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SPINEL–GARNET RELATIONSHIPS IN MANTLE XENOLITHS FROM THE MALAITA ALNÖITES, SOLOMON ISLANDS, SOUTH-WESTERN PACIFIC

by

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ABSTRACT

Xenolithic alnöites (*ca.* 34 Ma) intrude an unusually thickened portion of the Pacific Plate, known as the Ontong Java Plateau. Lherzolite xenoliths from the Kwaikwai intrusion on Malaita Island contain spinels with garnet rims; both primary and secondary clinopyroxenes and amphiboles are present. On the evidence of mineral composition and textures, several events are postulated to have affected the mantle below Malaita.

Cooling (during separation and formation of the thickened plate) resulted in spinel reacting with clinopyroxene and amphibole to form garnet. During reaction Cr increases (along with Fe) in the spinel, thus enlarging its stability field to greater pressures co-existing with garnet at 959 to 1 039 °C and 89 to 95 km. A late reheating mantle event possibly associated with alnöite eruption, produced a limited reversal of the reaction to form slivers of secondary clinopyroxene and amphibole, and aluminium and magnesium-rich rims in the spinels.

CONTENTS

I. INTRODUCTION

The Ontong Java Plateau (OJP) is an unusually thickened portion of the south-western Pacific Plate (Fig. 1; Kroenke, 1972) having some structural features of a microcontinent. Alnöite intrusions on Malaita Island, Solomon Islands, contain a suite of deep-seated xenoliths further emphasizing the unusual tectonic setting.

The identification of possible ultrabasic mantle boulders similar to those found in kimberlites in streams of central north Malaita, in 1951 (Rickwood, 1957) and coarse ilmenite and garnet gravels on the east coast of Malaita in 1956 by J.C. Grover (pers. comm.) led to a search for diamonds (Thompson, 1965; Gerryts, 1965). This proved fruitless and six samples collected *in situ* by Hackman were described by Allen and Deans (1965) as alnöites. The first substantial suite of mantle xenoliths from the Babaru'u alnöite locality on a tributary of the Faufaumela River (Figs. 2 and 3) were described by Nixon and Boyd (1979).

This investigation concerns a suite of garnet lherzolite xenoliths from Kwaikwai locality, situated on a tributary of the Auluta River (Fig. 3) approximately 5 km from Babaru'u. They provide further evidence of the anomalous nature of this part of the Pacific lithosphere and new information relating to its evolution.

II. TECTONIC SETTING

The Solomon Islands region is divided into three geologically distinct provinces by Coleman (1976): the Volcanic Province, an active young arc; the Central Province, an old arc; and the Pacific Province at the edge of the OJP (Fig. 2).

The active arc is a recent phenomenon (post 8 Ma) but has a complex history involving arc reversal during collision of the OJP with the Indo-Australian Plate (IAP) (Coleman and Kroenke, 1981). The OJP covers an area of 1 600 × 800 km. The crust has seismic velocities similar to normal oceanic crust, but each layer is abnormally thickened totalling up to 40 km (Coleman, 1976). The reason for this is unknown but Kroenke (1974) suggested that the OJP formed on the flank of an unusually slow spreading axis. Nur and Ben-Avraham (1982) have included OJP in their list of autochthonous terrains and have stressed a possible continental origin. During collision with the IAP the thickened lithosphere resisted subduction but was buckled along the western margin into a series of folds (Fig. 1). These are exposed on Malaita. Here calcareous sediments contain foraminiferal faunas which correlate with those from ocean floor drill cores on the OJP (Site 64; Fig. 1; Kroenke, 1972). Furthermore, underlying lavas can be traced offshore into prominent seismic reflector horizons in the ocean crust (Furumoto *et al.*, 1970). Pipe-like features revealed by seismic refraction surveys have been postulated to be alnöite plugs similar to those on Malaita, or even kimberlite pipes (Nixon, 1980).

III. THE ALNÖITES

Alnöite emplacement has been dated at approximately 34 Ma (Davis, 1977) at a time prior to plate collision when Malaita and the OJP was positioned considerably further eastwards. The crustal rocks through which the alnöites were intruded include tholeiites and alkali basalts (Rickwood, 1957; Hughes and Turner, 1977). These are probably Cretaceous although an older age cannot be ruled out. Such crustal events are significant because they could be reflected in mantle xenoliths erupted by the alnöites. In the Nauru Basin to the north and adjacent to the OJP, four episodes of Cretaceous volcanism have been determined by Schlanger *et al.* (1981): Pacific plate formation, *ca.* 155 Ma

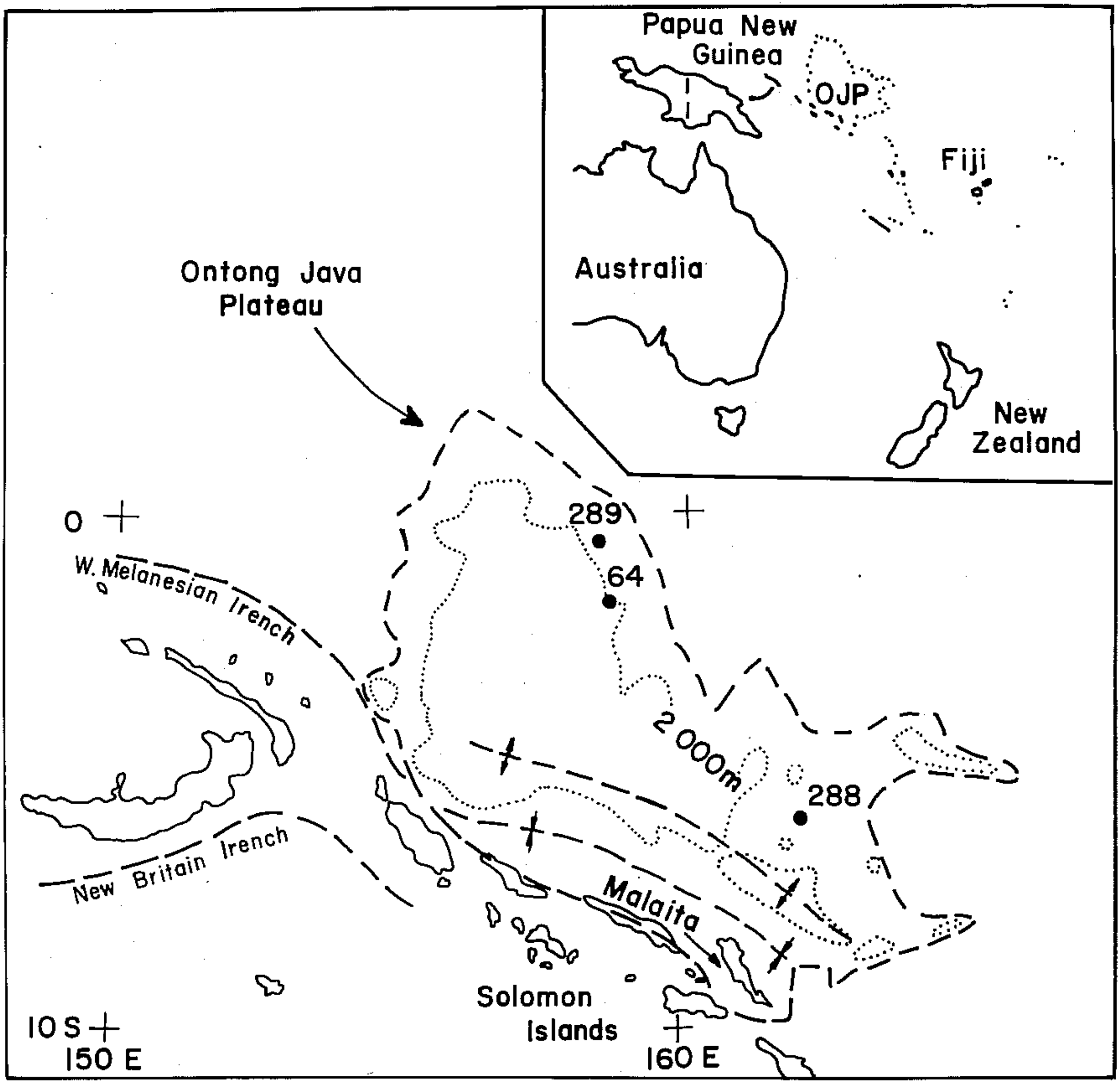

Figure 1
The Ontong Java Plateau in relation to the islands of the south-western Pacific. The outline is the 2 500 m isobath. Deep Sea Drilling Sites are numbered. Reproduced from Nixon (1980), MacMillan Press, with permission.

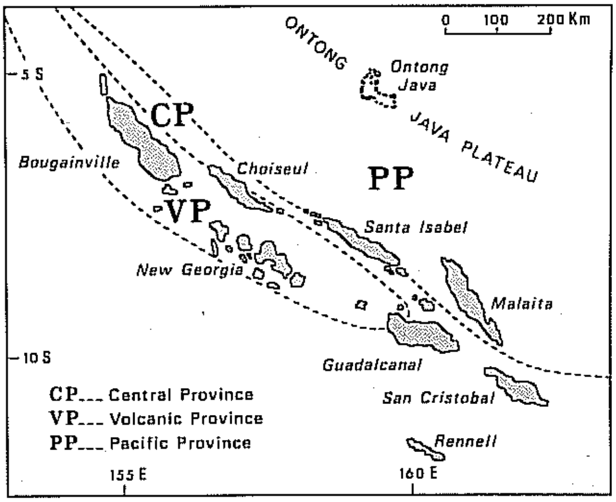

Figure 2
The Solomon Islands Arc (after Coleman, 1976).

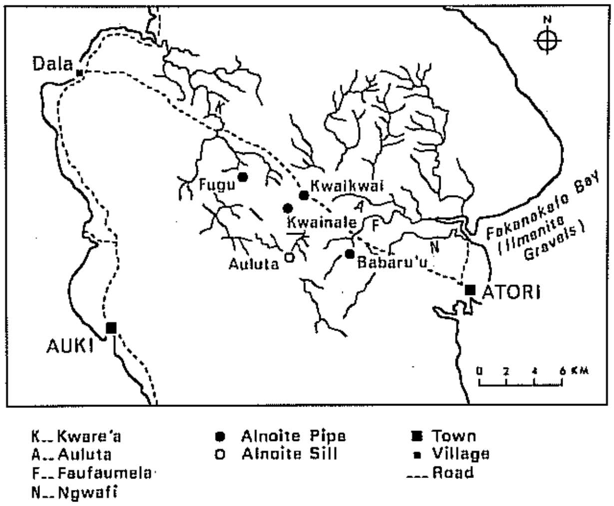

Figure 3
Central northern Malaita location map.

ago at a ridge crest; mid-plate lava flows, *ca.* 120 Ma; dolerite sill emplacement, *ca.* 110 Ma; and deep-water volcanism, *ca.* 95 to 75 Ma.

At both Babaru'u and Kwaikwai (Fig. 2) the alnöites are thought to be pipe-like bodies. Occasional steep contacts are apparent with the surrounding limestones, although exposures are poor. At Babaru'u, hard, black, fine-grained non-fragmental alnöite is flanked by a brecciated variety. The former contains phenocrysts (1–4 mm diameter) of spinel, olivine and clinopyroxene. The proportion of olivine microphenocrysts (Fo_{88}; Neal, unpublished data) varies between 25 and 35 per cent. Anhedral plates of ankermanite-soda melilite constitute up to a third of the rock (Nixon *et al.*, 1980). The groundmass consists of euhedral perovskite, magnetite, some apatite, K-poor nepheline and glass with late formed poikilitic phlogopite. The breccias contain about 30 per cent of xenoliths of country rock fragments, mantle peridotites, discrete nodules, and autoliths (xenocrysts with spherical envelopes of alnöite). The matrix is chalcedony, zeolite and calcite in which coarse (1 cm) phlogopite is embedded.

IV. MANTLE XENOLITHS AT KWAIKWAI

Mantle xenoliths are rounded and range up to 10 cm in diameter, occasionally reaching 25 cm. They consist of discrete nodules (megacrysts) of pyroxenes, garnet, ilmenite and pyroxene–ilmenite intergrowths — this suite is not dealt with here — and peridotites mostly of lherzolite composition. Estimated modes of the lherzolites (Table I) are approximate due to a combination of small nodule size and coarse grain size (several mm). In the eight specimens studied (7 gt sp lherzolites, 1 gt lherzolite) altered olivine > clinopyroxene > orthopyroxene. Garnet was present in all specimens although a spinel lherzolite has been described by Bielski-Zyskind *et al.* (1984). All textures are coarse granular.

TABLE I

Modal Mineralogy Estimated from Thin Section for Seven Garnet Spinel Lherzolites and one Garnet Lherzolite

	Olivine	Clino-pyroxene	Ortho-pyroxene	Garnet	Spinel	Amphibole
PHN 4002	65	15	10	4	3	2
PHN 4009	57	20	12	1	5	5
PHN 4013	56	13	12	6	3	10
PHN 4016	61	24	12	2	2	—
PHN 4034	69	9	2	2	—	18
PHN 4064	66	17	5	8	4	Tr.
PHN 4067	58	28	5	6	3	Tr.
PHN 4069	60	15	8	7	3	7

In thin section, all the garnet–spinel lherzolites contain dark brown spinel with embayed grain boundaries, mantled by a pink garnet envelope of varying thickness (up to 3 mm in PHN 4013 and 4069). The garnet rims appear to consist of composite grains, but there is no compositional difference between them.

Large primary clinopyroxenes (Cpx^1) up to 6 mm in diameter contain exsolution lamellae of pigeonite (?) possibly formed during eruption (cf. McCallister *et al.*, 1977). In PHN 4013, 4016 and 4069 small rods of spinel are exsolved. PHN 4013 and 4069 contain small discontinuous slivers of secondary clinopyroxene (Cpx^2) between the garnet and spinel (Fig. 4). The orthopyroxenes are smaller (1–4 mm diameter) and appear more altered and serpentinized than the clinopyroxenes.

Most of the rock consists of altered and serpentinized olivine in which much secondary calcite has developed. No fresh olivine was seen. Pargasitic amphibole ($Amph^1$; cf. Delaney *et al.*, 1979) forms primary discrete subhederal grains 0,2 to 1 mm diameter in PHN 4002, 4009, 4013, 4067 and 4069. A similar amphibole ($Amph^2$) occurs as small

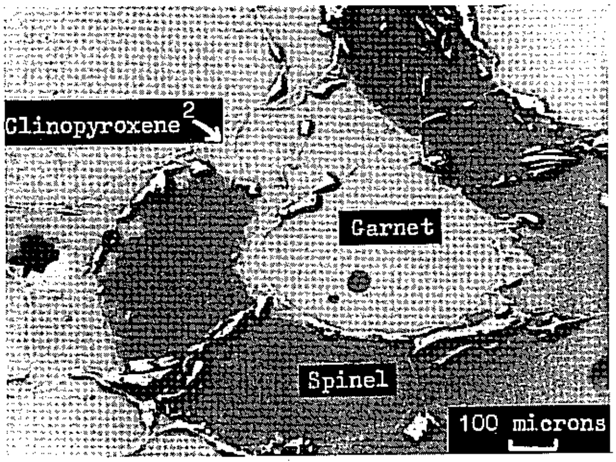

Figure 4

S.E.M. photograph illustrating slivers of secondary clinopyroxene (Cpx^2) between garnet and spinel in garnet lherzolite xenolith, PHN 4013, Kwaikwai, Malaita.

discontinuous slivers between garnet and spinel in PHN 4002, 4009, 4064 and 4067. These slivers have a similar habit to secondary clinopyroxene (Cpx^2) which, however, are not found in the same rocks with amphibole ($Amph^2$).

In the garnet lherzolite lacking spinel, PHN 4034, small (<1 mm diameter) garnet grains are set in a pargasitic amphibole. This is a major constituent of the nodule (*ca.* 18 %) and appears to be in equilibrium with the garnet.

V. GARNET–SPINEL CHEMICAL RELATIONSHIPS

The co-existence of garnet and spinel in mantle nodules has been documented from various localities. Most commonly they are discrete grains, either where spinel is present as grains in kelyphitic rims mantling garnet, or where garnet is an aluminous exsolution phase in pyroxene from spinel lherzolites. The occurrence of garnet mantling spinel as described here is also seen in xenoliths at Hawaii (Beeson and Jackson, 1970: Reid and Eggleton, 1977), Île Bizard, Quebec (Marchand, 1970; Raeside and Helmstaedt, 1982), Somerset Island, Canada (Mitchell, 1978), New South Wales (Ferguson *et al.*, 1977), the Colorado Plateau (Smith and Levy, 1976; Kirkley *et al.*, 1984), Azrou, Morocco (Moukadiri and Kornprobst, 1984), Frank Smith Mine, Republic of South Africa (Exley *et al.*, 1982), Dish Hill, California (Shervais *et al.*, 1973), and Obnezhennaya, USSR (J.J. Gurney, pers. comm.).

The garnet–spinel relationships illustrated in Fig. 4 indicate that the garnet has grown at the expense of spinel:

$$Sp + En + Di = Fo + Gross + Py \text{ (MacGregor, 1970)}$$

An important factor is the availability of reactants notably Ca. In PHN 4013 and 4069 garnet envelopes only develop where there is adjacent clinopyroxene (Cpx^1). The envelopes are generally complete although an incomplete envelope was noted in PHN 4016. Unrimmed spinels occur in PHN 4009, 4013, 4064 and 4069 in each case adjacent to, but separate from, enveloped spinels. PHN 4064 and 4069 also contain garnets lacking spinel cores which have reacted out.

Each garnet–spinel lherzolite illustrates the *partial* formation of pyrope-rich garnet at the expense of an originally aluminous spinel (Sp^1 in Table II). During reaction this becomes progressively closer to chromite composition (Sp^2 in Table II) and hence stable under progressively higher PT conditions within the garnet stability field (MacGregor, 1970; 1974). Core compositions of the spinel in any single nodule vary slightly — much more so than the garnets. Garnet composition (Table III) is approximately 27 per cent almandine, 58 per cent pyrope and 15 per cent grossular, except in PHN 4013 and 4069 which have higher grossular content (*ca*. 18 %), and slightly lower pyrope and almandine contents (*ca*. 56 % and 26 % respectively). In the spinel-free garnet lherzolite, PHN 4034, the garnet has the lowest almandine (15,4 %) but highest uvarovite (3,2 %) contents of all garnets.

TABLE II

Primary and Secondary Spinels from Garnet Lherzolite PHN 4009

	Spinel^1	Spinel^2
SiO_2	—	—
TiO_2	0,14	0,32
Al_2O_3	57,52	44,46
Cr_2O_3	8,93	21,11
Fe_2O_3	1,80	3,30
FeO	10,29	11,56
MnO	0,08	0,53
MgO	20,67	17,66
NiO	0,40	0,33
	99,83	99,27
	Normalized to 8 O atoms	
Si	—	—
Ti	0,006	0,013
Al	3,520	2,901
Cr	0,367	0,924
Fe^{3+}	0,128	0,132
Fe^{2+}	0,389	0,523
Mn	0,003	0,003
Mg	1,600	1,457
Ni	0,018	0,015
	6,031	5,968

VI. SECONDARY SPINELS, CLINOPYROXENES AND AMPHIBOLES

Most spinels have a narrow (10–50 μm) rim enriched in Mg and Al (Fig. 5) which is attributed to a late-stage reaction.

The secondary slivers of clinopyroxene probably arose at this time (Fig. 6). The clinopyroxene (Cpx^2) shows higher iron, aluminium and sodium than the primary clinopyroxene (Cpx^1) (Table IV) and, in addition, is slightly subcalcic as would be the case with a late heating event.

The secondary pargasitic amphibole shows relatively low calcium and titanium and higher aluminium and iron compared with the primary pargasite (Table V). Most xenoliths (those with amphibole) were clearly in the amphibole stability field prior to, and during, the reaction.

Figure 7 summarizes the compositional distinctions that can be made between garnets produced by the spinel-to-garnet reactions notwithstanding their close compositional range. PHN 4013 and 4069 have slivers of clinopyroxene (Cpx^2) between garnet and spinel, and plot separately from those with amphibole (Amph^2) between garnet and spinel. The former garnets have relatively higher Ca/(Ca + Mg) and Cr/(Cr + Al) reflecting the composition of clinopyroxene, rather than amphibole (Tables IV and V). Although more data are required it seems that the secondary reaction to form clinopyroxene (Cpx^2) is a reversal of the first in which clinopyroxene (Cpx^1) was consumed to form garnet. The same applies to both amphiboles (Amph^1 and Amph^2). In PHN 4016 there are no slivers of secondary clinopyroxene (Cpx^2) but evidence for the origin of the garnet is given by its position within the *amphibole field* (Fig. 7). It is not known what governs the participation of clinopyroxene or amphibole in any single nodule but bulk composition including availability of H_2O is clearly a possible factor.

It has been noted above that the garnet-forming reaction produces enrichment in Cr and Fe in the associated spinel. The narrow chrome- and iron-poor *rind* of the spinels is attributed to reversed secondary reactions. The spinel-free

TABLE III

Garnet Compositions from Garnet Spinel Lherzolites and one Garnet Lherzolite (PHN 4034). Analyses are Averages of 10 Point Counts

		4002	4009	4013	4016	4034	4064	4067	4069
SiO_2		41,76	41,88	41,65	42,19	42,31	42,06	42,11	41,91
TiO_2		0,09	0,07	0,08	0,10	0,11	0,01	0,15	0,08
Al_2O_3		22,90	22,98	22,62	22,96	22,20	22,85	22,84	22,30
Cr_2O_3		1,01	0,61	1,32	0,77	1,78	0,90	0,84	1,32
FeO		9,36	9,12	8,97	9,13	8,03	8,82	8,92	8,99
MnO		0,41	0,53	0,47	0,52	0,37	0,46	0,43	0,49
MgO		19,24	19,63	18,63	19,57	20,11	19,86	19,70	18,81
CaO		5,02	4,84	6,00	5,15	5,14	4,93	4,95	5,89
		99,79	99,66	99,74	100,39	100,05	99,89	99,94	99,79
				Normalized to 12 O atoms					
Si		2,985	2,991	2,989	3,004	3,007	2,997	3,001	3,004
Ti		0,005	0,004	0,005	0,005	0,006	0,005	0,008	0,005
Al		1,929	1,935	1,913	1,935	1,860	1,919	1,920	1,884
Cr		0,057	0,034	0,076	0,045	0,100	0,050	0,047	0,075
Fe		0,560	0,547	0,536	0,529	0,477	0,525	0,532	0,539
Mn		0,025	0,032	0,029	0,033	0,023	0,028	0,026	0,030
Mg		2,050	2,094	1,992	2,035	2,131	2,109	2,092	2,010
Ca		0,390	0,371	0,461	0,393	0,391	0,376	0,378	0,453
		8,001	8,008	8,001	7,979	7,995	8,009	8,004	8,000
Alm.	(%)	18.3	18,0	17,6	17,6	15,4	17,2	17,4	17,5
Py.	(%)	67,1	68,7	64,9	67,8	68,8	68,9	68,6	65,3
Gr.	(%)	12,8	12,2	15,0	13,1	12,6	12,3	12,4	14,8
Uv.	(%)	1,8	1,1	2,5	1,5	3,2	1,6	1,6	2,4

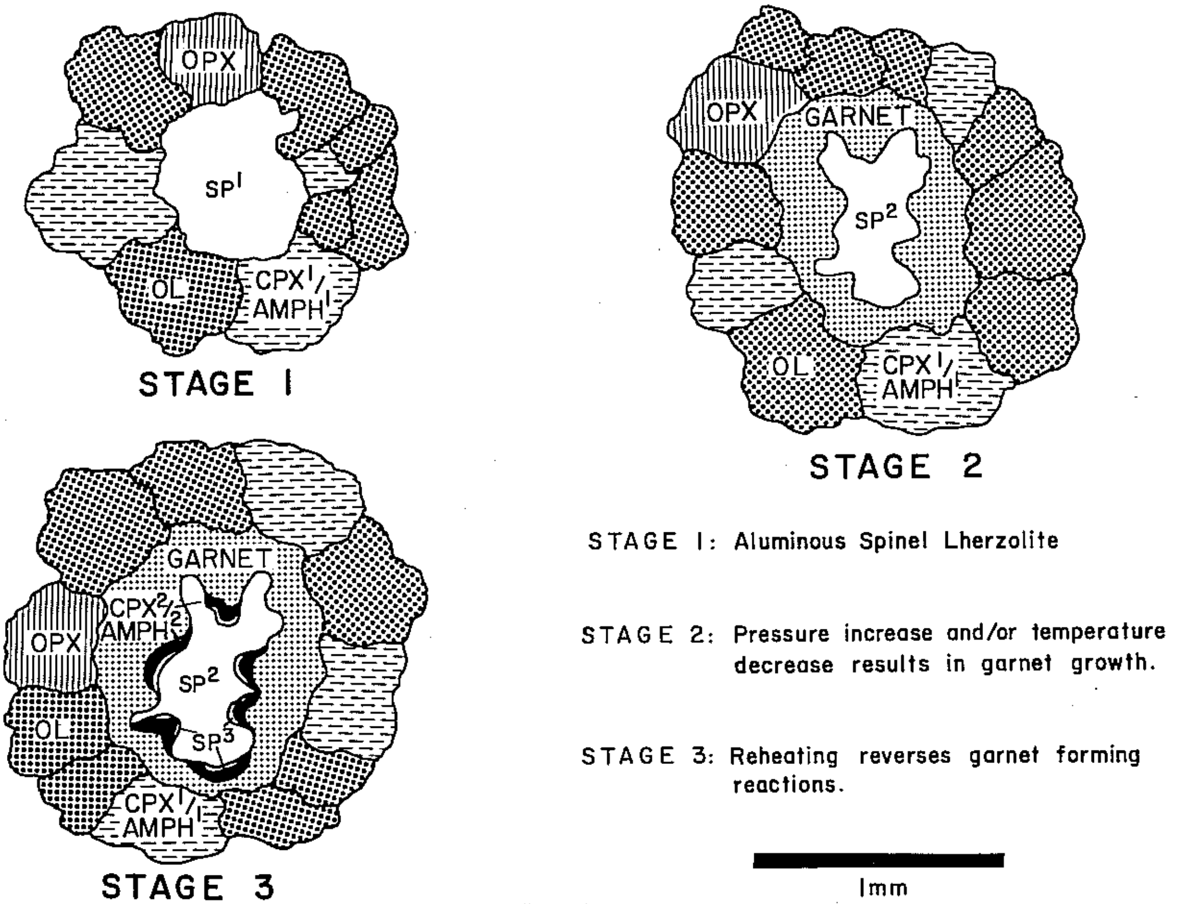

Figure 6

Schematic illustration of the textural evolution of garnet spinel lherzolites.

Stage 1: Aluminous spinel lherzolites, not described from Kwaikwai but seen at nearby Babaru'u.

Stage 2: Formation of garnet envelope mainly at the expense of spinel and clinopyroxene or amphibole; thought to be due to cooling but could result from a pressure increase.

Stage 3: Formation of slivers of secondary clinopyroxene or amphibole thus reversing the stage 2 reaction: a late reheating event.

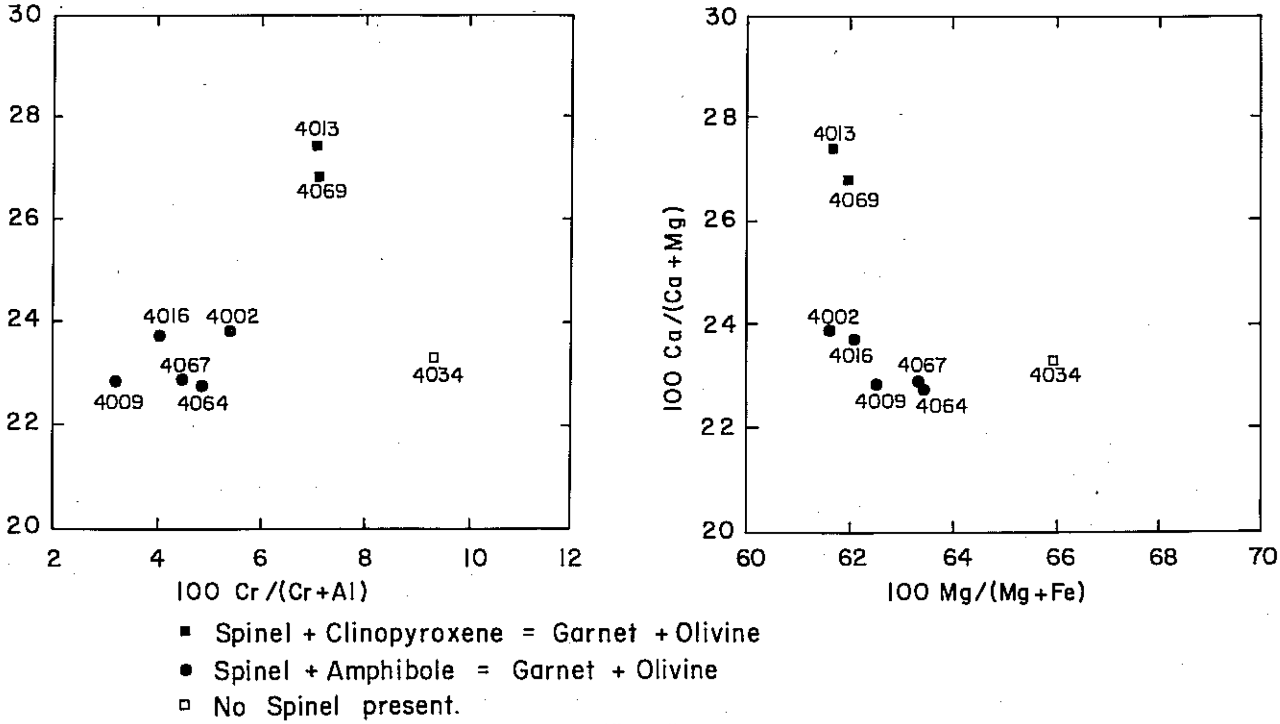

Figure 7

Compositions of garnets from Kwaikwai lherzolite xenoliths. Solid symbols: garnets around which slivers of secondary clinopyroxene (squares) and amphibole (circles) have formed. There are no secondary slivers around 4016 (see text). The secondary slivers result from a partial reversal of the garnet-forming reactions shown in gross terms. The open square is a garnet from lherzolite 4034 in which spinel is absent.

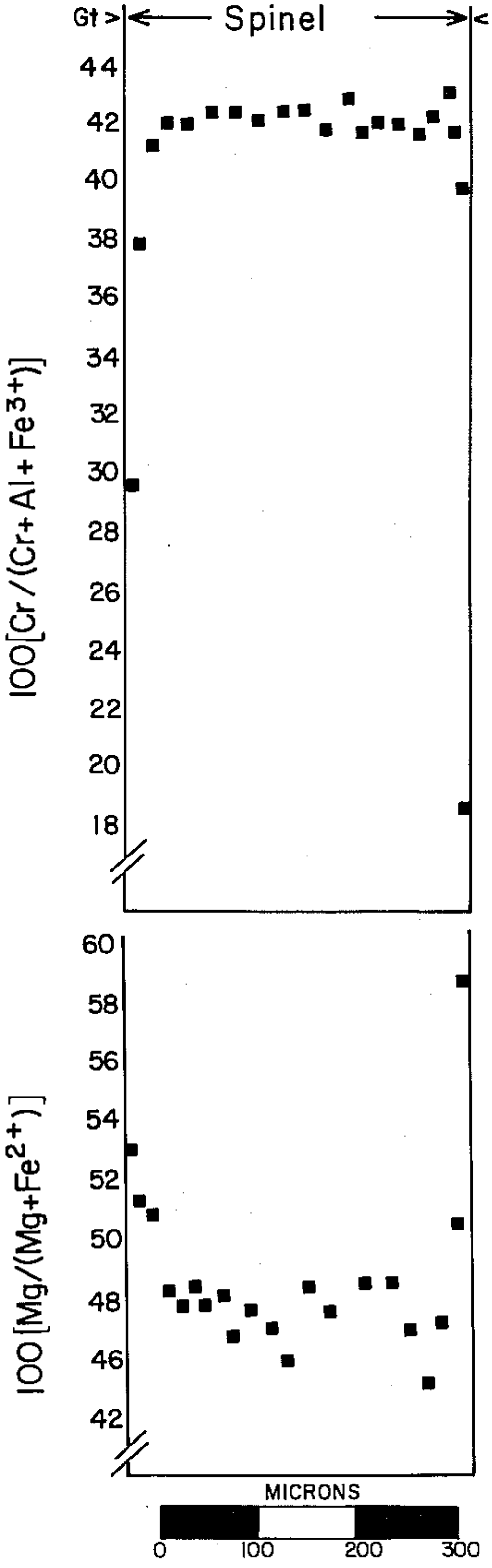

Figure 5
Compositional zoning in spinel from garnet lherzolite PHN 4069.

garnet lherzolite PHN 4034 has a garnet of distinctive depleted composition (Fig. 7). It is arguably a product of complete assimilation of spinel.

TABLE IV
Compositional Differences Between Cpx¹ and Cpx² from PHN 4013 and PHN 4069

	4013 Cpx[1]	4013 Cpx[2]	4069 Cpx[1]	4069 Cpx[2]
SiO_2	53,02	50,52	53,00	51,47
TiO_2	0,23	0,26	0,26	0,30
Al_2O_3	2,98	6,40	2,87	6,00
Cr_2O_3	0,63	1,05	0,64	0,81
FeO	2,72	4,51	2,68	4,16
MnO	0,07	0,19	0,05	0,30
MgO	16,50	15,77	16,36	16,11
CaO	23,04	19,89	22,63	19,70
Na_2O	0,87	1,22	0,77	1,14
	100,06	99,81	99,26	99,99
	Normalized to 6 O atoms			
Si	1,930	1,842	1,943	1,871
Ti	0,006	0,007	0,007	0,008
Al	0,128	0,285	0,126	0,258
Cr	0,018	0,032	0,018	0,029
Fe	0,083	0,140	0,081	0,139
Mn	0,002	0,007	0,001	0,009
Mg	0,893	0,860	0,886	0,871
Ca	0,899	0,775	0,881	0,753
Na	0,061	0,086	0,063	0,078
	4,020	4,034	4,006	4,016
$\frac{Ca}{(Ca+Mg)}$	0,502	0,474	0,498	0,464

TABLE V
Compositional Differences Between Amph¹ and Amph² from PHN 4002 and PHN 4009

	4002 Amph[1]	4002 Amph[2]	4009 Amph[1]	4009 Amph[2]
SiO_2	45,25	43,94	45,78	45,03
TiO_2	0,45	0,26	0,95	0,25
Al_2O_3	13,98	15,26	12,09	14,80
Cr_2O_3	0,88	0,26	0,75	0,59
FeO	5,98	6,71	4,44	5,73
MnO	0,09	0,26	0,75	0,60
MgO	17,45	16,93	18,88	18,58
CaO	10,04	9,34	10,14	8,73
Na_2O	4,20	4,72	4,21	3,94
K_2O	—	0,30	0,67	0,25
	98,32	97,98	98,66	98,50
	Normalized to 23 O atoms			
Si	6,379	6,236	6,472	6,312
Ti	0,048	0,028	0,101	0,028
Al	2,323	2,553	2,016	2,560
Cr	0,098	0,073	0,084	0,068
Fe	0,689	0,778	0,525	0,704
Mn	0,011	0,032	0,011	0,034
Mg	3,666	3,581	3,978	3,903
Ca	1,517	1,420	1,536	1,375
Na	1,148	1,299	1,155	1,120
K	—	0,054	0,121	0,046
	15,879	16,054	15,999	16,150

VII. DISCUSSION AND CONCLUSIONS

In order to determine the PT equilibration conditions the garnet–spinel barometer of O'Neil (1980) was applied to the lherzolite mineral assemblages using core (Sp²) compositions. The orthopyroxene barometer of Wood (1974) was not used, because of variable alumina contents, except in spinel-free garnet lherzolite PHN 4034. The thermometer of Ellis and Green (1979) was applied to equilibrated core clinopyroxene (Cpx¹) and garnet compositions.

Calculated depths and temperatures are shown in Fig. 8. The plots are consistent with the experimental data of Stewart (1980) for garnet–amphibole co-existence ranges (89–95 km and 959–1 039 °C) although it should be noted

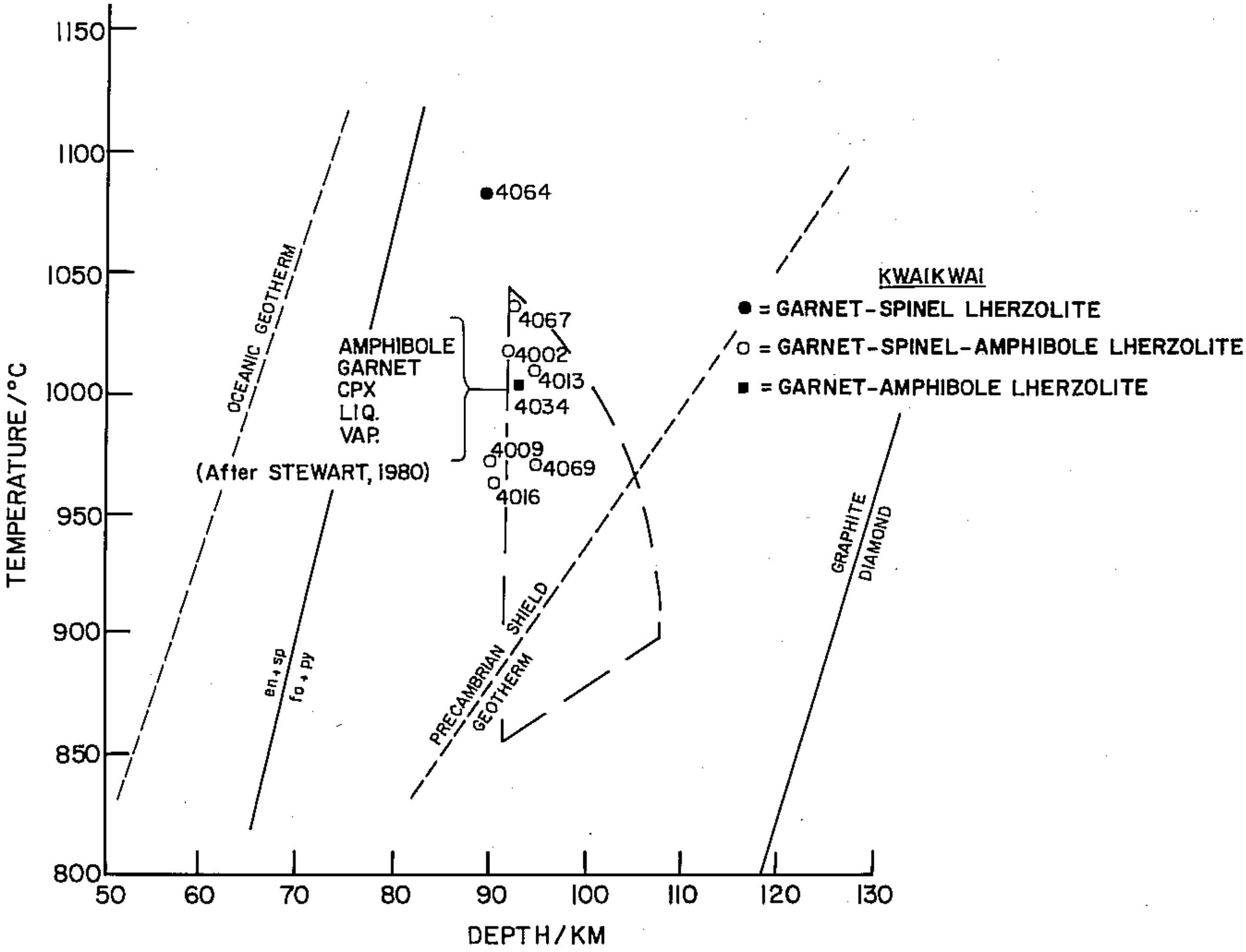

Figure 8

Temperature–depth plot from garnet spinel lherzolites and one garnet lherzolite from Kwaikwai, Malaita. Amphibole garnet co-existence range is after Stewart (1980). Continental and oceanic geotherms after Green and Ringwood (1967). En + Sp = Fo + Py boundary (for chrome free systems) after MacGregor (1974). Graphite–diamond boundary after Kennedy and Kennedy (1976).

that these relate to natural kaersutite. Amphibole-free garnet lherzolite, PHN 4064, plots outside this experimental co-existence range.

The mineral compositions and textures of the xenoliths are the result of lithospheric events that occurred during the formation of the OJP culminating in the eruption of the alnöites. A possible sequence is as follows:

(i) Original oceanic lithosphere formed at a slow spreading axis (Coleman and Kroenke, 1981). The uppermost mantle, composed of depleted spinel peridotite, by analogy with ophiolites, is represented by sporadic garnet free xenoliths, e.g. Bielski-Zyskind *et al.* (1984) of shallow origin.

(ii) The appearance of garnet, not usually found in "oceanic" xenoliths is related to an origin at greater depths within a thickened lithosphere. From evidence given above the garnet results from reaction of primary aluminous spinel with clinopyroxene or amphibole, brought about by increased pressure or cooling. A lowering of temperature would take place during plate separation from a hot spreading centre, as is envisaged during the evolution of the OJP, and this is the most likely cause.

(iii) The slivers of secondary clinopyroxene and amphiboles and associated features are related to a final "reheating" event, logically explained as an igneous phenomenon. The alkali basalts and tholeiites of Malaita are probably late Mesozoic and crustal products of the spreading regime, and hence predate the cooling event referred to in (ii). It is postulated, therefore, that the textures resulted from a later Cretaceous event such as described by Schlanger *et al.* (1981) or from alnöite generation itself, possibly its mantle diapiric precursor.

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