sr and Pb isotopic composition of gabbros from Layer 3 of the oceanic crust, O.D.P. Leg 118, Hole 735B. *Geological Society of America Abstracts with Programs*, A158.

KRETZ, R. 1982. Transfer and exchange equilibria in a portion of the pyroxene quadrilateral as deduced from natural and experimental data. *Geochimica et Cosmochimica Acta*, **46**, 411–421.

KUSHIRO, I. 1972. Effect of water on the composition of magmas formed at high pressures. *Journal of Petrology*, **13**, 311–334.

LEAKE, B. E. 1978. Nomenclature of amphiboles. *Canadian Mineralogist*, **16**, 501–520.

LINDSLEY, D. H. & ANDERSEN, D. J. 1983. A two-pyroxene geothermometer. Proceedings of the Thirteenth Lunar and Planetary Science Conference, Part Two. *Journal of Geophysical Research*, **88**, (supp.), A887–A906.

LIPPARD, S. J., SHELTON, A. W. & GASS, I. G. 1986. *The Ophiolite of Northern Oman*. Geological

Society, London, Memoir, **11**.

McKay, D. B. & Mitchell, R. H. 1988. Abundance and distribution of gallium in some spinel and garnet lherzolites. *Geochimica et Cosmochimica Acta*, **52**, 2867–2870.

Menzies, M. A. 1975. Spinel compositional variation in the crustal and mantle lithologies of the Othris ophiolite. *Contributions to Mineralogy and Petrology*, **51**, 303–309.

—— & Allen, C. 1974. Plagioclase lherzolite-residual mantle relationships within two eastern Mediterranean ophiolites. *Contributions to Mineralogy and Petrology*, **45**, 197–213.

Mercier, J.-C.C., Benoit, V. & Girardeau, J. 1984. Equilibrium state of diopside-bearing harzburgites from ophiolites: geobarometric and geodynamic implications. *Contributions to Mineralogy and Petrology*, **85**, 391–403.

Moody, J. B. 1979. Serpentinites, spilites and ophiolite metamorphism. *Canadian Mineralogy*, **17**, 871–887.

Moores, E. M. 1982. Origin and emplacement of ophiolites. *Reviews of Geophysics and Space Physics*, **20**, 735–760.

Nakamura. N. 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. *Geochimica et Cosmochimica Acta*, **38**, 757–775.

Natland, J. H. 1981. Petrography and mineral compositions of gabbros recovered in Deep Sea Drilling Project Hole 453 on the western side of the Mariana Trough. *In*: Hussong, D. M., Uyeda, S. *et al.* (eds) *Initial Reports DSDP*, **60**, 579–599.

O'Hara, M. J. 1977. Geochemical evolution during fractional crystallisation of a periodically refilled magma chamber. *Nature*, **266**, 503–507.

Ozawa, K. 1983. Evaluation of olivine–spinel geothermometry as an indicator of thermal history for peridotites. *Contributions to Mineralogy and Petrology*, **82**, 52–65.

—— 1986. Partitioning of elements between constituent minerals in peridotites from the Miyamori ultramafic complex, Kitakami mountains, northeast Japan: estimation of $P-T$ conditions and igneous composition of minerals. *Journal of the Faculty of Sciences, Univ. Tokyo, Section II*, **21**, 115–137.

—— 1987. Petrology of aluminous spinel peridotites and pyroxenites of the Miyamori ultramafic complex, northeast Japan. *Journal of the Faculty of Sciences*, Univ. Tokyo, Section II, **21**, 309–332.

—— 1988. Ultramafic tectonite of the Miyamori ophiolitic complex in the Kitakami Mountains, northeast Japan: hydrous upper mantle in an island arc. *Contributions to Mineralogy and Petrology*, **99**, 159–175.

Pallister, J. S. & Hopson, C. A. 1981. Samail ophiolite plutonic suite: field relations, phase variation, cryptic variation and layering, and a model of a spreading ridge magma chamber. *Journal of Geophysical Research*, **86**, 2593–2644.

Rice, J. M. 1983. Metamorphism of rodingites: Part 1. Phase relations in a portion of the system CaO-MgO-Al_2O_3-SiO_2-CO_2-H_2O. *American Journal of Science*, **283A**, 121–150.

Ross, C. S., Foster, M. D. & Myers, A. T. 1954. Origin of dunites and of olivine-rich inclusions in basaltic rocks. *American Mineralogist*, **39**, 693–737.

Shapiro, L. & Brannock, W. W. 1962. *Rapid analysis of silicate, carbonate and phosphate*. US Geological Survey Bulletin, **1144-A**.

Smith, T. E., Huang, C. H., Walawender, M. J., Cheung, P. & Wheeler, C. 1983. The gabbroic rocks of the Peninsular Ranges batholith, southern California: cumulate rocks associated with calc-alkalic basalts and andesites. *In*: Aramaki, S. & Kushiro, I. (eds) *Arc Volcanism. Journal of Volcanology and Geothermal Research*, **18**, 249–278.

Soeria Atmadja, R. 1981. Ophiolites in the Halmahera paired belts, East Indonesia. *In*: Barber, A. J. & Wiryosujono, S. (eds) *The Geology and Tectonics of Eastern Indonesia*. Special Publication of the Geological Resources and Development Centre, Bandung, **2**, 363–372.

Stern, R. J. 1979. On the origin of andesite in the northern Mariana island arc: implications from Agrigan. *Contributions to Mineralogy and Petrology*, **68**, 207–219.

Streckeisen, A. L. 1974. Classification and nomenclature of plutonic rocks. Recommendations of the IUGS subcommission on the systematics of igneous rocks. *Geologische Rundschau*, **63**, 773–786.

Sukamto, R., Apandi, T., Supriatna, S. & Yasin, A. 1981. The geology and tectonics of Halmahera Island and surrounding areas. *In*: Barber, A. J. & Wiryosujono, S. (eds) *The Geology and Tectonics of Eastern Indonesia*. Special Publication of the Geological Resources and Development Centre, Bandung, **2**, 349–362.

Thirlwall, M. F. 1982. A triple-filament method for rapid and precise analysis of rare-earth elements by isotope dilution. *Chemical Geology*, **35**, 155–166.

Thy, P. 1987*a*. Petrogenetic implications of mineral crystallisation trends of Troodos cumulates, Cyprus. *Geological Magazine*, **124**, 1–11.

—— 1987*b*. Magmas and magma chamber evolution, Troodos ophiolite, Cyprus. *Geology*, **15**, 316–319.

Vance, J. A. 1961. Polysynthetic twinning in plagioclase. *American Mineralogist*, **46**, 1097–1119.

Walsh, J. N. 1980. The simultaneous determination of the major, minor and trace constituents of silicate rocks using inductively coupled plasma spectrometry. *Spectrochimica Acta*, **35B**, 107–111.