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THE INSTABILITY OF PLAGIOCLASE IN PERIDOTITE AT HIGH PRESSURE

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Experimental crystallization of forsterite + anorthite (2.2: 1 molar ratio) in a piston-cylinder solid-media apparatus shows that forsterite and anorthite are stable at less than 8.5 ± 0.5 kb at 1250°C, but forsterite + orthopyroxene + clinopyroxene + spinel is the stable assemblage at higher pressures. The fayalite + anorthite assemblage is stable to 7-7.5 kb at 1050°C and to 6-6.5 kb at 900°C, and at higher pressure is replaced by almandine-grossular garnet. Reactions between magnesian olivine (Fo₉₂) and labradorite (An₅₀), and between olivine and plagioclase in a complex peridotite composition (pyrolite), show that there is a 5-phase field of olivine + orthopyroxene + clinopyroxene + plagioclase + aluminous spinel between 9 kb and 11-14 kb (depending on composition) at 1200°C. At higher pressures plagioclase is absent and at lower pressures pyroxenes are absent or present in smaller amounts, and alumina-rich spinel is absent. The experimental data are applied in discussions of corona formation and of the stability of plagioclase in peridotite compositions.

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Introduction

Olivine and plagioclase are in reaction relationship at high pressure and are replaced by assemblages including garnet or pyroxenes + spinel. These reactions are well illustrated by corona textures in troctolitic and anorthositic rocks, and experimental studies of olivine and plagioclase reactions are desirable for interpretation of such coronas. Kushiro & Yoder (1966) have studied reactions between the end members forsterite and anorthite, but there is uncertainty in applying these data to the natural rocks, in which olivines are more iron-rich; the plagioclase (even in very magnesian peridotites) is usually labradorite or bytownite. Reactions between the olivine and plagioclase in complex basaltic compositions have been studied by Green & Ringwood (1967a), T. H. Green (1967), Ito & Kennedy (1968), Irving & Green (1969), and in a nephelinitic composition by Bultitude (1968). These studies show that the reactions between olivine and plagioclase cannot be considered independently of the presence of other phases, notably clinopyroxene and nepheline, and that the conditions of reaction and the nature of the products are sensitive to bulk composition. The reactions in basaltic compositions eliminate olivine from the low pressure assemblages and plagioclase persists to higher pressures in assemblages with pyroxenes + spinel or garnet. In peridotite compositions, however, olivine will persist at high pressure and plagioclase disappear. A knowledge of the pressure

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required for elimination of plagioclase, particularly near the peridotite solidus, is most important for the hypothesis of partial melting in the upper mantle and variations in upper mantle mineralogy. The present investigation began as an attempt to ascertain the limits of stability of plagioclase in 'pyrolite' composition, i.e. a complex peridotite composition suggested as the mean composition of the upper mantle (Ringwood 1962, 1966a, b; Green & Ringwood 1963). The simple systems forsterite (Fo_{100}) + anorthite, fayalite (Fo_0) + anorthite, and olivine (Fo_{90}) + labradorite (An_{59}) were studied to throw further light on the complex reactions in the pyrolite composition.

Experimental methods

Experiments were carried out in a solid-media apparatus similar to that described previously (Boyd & England, 1960; Green & Ringwood, 1967a). Sample capsules were of either platinum or graphite, the former having the advantage that sealing by welding can exclude water, but the disadvantage that some iron may be lost from the sample due to solid solution in the platinum. For this reason, runs on the fayalite + anorthite mix were carried out in graphite capsules. In runs in graphite capsules, water vapour from dehydration of the talc pressure medium cannot be entirely excluded and may result in lowering of solidus temperatures, particularly in long runs. No reduction of fayalite to metallic iron was observed in any of the runs: any such reduction would be also accompanied by appearance of pyroxene in the fayalite + anorthite mix.

Reactants and products were identified by optical examination and X-ray powder diffraction. Experimental difficulty was experienced in the simple $\text{Fo} + \text{An}$ and $\text{Fa} + \text{An}$ systems in the sluggish nucleation and growth of phases and in the metastable persistence of low pressure phases. Runs were thus seeded with 10–15% of the synthesized high pressure assemblage containing garnet or spinel + pyroxene. Experiments close to the reaction boundaries required identification of rather small degrees of growth or corrosion of the seed phases. Runs were not seeded with the low pressure assemblages in all cases, since it was shown that olivine and plagioclase nucleated rapidly from the glass within the first few minutes at pressures near their stability limits.

Equations (1), (3) and (9) on the following pages illustrate the expected reactions, and to ensure the presence of an excess of olivine in all high pressure assemblages, the olivine: anorthite mixtures were prepared in the molecular ratio 2.2 : 1, i.e. 10% excess olivine over that required for equation 1 with $x = 0$. Similarly, olivine is present in excess (in relation to equation (9)) in the olivine + labradorite mix (olivine (Fo_{90}) : labradorite (An_{50}) = 1.8 : 1 mol.ratio) and in the pyrolite mix (Table 1).

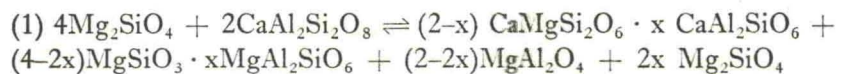
The fayalite and anorthite used in the experiments were pure synthetic phases (from Tem-Pres. Inc.); forsterite was synthesized at high tempera-

ture, olivine (Fo₉₀) and labradorite (An₅₉) were natural analyzed minerals, and the pyrolite mixture was prepared from reacted oxides. As with previously reported experiments on the pyrolite composition, the masking of minor phases by abundant olivine was avoided by using a composition (Table 1) equivalent to 'pyrolite less 40% olivine (Fo_{91.6})' (Green & Ringwood 1967c, p. 152).

Experimental data

Forsterite + Anorthite

Using glass seeded with 10% of the higher pressure assemblage of orthopyroxene_{ss} + clinopyroxene_{ss} + spinel + olivine, the experiments yielded forsterite + anorthite assemblage at 8.1 kb at 1250°C, but yielded the orthopyroxene_{ss} + clinopyroxene_{ss} + forsterite assemblage at 9 kb, 1250°C. In the experiments in which no seed of the spinel + pyroxenes assemblage was added, the forsterite + anorthite assemblage persisted at 9 kb, 1250°C, and yielded pyroxenes + spinel at 9.9 kb, 1250°C. A similar result was obtained using unseeded glass at 1300°C. The data demonstrate the unsuitability of using unseeded glass or low pressure assemblages in runs up to 3 hrs at T = 1250°C to establish the boundary between olivine + anorthite and pyroxenes + spinel assemblages. This is important in evaluating the data of Kushiro & Yoder (1966), who used glass or finely crystalline Fo + An in their studies on the forsterite + anorthite join, and only used the seeding technique (5% Ga + Cpx ± Fo added to the Fo + An crystalline mix) in runs near the garnet boundary. The present study, using solid media apparatus with a -10% pressure correction applied (Green, Ringwood & Major 1966), gives a reversal across the reaction boundary between 8.1 kb and 9.0 kb at 1250°C, i.e. consistent with Kushiro and Yoder's boundary. The reaction may be written as follows (Kushiro & Yoder 1966):



If further experiments in gas apparatus could demonstrate the stability relations suggested by Kushiro and Yoder's synthesis runs, then comparison with the solid media apparatus data would confirm the validity of the (-10%) pressure correction for the solid media apparatus (1/2" piston) at or near 10 kb.

The boundary between An + Fo and Cpx + Opx + Sp ± An or Fo, as drawn by Kushiro & Yoder (1966, Figs. 1 & 2), has a steep slope (dT/dP), and it has been suggested by Kushiro & Yoder (1966, p. 347-8) that this may intersect the boundary for the incoming of garnet at lower temperatures (estimated near 6 kb and 700°C) leading to an invariant point in the Fo + An system at which six phases (Fo, An, Sp, Ga, Opx_{ss}, Cpx_{ss}) may coexist. MacGregor (1967) also illustrated (Fig. 12.2) such an invariant point. This has important implications for metamorphic petrology, but it

Table 1. Column 1: Model 'pyrolite'; Column 2: 'Pyrolite minus 40% olivine' used in experimental runs. Both compositions retain excess olivine in the high pressure assemblages

	1	2	C.I.P.W. Norm	1	2
SiO ₂	45.20	47.84	Or	0.8	1.3
TiO ₂	0.71	1.18	Ab	5.0	8.3
Al ₂ O ₃	3.54	5.90	An	6.6	11.0
Cr ₂ O ₃	0.43	0.72	Di	6.8	11.3
Fe ₂ O ₃	0.48	0.80	Hy	15.8	26.4
FeO	8.04	8.21	Oi	62.5	37.5
MnO	0.14	0.13	Ilm	1.3	2.2
NiO	0.20	0.18	Mt	0.7	1.1
MgO	37.48	28.73	Ap	0.6	1.0
CaO	3.08	5.14			
Na ₂ O	0.57	0.95			
K ₂ O	0.13	0.22			

should be pointed out that the experimental evidence for intersection of the two boundaries is subject to doubt. The persistence of Fo + An (1 : 1 mix) in a 2 hr run at 1200°C 8 kb was taken by Kushiro & Yoder 1966 (Fig. 1, Table 1) as indicating stability of that assemblage, but in the light of the present experiments showing the necessity of seeding with pyroxenes + spinel at 1250°C, 3 hr runs, the Fo + An may have been metastable. Other data on the Fo + An, (1 : 1 or 2 : 1) mixes, permit a much smaller slope (dT/dP). Similarly, in their studies on the appearance of garnet in the Fo + An (1 : 1 and 2 : 1) mixes, Kushiro & Yoder used (Fo + An) glass or (Fo + An) finely crystallized material and seeded some runs with 5% Ga + Cpx ± Fo. However, the (Fo + An) assemblage is metastable on the low pressure side of the reactions under study, i.e.:

- (2) $\text{Opx}_{\text{ss}} + \text{Cpx}_{\text{ss}} + \text{An} \rightleftharpoons \text{Garnet} \pm \text{Cpx}$ (1 : 1 mix)
 (3) $\text{Opx}_{\text{ss}} + \text{Cpx}_{\text{ss}} + \text{Fo} \rightleftharpoons \text{Garnet} + \text{Fo} \pm \text{Cpx}$ (2 : 1 mix)

Thus, the metastable growth of garnet seeds instead of $\text{Cpx}_{\text{ss}} + \text{Opx}_{\text{ss}} + \text{Sp}$ is possible. It should be noted that Kushiro & Yoder (1966, Figs. 1 & 2, Tables 1 & 2) obtained $\text{Opx}_{\text{ss}} + \text{Cpx}_{\text{ss}} + \text{Sp} + \text{Fo}$ from runs, seeded with garnet, at 1160°C, 14 kb, 4 hrs (1 : 1 mix) and from runs at 1175°C, 18 kb, 1½ hrs and 1225°C, 18½ kb, 1½ hrs (2 : 1 mix). These results were regarded as erroneous by the authors, but, if valid, they imply a steeper slope (dT/dP) for the boundaries marking the incoming of garnet.

Thus it is emphasized that neither the previous studies nor the present study are adequate to define dT/dP for the reaction between forsterite and anorthite to yield pyroxenes and spinel, nor of the latter assemblage to yield garnet ± olivine. Petrological application of the experimental data in the Fo + An system must recognize the experimental uncertainties and difficulty. The authors consider that at present there is no evidence either from natural highly magnesian peridotites nor from the experimental study, that reactions (1) and (3) intersect under geologically significant conditions.

Table 2. Results of experiments on the stability of plagioclase in olivine-rich compositions. Unless otherwise stated (see footnotes), the identification of olivine, pyroxenes, garnet and plagioclase is based on X-ray diffraction data. Spinel was readily identified optically and confirmed by X-ray data in most cases.

Abbreviations: Fo - forsterite, Fa - fayalite, Ol - olivine, Px - pyroxene, Sp - spinel, An - anorthite, Pl - plagioclase, Ga - garnet

Corrected pressure Kb	Temperature °C	Time Hrs.	Reactants	Products
FORSTERITE + ANORTHITE				
8.1	1250	4	Glass + 10% Seed (Px + Sp)	Fo + An
9.0	1250	4	" " " "	Fo + Px ¹ + Sp
9.0	1250	3	Glass + quench Fo	Fo + An
9.9	1250	3	Glass	Fo + Px ¹ + Sp
9.0	1300	1	Glass + quench Fo	Fo + An
9.9	1300	1	" " "	Fo + Px ¹ + Sp
9.9	1300	1	Glass	Fo + Px ¹ + Sp
FAYALITE + ANORTHITE (runs in graphite capsules)				
8.1	1100	6	Fa + An	Fa + An + glass
9.0	1100	6	" "	Fa + Ga + glass
8.1	1100	6	Glass	Fa + An + glass
9.0	1100	6	" "	Fa + Ga + glass
9.0	1100	1	" "	Fa + Ga + An + glass
7.2	1100	6	Glass + 10% Seed (Ga + Fa)	Hercynite + glass
7.2	1100	2	" " " "	Fa + Hercynite + glass
8.1	1100	6	" " " "	Fa + An + Ga + glass (glass appears local)
6.3	1050	3	" " " "	Fa + An No garnet
7.2	1050	3	" " " "	Fa + An + Ga Minor garnet
7.2	1050	24	" " " "	Fa + An + Ga Minor garnet. Coarser grained but similar in garnet content to 3 hr run
8.1	1050	3	" " " "	Fa + An + Ga Common garnet, minor anorthite
5.4	900	24	" " " "	Fa + An (+ Ga) Garnet rare and crystals corroded
6.3	900	24	" " " "	Fa + An + minor garnet
6.3	900	88	" " " "	Fa + An + trace garnet, less garnet than in 24 hr run
7.2	900	24	" " " "	Fa + Ga + An. Garnet common, minor anorthite
8.1	900	26	" " " "	Fa + Ga No pyroxene or anorthite

If equation 5 represents a stable equilibrium relation, then it is possible that the olivine + labradorite mix could yield assemblages of orthopyroxene + olivine + plagioclase + nepheline at intermediate pressures. However, Bultitude (1968) has demonstrated the instability of nepheline + plagioclase + pyroxene + olivine assemblages relative to plagioclase + spinel + pyroxene in complex olivine nephelinite at very low pressure — probably due to combination of reactions (7), (8).

olivine-rich compositions. Unless orthopyroxenes, garnet and plagioclase is optically and confirmed by X-ray data

orthopyroxene, Sp - spinel, An - anorthite,

Products

An
 Px¹ + Sp
 An
 Px¹ + Sp
 An
 Px¹ + Sp
 Px¹ + Sp

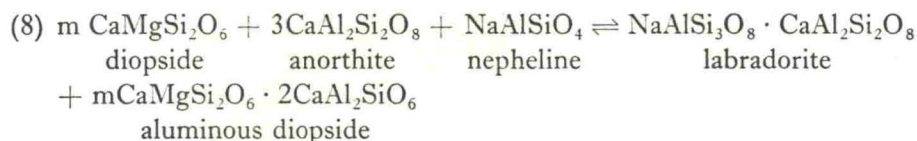
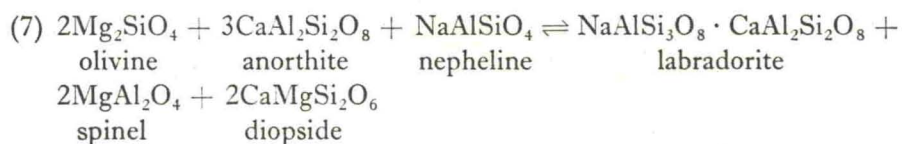
 An + glass
 Ga + glass
 An + glass
 Ga + glass
 Ga + An + glass
 Hercynite + glass
 An + Ga + glass
 appears local)
 An No garnet
 An + Ga Minor garnet
 An + Ga Minor garnet. Coarser
 garnet but similar in garnet content to
 run
 An + Ga Common garnet,
 minor anorthite
 An (+ Ga) Garnet rare and
 orthopyroxene corroded
 An + minor garnet
 An + trace garnet, less garnet
 in 24 hr run
 Ga + An. Garnet common,
 minor anorthite
 Ga No pyroxene or anorthite

Corrected pressure Kb	Temperature °C	Time Hrs.	Reactants	Products
OLIVINE (Fo ₉₂) + LABRADORITE (An ₅₉) (runs in platinum capsules)				
9.0	1100	4	Ol + Pl	Ol + Pl
11.2	1100	4	Ol + Pl	Ol + Pl + Px ¹ + Sp
4.5	1100	2	Glass	Ol + Pl
6.7	1100	4	"	Ol + Pl
9.0	1100	2	"	Ol + Pl
11.2	1100	3	"	Ol + Pl + Px ² + minor Sp
13.5	1100	4	"	Ol + Pl + Px ¹ + Sp Weak plagioclase reflections
9.0	1150	2	Ol + Pl	Ol + Pl
11.2	1200	1	Ol + Pl	Ol + Pl + minor Px ²
11.2	1200	2	Glass	Ol + Pl + Px ¹ + Sp Moderately strong plagioclase, weak orthopyroxene and spinel reflections.
11.2	1200	2	Ol + Px + Sp ⁴	Ol + Pl + Px ¹ + Sp Weak but definite plagioclase reflections
12.4	1200	2	Glass	Ol + Pl + Px ¹ + Sp Weak plagioclase reflections
13.5	1200	2	Glass	Ol + ? Pl ³ + Px ¹ + Sp
15.7	1200	1	Glass	Ol + Px ¹ + Sp
15.7	1200	4	Ol + Pl	Ol + Px ¹ + Sp
18.0	1200	4	Ol + Pl	Ol + Px ¹ + Sp + trace Ga
20.2	1200	4	Ol + Pl	Ol + Px ¹ + Ga Very weak orthopyroxene reflections
18.0	1300	1	Ol + Pl	Ol + Px ¹ + Sp
20.2	1300	1	Ol + Pl	Ol + Px ¹ + Sp + minor Ga Very weak orthopyroxene reflections
PYROLITE (runs in platinum capsules)				
2.2	1100	2	Ol + Px ² + Pl	Ol + Px ² + Pl + ? Sp
4.5	1100	4	Ol + Px ² + Pl	Ol + Px ¹ + Pl + Sp minor orthopyroxene and rare green-brown spinel
6.7	1100	2	Ol + Px ² + Pl	Ol + Px ¹ + Pl + Sp minor orthopyroxene
9.0	1100	3	Ol + Px ² + Pl	Ol + Px ¹ + Pl ³ + Sp More orthopyroxene than previous runs
4.5	1200	1	Ol + Px ² + Pl	Ol + Px ² + ? Pl ³ + Sp + glass
6.7	1200	2	Ol + Px ² + Pl	Ol + Px ¹ + Pl ³ + Sp + glass Enstatite laths with included plagioclase and spinel
9.0	1200	2	Ol + Px ² + Pl	Ol + Px ¹ + Pl ³ + Sp Ol/Op _x > 11.2 kb, 13.5 kb runs
11.2	1200	1	Ol + Px ² + Pl	Ol + Px ¹ + Pl ³ + Sp Ol/Op _x > 13.5 kb run
13.5	1200	2	Ol + Px ² + Pl	Ol + Px ¹ + Sp } Similar Ol/Op _x ratios
15.8	1200	2	Ol + Px ² + Pl	Ol + Px ¹ + Sp }

Footnotes :

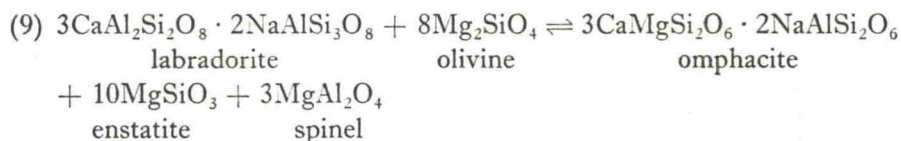
1. Pyroxene includes clinopyroxene and orthopyroxene, the latter identifiable on X-ray diffraction pattern.
2. Pyroxene mainly clinopyroxene. Orthopyroxene not identifiable by X-ray diffraction.
3. Plagioclase probably present in amount below detection limit by X-ray diffraction. Discontinuous grains of low (< 1.65) refractive index phase observed optically.
4. Synthesized at 15.7 kb, 1200°C.

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 ery low pressure —



In the light of this study it appears unlikely that nepheline and enstatite will coexist at moderate pressures in either basaltic compositions or in the olivine + labradorite mix.

There is no evidence amongst natural enstatites of high pressure origin nor from experimental studies, for significant solid solution of jadeite in enstatite or vice versa. Thus, the minimum conditions required for reaction (6) are those delimiting the jadeite stability field (Robertson, Birch & MacDonald 1957), i.e. approximately 21.5 kb at 1100°C or 23 kb at 1200°C. However, in the olivine + labradorite mix, reaction between olivine and anorthite molecule at lower pressures according to reaction (1) yields diopside. Diopside-jadeite solid solution (omphacite) is stable at lower pressures than pure jadeite (Kushiro 1965b), and reaction between olivine and labradorite to eliminate plagioclase will occur at lower pressures than reaction (6). The reaction between olivine and labradorite may be approximated as follows:



Extrapolation of the experimental data of Kushiro (1965b) and Birch & LeComte (1960) on omphacite + quartz and on jadeite and jadeite + quartz stability, suggests approximately 15 kb at 1100°C or 17 kb at 1200°C for elimination of plagioclase from the olivine + labradorite mix by equation (9). This is an approximation since the effects of Al-pyroxene solid solution and enstatite solid solution on the nature and stability of the clinopyroxene phase have not been considered.

The experimental data of Table 2 show that the first observable pyroxene + spinel occurs at 11.2 kb at both 1100°C and 1200°C. The data suggest that a slightly higher pressure is required for the beginning of reaction between magnesian olivine and labradorite than between forsterite and anorthite. However, this conclusion should be treated with some caution as the runs were not seeded with the high pressure assemblage, and metastable persistence of the olivine + labradorite assemblage in the 9 kb runs is possible. The data demonstrate the persistence of plagioclase to a higher pressure than for the Fo + An and Fa + An mixes, and the existence of

$3\text{O}_8 \cdot \text{CaAl}_2\text{Si}_2\text{O}_8 +$
labradorite

$\text{AlSi}_3\text{O}_8 \cdot \text{CaAl}_2\text{Si}_2\text{O}_8$
labradorite

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be approximated as

$\text{Si}_2\text{O}_6 \cdot 2\text{NaAlSi}_2\text{O}_6$
omphacite

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a five phase (olivine + orthopyroxene + clinopyroxene + plagioclase + spinel) stability field. At 1100°C plagioclase is present in the 13.5 kb run, and at 1200°C plagioclase disappears between 13.5 kb and 15.7 kb. Since the reactants were either glass or crystalline olivine + labradorite, metastable persistence of plagioclase to a higher pressure is possible in these runs, and the boundary for the stability field for plagioclase could not be very tightly located by reversals (i.e. growth of plagioclase from Ol + Px + Sp assemblages), because of the difficulty of distinguishing small amounts of plagioclase from possible incipient melting. However, a reversal was obtained in a run at 11.2 kb, 1200°C in which reactants of the Ol + Px + Sp assemblage were re-run and yielded the plagioclase-bearing, 5-phase assemblage. In contrast, anorthite is absent at pressures greater than 8.5 kb at 1200°C in the Fo + An mix.

In the higher pressure experiments on the olivine + labradorite mix, garnet appears from reactions involving spinel and pyroxene solid solution. Garnet first appears in minor amounts in the 18 kb, 1200°C run and between 18 kb and 20.2 kb at 1300°C. These conditions are similar to those at which garnet crystallized in the system Fo + An (2 : 1 mol.ratio) (Kushiro & Yoder 1966), and in diopside + enstatite + spinel systems (MacGregor 1965), but at considerably lower pressure than the appearance of garnet in the pyrolite composition (Green & Ringwood 1967c, 1969). The latter boundary has been confirmed by reversals, and the data illustrate the difficulty in extrapolation from simple to complex system — the presence of chromite solid solution in the spinel probably stabilizes the spinel bearing assemblage to higher pressures.

Pyrolite

The pyrolite composition, even at low pressures, contains the five phase assemblage olivine + orthopyroxene + clinopyroxene + plagioclase + spinel. However, at low pressures the orthopyroxene is a minor phase, olivine is a major phase and the uncommon spinel grains are brown in colour (with the presence of 0.72% Cr_2O_3 , in the experimental mix the brown spinel is regarded as chromite-rich). The reaction between plagioclase and olivine yields a marked increase in orthopyroxene and spinel and a decrease in plagioclase; the spinel also changes to pale green in colour as it becomes more abundant. The highest pressure run in which plagioclase is considered to be stable is at 11.2 kb; this is based on the constancy of the Ol/Opx ratio (as deduced from relative intensities of characteristic X-ray reflections), and on the absence of low R. I. grains at higher pressures. Definitive plagioclase X-ray reflections could not be observed in any runs at pressure of 9 kb or more.

It may be inferred that the plagioclase (normative labradorite) in the pyrolite composition should disappear at lower pressures than in the olivine + labradorite mix, because of the presence of diopside in the low pressure

assemblage. The clinopyroxene solid solution formed at the highest pressures in the pyrolite mix would thus have a lower jadeite/diopside ratio than that of the olivine + labradorite mix. Consideration of the experimental data and comparison with the Fo + An and olivine + labradorite mixes leads to the conclusion that plagioclase persists to 11–12 kb at 1200°C, but the interval 8–11 kb is one in which plagioclase decreases in amount with increasing pressure. The decrease in plagioclase is accompanied by increase in spinel and pyroxene.

At higher pressures the olivine + pyroxenes + spinel assemblage gives way to olivine + pyroxenes + garnet ± spinel assemblage (Green & Ringwood 1967c, 1969).

Effect of Fe/Mg variation in olivine

The extrapolation, assuming positive dT/dP , of the boundaries between high and low pressure assemblages in both the Fa + An and Fo + An systems suggests that there is little pressure difference at a given temperature between the high pressure stability limit of iron-rich olivine and anorthite and magnesian olivine and anorthite. There is, however, a very large difference in the pressure required to form garnet — the almandine-grossular garnet (Alm₆₇Gross₃₃) appearing directly from olivine + anorthite reaction at 7 kb, 1000°C, whereas the pyrope-grossular garnet would appear at 13–15 kb, 1000°C from the olivine + pyroxenes + spinel assemblage in the magnesian composition (Kushiro & Yoder 1966). Reconnaissance studies on reactions between anorthite and olivine of various Fe/Mg values confirm the general conclusion that at temperatures near 1000°C the high pressure stability limit of plagioclase + olivine is relatively insensitive to Fe/Mg, but the nature of the reaction products is very sensitive. For olivines of intermediate Fe/Mg ratio, the olivine + anorthite assemblage gives way at higher pressures to olivine + spinel + Fe-rich garnet + pyroxenes. The spinel decreases whereas garnet increases in amount and becomes more magnesian with increasing pressure.

Applications of experimental data

The experimental data presented have their main application in evaluating the near-solidus stability of plagioclase in olivine-rich, peridotitic compositions. In the olivine-normative basaltic compositions studied previously (Green & Ringwood 1967a), reaction between olivine and plagioclase occurred mainly between 8 kb and 11 kb, resulting in elimination of olivine, but persistence of plagioclase in px + pl + sp or px + pl + ga ± qz assemblages to higher pressures. In the ultramafic composition it is plagioclase which is eliminated, and olivine persists to higher pressures with spinel and aluminous pyroxenes. At high temperatures (>1000°C) the olivine + orthopyr-

oxene + clinopyroxene + spinel assemblage in ultramafic rocks overlaps the stability field of the intermediate pressure granulites (opx + cpx + plag ± ga, opx + cpx + plag + qz) and high pressure granulites (cpx + ga + plag ± qz), and in some compositions such as the pyrolite (Green & Ringwood 1967c), overlaps into the eclogite field at high temperatures. (Facies terms are used in the sense of Green & Ringwood 1967a).

The reliable extrapolation of the boundary between plagioclase-bearing and plagioclase-free peridotite to lower temperatures is not possible from the data presented. Assuming a moderate to large slope (dT/dP) for the boundary in pyrolite composition, the intersection of estimated geothermal gradients with this boundary would allow some estimation of the potential role of plagioclase peridotite ('plagioclase pyrolite') in the upper mantle (Ringwood 1966b, Green & Ringwood 1967c). It is clear from the present data and these earlier papers that plagioclase pyrolite could only occur beneath a normal continental crust (25-40 km) under conditions of extremely high geothermal gradient, and even then would be limited to a zone of <10 km thickness. In oceanic regions, plagioclase pyrolite is potentially more important at depths from 10-40 km, but uncertainty of the extrapolation to low pressure prevents firm conclusions. In regions of very high heat flow, such as mid-oceanic ridges, plagioclase pyrolite is probably present but restricted to levels above 40 km.

The data also permit some further deductions on the conditions of crystallization of the uncommon high temperature peridotite intrusions, such as Lizard (Green 1964a, 1967), Tinaquillo (MacKenzie 1960) and Serania de la Ronda (Dickey 1969). In the Lizard peridotite, accepting a temperature of 1000°C-1200°C for the body during diapiric emplacement, the movement of the body from the field of stability of the olivine + aluminous pyroxenes + aluminous spinel to stability of olivine-pyroxenes + plagioclase (labradorite) implies movements from depths of at least 35 km to depths of 25-30 km or less. In the Tinaquillo example, accepting a similar temperature of crystallization, the absence of plagioclase and presence of spinel porphyroblasts and zoned pyroxenes (Green 1963) implies final equilibration of the peridotite mineralogy at depths of at least 35 km. Final crystallization at lower temperatures (800-900°C) would allow crystallization at somewhat shallower depths (≈ 30 km). The nature of the basic granulites of the aureoles of the two peridotites provides interesting comparisons in that the Lizard aureole does not contain almandine-pyrope garnet, but the granulites are characteristically opx + cpx + plag, locally with olivine (Green 1964b). The Lizard metamorphics are thus 'low-pressure granulites'. On the other hand, the Tinaquillo peridotite has granulites with cpx + ga + plag ± hornblende at the outer margin and cpx + opx + ga (minor) ± hornblende in included blocks. The Tinaquillo metamorphics are thus intermediate pressure granulites. The experimental data on basic and ultramafic rocks at high pressures provides confirmation of the compatibility of the recrystallized assemblages in the ultramafic bodies

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and their aureoles, and allows some estimation of their conditions of crystallization (Green 1967, O'Hara 1967).

An olivine tholeiitic or picritic magma, crystallizing in the lower crust at depths corresponding to 6–10 kb, might yield accumulates containing olivine, pyroxenes and plagioclase. Cooling of such accumulates at constant pressure would result in incompatibility of olivine and plagioclase, while temperatures were quite high (≈ 800 – 1000°C). The extent of reaction would be kinetically controlled largely by the cooling rate of the body. It is considered that these conditions would lead to corona formation, often of concentric multistage type (Griffin & Heier 1969, Griffin 1970), as the olivine and plagioclase passed successively through stability fields of pyroxenes + spinel, pyroxenes + spinel + garnet, pyroxenes + garnet. The widespread occurrence of corona textures in basic rocks of the metamorphic terrains of western Norway (Gjelsvik 1952) may reflect the high pressure cooling histories of varied igneous intrusives emplaced in a pre-Caledonian, metamorphic lower crust. The occurrences of high pressure coronas and assemblages (including eclogites and garnet peridotites) in the 'axial' Caledonide zone may thus be a consequence of tectonic exposure of pre-Caledonian lower crust, rather than indicative of particularly high pressure during later Caledonian regional metamorphism. Corona textures with pyroxenes + spinel around magnesian olivine or garnet + clinopyroxene around more Fe-rich olivine are considered to imply falling temperatures in the range 1100 – 800°C at pressures of 6–10 kb (depths of 20–35 km).

The experimental data are also relevant to melting studies on peridotitic compositions. The pressure interval of 8–12 kb, at solidus temperatures, is also the pressure range over which melting of pyrolite composition produces liquids of high-alumina type in equilibrium with residual olivine, aluminous orthopyroxene and clinopyroxene (Green, Green & Ringwood 1967, Green & Ringwood 1967b). In the 5-phase subsolidus assemblage, the minor plagioclase enters the basaltic liquid at temperatures only slightly above the solidus, and this is a major factor in producing the high alumina liquids.

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