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Factors Governing the Stability of Plagioclase at High Pressures as Shown by Spinel-Gabbro Xenoliths from the Kerguelen Archipelago

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Abstract

Spinel gabbro xenoliths are found together with biotite-bearing spinel lherzolite inclusions in a lava flow on Kerguelen Island, south Indian Ocean. The gabbroic rocks show evidence of reaction between plagioclase and olivine to produce spinel and pyroxenes. The reaction was arrested by the depletion of olivine while plagioclase still remained. The albite component of plagioclase appears to have entered the reaction to a lesser extent than did the anorthite component. The reaction was reversed when the rocks were reheated at low pressures by the magma that carried them to the surface. There is no apparent genetic relation between the spinel gabbro and the lherzolite inclusions in the same flow.

Introduction

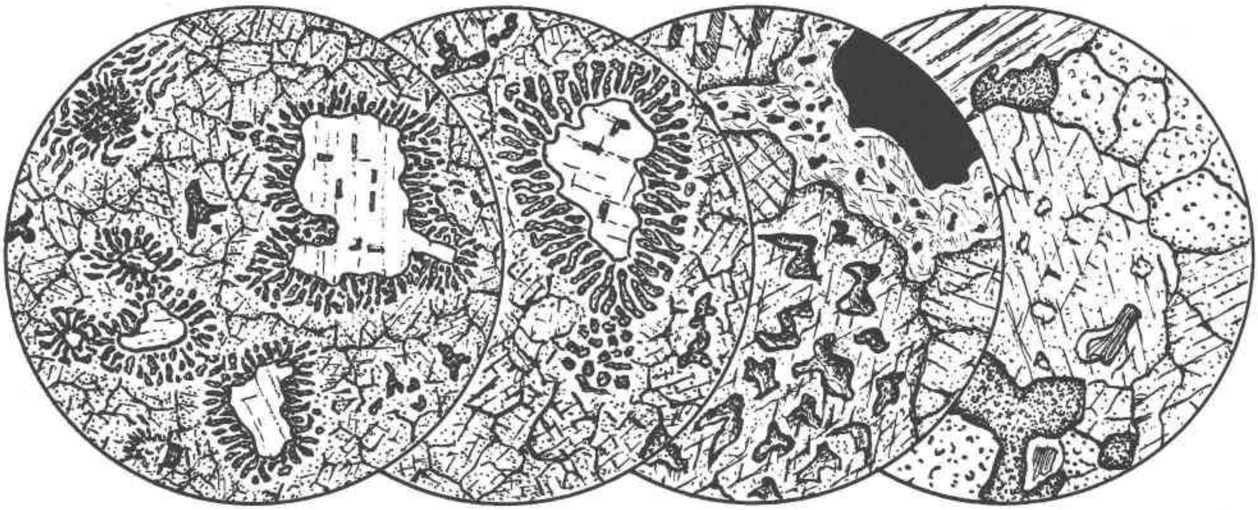
In an earlier paper in this journal, J. L. Talbot and his co-workers (1963) presented data on a remarkable assemblage of gabbroic and peridotitic inclusions from lavas of the Kerguelen Archipelago in the south Indian Ocean. Although their attention was directed mainly toward olivines in the ultramafic rocks, they also mentioned a variety of spinel-rich gabbros found in subordinate amounts in the same lava flow. We have been fortunate in obtaining a small collection of specimens, which Dr. J. Nougier, a member of the French scientific party on Kerguelen, generously supplied to scientists of the H. V. Horizon on the occasion of its visit to the archipelago in 1962. In addition, Dr. Talbot has provided us with several specimens collected by A. B. Edwards in 1929-30.

Several recent experimental studies have predicted that spinel gabbros would result from a high-pressure reaction between plagioclase and olivine. Although similar rocks occur in high-grade metamorphic series, such as those of Norway (Griffin, 1971), spinel gabbros are exceptionally rare as inclusions in lavas.

The geology and petrology of parts of the Kerguelen Archipelago have been described by a number of workers, notably Lacroix (1915), Aubert de la Rue (1932, 1956, 1962), Edwards (1938), and Nougier (1965). The islands are the emergent part of a much wider platform, probably of continental character, that is composed largely of alkaline lavas with subordinate plutonic rocks and late Mesozoic to early Tertiary sedimentary rocks. The lavas include a wide variety of analcite basanites, trachytes, phonolites and limburgites. Xenoliths have been found mainly in the olivine-rich alkali basalts and trachybasalts; they include spinel lherzolite, biotite-hornblende pyroxenite and spinel gabbro.

Spinel-biotite lherzolite inclusions

The most common xenoliths are peridotites consisting of about equal proportions of olivine, enstatite and diopside with subordinate amounts of brown chromian spinel and red biotite. The texture of a typical specimen (Fig. 1) is allotriomorphic granular. The olivine is deformed and has a strong preferred orientation. We have separated and analyzed the pyroxenes and spinel from one of the same specimens (K29A = our number I-73) for which Talbot and his associates (1963) provided data on the olivine (FeO 8.15 to 8.44 percent, Ni 0.254 to 0.281 percent, Mn 0.11 to 0.12 percent). The pyroxenes (Table 2, no. 1 and 2) are characterized by high



I-74 I-75 I-76 I-73

FIG. 1. Textural relations of inclusions. I-74 and I-75 are spinel gabbros with embayed plagioclase (unstippled) surrounded by coronas of spinel (small elongate grains with heavy stippling) and pyroxene (lightly stippled with cleavage). I-76 is a similar rock that has been reheated by its host lava while in transit to the surface. A large nearly opaque grain of spinel in the upper right has partially reacted with the surrounding pyroxene to form a zone of olivine and plagioclase. All of the olivine is new altered to serpentine and magnetite and part of the plagioclase is altered to prehnite. I-73 is a biotite-bearing lherzolite with olivine (upper right), enstatite (top), clinopyroxene (lower right), irregular large grains of brown spinel (heavily stippled), and small flakes of brown biotite.

MgO, low alumina and titania and moderately high Cr_2O_3. The brown spinel (Table 3, no. 1) is predominantly chromite with subordinate amounts of magnetite and magnesium spinel.

Spinel-gabbro inclusions

The gabbroic rocks consist of bytownite, two pyroxenes, and green spinel and have the chemical composition of olivine basalts (Table 1). The compositional variations shown by the three analyzed specimens are those that would result from differing proportions of olivine and plagioclase phenocrysts, although the rocks now contain no olivine and lack phenocrysts. The modal compositions of the analyzed specimens are also given in Table 1, and the textural relations of the essential minerals are illustrated in Figure 1.

Pyroxenes are of two types, a pale-green diopsidic augite and a weakly pleochroic bronzite. The two are closely associated in a granular intergrowth of equidimensional grains measuring 1 to 2 mm across. No zoning or exsolution lamellae have been detected in the analyzed pyroxenes. The chemical compositions given in Table 2 (I-74 and I-75) were obtained by electron microprobe analyses. They show small but consistent differences in the Fe/Fe + Mg ratios in both the Ca-rich and Ca-poor pyroxenes of the two specimens. On the other hand, the alumina contents show no regularity in their variation; both pyroxenes in each rock contain between 6.5 and 8.0 percent Al_2O_3.

Plagioclase occurs in two forms, most commonly in relatively large crystals up to 2 or 3 mm across, but elsewhere in the same specimens in granular aggregates of smaller grains. Plagioclase of the first type is twinned according to the albite, carlsbad and pericline laws and commonly displays patchy normal zoning from calcic bytownite to sodic labradorite. The smaller granular type is rarely twinned or zoned; its composition is close to medium labradorite. Many of the larger plagioclases have concave outlines, and the zoning generally conforms to the irregularities of form (Fig. 2). Twinning is less common in the outer zoned margins than in the more homogeneous interior.

Green spinel forms anhedral grains up to 0.5 mm in diameter. It is intergrown with both pyroxenes, especially in zones adjacent to the embayed faces of the large plagioclase crystals around which it forms a crudely radial corona. In a few places the spinel forms small plates along the (010) and (001) cleavage planes of plagioclase. Its chemical composition (Table 3) is characterized by high Al_2O_3 and low Cr_2O_3; the Fe/Mg + Fe ratio of 0.3 is about twice that of the co-existing pyroxene.

Altered spinel gabbro inclusions

The margins of some of the gabbroic xenoliths show evidence of strong alteration, apparently as the result of reheating by the enclosing lava. (See example in Figure 1). The original spinel and adjacent pyroxenes are partially or wholly converted to opaque oxides, serpentine, plagioclase and prehnite. The pyroxenes show broad exsolution lamellae of hypersthene and Ca-rich augite.

Origin

The present mineral assemblage of the spinel gabbro xenoliths appears to be the product of recrystallization of what was originally a porphyritic olivine gabbro. This inference is supported by (1) the nature of the chemical differences of the rocks, which can be accounted for by variations in their original olivine and plagioclase contents; (2) the spatial relations of spinel in pyroxenes around embayed plagioclase; and (3) the absence of olivine from the present mineral assemblage. These features indicate that a reaction between olivine and plagioclase produced pyroxenes and aluminous spinel and that this reaction proceeded until one of the reactants, olivine, disappeared.

The conditions of stability of plagioclase and aluminous spinel in the presence of olivine were first investigated by Kushiro and Yoder (1966) in their study of the anorthite-forsterite join at elevated pressures. The same reaction was studied in basaltic compositions by Green and Ringwood (1967) and in peridotitic compositions by Green and Hibberson (1970). The later studies have indicated that moderate amounts of sodium, iron, and other components do not significantly alter the stability range in which plagioclase and olivine can coexist, although they have an important effect on the stability range of spinel with respect to garnet. In basaltic compositions, the reaction of olivine with plagioclase with increasing pressure or falling temperature was found to proceed until the olivine was totally consumed; in a more olivine-rich peridotite composition, plagioclase is the first mineral to disappear and the reaction stops while the rock still contains olivine.

TABLE 1. Compositions of Spinel Gabbro Inclusion

	I-74	I-75	I-76
	Chemical Compositions		
SiO_2	47.98	46.56	47.48
TiO_2	0.20	0.19	0.35
Al_2O_3	17.74	13.65	16.81
Fe_2O_3	1.35	2.46	0.94
FeO	3.12	4.53	4.10
Cr_2O_3	0.17	0.28	0.33
MnO	0.09	0.11	0.09
MgO	11.07	17.19	11.02
CaO	15.82	13.49	16.07
Na_2O	1.23	0.77	1.57
K_2O	0.12	0.04	0.15
H_2O+	0.80	0.70	1.06
H_2O-	0.24	0.17	0.24
P_2O_5	0.03	0.02	tr.
Total	99.97	100.16	100.21
	Molecular Norms		
Ap	0.05	0.05	tr.
Il	0.28	0.26	0.48
Or	0.75	0.25	0.90
Ab	10.95	6.75	8.00
An	42.05	32.75	37.83
Cr	0.18	0.30	0.36
Mt	1.38	2.50	0.98
Di	28.44	25.96	33.08
Hy	4.12	9.28	--
Ol	11.79	21.90	14.33
Ne	--	--	3.04
	Modal Composition		
Plagioclase	20.5	11.8	18.3
Clinopyroxene	52.9	50.9	63.1
Orthopyroxene	15.7	30.5	5.6
Spinel	8.9	6.6	7.4
Alteration products	2.0	0.2	5.6

Figure 3 shows the upper limit for the stable coexistence of olivine and plagioclase as defined by the existing experimental data. The curve represents the combined effects of at least three reactions:

$$\underset{\text{anorthite}}{CaAl_2Si_2O_8} + \underset{\text{olivine}}{2(Mg, Fe)_2SiO_4} \underset{\rightarrow}{\longrightarrow} \underset{\text{Ca-rich pyroxene}}{Ca(Mg, Fe)Si_2O_6}$$

$$+ \underset{\text{Ca-poor pyroxene}}{(Mg, Fe)_2Si_2O_6} + \underset{\text{spinel}}{(Mg, Fe)Al_2O_4} \qquad (1)$$

$$\underset{\text{anorthite}}{2CaAl_2Si_2O_8} + \underset{\text{olivine}}{2(Mg, Fe)_2SiO_4}$$

$$\underset{\rightarrow}{\longrightarrow} \underset{\text{Tschermakitic pyroxenes}}{Ca(Mg, Fe)Si_2O_6 \cdot CaAl_2SiO_6}$$

$$+ (Mg, Fe)_2Si_2O_6 \cdot (Mg, Fe)Al_2SiO_6 \qquad (2)$$

$$\underset{\text{albite}}{NaAlSi_3O_8} + \underset{\text{olivine}}{(Mg, Fe)_2SiO_4} \underset{\rightarrow}{\longrightarrow} \underset{\text{jadeite}}{NaAlSi_2O_6}$$

$$+ \underset{\text{Ca-poor pyroxene}}{(Mg, Fe)_2Si_2O_6} \qquad (3)$$

TABLE 2. Chemical Composition of Pyroxenes from Lherzolite (I-73) and Spinel Gabbro (I-74 and I-75) Inclusions*

	I-73		I-74				I-75					
	Cpx	Opx	Cpx	Cpx	Opx	Opx	Cpx	Cpx	Cpx	Opx	Opx	Opx
SiO_2	52.72	56.29	50.09	49.05	50.73	50.67	51.06	47.98	51.22	52.51	52.43	52.93
TiO_2	0.45	0.18	0.62	0.25	0.05	0.07	0.50	0.51	0.36	0.07	0.07	0.06
Al_2O_3	3.60	2.10	6.68	8.06	7.74	7.15	6.94	7.06	7.37	6.95	6.53	6.84
Fe_2O_3	0.57	0.10										
FeO	1.65	5.29	4.45	4.46	11.48	11.46	3.96	3.93	4.09	10.45	10.32	10.51
Cr_2O_5	1.18	0.62	0.33	0.13	0.00	0.04	0.46	0.40	0.34	0.09	0.08	0.07
MnO	0.13	0.15	0.11	0.13	0.16	0.18	0.11	0.09	0.12	0.17	0.17	0.17
MgO	17.14	34.28	14.08	13.72	27.95	28.26	14.25	14.21	14.31	28.86	29.39	28.75
CaO	21.59	0.79	21.96	21.23	0.80	0.75	21.88	22.09	21.67	0.76	0.70	0.66
Na_2O	0.88	0.00	1.04	1.23	0.13	0.08	0.92	0.87	0.86	0.07	0.06	0.04
K_2O	0.04	0.00	-	-	-	-	-	-	-	-	-	-
H_2O-	0.03	0.06	-	-	-	-	-	-	-	-	-	-
	99.98	99.86	99.35	98.25	99.04	98.65	100.07	97.14	100.34	99.92	99.76	100.05
$NaCrSi_2O_6$	2.4	1.7**	1.0	0.4	0.0	0.1	1.3	1.1	1.0	0.2	0.2	0.2
$NaFeSi_2O_6$	1.6	0.0	4.3	7.8	0.9	0.5	3.2	5.1	1.8	0.2	0.2	0.2
$NaAlSi_2O_6$	2.4	-	2.0	0.6	-	-	2.0	0.0	3.3	-	-	-
$CaTiAl_2O_6$	1.2	0.5	1.7	0.7	0.1	0.2	1.4	1.5	1.0	0.1	0.2	0.2
$CaAl_2SiO_6$	5.2	-	11.7	16.5	-	-	12.6	13.9	13.1	-	-	-
$(Mg,Fe)Al_2SiO_6$	-	2.9	-	-	15.6	14.4	-	-	-	14.2	13.1	14.0
$Ca_2Si_2O_6$	38.5	0.7	36.3	33.3	2.9	2.8	35.9	35.8	35.0	2.8	2.4	2.3
$Mg_2Si_2O_6$	46.0	86.5	38.2	37.6	65.4	66.8	37.8	38.9	38.6	68.7	70.0	69.5
$Fe_2Si_2O_6$	2.7	7.7	4.8	3.2	15.1	15.3	4.7	3.7	5.8	14.1	14.0	14.2

* *Lherzolite pyroxenes were analyzed by wet chemical methods, others by electron microprobe. In calculating the molecular proportions of pyroxenes analyzed by microprobe, sufficient Fe has been taken as* Fe^{3+} *to balance the pyroxene formula.*

***$CaCrAlSiO_6$.*

Each reaction has its own reaction coefficient and will proceed to differing degrees of completion depending on various chemical and physical conditions. It is clear that in reality the curve in Figure 3 must be a zone of finite width.

If we are correct in deducing that the rock was originally a basaltic liquid with differing amounts of phenocrysts, it follows that the reaction between olivine and plagioclase resulted from a fall in temperature into the stability field of spinel at essentially constant pressure (A to B in Figure 3). The second possibility, an increase of pressure resulting from displacement of the rock to greater depths without an increase of temperature, is geologically less plausible.

The normal zoning of the plagioclase probably reflects less complete reactions involving albite and jadeite (equation 3) relative to those yielding spinel or Tschermakitic pyroxenes. As the jadeite content of the clinopyroxene approached its saturation limit for the prevailing conditions, albite ceased to react and was residually enriched as the outer zones of the plagioclase crystals were further depleted in anorthite. Finally, when olivine was consumed, the reaction came to an end with plagioclase remaining as relicts of originally larger and more abundant crystals.

Reheating of the xenoliths during their transit to the surface in the rising basaltic magma resulted in a reversal of the reaction (B to C in Figure 3), so that spinel enclosed in pyroxenes gave place to plagioclase and olivine. Subsequently, the olivine was completely altered to serpentine and magnetite, and plagioclase has partially altered to prehnite. This reversed reaction affected only small xenoliths or the marginal parts of larger ones, possibly because of the rapid rise of the magma with its inclusions.

The relation of the gabbros to the spinel lherzolites with which they are associated is more difficult to define. If the two rocks are genetically related, the lherzolite could be a mantle rock from which a basaltic liquid could be derived by partial melting or, alternatively, the lherzolite could be either the residue left after extraction of basalt or a crystal-cumulate precipitated from such a liquid. The Mg/Mg + Fe ratios of the rocks and minerals are consistent with

FIG. 2. Embayed plagioclase in which the sodic zone conforms to the irregular outline of the grain. Small inclusions of spinel are also surrounded by more sodic plagioclase. Twinning is still preserved in the interior calcic portion of the plagioclase. (Sample I-74)

any of these three possibilities, but our earlier conclusion that the gabbro was originally an olivine basalt with phenocrysts of olivine and plagioclase would be inconsistent with any of these choices.

It is obvious that a liquid that is crystallizing plagioclase and olivine cannot have a liquidus relation to the lherzolite at the same pressure. It seems more likely that the liquid was originally generated at a greater depth, rose to an intermediate level, and precipitated olivine and plagioclase in response to the expansion of the stability fields of these minerals with declining pressure and temperature. A basaltic liquid that crystallizes at an intermediate depth in the mantle could in this way be left in proximity with rocks to which it bears no direct genetic relation.

Conclusions

The spinel gabbro xenoliths are best explained as the product of a basaltic liquid that contained differing amounts of olivine and plagioclase phenocrysts and crystallized as an olivine gabbro when arrested in its upward course at a depth of about 25 to 30 kilometers. Subsolidus cooling led to a reaction between olivine and plagioclase to produce aluminous spinel and pyroxenes. The reaction was terminated by depletion of olivine while plagioclase was still present. The albite component of plagioclase entered the reaction to a lesser degree than did the anorthite component.

A new pulse of magma brought the spinel gabbro inclusions to the surface along with inclusions of lherzolite. Reheating of the gabbro at lower pressures caused a reversed reaction in which spinel and pyroxene were converted back to olivine and plagioclase. Under hydrothermal conditions this assemblage was almost totally altered to serpentine, magnetite and prehnite.

The relations we observe in these rocks confirm the predictions of Kushiro and Yoder (1966) that a gabbro that originally contained a higher molecular proportion of anorthite over olivine can have plagioclase as a stable mineral at pressures above those at which aluminous spinel appears. It would appear that significant amounts of albite in the plagioclase extend the range of pressures at which plagioclase may persist in conventional gabbroic compositions.

TABLE 3. Chemical Compositions of Spinels from Lherzolite and Spinel Gabbro Inclusions*

	1. I-73 lherzolite	2. I-74 gabbro	3. I-74 gabbro	4. I-75 gabbro
Al_2O_3	13.76	66.26	67.08	67.25
Cr_2O_3	33.46		0.99	0.86
Fe_2O_3	14.88	0.60	0.26	0.08
FeO	23.18	14.31	14.70	13.73
MnO	0.17	0.18	0.08	0.05
MgO	9.58	18.46	18.40	18.94
TiO_2	4.57	0.22	0.02	0.02
CaO			0.26	0.27
Total	99.60	100.02	101.79	101.20
	Cation Proportions**			
Al	4.276	15.839	15.798	15.845
Cr	6.966		0.156	0.137
Fe'''	2.950	0.093	0.038	0.012
Fe''	5.105	2.427	2.456	2.295
Mn	0.038	0.030	0.013	0.008
Mg	3.760	5.578	5.479	5.641
Ti	0.905	0.034	0.004	0.004
Ca			0.055	0.058
X + Y	24.000	24.001	23.999	24.000

*No. 1 and 2 are based on wet chemical methods, no. 3 and 4 on electron microprobe analyses.
**based on 32 oxygens.

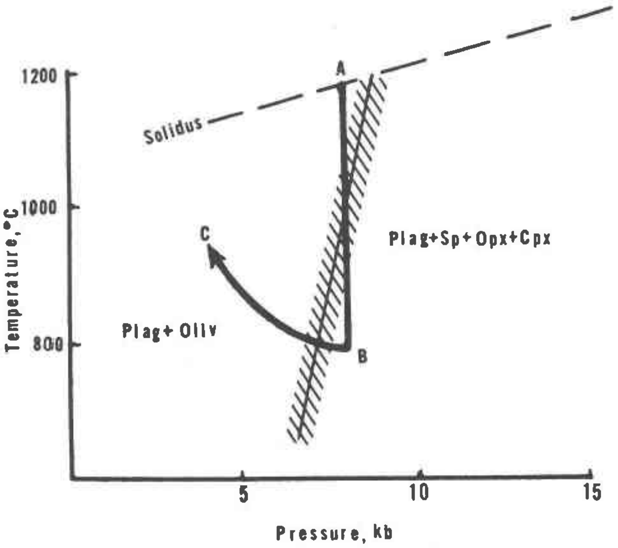


FIG. 3. Diagram of the stability fields of plagioclase, olivine, and spinel in rocks of basaltic composition at high temperatures and pressures. Boundary between the plagioclase + olivine field and that of plagioclase + spinel + pyroxene is taken from Kushiro and Yoder (1966) and Greene and Hibberson (1970) with range of uncertainty indicated by diagonal ruling. Arrow from A to B indicates the postulated cooling of an olivine basalt from its liquidus under isobaric conditions with a resulting reaction of olivine with plagioclase to form spinel and pyroxene with remnant plagioclase. This reaction is reversed during the reheating of the rocks as they rose in the erupting magma (B to C).

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