A Comparison of Recent Experimental Data
on the Gabbro-Garnet Granulite-Eclogite
Transition

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ABSTRACT: Recent experimental data presented by Ito and Kennedy on the mineralogical variations in the gabbro to eclogite transformation are shown to be consistent with earlier experiments on a variety of basaltic compositions. The new results support for a specific composition, two of the major conclusions of our previous work:

1. The gabbro to eclogite transformation takes place through a rather broad transition interval in which assemblages appropriate to high pressure granulite assemblages are formed.

2. The slope of the gabbro to eclogite transition interval is such that eclogite is the stable mineralogy for dry basaltic rocks along normal geothermal gradients in the continental crust (stable or shield regions).

Introduction

The crystallization of a variety of basaltic rocks at sub-solidus conditions at temperatures of $1100^{\circ}C$ to $1250^{\circ}C$ and at pressure up to 40kb was reported by Ringwood and Green (1964, 1966), Green and Ringwood (1967a), T.H. Green (1967). Similar experiments on a rhyodacite composition (Green and Lambert, 1965) and on andesite and gabbroic anorthosite compositions (T.H. Green, 1970) have also been published. These experiments established a general pattern of mineralogical variation with increasing pressure from low pressure pyroxene + plagioclase ± olivine assemblages through pyroxene + plagioclase + garnet ± quartz assemblages to plagioclase-free assemblages dominated by garnet + clinopyroxene. It was shown that the width of the mineralogical transition zone is strongly controlled by the chemical composition of the rock, parameters of importance including the degree of silica saturation, the $\frac{Ab}{Ab+An}$ ratio of the plagioclase and the $\frac{Mg}{Mg+Fe^{++}}$ ratio of the rock.

Cohen, Ito and Kennedy (1967) published data on the mineralogy of an olivine tholeiite (NM5) at pressures up to 40kb and at temperatures thought to be sub-solidus. Their results gave a much narrower pressure interval for the pyroxene + garnet + plagioclase field (garnet granulite) than predicted for the NM5 composition from a comparison with the spectrum of compositions studied in the Canberra laboratory. Ito and Kennedy (1968, p.179) contrasted their narrow pressure interval for the gabbro-eclogite transition with the broader interval in the Canberra results and noted(p.179) "It seems barely possible that the continental Mohorovicic discontinuity can be a phase change if the transition takes place over an interval of

4kb but it seems quite impossible if the transition takes place over
an interval of 9kb". Subsequently, Ito and Kennedy (1970, 1971)
have re-investigated the sub-solidus mineralogy of NM5 at high pres-
sures and obtained results differing drastically from their previous
data. The pressure interval between appearance of garnet and dis-
appearance of plagioclase is now reported as ∼17kb on the solidus
or ∼15kb at $1100^{o}C$. In presentation of their more recent data,
Ito and Kennedy (1971) also state that their new data are "remarkably
in contrast to those published by Green and Ringwood (1967a)". The
authors do not detail where the supposed conflict in experimental
data occurs but make the unjustified inference that the problem of
melting which in part invalidated their own earlier results also
invalidates the Ringwood and Green (1966), Green and Ringwood (1967)
and Green (1967, 1970) work. Ito and Kennedy therefore state that
our conclusions on eclogite stability in the crust and upper mantle
cannot be justified. It will be shown in the following discussion
that the latest Ito and Kennedy work is in excellent agreement with
our earlier work and conclusions, and, indeed, adds little informa-
tion not already demonstrated in that work. Furthermore, the
conclusions of Ito and Kennedy (1971) on the role of garnet granu-
lite and eclogite in orogenic regions where the M-discontinuity
cannot be clearly identified, closely follow those of our 1966 paper.
In contrast to their 1967 paper, Ito and Kennedy (1970) abandoned
the gabbro-eclogite transformation as the explanation for the
existence of the continental shield M-discontinuity, requiring this
to be caused by a chemical change from 'granitic crust' to eclogitic
'upper mantle'. In oceanic regions, Ito and Kennedy assert that

the M-discontinuity can be caused by the gabbro to eclogite trans-
formation and thus regard eclogite as the major rock type of the
upper mantle. It can be shown that their own experimental data,
confirming our previous experiments, do not support these conclusions.

Experimental Determination of the Solidus in Basaltic Compositions

In Figure 1, we compare the solidus for NM5 as determined
by Ito and Kennedy (1971) with that of Cohen, Ito and Kennedy
(1967), and Ito and Kennedy (1970). The drastic lowering of the
solidus in the latest results is due to their recognition that the
absence of quartz in the eclogite field is due to melting and not
to SiO_2 solid solution in the omphacitic pyroxene (Cohen et al.,
1967, p. 509-510). It can be seen from Fig. 1 that the solidus of
NM5 is now almost identical with that deduced by Green and Ringwood
(1966, 1967a) for their quartz tholeiite. Since in both NM5 and
the quartz tholeiite compositions the solidus at high pressure is
for mineral assemblages with pyroxene (omphacitic) + garnet ±
plagioclase (sodic) + quartz, a close similarity is predictable and
the new data removes the anomaly present in the earlier Cohen et al.
(1967) and Ito and Kennedy (1970) results. However, Ito and Kennedy
(1971), while recognizing the mineralogical similarity between
eclogitic assemblages in NM5 and the quartz tholeiite compositions,
do not compare the near-identical solidi illustrated in Fig. 1. The
solidus for an olivine tholeiite composition (20% normative olivine)
is plotted in Fig. 1 also and differs considerably from the quartz
eclogite solidi (Green and Ringwood, 1967b). This olivine tholeiite
theoretically contains a small amount of olivine in eclogite

mineralogy if TiO_2 is calculated as rutile or a small amount of quartz if TiO_2 is calculated as ilmenite - thus the real high pressure assemblage is predicted to be garnet + pyroxene + very minor ilmenite + very minor rutile. The higher solidus temperature of this olivine tholeiite (quartz-free eclogite) does not conflict with the data from the quartz tholeiites and indeed provides support for the concept that the garnet + pyroxene join acts as a thermal divide between lower temperature solidi in either olivine eclogite or quartz eclogite compositions (O'Hara, 1963). Confirmatory evidence for the difference in slope between solidi of quartz-free eclogite and quartz eclogite may be found in Irving and Green, (1970). It should be noted, however, that the solidi of all quartz eclogites or of all quartz-free eclogites, will not be identical but will depend on Fe/Mg ratio of the pyroxene and garnet, on jadeite + acmite solid solution in the clinopyroxene and on the presence or absence of minor phases such as kyanite, apatite, K-feldspar, etc. The experimental problem of detecting small amounts of melting may also prevent detection of small differences in solidus temperatures.

Width of the Gabbro to Eclogite Transition Interval

The NM5 composition at low pressures has an olivine gabbro mineralogy (olivine + pyroxene + plagioclase) but at higher pressure passes through a transitional garnet granulite assemblage (garnet + pyroxenes + plagioclase ± quartz) to an eclogite assemblage (garnet + pyroxene (omphacite) + quartz). In Fig. 1, the

width of the garnet granulite transition interval as redetermined
by Ito and Kennedy (1971) is compared with that of quartz tholeiite
B of Green and Ringwood (1967a).   Fig. 2 illustrates a comparison
of the width at $1100^{o}C$ of the garnet granulite transition interval
of NM5 with those determined for a variety of basaltic and more
siliceous compositions in the Canberra laboratory.   In Table 2,
we have listed some of the chemical parameters important in deter-
mining reactions in the gabbro to eclogite transition for a variety
of basalts studied experimentally.   Comparison of simple oxide
contents or of CIPW norms of the compositions can be made by
reference to the original papers and to Table 1.

The incoming of garnet in NM5 composition results from
the olivine + plagioclase reaction.   The pressure (Fig. 2) required
for the first appearance of garnet in NM5 at $1100^{o}C$ is 10.5 kb
which is lower than that for garnet appearance in the high-alumina
basalt (12 ± 0.5kb) but marginally higher than that in the alkali-
poor olivine tholeiite.   The differences are caused by the lower
$\frac{Mg}{Mg+Fe^{++}}$ ratio of NM5 compared to the high alumina basalt (Green
and Ringwood, 1967a , p.787, Green and Hibberson, 1970) and the
higher anorthite content of the plagioclase of the alkali-poor
olivine tholeiite (An_{83} compared with An_{56} (NM5) and An_{57} (high alu-
mina basalt)) (Green and Hibberson, 1970).   The data on appearance
of the garnet in NM5 are thus in excellent agreement with the
previous Canberra data on olivine tholeiite compositions.   The
appearance of garnet in hypersthene + quartz normative (low pressure)
compositions occurs at higher pressures and reflects the higher
pressure required for the hypersthene + plagioclase reaction to
yield garnet + quartz (cf. Kushiro and Yoder, 1964).

The disappearance of plagioclase in basaltic compositions involves elimination of the albite component by solid solution as jadeite in the clinopyroxene and elimination of anorthite component either by reaction with olivine or enstatite, or (in rocks with high $\frac{An}{Ol+Hy/2}$ ratios) by anorthite breakdown to yield higher grossular solid solution in garnet + kyanite + quartz. In Table 2, the compositions of pyroxene and garnet in the various basalts, at pressures sufficient to eliminate plagioclase, are tabulated and the mineralogical character of the final eclogite assemblage is noted. The molecular ratio $\frac{An+Ab}{Di+Ol+Hy/2+Mt+Ilm}$ also is significant as the lower this ratio (for value <1) the lower the pressure required for disappearance of plagioclase. It is to be noted that unlike the high alumina basalt (modelled on the average oceanic tholeiite of Engel et al. 1965, see Table 1) or the andesite composition, the basalt NM5 does not yield quartz + kyanite eclogite. In this composition, the high anorthite content is compensated by the high olivine + hypersthene content. The disappearance of plagioclase in NM5 composition is thus determined by the $pyroxene_1$ + plagioclase → $pyroxene_2$ + quartz reaction where $pyroxene_2$ has higher jadeite content than $pyroxene_1$. From Table 1, it can be seen that the jadeite content of the eclogitic pyroxene decreases in the sequence NM5, quartz tholeiite B, quartz tholeiite A to alkali-poor olivine tholeiite. The pressure required for plagioclase disappearance decreases consistently in the same sequence.

The fact that the Ito and Kennedy (1971) data closely confirm the previous data of Green and Ringwood (1967a) on quartz tholeiite B can be demonstrated in another way. Ito and Kennedy

(1971) note that above 20kb at $1100^{o}C$ the pyroxene in their composition is omphacitic and although minor plagioclase is present, the mineral assemblage is called plagioclase eclogite. This usage of the terms eclogite and plagioclase eclogite is in agreement with the discussion in Green and Ringwood (1967a, pp. 811-812). In their Fig. 4, Ito and Kennedy (1971) give the density difference for NM5 mineralogy between the lower pressure boundaries of the eclogite field and the plagioclase eclogite field as 3.45 - 3.36 = 0.09 gm/cc. Their actual measurments at $1200^{o}C$ give 3.44 - 3.33 = 0.11 gm/cc. If we take 0.10 gm/cc as the difference in density between the eclogite and plagioclase eclogite (20kb, $1100^{o}C$) mineralogies, then we may calculate, from the nature of the reactions eliminating plagioclase, that the plagioclase eclogite at 20kb, $1100^{o}C$ contains 9.3% plagioclase (assuming composition An_{17}). The chemical composition of the <u>eclogite component</u> of NM5 at 20.5kb, $1100^{o}C$, i.e. after removal of the 9.3% plagioclase, is given in Table 1. The pyroxene in the plagioclase eclogite at 20.5kb, $1100^{o}C$ is calculated as $Jd_{41}Di_{59}$ which is almost identical in $\frac{Jd}{Jd+Di}$ ratio to that of quartz tholeiite B($\frac{Jd}{Jd+Di}$ = 43) although quartz tholeiite B also contains 19% acmite solid solution. It is apparent from the chemical parameters in Table 2 that the disappearance of plagioclase in quartz tholeiite B which we determined at 20 ± 1kb at $1100^{o}C$ is entirely consistent with Ito and Kennedy's data producing a quartz + plagioclase eclogite from NM5 composition at 20.5kb, $1100^{o}C$ in which the pyroxene is $Jd_{41}Di_{59}$ and the garnet has 21 mol% grossular.

'Fine Structure' of the Gabbro to Eclogite Transformation

Green (1967) published a density vs pressure curve for experimental runs on an alkali basalt composition. The garnet granulite transitional mineralogy correlated with a more rapid rate of density increase in the 10-20kb pressure interval. Ito and Kennedy (1970) published similar data through which they drew a curve with two regions of very rapid increase in density which they correlated with the incoming of garnet and outgoing of plagioclase, respectively. Ito and Kennedy (1971) showed that their previous data were obtained on runs quenched from above the solidus and gave a revised and slightly 'smoothed' curve for densities determined at 1200°C but continued to maintain that their data justified recognition of two sharp density increases. Their experimental data are shown in Fig. 3, with symbol size indicating uncertainty of $\pm$ .01 gm/cc in ρ for the determination - this estimate is conservative. We contend that there is no experimental justification for the stepped density vs pressure curve drawn by Ito and Kennedy although we agree that the slope of the density vs pressure curve for this composition is probably slightly steeper in the 11-16kb pressure interval (where the olivine + hypersthene + plagioclase → garnet + quartz reaction is of major importance) than in the 16-25kb interval (where the reaction is dominantly pyroxene$_1$ + plagioclase → pyroxene$_2$ + quartz). The NM5 composition, with exceptionally low normative diopside and high anorthite and olivine + hypersthene contents (Table 1), is one in which the reaction forming garnet at the expense of anorthite is accentuated and the low diopside content inhibits the rate of take-up of jadeite

solid solution.   Ringwood and Green (1966) and Green and Ringwood
(1967) had previously called attention to the effect of chemical
composition in determining the relative importance of component
reactions in the gabbro-eclogite transformation.   It must also be
stated that theoretical consideration of these component reactions,
all involving solid solutions with end members having very different
stability fields, shows that the incoming of garnet or disappearance
of plagioclase must occur gradually over a P,T interval with com-
positions of solid solutions changing until one of the phases
involved in the reaction disappears.   The failure of Ito and
Kennedy to observe change in the $\frac{Mg}{Mg+Fe}$ ratio of garnet through the
garnet granulite stability field is inconsistent with theoretical
analysis of the reactions involved or with the published garnet
compositions of Green and Ringwood (1967a), T.H. Green (1967)
and may be due to problems in iron contamination of their charge.
Although Ito and Kennedy (1971), quoting Banno (1970), argue that
pressure effect on the Fe-Mg distribution coefficient between
garnet and pyroxene may cause garnet to become more Fe-rich with
increasing pressure, this effect is minor (Banno, 1970).   Further-
more, this effect is irrelevant to the reaction being considered,
which is the production of garnet (± clinopyroxene, ± quartz) at
the expense of olivine, orthopyroxene and plagioclase and is not
simply an exchange reaction between garnet and clinopyroxene
solid solutions. Ito and Kennedy (1970 and 1971) attach consider-
able geophysical significance to the presence of 'steps' in the
density vs pressure curve correlating these with seismic velocity
'discontinuities' in the deep crust or crust-mantle boundary.   In

attempting this application of their data, Ito and Kennedy argue

for a major significance for the results of NM5 composition on the

basis of similarity of NM5 composition to the average composition

of oceanic tholeiites (Table 1, Table 2).   However, the compari-

sons of Table 1 and Table 2 demonstrate important differences in

both chemical composition and eclogite mineralogy between NM5

and average oceanic tholeiite.   In addition, more recent data on

deep-sea basalts shows very clearly that there is large variation

in chemical composition between individual samples.   Thus, even if

it could be convincingly demonstrated that there are sharp minera-

logical boundaries for a specific basalt composition, these

'discontinuities' would be diffuse or smeared out if present in a

sequence of chemically diverse individual lava flows or intrusions.

Extrapolation of Phase Boundaries to Low Temperature.

Ito and Kennedy (1971) state "Our results on the stabi-

lity field of eclogite are remarkably in contrast to those published

by Green and Ringwood (1967a)".   This statement is untrue.   In

Figs. 1 and 2 and the preceding sections, we have shown that the

experimental results obtained at $1100^{o}C$ and on the solidus by Ito

and Kennedy are in excellent agreement with our own experimental

data.   In Fig. 4, we compare the extrapolation to lower tempera-

tures which we have previously made with that now advocated by Ito

and Kennedy (1971).   The latter authors note the difference in

slope of our line of best fit (27.5 bars/^{o}C between $1000^{o}C$ and

$1250^{o}C$) for the outgoing of plagioclase in quartz tholeiite B

composition, relative to their chosen line of best fit (20 bars/^{o}C

between $800^{\circ}C$ and $1200^{\circ}C$) for NM5 composition. However, we recog-
nized the limitations of our data in defining accurate slopes for
the phase boundaries and application of our estimates of precision
in P,T measurement would allow slopes of 18-36 bars/$^{\circ}C$ between
$1000^{\circ}C$ and $1250^{\circ}C$ for the boundary marking the outgoing of plagio-
clase.   Thus we did <u>not</u> take 27.5 bars/$^{\circ}C$ as the slope of the
plagioclase-out boundary and in fact devoted considerable discussion
(Ringwood and Green 1966, p.399-402) to the extrapolation of our
experimental boundaries to lower temperatures.   We noted that
both the incoming of garnet and outgoing of plagioclase are complex
reactions involving solid solutions of plagioclase, pyroxenes,
olivine and garnet.   The net result of this discussion was the
extrapolation of the plagioclase-out boundary at 24 bars/$^{\circ}C$ -
this is illustrated in figs. 1 and 4.   Ito and Kennedy (1971)
argue that the slope for the simple system reaction albite $\rightarrow$
jadeite + quartz is now well determined at 20 bars/$^{\circ}C$ and that
this slope is consistent with their data on the outgoing of plagio-
clase in NM5.   Accordingly, the outgoing of plagioclase boundary
for NM5 is extrapolated at 20 bars/$^{\circ}C$ in Fig. 4.   Ito and Kennedy's
argument, that where the outoing of plagioclase is due to the
pyroxene$_1$ + plagioclase $\rightarrow$ pyroxene$_2$ + quartz reaction, then the
20 bar/$^{\circ}C$ slope should be applied, is only an approximation.   Thus
the plagioclase present is not pure albite and its disappearance
involves coupled reactions.   The anorthite component either
reacts with enstatite solid solution in the clinopyroxene to yield
garnet + quartz or alternatively breaks down to yield grossular
solid solution + kyanite + quartz (as in the compositions studied
by Green, 1967; see also Table 2).

The approximation suggested by Ito and Kennedy for extrapolation of the gabbro to eclogite boundaries has been applied in figure 4 as it is based on at least as good arguments as the 24 bars/^{o}C slope used in our earlier work. Thus the garnet-granulite → plagioclase eclogite boundary for NM5, which is equivalent to the disappearance of plagioclase in the rock composition of Table 1, column 2, has been extrapolated and intersects the temperature axis at 100°C. Extrapolation of the plagioclase-out boundary for quartz tholeiite B (2 in Fig. 4) at 20 bars/^{o}C would give an identical lower boundary to the eclogite field. A similar exercise could be carried out for plagioclase disappearance in compositions 1-10 (Fig. 2, Fig.4). It is seen from Fig. 4 that the temperature on the garnet granulite to eclogite boundary at a pressure corresponding to the base of the normal continental crust (10kb) is 600°C if the extrapolation at 20 bars/^{o}C from Ito and Kennedy's experimental data is followed* (compared to 670° from the Ringwood and Green (1966) extrapolation). If the temperature at the base of the stable continental crust is <600°C, then eclogite would be the stable mineralogy of quartz tholeiite B composition throughout the continental crust. Similarly, quartz + plagioclase eclogite or quartz eclogite (± kyanite) would be the stable form of NM5 basalt, the high alumina basalt (1) or andesite (9) throughout the continental crust. The discussion and argument of Ringwood

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* The temperature for the garnet granulite to plagioclase eclogite boundary is 530°C at 10kb if the 18 bars/^{o}C slope of Ito and Kennedy (1971, Fig. 4) is used. However, this slope is arbitrary whereas Ito and Kennedy have presented a reasoned argument for the 20 bars/^{o}C slope. If this reasoned argument is not accepted then the only relevant experimental data are those on quartz tholeiite B (Green and Ringwood, 1967) i.e. 27±9 bars/^{o}C.

and Green (1966, p.398-423) will apply to the gabbro-garnet granulite-eclogite transformation and its geophysical significance whether the Ito and Kennedy 20 bars/^{O}C or the Green and Ringwood 24 bars/^{O}C slopes are used for extrapolation. This particularly applies to the argument that since the geothermal gradient and garnet granulite boundary are subparallel in the 0-10kb interval, no large mineralogical change (without chemical change) can occur over a small depth interval along the geothermal gradient. It may be noted that the boundary advocated by Ito and Kennedy (1971) for the upper pressure limit of the gabbro field is identical to that shown by Green and Ringwood 1967a, Fig. 8 for the upper pressure limit of their low pressure granulite field, i.e. the reaction of olivine + plagioclase to yield garnet or spinel + pyroxenes (see Fig. 4).

Conclusions

The recent experimental studies by Ito and Kennedy (1971) provide improved data on the position of phase boundaries of the gabbro, garnet granulite and eclogite assemblages for a specific olivine tholeiite composition. Ito and Kennedy's conclusion that their new data are inconsistent with earlier data obtained in our own laboratory is shown to be incorrect and apparently based on an inadequate understanding of the role of chemical differences between the various basalts. We have shown that the curves for the solidus, the incoming of garnet, and the out-going of plagioclase determined by Ito and Kennedy (1971) are consistent, within experimental uncertainty, in both position

and slope with boundaries determined in our laboratory on relevant basaltic compositions.   Ito and Kennedy (1970, 1971) have failed to unequivocally demonstrate their assertion that there are two 'sharp' increases in density within the gabbro to eclogite transition marking the appearance of garnet and rapid decrease in plagioclase, respectively.   Thus we consider that Ito and Kennedy's attempt to relate these 'sharp' density increases to 'Conrad' and Mohorovicic Discontinuities is without foundation, even for the specific basalt composition which they studied.

The experimental work by Ito and Kennedy confirms, for their olivine tholeiite composition, two of the major conclusions from our earlier studies:

1. The transition between gabbroic and eclogitic mineral assemblages occupies a broad pressure interval between the incoming of garnet and disappearance of plagioclase.   The positions of the boundaries and the width of the field for the transitional garnet granulite mineral assemblage are sensitive to variations in the chemical compositions of basalts.

2. The extrapolation of experimentally determined boundaries to lower temperatures suggests that eclogite mineralogy is stable in dry basaltic rocks along normal geothermal gradients throughout the continental crust in stable or shield regions.   This aspect of the experimental study has been treated fully previously (Ringwood and Green 1966, Green and Ringwood 1967a).

These two conclusions, using arguments developed previously (Ringwood and Green, 1966), effectively eliminate the gabbro-eclogite transition as an explanation for the existence of the M-discontinuity in oceanic or stable continental crustal environments and render it highly improbable that eclogite is the major constituent rock type of the upper mantle.

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TABLE 1

Comparison of chemical compositions of basalt composition (NM5)
used by Ito and Kennedy (1970, 1971) with the quartz tholeiite
B and high alumina basalt compositions studied in the Canberra
laboratory. Attention is directed to the exceptionally low
normative diopside content of NM5 and the high normative
olivine content - in these respects this composition is very
unlike the average oceanic tholeiite of Engel et al. (1965).
The calculated composition of the 'eclogite component' (garnet
+ pyroxene + quartz) of NM5 at 20.5kb, 1100°C is also listed
for comparison

	NM5	NM5-9.3% plagioclase (An$_{17}$) Ito and Kennedy (1971)	Quartz Tholeiite B Green and Ringwood (1967a)	High Alumina Basalt T.H.Green (1967)	Average Oceanic Tholeiite Engel et al. (1965)
SiO_2	49.93	48.47	52.16	50.3	49.94
TiO_2	1.34	1.48	1.86	1.7	1.51
Al_2O_3	16.75	16.17	14.60	17.0	16.69
Fe_2O_3	-	-	2.46	1.5	2.01
FeO	11.40	12.60	8.39	7.6	6.90
MnO	0.18	.20	0.14	0.16	-
MgO	7.59	8.36	7.36	7.8	7.28
CaO	9.33	9.91	9.44	11.4	11.86
Na_2O	2.92	2.20	2.68	2.8	2.76
K_2O	0.37	0.41	0.73	0.18	0.16
P_2O_5	0.19	0.21	0.18	-	0.16
CIPW norms:					
Qz	-	-	2.5	-	-
Or	2.2	2.2	4.8	1.1	1.1
Ab	24.6	18.4	22.1	23.7	23.6
An	31.4	33.3	25.5	33.3	32.5
Di	11.5	12.3	17.1	18.9	20.8
Hy	13.2	15.4	20.6	11.9	11.6
Ol	14.1	15.1	-	6.2	4.0
Ilm	2.6	2.9	3.6	3.2	2.9
Ap	0.4	0.4	0.4	-	0.3
Mt	-	-	3.6	2.2	2.9

TABLE 2.

Comparison of compositions of basalts studied by
Green and Ringwood (1966, 1967) with that of NM5
(Ito and Kennedy, 1967, 1971), with eclogite
component of NM5 at 20.5kb, 1100°C and with
average oceanic tholeiite.

	Andesite T.H.Green, 1970	NM5 Ito & Kennedy 1971	Average Oceanic Tholeiite (Calculated)
Composition of eclogitic pyroxene	$Jd_{77}Di_{23}$	$Jd_{52.5}Di_{47.5}$	$Jd_{23}Ac_{10}Di_{65}$
Grossular content of eclogite garnet*1	Gr_{40}*	Gr_{23}*1	Gr_{28}*
Molecular ratio:			
$\dfrac{An + Ab}{Di+Ol+Hy/2+Ilm+Mt}$	1.95	1.00	1.03
(wt.%) Normative olivine or quartz	- 9	14 -	4.0 -
$\dfrac{100Mg}{Mg+Fe^{++}}$	49	53	65
Basalt type	(Andesite)	Olivine tholeiite	Olivine tholeiite
Eclogite type	Qz + Ky	Qz	Qz + Ky
Pressure (kb) for plagioclase disappearance at 1100°C	26±1	26	
Pressure (kb) for garnet appearance at 1100°C	13.5±1	10.5	

* Calculated   1 Measured

High Alumina Basalt (T.H. Green, 1967, Ringwood & Green, 1966)	Quartz Tholeiite B (Green and Ringwood, 1967a)	NM5-9.3% Plagioclase (Eclogite component of plagioclase eclogite)	Quartz Tholeiite A (Green and Ringwood, 1967a)	Alkali-poor olivine tholeiite (Green & Ringwood 1967a)
$Jd_{31}Ac_8Di_{61}$	$Jd_{35}Ac_{19}Di_{46}$	$Jd_{41}Di_{59}$	$Jd_{17}Ac_{25}Di_{58}$	$Jd_{11}Ac_3Di_{86}$
Gr_{28}*1	Gr_{28}*1	Gr_{21}*	Gr_{28}*	Gr_{19}1
1.01	0.85	0.83	0.70	0.53
6	- 2.5	15.1 -	- 3	23 -
65	61	53	61	66
Olivine tholeiite	Quartz tholeiite	Olivine tholeiite	Quartz tholeiite	Olivine tholeiite
Qz + Ky	Qz	Qz	Qz	No Qz or Ky
23.5±1	20±1	20.5	18±1	13±5
12±0.5	14±0.5	10.5	14±0.5	9.5±5

FIGURE CAPTIONS

Fig. 1. Comparison of experimentally determined solidi and
subsolidus boundaries. Dashed lines refer to the/solidus
^{sub}
garnet appearance and plagioclase disappearance of Ito
and Kennedy (1971) and the previous data for the same
olivine tholeiite by Cohen, Ito and Kennedy (1967). The
short lines marked by question marks are the approximate
boundaries for garnet appearance and plagioclase disap-
pearance as determined in 1967.   The solid lines marked
'Qz tholeiite' refer to the experimentally determined
boundaries of Green and Ringwood 1967.   The dotted lines
for plagioclase disappearance and garnet appearance
illustrate the slopes for those boundaries actually used
for extrapolation to lower temperatures - these lie well
within experimental error in relation to the solid lines
which were drawn from the experimental points. The line
marked olivine tholeiite is the solidus for a composition
yielding quartz-freee eclogite (garnet + clinopyroxene +
rutile + ilmenite) and contrasts with the solidi for the
two quartz eclogite compositions.

Fig. 2. Diagram illustrating the effect of chemical composition
on the pressure required for the incoming of garnet
(lower boundary) and the outgoing of plagioclase (upper
boundary). All data are at $1100^\circ C$; compositions 1-6 are
from Ringwood and Green (1966); 7,8,9,10 are compositions
from the references shown.

Figure Captions (contd.)

Fig. 3.   A replot of Ito and Kennedy's (1971) data (fig. 3) on
density of experimental charges at $1200^{\circ}C$ and various
pressures.   The data points are shown with a size
representing an uncertainty of ± .01 in density. Possible
errors are due to measurement using very small samples, and
the estimated porosity (Ito and Kennedy, 1971) and unknown
permeability of the samples. Additional errors may have
resulted from the necessity to grind off the outer iron-
enriched layers of the sample (Ito and Kennedy, 1970) and
from partial melting (the solidus lies below $1200^{\circ}C$ at
<15kb). The maximum observed difference between nominally
identical runs ($1200^{\circ}C$ ∿12kb)is also illustrated.

Fig. 4.   Comparison of extrapolation to lower temperatures of
phase boundaries between eclogite, garnet granulite and
gabbroic mineral assemblages as advocated by Ringwood
and Green (1966), Green and Ringwood (1967a) (dashed
lines and vertically and horizontally shaded fields labelled
G. & R.) with the extrapolations advocated by Ito and
Kennedy (1971) (stippled fields, lines labelled I. & K.).
The numbered crosses at $1100^{\circ}C$ mark the disappearance of
plagioclase in the compositions 1-10 of fig. 2. According
to the arguments of Ito and Kennedy (1971) lines at 20
bars/$^{\circ}C$ could be drawn through each of these points to
extrapolate the disappearance of plagioclase to lower

temperatures - such a line for quartz tholeiite B

composition (2) would be coincident with the garnet

granulite → plagioclase eclogite boundary of Ito and

Kennedy (1971) (or garnet granulite → eclogite boundary

for composition of column 2, Table 1) <u>if these are also</u>

<u>extrapolated at 20 bars/^{o}C.</u>   The light dashed line

labelled I & K is the line taken from Ito and Kennedy's

own fig. 4 marking the low pressure boundary of their

plagioclase eclogite field.   Ito and Kennedy (1971)

drew this line at 18 bars/^{o}C without justifying this by

either experiment or argument.   If indeed it is argued

that this boundary is more complex than the plagioclase-

out boundary for NM5 and thus Ito and Kennedy's arguments

for a 20 bar/^{o}C slope are not acceptable, then it must

be admitted that the only evidence on the slope of this

boundary is that it lies within the experimental limits

of our quartz tholeiite B data, i.e. between 18 and 36

bars/^{o}C.