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Equilibration conditions of upper-mantle eclogites: implications for kyanite-bearing and diamondiferous varieties

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ABSTRACT. New mineral data for kyanite-bearing eclogites supplement existing data for eclogite nodule suites from the Roberts Victor and Bellsbank kimberlite intrusions, South Africa. Calculation of equilibration temperatures using the refined K_D calibration of Ellis and Green (1979) indicates that the majority of these eclogites equilibrated over a considerably narrower range (940-1185 °C) than implied by earlier estimates which did not take account of the influence of the Ca-component of garnet on K_D. Most of the Roberts Victor diamondiferous eclogites appear to have equilibrated in the lower part of this range, whilst the equilibration temperatures for the Roberts Victor diamond-free eclogites extend to higher values than those from Bellsbank. The petrogenetic implications of the (calculated) temperature and pressure equilibration conditions for these eclogite suites are discussed with particular reference to possible upper-mantle geotherms and available data on the graphite-diamond transition boundary.

IN most of the kimberlites of southern Africa, eclogite nodules are greatly subordinate in numbers to peridotite nodules, of which garnet lherzolites are a characteristic and widely prevalent type (Mathias *et al.*, 1970; Carswell, 1980; etc.). However, the kimberlites of the Roberts Victor Mine some 40 km east of Bishof in the Orange Free State and of the Bellsbank Main and Bobbejaan fissures at Bellsbank some 50 km north of Barkly West in the Cape Province are unusual in that nodules of eclogite are much more abundant than peridotite suite nodules (Rickwood, 1969; Rickwood *et al.*, 1969). The nodule suites in the Rietfontein kimberlite further west in Cape Province (Gurney *et al.*, 1971) and in the Orapa kimberlite in Botswana (Shee and Gurney, 1979) are apparently also exceptional in this respect.

Reddish-orange garnet and green omphacitic clinopyroxene are the dominant mineral phases in the Roberts Victor and Bellsbank eclogites, but additional primary phases include kyanite, corundum, rutile, graphite and, or, diamond. Mineralogical considerations suggest that the majority of such eclogite nodules are of upper-mantle origin, as distinct from the eclogite nodules of lower crustal origin (Griffin *et al.*, 1979) observed in the Monastery Mine and North Lesothan kimberlites emplaced around the edge of the Kaapvaal craton. Certainly the earlier suggestion by Nixon *et al.* (1963) that kyanite-bearing eclogites are necessarily of crustal origin can be discounted because of the discovery of diamond in certain of these nodules (Dawson, 1968; Rickwood and Mathias, 1970; Switzer and Melson, 1969).

In this paper we present new mineral analyses for a number of kyanite-bearing eclogites from the Roberts Victor, Bellsbank Main and Bobbejaan kimberlites to supplement existing data for these localities which are mostly on the essentially bimineralic and diamond-bearing eclogite varieties. Since the outcrops of the Main and Bobbejaan fissures in the Bellsbank area are only about a kilometre apart and they apparently contain similar nodule suites, they may perhaps be linked at depth, and so for the purposes of comparison with the eclogite nodule suite in the Roberts Victor Mine kimberlite some 125 km away, we have pooled the data on the eclogites from these two dykes and refer to them simply as 'Bellsbank'.

Petrography

MacGregor and Carter (1970) recognized two groups of eclogite nodules from the Roberts Victor Mine kimberlite, primarily on the basis of textural distinctions. Their Group I eclogites were considered to show cumulate textures sometimes with a well-defined mineralogical layering, whereas Group II eclogites were said to have a tightly interlocking texture sometimes with a crude planar fabric reflecting metamorphic recrystallization of what were interpreted as high-pressure liquid precipitates. However, the textural and chemical basis for this subdivision does not appear to have found favour with later workers (e.g. Lappin and Dawson, 1975; Harte and Gurney, 1975; Lappin, 1978). In general it seems likely that such eclogite nodules represent disrupted fragments of high-pressure magmatic precipitates whose present mineralogy and textures reflect varying responses at subsolidus temperatures to subsequent tectono-metamorphic processes.

Bellsbank Main Fissure. The two analysed kyanite eclogites from this locality (CK/3 and CK 22/7) were similar sized (2 by 2 cm) fragments from the mine concentrate piles. They contain elongate pale-blue kyanite crystals (typically 300–400 microns across) which occur both marginal to and enclosed within the pale honey-coloured garnets and fairly unaltered pale-green clinopyroxenes. However, CK 22/7 also shows striking exsolution of sub-parallel plates of garnet (150–200 microns across) and kyanite (averaging about 50 microns across) within clinopyroxene grains. Lappin (1978) has previously described a 'necklace texture' of alternate millimetre-sized garnet and kyanite crystals along clinopyroxene grain boundaries in a Roberts Victor Mine grospydite nodule which he interpreted as reflecting incoherent grain-boundary exsolution of these minerals from the high-Al clinopyroxenes. The recognition of structurally coherent lamellae of both garnet and kyanite in clinopyroxene grains in nodule CK 22/7 strongly suggests an exsolution origin for at least some of the garnet and kyanite from what must originally have been extremely aluminous clinopyroxenes in certain of these kyanite-bearing eclogite nodules. It is worth noting that O'Hara and Yoder (1967) reported an orientated intergrowth of kyanite in clinopyroxene in a kyanite eclogite from the Dodoma mine, Tanzania. Their view that this kyanite had exsolved from an originally more aluminous higher-temperature clinopyroxene was strengthened by their demonstration that on heating a sample of this eclogite to 1525 °C at 30 kb pressure, nearly all the kyanite disappeared leaving clinopyroxene and garnet as the major crystalline phases at the beginning of melting.

Bellsbank Bobbejaan Fissure. The three analysed kyanite eclogites from this nearby locality (CK 27/3, CK 27/4, and CK 27/7) were again just small fragments (maximum size 3 by 4 cm) from the mine concentrates. All three contain laths of pale-blue kyanite (up to 3 mm long in CK 27/4, but < 1 mm long in the other two samples) enclosed within and adjacent to both the pale honey-coloured garnets and pale-green clinopyroxenes. In CK 27/7 there are also large (up to 2 mm across) primary corundum grains.

Roberts Victor Mine. By contrast, the analysed sample (RV 9) from this locality was a large, 8 by 10 cm, mineralogically banded eclogite nodule in which the following contrasting layers can be recognized:

LAYER A (> 5 cm thick) contains large (up to 3 mm long) deep-blue kyanites both enclosed within, and marginal to, the pale-red garnets and greyish altered clinopyroxene.

LAYER B (about 0.5 cm thick) contains rarer small (< 0.5 mm long) kyanites enclosed in garnets and less altered yellowish-green clinopyroxenes.

LAYER C (about 1.5 cm thick) is garnet-rich and lacks kyanite but does contain a little clinopyroxene.

LAYER D (> 2 cm thick) contains more nearby equal amounts of garnet and clinopyroxene together with a high content of mid-brown mica, but no kyanite.

Brown phlogopitic mica, which is taken to be of replacement origin, is a conspicuous mineral in most eclogite nodules in kimberlites, being concentrated along the boundaries of the primary mineral grains and in fractures through the garnets.

Alteration features. Although clinopyroxene is sufficiently well preserved in sample CK 22/7 to show exsolution textures, in all analysed samples it shows at least some marginal alteration of the type seemingly characteristic of most kyanite eclogite nodules in kimberlites (Switzer and Melson, 1969; Mathias *et al.*, 1970). In the most extreme samples (CK 27/4, 27/7, and RV9 layer A), the highly altered clinopyroxenes are grey in hand specimen and dark brown, nearly opaque, in transmitted light. Only isolated relic cores of fresh clinopyroxene are retained in these instances and the semi-opaque altered portions are optically irresolvable. However, locally the altered areas are more transparent and may be seen to consist of intergrowths of secondary pyroxene, plagioclase, spinel, hornblende, mica, calcite, and patches of pale-brown, largely devitrified, glass. The alteration characteristics of the clinopyroxene are thus similar to those previously described by Switzer and Melson (1969) and Lappin (1978), and attributed by them to partial melting in response to incorporation within, and eruption of, the host kimberlite. Veins of secondary clinopyroxene and plagioclase, with amphibole, mica, and calcite as common additional phases, cut across garnet grains in some cases and testify to the mobilization of a partial melt phase commonly modified through the addition of H_2O, CO_2, and K_2O.

In three of the samples, namely CK22/3, 27/3, and 27/4, kyanite grains show clear evidence of replacement by intergrowths of acicular corundum crystals with interstitial plagioclase ranging in composition from An_{29-42} similar to that illustrated by Dawson (1980, fig. 66). This secondary replacement would appear to relate to breakdown in the stability of kyanite with the jadeite and Ca-tschermak's molecules in the clinopyroxenes—according to the following reactions:

$$NaAlSi_2O_6 + Al_2SiO_5 \rightleftharpoons Al_2O_3 + NaAlSi_3O_8$$
$$CaAl_2SiO_6 + Al_2SiO_5 \rightleftharpoons Al_2O_3 + CaAl_2Si_2O_8$$

Switzer and Melson (1969) noted the common occurrence of corundum at kyanite margins but considered that neither the garnet nor the kyanite was involved in a major way in the generation of the partial melt. However, in the nodules which we have examined it does appear that kyanite has also been commonly, though not invariably, so involved and that breakdown of the aluminous clinopyroxene-kyanite assemblage has led, by way of an intermediate partial melt, to its replacement by an assemblage of plagioclase + corundum + a much less aluminous clinopyroxene (the place of which has often been taken by hornblende and, or, mica where appreciable H_2O and, or, K_2O has been introduced).

Mineral chemistry

The constituent minerals in these kyanite eclogites were analysed by electron microprobe. In all samples, other than RV9, the analysis given is the mean of several point analyses.

Garnet analyses are given in Table I. With the obvious exception of the layered sample RV9, little variation was found in the compositions of different grains; nor is any consistent and significant zoning present. Other than for a slightly higher Na_2O content, the lamellar garnets exsolved from the clinopyroxenes in sample CK 22/7 have essentially the same composition as the larger discrete garnets. However, the garnets in kyanite-bearing eclogites have appreciably higher CaO (grossular) contents than those in associated kyanite-free eclogites (see also fig. 1), a feature which is even more apparent in the compositionally even more extreme grospydite nodules (O'Hara and Mercy, 1966; Smyth and Hatton, 1977; Lappin, 1978; Dawson, 1980).

All iron in the garnets has been assumed to be divalent in the microprobe analyses as presented. The contents of trivalent cations in the structural formulae indicate that Fe^{3+} contents are almost certainly low. This was confirmed by a 'wet' chemical determination of FeO and Fe_2O_3 in a mineral separate of garnet from RV9 which gave values of 12.90 and 1.64 wt %, respectively. In the absence of data on the Fe_2O_3 contents of most of the garnets, the X^{gt}_{Ca} values (Ca/(Ca + Mg + Fe + Mn)) in Table I may be taken to provide a reasonable approximation of the proportion grossular end-member in these garnets. On this basis, the garnets in all the analysed kyanite-bearing samples contain less than 50 mol % grossular and these samples are hence classified as kyanite eclogites rather than grospydite (Sobolev *et al.*, 1968; Lappin, 1978).

Clinopyroxene analyses (Table II) again show major differences in composition between kyanite-bearing and kyanite-free eclogites with the former having appreciably higher Na_2O contents (see also fig. 1). Jadeite contents in the clinopyroxenes, calculated assuming zero acmite content (since $Fe^{2+}/(Fe^{2+} + Fe^{3+})$ ratios have not been determined) are extremely high in all the kyanite eclogites, ranging from 54–71 mol %, but drop to 25–32 mol % in the kyanite-free layers in sample RV9. In all cases the jadeite/Ca tschermak's molecule ratio is very high as is to be expected in high-pressure eclogite-facies clinopyroxenes (White, 1966; Kushiro, 1969).

Kyanite and *corundum* analyses (Table III) involved long counting times in order to improve the analytical accuracy for the various minor elements. These kyanites and corundums all contain low, but nevertheless significant, amounts of Fe and Cr. The most intensely blue-coloured kyanite, that in RV9, has the highest total Fe as Fe_2O_3 content. However, the Fe_2O_3 and Cr_2O_3 contents in all these analysed kyanite are small compared with the values of 0.79 and 4.80 wt %, respectively, determined by Sobolev *et al.* (1968) in an intensely blue kyanite from a chrome-rich band in a grospydite nodule from the Zagadochnaya kimberlite pipe in Yakutia. Even higher Cr_2O_3 contents (up to 12.86 wt %, equivalent to up to 18 mol % admixture of Cr_2SiO_5) have been reported by Sobolev *et al.* (1968) for kyanites intergrown with green–violet garnets from the same kimberlite. From the analyses in Table III it is apparent that the secondary corundums developed in the reaction coronas around kyanites have higher Fe_2O_3 and Cr_2O_3 contents than the primary corundums.

Equilibration conditions

The eclogite nodule suites from the Roberts Victor and Bellsbank kimberlites both show an over-all tendency (figs. 1A–B) for higher grossular contents in garnets and higher jadeite contents in coexisting clinopyroxenes in the kyanite-bearing samples. Such a trend is well illustrated by the analyses of the mineral phases in the layered eclogite, sample RV9, but curiously is not shown in the clinopyroxenes in an eclogite nodule analysed by Lappin and Dawson (1975) which contained both kyanite-free and kyanite-bearing bands (as in RV9).

TABLE I: Analyses of Garnets from Kyanite Eclogite Nodules

	RV9 LAYER A	RV9 LAYER B	RV9 LAYER C+	RV9 LAYER D+	CK22/3	CK22/7	CK27/3	CK27/4	CK27/7
SiO_2	39.23	40.6	40.8	40.8	40.1	39.6	40.0	39.8	40.1
TiO_2	0.43	0.33	0.35	0.32	0.11	0.16	0.13	0.12	0.13
Al_2O_3	22.2	22.5	22.1	22.1	23.0	22.9	23.1	23.0	23.2
Cr_2O_3	0.04	0.03	0.11	0.11	0.06	0.06	0.02	0.05	0.01
*FeO	14.9	15.5	16.9	17.9	9.59	10.2	11.0	10.6	10.2
MnO	0.39	0.44	0.64	0.68	0.15	0.15	0.14	0.13	0.12
MgO	7.30	10.8	13.6	13.9	11.9	9.84	12.0	11.8	12.5
CaO	15.6	10.6	5.80	5.07	15.7	17.3	14.2	14.4	13.9
Na_2O	0.14	0.12	0.13	0.08	0.03	0.09	0.02	0.02	0.02
TOTAL	100.2	100.9	100.4	100.9	100.6	100.3	100.6	99.9	100.2

Structural Formulae on the Basis of 12 Oxygens

	RV9 LAYER A	RV9 LAYER B	RV9 LAYER C+	RV9 LAYER D+	CK22/3	CK22/7	CK27/3	CK27/4	CK27/7
Si	2.963	3.000	3.009	3.002	2.938	2.935	2.932	2.939	2.940
Ti	0.024	0.018	0.019	0.018	0.006	0.009	0.007	0.007	0.007
Al	1.973	1.958	1.921	1.915	1.985	2.001	1.998	2.002	2.004
Cr	0.002	0.002	0.006	0.006	0.004	0.004	0.001	0.003	0.006
Fe	0.943	0.956	1.044	1.103	0.587	0.631	0.676	0.655	0.625
Mn	0.025	0.028	0.040	0.042	0.009	0.009	0.009	0.008	0.008
Mg	0.822	1.195	1.499	1.527	1.297	1.086	1.317	1.297	1.371
Ca	1.261	0.836	0.458	0.400	1.234	1.372	1.120	1.140	1.095
Na	0.020	0.017	0.019	0.011	0.004	0.013	0.003	0.003	0.003
TOTAL	8.033	8.010	8.015	8.024	8.064	8.060	8.063	8.054	8.059
X_{Ca}^{gt}	0.413	0.277	0.151	0.130	0.395	0.443	0.359	0.368	0.353

* Total Fe as FeO $X_{Ca}^{gt} = Ca/(Ca + Mg + Fe + Mn)$

\+ Layers C and D in Nodule RV9 are Kyanite Free

TABLE II: Analyses of Clinopyroxenes from Kyanite Eclogite Nodules

	RV9 LAYER A	RV9 LAYER B	RV9 LAYER C+	RV9 LAYER D+	CK22/3	CK22/7	CK27/3	CK27/4	CK27/7
SiO_2	56.8	57.2	56.3	55.4	56.0	55.7	56.8	55.7	55.4
TiO_2	0.33	0.28	0.35	0.30	0.12	0.15	0.18	0.16	0.18
Al_2O_3	18.8	19.4	7.55	5.65	15.6	17.4	16.7	15.9	17.0
Cr_2O_3	0.02	0.04	0.14	0.16	0.09	0.06	0.07	0.05	0.04
*FeO	2.10	1.96	5.45	6.11	1.19	1.04	1.10	1.40	0.99
MnO	0.03	0.01	0.09	0.14	0.01	0.01	0.02	0.01	0.01
MgO	4.68	4.26	11.2	12.4	7.54	6.54	6.72	7.20	6.72
CaO	8.45	7.10	14.4	15.6	11.7	10.8	10.4	11.2	10.7
Na_2O	9.26	10.2	5.10	4.09	8.39	8.88	9.01	8.60	8.71
TOTAL	100.5	100.5	100.6	99.8	100.6	100.6	101.0	100.2	99.7

Structural Formulae on the Basis of 6 Oxygens

	RV9 LAYER A	RV9 LAYER B	RV9 LAYER C+	RV9 LAYER D+	CK22/3	CK22/7	CK27/3	CK27/4	CK27/7
Si	1.955	1.966	2.005	2.005	1.944	1.930	1.955	1.943	1.933
$Al^{[4]}$	0.045	0.034	0.000	0.000	0.056	0.070	0.045	0.057	0.067
$Al^{[6]}$	0.721	0.750	0.317	0.241	0.584	0.640	0.633	0.596	0.632
Ti	0.009	0.007	0.009	0.008	0.003	0.004	0.005	0.004	0.005
Cr	0.001	0.001	0.004	0.005	0.002	0.002	0.002	0.002	0.001
Fe	0.060	0.056	0.162	0.185	0.035	0.030	0.032	0.041	0.029
Mn	0.001	0.000	0.003	0.004	0.000	0.000	0.001	0.000	0.000
Mg	0.240	0.218	0.596	0.667	0.390	0.338	0.345	0.374	0.350
Ca	0.311	0.261	0.552	0.604	0.434	0.400	0.384	0.418	0.401
Na	0.619	0.683	0.352	0.287	0.565	0.597	0.601	0.582	0.590
TOTAL	3.962	3.976	4.000	4.006	4.013	4.011	4.003	4.017	4.008

* Total Fe as FeO + Layers C and D in RV9 are Kyanite free

TABLE III: Analyses of Kyanites and Corundums from Kyanite Eclogite Nodules

	KYANITES						CORUNDUMS PRIMARY	CORUNDUMS SECONDARY
	RV9	CK22/3	CK22/7	CK27/3	CK27/4	CK27/7	CK27/7	CK27/4
SiO_2	36.8	36.7	36.6	37.0	36.6	36.7	0.01	0.00
TiO_2	0.11	0.02	0.02	0.03	0.03	0.02	0.03	0.03
Al_2O_3	63.1	62.8	62.3	63.7	62.3	62.3	99.8	99.7
Cr_2O_3	0.04	0.13	0.07	0.05	0.08	0.07	0.06	0.13
$*Fe_2O_3$	0.26	0.18	0.13	0.13	0.22	0.13	0.16	0.46
MnO	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00
MgO	0.07	0.02	0.01	0.01	0.02	0.01	0.03	0.00
CaO	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00
TOTAL	100.4	99.9	99.1	100.9	99.3	99.2	100.1	100.3

* All Fe expressed as Fe_2O_3

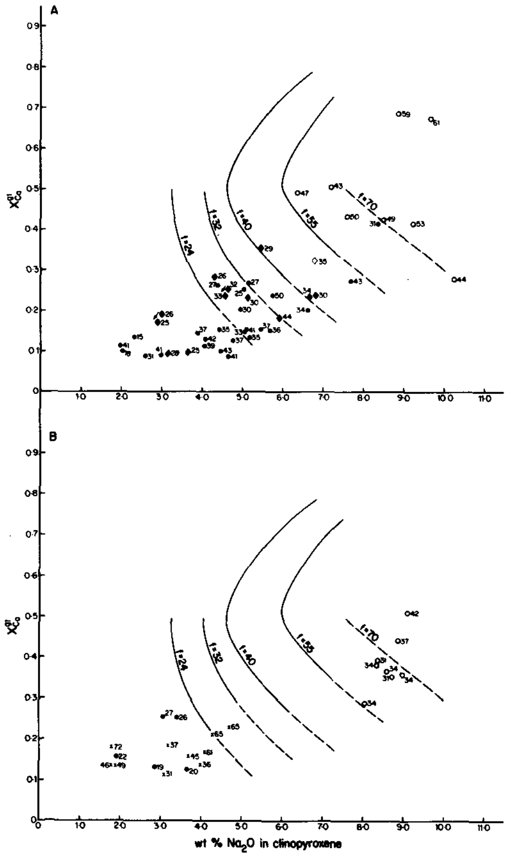


FIG. 1. Plot showing the relationship between the Ca (grossular) content of garnet and Na_2O content of coexisting clinopyroxene in the various eclogite nodule types from A. Roberts Victor Mine, B, Bellsbank Main and Bobbejaan fissures.

Closed ornaments—kyanite free; open ornaments—kyanite-bearing. Diamond ornament signifies diamond bearing. Arrows indicate zoning trends. For comparative purposes the compositions of the coexisting phases in lower crustal eclogites from the Monastery Mine and Northern Lesotho kimberlites (Griffin *et al.*, 1979) are shown by crosses on diagram B.

The numerals adjacent to all points are the 'f' numbers (100 Fe/(Fe + Mg) in garnet) which should be compared with the 'f' lines which are from Sobolev *et al.* (1968, fig. 12).

Sobolev *et al.* (1968) noted, for the kyanite eclogite-grospydite nodule suite from the Zagadochnaya pipe, that in different nodules clinopyroxenes with different Na_2O contents coexist with garnets with essentially the same grossular content. They attributed this to the effect of increased Fe/(Fe + Mg) ratios in the case of those samples with the most sodic clinopyroxenes. Whilst fig. 1A and B show that there is a definite tendency for more grossular-rich garnets to coexist with more sodic clinopyroxenes in the more ferriferous assemblages, as monitored by the Fe/(Fe + Mg) ratio in the garnet, the mineral composition relationships in the Roberts Victor and Bellsbank eclogites neither correspond to, nor are as simple as, those illustrated by Sobolev *et al.* (1968, fig. 12). The lack of correspondence may well largely reflect higher equilibration pressures for these eclogite suites since they contain associated diamond-bearing samples, suggesting pressures of the order of 40–50 kb compared with 20–30 kb estimated by Sobolev *et al.* (1968) for the Zagodochnaya nodules. It seems likely that the compositions of the coexisting garnets and clinopyroxenes in eclogites are controlled by the interplay of several factors, the most important of which are probably the Fe/(Fe + Mg), Na/(Na + Ca) and Al/(Al + Si) ratios in the rock and the pressure (and to a lesser extent the temperature) of equilibration. For example, the eclogite nodules in the Monastery Mine and Northern Lesotho kimberlites, interpreted as being of lower crustal derivation (Griffin *et al.*, 1979), contain low-grossular garnets, and clinopyroxenes with comparatively low-jadeite contents (fig. 1B) despite the highly ferriferous nature of many of these nodules—doubtless reflecting their much lower pressure-temperature equilibration conditions.

It is well known that Fe^{2+}-Mg^{2+} partitioning between coexisting garnets and clinopyroxenes is strongly temperature dependent and hence provides a potentially valuable mineralogical thermometer applicable to eclogites (Banno, 1970; Råheim and Green, 1975). However, Råheim and Green (1974) in their experimental calibration of $K_D = \frac{(FeO/MgO)_{gnt}}{(FeO/MgO)_{cpx}}$ indicated that K_D is significantly dependent on pressure as well as temperature.

K_D values, calculated assuming all Fe as Fe^{2+} in both minerals, are listed in Table IV both for the newly analysed kyanite eclogites and previously analysed associated eclogites from the Roberts Victor, Bellsbank Main and Bobbejaan localities (data from references listed in Table IV). The observed variations in K_D values (2.13–5.74 for Roberts Victor Mine eclogites and 3.35–6.84 for Bellsbank area eclogites in Table IV) have led some authors (MacGregor and Carter, 1970; Reid *et al.*, 1976) to previously suggest that such eclogites have equilibrated over a wide range of temperatures and hence were probably derived from a considerable depth range in the upper mantle.

As diamondiferous eclogites have been reported from each of these localities at least some of the eclogite nodules in these particular kimberlites must have equilibrated within the diamond

TABLE IV A: Eclogite Nodules from Roberts Victor Mine

Sample Number	X^{gt}_{Ca}	K_D^{+}	T°C at 47 Kb Råheim & Green (1974)	T°C at 47 Kb Ellis & Green (1979)	Reference	Special Features
RV9/A	0.413	4.55	1032	1138	1	Kyanite
RV9/B	0.277	3.10	1177	1177	1	Kyanite
RV9/C	0.151	2.56	1262	1137	1	Garnet Rich
RV9/D	0.130	2.61	1253	1105	1	-
1175	0.203	3.74	1102	1021	2	-
1178	0.154	2.56	1261	1135	2	-
1185	0.136	2.90	1205	1061	2	-
1187	0.087	2.19	1339	1145	2	-
1188	0.264	4.92	1006	974	2	Primary ? Amphibole
1190	0.267	3.42	1137	1122	2	-
1191	0.236	2.91	1204	1164	2	-
1692	0.154	2.68	1241	1118	2	-
1698	0.100	3.06	1182	1002	2	-
SRV1	0.502	5.42	976	1146	3	Kyanite + Coesite Grospydite
111060	0.324	4.58	1030	1054	4	Kyanite + Diamond
110752	0.489	5.74	958	1113	4	Kyanite
RV15	0.422	4.66	1024	1136	5	Kyanite
8534/1	0.685	4.55	1032	1385	6	Kyanite Grospydite
8534/2	0.671	4.41	1043	1388	6	Kyanite Grospydite
6913/1	0.274	3.76	1100	1087	7	-
6913/2	0.431	4.80	1014	1132	7	Kyanite
6914	0.414	3.46	1133	1262	7	Graphite
R1	0.231	3.97	1080	1024	8	Diamond
R2	0.098	2.65	1246	1063	8	Diamond
R3	0.282	4.55	1032	1019	8	Diamond
R4	0.183	3.30	1152	1054	8	Diamond
R5	0.094	2.70	1238	1051	8	Diamond
R6	0.355	3.97	1080	1141	8	Diamond
R7	0.231	3.53	1124	1072	8	Diamond
R8	0.237	3.54	1124	1077	8	Diamond
R9	0.267	3.72	1104	1085	8	Diamond
KA1	0.202	2.87	1210	1136	9	-
KA2	0.147	2.42	1290	1162	9	-
KA3	0.128	2.50	1273	1124	9	-
KA4	0.102	2.29	1315	1138	9	-
KA5	0.094	2.14	1350	1165	9	-
KA6	0.087	2.13	1353	1159	9	-
11063	0.153	2.41	1291	1170	10	-
11062	0.146	2.50	1273	1143	10	-
11060	0.135	2.53	1267	1125	10	-
11061	0.114	2.44	1285	1120	10	-
11064	0.115	2.30	1314	1152	10	-
HRV247-BAC	0.191	3.67	1109	1017	11	Diamond + Graphite
HRV247-BAE	0.175	3.61	1115	1007	11	Diamond + Graphite
HRV247-FC	0.254	4.10	1069	1034	11	Diamond + Graphite
HRV247-FE	0.239	4.13	1066	1016	11	Diamond + Graphite

TABLE IV B : Eclogite Nodules from the Bellsbank Main and Bobbejaan Fissures

Sample Number	X^{gt}_{Ca}	K_D^{+}	T°C at 47 Kb Råheim & Green (1974)	T°C at 47 Kb Ellis & Green (1979)	Reference	Special Features
CK27/3	0.359	5.59	966	1011	1	Kyanite
CK27/4	0.368	4.63	1026	1090	1	Kyanite
CK27/7	0.353	5.51	970	1011	1	Kyanite + Corundum
1829/1	0.156	3.68	1108	982	2	-
1829/2	0.126	5.54	968	814	2	-
2029/1	0.511	6.84	907	1067	2	Kyanite + Corundum
2029/2	0.381	5.70	960	1024	2	Kyanite + Corundum
2031/1	0.290	4.31	1051	1047	2	-
2031/2	0.253	4.42	1042	1003	2	-
2031/3	0.253	6.12	939	891	2	-
2032/2	0.132	3.35	1145	997	2	-
CK22/3	0.394	5.11	994	1075	1	Kyanite
CK22/7	0.443	6.51	921	1028	1	Kyanite

+ All Fe as Fe^{2+} in K_D Calculation

References:

1. This paper
2. Bishop et al. 1978
3. Smyth & Hatton 1977
4. Switzer & Melson 1969/Sobolev 1977
5. Sobolev 1974
6. Lappin 1978
7. Lappin & Dawson 1975
8. Reid et al. 1976
9. Kushiro & Aoki 1968
10. O'Hara et al. 1975
11. Hatton & Gurney 1979

stability field. Graphite, rather than diamond, has been observed in a few of the eclogites (e.g. 6914 of Lappin and Dawson, 1975), whilst Hatton and Gurney (1979) have described an eclogite nodule (HRV 247) from Roberts Victor Mine which contains numerous grains of diamond and graphite, both considered to be primary constituents. Possible upper-mantle geotherms defined by preferred pressure and temperature estimates for garnet lherzolite nodules in kimberlites from southern Africa (Carswell and Gibb, 1980; and fig. IV) intersect the various theoretically and experimentally determined diamond$\rightleftharpoons$graphite equilibrium curves in the 39–51 kb range. In the absence of any method by which we could obtain a precise fix on the equilibration pressure for particular eclogite nodules from mineralogical considerations alone we assumed a pressure 47 kb in order to calculate an equilibration temperature for each eclogite nodule from the K_D value. Using the equation given by Råheim and Green (1974) temperatures ranging from 958 to 1353 °C for the Roberts Victor mine and from 907 to 1145 °C for the Bellsbank eclogite suites were obtained (Table IV). Assuming any other constant pressure would likewise yield large temperature ranges for these suites, thus precluding the possibility that all nodules were derived from a relatively narrow range of depths in the upper mantle.

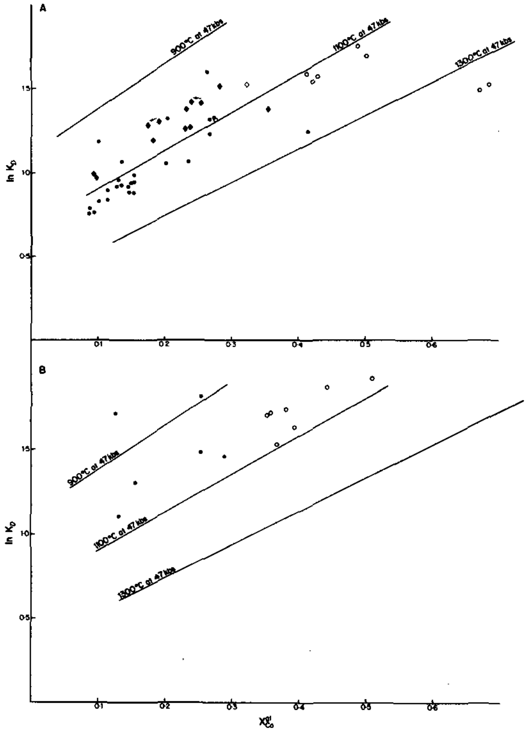


FIG. 2. Plot showing the relationship between *ln* K_D and the mole fraction of Ca in the garnet for the various eclogite nodule types from A. Roberts Victor Mine, B. Bellsbank Main and Bobbejaan fissures.

Sample ornaments as in fig. 1.

The solid lines on these diagrams show the predicted variation in *ln* K_D with X_{Ca}^{gt} at particular *PT* values as calculated from equation (9) of Ellis and Green (1979).

However, it is apparent from Table IV that the K_D values in kyanite eclogite and grospydite nodules are generally higher than in the kyanite-free essentially bimineralic eclogites, suggesting that there may be a significant compositional influence on K_D. This is born out by plots (fig. 2A and B) of *ln* K_D *v.* X_{Ca}^{gt} for these eclogite nodule suites which demonstrate that K_D values are considerably higher in those eclogites with the more calcic garnets. Moreover, Ellis and Green (1979) have recently demonstrated experimentally that a combination of non-ideal Ca–Mg substitutions in coexisting garnets and clinopyroxenes results in composition changes which profoundly influence the Fe^{2+}-Mg^{2+} partition coefficient values; and that the net effect of these compositional changes on K_D is conveniently monitored by X_{Ca}^{gt}. Equilibration temperature estimates for the individual eclogite nodules calculated by this same equation, again at an assumed pressure of 47 kb, are listed in Table IV. These values indicate that when allowance is made for the observed compositional influence on K_D then the temperature estimates for the majority of eclogite nodules from both the Roberts Victor Mine and Bellsbank area localities are much more tightly grouped, pointing to derivation from a more restricted source region in the upper mantle than indicated by the values calculated from the Råheim and Green (1974) equation. For example, the Ellis and Green (1979) equation yields equilibration temperatures which cluster around 1100 °C at an assumed 47 kb pressure for most of the eclogite nodules from Roberts Victor Mine (fig. 2A). Although there is an overlap in the ranges of equilibration temperatures for the diamond-bearing and diamond-free eclogites from this locality, there are nevertheless differences in the mean equilibration temperature estimates for these two groups (1051 and 1126 °C, respectively) which may be significant. Nevertheless, there is the possibility that the difference may be solely due to the presence or absence of free carbon.

We consider that the particularly high calculated temperatures for the two layers in the grospydite nodule 8534 of Lappin (1978) may be erroneous and hence have not included them in the calculated mean temperature value for the diamond-free nodules from Roberts Victor Mine. We suspect that these anomalously high temperature values are attributable to either non-equilibration between the garnets and clinopyroxenes in this sample which shows textural evidence of exsolution of kyanites and garnets from pyroxene, or the fact that the minerals in this particularly ferriferous nodule contain appreciable Fe^{3+} not taken into account in the calculation of the K_D values.

Although the assumption which we have made in all cases of all Fe as Fe^{2+} in both garnets and clinopyroxenes is unlikely to be strictly correct, $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ ratios in upper-mantle minerals are likely to be very low (c.f. Burns *et al.*, 1972), particularly in diamond- or graphite-bearing assemblages. Also, since the oxidation state of the upper mantle is unlikely to vary greatly, at least the temperature estimates based on K_D values with all Fe as Fe^{2+} should be valid on a relative basis for the eclogite nodule suites. We have tried calculating $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ ratios for the minerals on the basis of charge balance in the structural formulae (Neumann, 1976) but it is clear that the errors inherent in this procedure are too large, especially for the clinopyroxenes with low total Fe. In the absence of analytically determined $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ ratios in the minerals for the majority of these eclogite nodules, it is therefore necessary to base any discussion of the relative equilibration temperatures of these nodules on K_D values which assume all Fe as Fe^{2+}, but it should be borne in mind that in absolute terms such temperature estimates are likely to be maxima. Certainly K_D values which include only analytically determined Fe^{2+} contents are much higher in the six Roberts Victor Mine eclogite samples for which Kushiro and Aoki (1968) analysed bulk mineral separates and consequently yield Ellis and Green (1979) temperature estimates which are on average some 178 °C lower. On the other hand, the analytically determined $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ ratios in certain other eclogites (Switzer and Melson, 1969; Sobolev, 1977; O'Hara *et al.*, 1975) do not indicate such consistent substantial over-estimation of equilibration temperatures when all Fe is taken as Fe^{2+} in the calculation of K_D values.

The variation in the equilibration temperature estimates obtained for different portions of layered eclogite nodules (e.g. 72 °C in the case of RV9) suggests that additional composition influences and, or, analytical errors may account for at least some of the over-all variation in the values obtained for the various eclogite nodules. Exsolution textures (c.f. Lappin, 1978; Harte and Gurney, 1975) clearly demonstrate that at least some, and possibly all, of the eclogites originally crystallized at substantially higher temperatures, most likely as crystal cumulates from trapped upper-mantle partial melts. It would appear that at solidus temperatures at least some of the present garnet and kyanite in the kyanite eclogites was occluded in even more aluminous pyroxenes.

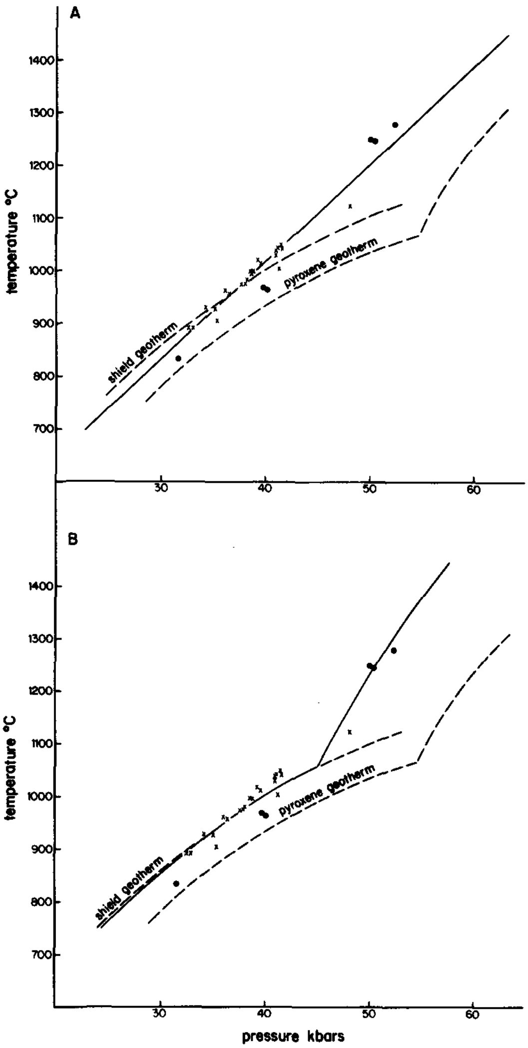
As suggested previously, with reference to eclogite nodule 8534 of Lappin (1978), some of the variation in the temperature estimates for the different eclogite nodules may reflect failure of the mineral assemblages in certain nodules to fully re-equilibrate subsequent to their initial igneous crystallization.

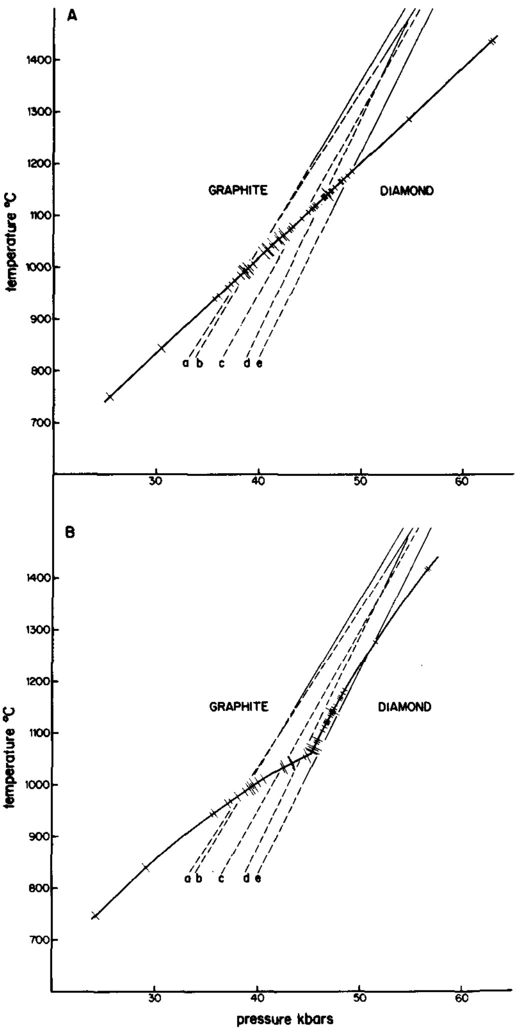
We are tempted to conclude that the unusually high proportion of eclogite nodules in the Roberts Victor and Bellsbank kimberlites reflects the fact that each kimberlite during its ascent happened to intersect substantial layered complexes of such cumulates (varying from essentially bimineralic eclogites to grospydites) close to the site of initiation of their rapid eruption through an otherwise peridotitic upper mantle. However, there is no *a priori* justification for our initial assumption that all these eclogite nodules have come from essentially the same depth and hence have all equilibrated at much the same pressure, and indeed the fact that certain nodules contain diamond and others graphite strongly suggests that this is unlikely.

Implications for geothermal gradients

From their K_D values, we can represent the equilibration conditions for individual nodules by a line in P (pressure)-T (temperature) space. On the assumption that each nodule equilibrated at the ambient conditions of its site of derivation, it is possible to uniquely fix the PT equilibration conditions for each nodule on the basis of the intersection of the PT line with the likely upper-mantle geotherm. The latter may be predicted either from geophysical considerations (e.g. Clark and Ringwood, 1964) or from consideration of other nodule types (especially garnet lherzolites) found in kimberlites which enable determination of unique PT estimates (e.g. Boyd, 1973). Unfortunately such nodule types are rare in the particular kimberlites under consideration and currently no analyses are available. We have therefore deduced the likely geotherm in the upper mantle beneath these kimberlites from analyses of peridotite nodules in adjacent kimberlite diatremes.

In fig. 3A and B we present two possible alternative upper-mantle geotherms based on 'preferred' (Carswell and Gibb, 1980) PT estimates for garnet lherzolite and pyroxenite nodules from the Frank Smith Mine (data from Boyd, 1974) and for garnet lherzolite nodules from the Kimberley Mines (data from Boyd and Nixon, 1978, and Bishop *et al.*,





FIGS. 3 and 4. FIG. 3 (*left*). Diagrams showing alternative linear (A) and inflected (B) Late Cretaceous palaeogeotherms for the upper mantle beneath this part of South Africa based on *PT* estimates for garnet lherzolite nodules from the Kimberley Mines kimberlites (crosses) and garnet lherzolite-pyroxenite nodules from the Frank Smith Mine (closed circles). Also shown are the 'Pyroxene' geotherm for Northern Lesotho from Boyd (1973) and the 'Shield' geotherm of Clark and Ringwood (1964). FIG. 4 (*right*). Diagrams showing the *PT* estimates for the eclogite nodules as deduced from the intersection of *PT* lines based on K_D values with the alternative linear (A) and inflected (B) Late Cretaceous palaeogeotherms indicated in fig. 3. The bar symbols in order of decreasing lengths signify Roberts Victor diamond-bearing eclogites; Roberts Victor diamond-free eclogites; and Bellsbank area eclogites; respectively. The various diamond-graphite equilibrium boundaries are from (a) Strong and Chrenko (1971); (b) Bundy *et al.* (1961); (c) Berman (1979); (d) Strong and Hanneman (1967); and (e) Kennedy and Kennedy (1976).

1978). The inflected geotherm in fig. 3B has the form of the 'Pyroxene Geotherm' favoured by Boyd (1973, 1974) although it is somewhat displaced in absolute terms with the lower-temperature limb essentially coincident with the 'Shield Geotherm' of Clark and Ringwood (1964).

In fig. 4A and B we show the deduced *PT* estimates for individual eclogite nodules based on the intersection of the K_D-determined *PT* lines with the two possible geotherms. [Note that the different bar symbols across the geotherms do not signify a *PT* range but are used simply as a means of distinguishing between different groups of eclogite nodules. The only points of relevance in *PT* terms are the intersections of the bars with the geotherms.] Projecting the *PT* line for individual nodules on to the geotherms extends the implied ranges of equilibration temperatures for the suites of nodules compared to those obtained assuming a single pressure value.

As discussed above, the two highest *PT* points (for the two layers in nodule 8534) are most likely erroneous, as probably also is the next highest point which is for the graphite-bearing eclogite 6914 of Lappin and Dawson (1975). On the other hand, the two lowest *PT* estimates which are for the bimineralic eclogites 2031/3 and 1829/2 from Bellsbank–Bobbejaan fissure, may well genuinely reflect substantially higher levels of derivation for these two nodules. Although these particular nodules are not especially ferriferous, it is tempting to equate them with the suite of eclogite nodules of postulated lower crustal origin (Griffin *et al.*, 1979) observed in certain other kimberlites in southern Africa. Preferred *PT* estimates for garnet granulite and garnet websterite nodules associated with the latter group of eclogites, and likewise taken to have been derived from the lower crust, are 654 ± 34 °C and 10.8 ± 3.1 kb (Carswell and Griffin, in prep.). Assuming a comparable equilibration pressure of 10 kb, lowers the equilibration temperature estimates for these two Bobbejaan eclogites even further (to 753 and 703 °C, respectively). Making due allowance for possible further lowering of these temperature estimates if K_D values had been based on analytically determined Fe^{2+} values rather than taking all Fe as Fe^{2+}, it certainly seems conceivable that these two particular eclogites have been derived from the lower crust.

The equilibration temperature estimates for the rest of the eclogite nodules on the geotherms in fig. 4A and B all lie between 940 and 1185 °C and, if correct, point to derivation of these eclogites from depths between 110 and 150 km, although only down to about 135 km in the case of the analysed Bellsbank area eclogite nodule suite. Unfortunately no analyses are available for diamond-bearing eclogites from the Bellsbank localities, but there does appear to be an unexpected, but none the less significant, tendency for the diamond-bearing eclogites from Roberts Victor Mine to have equilibrated at somewhat lower *PT* values, and hence to have come from somewhat shallower depths, than the majority (though not all) of the associated diamond-free eclogites.

Diamondiferous eclogites

It is important to assess the validity of above *PT* estimates in the light of both theoretical predictions and direct experimental evidence on the pressure-temperature conditions for the diamond $\rightleftharpoons$ graphite equilibrium boundary, for which five alternative positions are indicated in fig. 4. Boundary (e) represents the most recent experimental determination of Kennedy and Kennedy (1976) which they state to be almost coincident with the earlier and previously much quoted boundary of Bundy *et al.* (1961). However, we have replotted, as boundary (b), the experimentally determined boundary of Bundy *et al.* (1961) and find that it lies at substantially lower pressures than that of Kennedy and Kennedy (1976). Bundy *et al.* (1961) in fact indicated a *PT* band between the diamond and graphite stability fields on the basis of several different experiments. The boundary (b) which we have drawn represents a mean position drawn along this band, such that the error brackets on this boundary in pressure terms are roughly ± 1.2 kb. Also shown in fig. 4 are boundaries (a) and (d) based on gross linear extrapolations of two different pairs of high-temperature equilibration points, experimentally determined by Strong and Chrenko (1971) and Strong and Hanneman (1967), respectively; and boundary (c) which is the thermodynamically calculated boundary of Berman (1979). These various boundaries thus indicate that the degree of uncertainty over the precise location of the diamond $\rightleftharpoons$ graphite equilibrium boundary amounts to some 5 kb in pressure terms at the likely equilibration temperatures of these eclogite nodules.

From fig. 4 it is immediately apparent that on the basis of the diamond $\rightleftharpoons$ graphite boundary of Kennedy and Kennedy (1976), the *PT* estimates for all the diamond-bearing eclogites fall outside the diamond stability field, regardless of which geotherm is assumed. This could be interpreted as indicating inaccuracies in the methods used either in determining these *PT* estimates or in delimiting the geotherms. However, if the alternative diamond $\rightleftharpoons$ graphite boundaries of Bundy *et al.* (1961) and Strong and Chrenko (1971) are taken to be correct, then the *PT* estimates for all the diamond-bearing eclogites lie essentially within the diamond stability field. It may be fortuitous but it is none the less encouraging to note that the diamond-bearing eclogite which plots with lowest *PT* equilibration values on the geotherms (essentially at the intersection of the geotherms with the Bundy *et al.* (1961) and Strong and Chrenko (1971) diamond $\rightleftharpoons$ graphite equilibrium boundaries) is nodule HRV 247 of Hatton and Gurney (1979) reported to contain coexisting primary diamond and graphite.

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[Note: Enlarged copies of the four figures are available on request from the authors.]