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PETROGENESIS OF ULTRABASIC AND BASIC INCLUSIONS IN ALKALI BASALTS, IKI ISLAND, JAPAN

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ABSTRACT

Ultrabasic and basic inclusions up to 5 cm in size occur in some of the alkali basalts and allied rocks of Iki Island, Japan. These inclusions are divided into two groups: (1) spinel-bearing wehrlite, pyroxenite and gabbro, and (2) magnetite-bearing gabbro and anorthosite. The first group is characterized by pyroxene-spinel symplectites produced by reaction between olivine and plagioclase. New analyses are presented for one host basalt, three inclusions, six plagioclases, two olivines, one aluminous bronzite in symplectite, one spinel, and three augites.

From the mineralogy, petrography and chemistry of the inclusions and the results of recent high-pressure experimental studies, it is concluded that the spinel-bearing inclusions formed at a depth of 25 to 35 km.

INTRODUCTION

Certain alkali basalts (defined by Kuno, 1960) and allied rocks of the Quaternary alkali basalt province of Japan contain ultrabasic and basic inclusions. These inclusions represent a wide range of rock types including various types of dunite, peridotite, pyroxenite, gabbro, norite, anorthosite and hornblendite; of these, gabbro is most abundant. Although more than 30 localities are known in Japan, systematic studies of these inclusions have not previously been reported.

Some of the alkali basalts of Iki Island in southwestern Japan contain ultrabasic and basic inclusions such as wehrlite, pyroxenite, gabbro and anorthosite. Some are characterized by mineral assemblages that reflect high pressure and high temperature conditions. Namely, coexisting olivine and plagioclase react and form aluminous augite, aluminous bronzite and spinel, showing the stability limits of them in analogous experimental system (Kushiro and Yoder, 1966).

The principal purpose of the present investigation is to describe the chemical characteristics of the minerals in these inclusions and to discuss the origin of the inclusions.

PETROGRAPHY

The geology, mineralogy, and petrochemistry of the alkali basalts and allied rocks of the Iki Island area of southwestern Japan have been described and discussed elsewhere (Aoki, 1959, 1963a, 1963b, 1964, 1966). The ultrabasic and basic inclusions occur in alkali basalts and trachyandesites, but do not seem to be associated with trachytes or pantellerites. They vary from rounded to angular and rarely lenticular in shape. They range up to 5 cm in size and have sharp boundaries against the enclosing basalts. They are commonly friable.

The ultrabasic and basic inclusions of Iki Island are divided into the following two groups according to their characteristic primary mineral assemblage: (1) spinel-bearing and magnetite-free wehrlite, pyroxenite and gabbro; and (2) spinel-free and magnetite-bearing gabbro and anorthosite.

The primary and secondary mineral assemblages of the inclusions are given in Table 1. No primary orthopyroxene or garnet has been identified in any of the inclusions.

TABLE 1. PRIMARY AND SECONDARY MINERAL ASSEMBLAGES OF THE ULTRABASIC AND BASIC INCLUSIONS

		Primary mineral assemblage					Secondary mineral assemblage		
	Mineral / Rock type	Plagioclase	Olivine	Clinopyroxene	Spinel	Magnetite	Aluminous clinopyroxene	Aluminous orthopyroxene	Spinel
	Wehrlite	+	+	+	+		+	+	+
			+	+	+				
I	Pyroxenite	+	+	+	+		+	+	+
			+	+	+				
	Gabbro	+	+	+	+		+	+	+
	Gabbro	+	+	+		+			
II		+		+		+			
	Anorthosite	+	+	+		+			
		+		+		+			

Host rocks. Chemical analyses and norms of host rocks are given in Table 2. All are silica undersaturated alkali basalts characterized by slightly higher SiO_2 and alkalis but lower total iron, MgO and CaO than the average alkali olivine basalt of southwestern Japan (Aoki and Oji, 1966). A typical alkali basalt from Komaki (No. 1, Table 2) consists of olivine phenocrysts in a groundmass of plagioclase, potassic plagioclase, anorthoclase, olivine, augite, iron ore, and apatite. In contrast, the trachyandesite of Yokouchi (No. 2, Table 2) has olivine, hypersthene, plagioclase, titanaugite, apatite and kaersutite as phenocrysts and has

TABLE 2. CHEMICAL ANALYSES AND NORMS OF THE HOST ROCKS

	1	2		1	2
SiO_2	50.53	48.97	Or	12.01	14.62
TiO_2	2.19	2.40	Ab	32.28	31.34
Al_2O_3	16.82	16.90	An	22.71	21.71
Fe_2O_3	1.74	3.50	Ne		0.43
FeO	7.00	6.23	Wo	4.27	4.13
MnO	0.13	0.52	En	5.23	2.70
MgO	6.06	5.28	Fs	2.77	1.14
CaO	7.32	7.35	Fo	6.94	7.35
Na_2O	3.82	3.80	Fa	4.06	3.40
K_2O	2.03	2.47	Mt	2.53	5.08
H_2O^+	1.15	1.18	Il	4.16	4.56
H_2O^-	0.46	0.68	Ap	1.24	1.78
P_2O_5	0.53	0.75			
Total	99.78	100.03			

1. Olivine alkali basalt, Komaki, Numazu, Iki Island.
2. Hypersthene bearing titanaugite olivine kaersutite trachyandesite, Yokouchi, Numazu, Iki Island (Aoki, 1959).

Analyst, K. Aoki

olivine, titanaugite, plagioclase, potassic plagioclase, anorthoclase, iron ore and apatite as groundmass minerals.

Spinel-bearing ultrabasic and basic inclusions (Group 1). Although wehrlites have a wide range of modal composition, the essential constituents are olivine and augite with subordinate green spinel and/or calcic plagioclase. Wehrlites are gradational into pyroxenites as the proportion of clinopyroxene increases and into gabbro with increasing plagioclase. Wehrlites are typically xenomorphic-granular in texture. Olivine is noticeably inequigranular, ranging from 0.5 to 4 mm in size, and commonly displays wide-spaced translation lamellae subparallel to (100) and undulating extinction. It is homogeneous and free of inclusions such as chromian spinel. Augite is medium to very coarse grained and is up to 4 mm in length. It is dark green or black in hand specimen. It occurs as prismatic subhedra to anhedra and shows simple twinning on (100). It is often strained and shows wavy extinction. No pleochroism is observed in any orientation. Some have exsolution lamellae of bronzite parallel to (100) of the host crystal. The lamellae are generally about 0.04 mm apart and up to 0.002 mm thick. Rarely, the lamellae attain a thickness of 0.01 mm. The optic angle $2V_X$ of bronzite is about 80°, corresponding to Fs_{18}. Spinel occurs as both equant and anhedral to subhedral grains up to 4 mm in size or as irregular, wormy intergrowths with augite. It is clear green in color.

Two types of pyroxenites are recognized. Both types consist of augite and a little olivine with spinel. One type is coarse-grained with xenomorphic-granular texture and is gradational into wehrlite, whereas the other consists of dark clots of large augite crystals which enclose smaller grains of olivine and augite. Olivine and augite of the former are essentially the same as those of wehrlite. Augite of the latter has stout subhedral prismatic form up to 2 cm in length. Simple twinning on (100) is common. Exsolution lamellae of bronzite are developed along (100), usually about 0.02 apart and less than 0.001 mm thick. The zones along margins or cracks in the augites are spongy with many small pores filled with olivine and plagioclase of the same composition as the ground mass minerals of the host basalt. Spinel occurs as equant anhedral to euhedral interstitial grains less than 0.4 mm in size.

Gabbros are also divided into two types by their fabric. One type has xenomorphic-granular texture and grades into wehrlite with decreasing plagioclase. The other is made up of large clusters of augite (up to 1 cm in length) and plagioclase (less than 0.6 mm in length) with small interstitial grains of olivine, augite, plagioclase and spinel. The latter type is very heterogeneous, even in small inclusions. Plagioclase is anhedral to subhedral in form and is always twinned according to the albite, Carlsbad and pericline laws. Zonal structure is weak and is confined to the peripheral part of the crystals.

Aluminous augite, aluminous bronzite and spinel symplectite. Coarse-grained pyroxene-spinel symplectite commonly occurs between olivine and plagioclase grains, especially in gabbro inclusions (Fig. 1). It does not occur in plagioclase-free wehrlite or pyroxenite. Olivine and plagioclase are invariably corroded with deep embayment of the crystal outlines. Small plagioclase grains in wehrlite and the olivine in gabbro are commonly replaced by symplectite.

Bronzite always rims the olivine and the allotoriomorphic intergrowths of augite and spinel. The bronzite mantles are generally 0.1 to 0.8 mm thick. The bronzite is free of inclusions but passes abruptly into the spinel-augite intergrowths. It is very weakly pleochroic with X very pale brown and Z very pale green. There is a distinct cleavage parallel to (110). Most of the bronzite is intergrown with augite and spinel. Some of the bronzite mantles have reacted with the liquid penetrating along grain boundaries to produce small aggregates of euhedral to granular olivine and minor amounts of interstitial plagioclase. This reaction is observed between enstatite in lherzolite inclusions and their host rocks

(Wilshire and Binns, 1961). The plagioclase is probably derived from small amounts of $CaSiO_3$ and $MgAl_2SiO_2$ originally contained in the bronzite. In such cases, the symplectite shows more complex texture.

Augite forms relatively large anhedral plates up to 2 mm long with graphic intergrowths of spinel. In some cases it is associated with bronzite. It does not occur as independent crystals or as mantles enclosing olivine. No pleochroism is apparent.

Spinel may be angular, wormy, thread-like, or roughly octahedral in form. It reaches 0.8 mm in maximum dimension and is always intergrown with augite or bronzite where it is adjacent to these pyroxenes. Its green color is paler than that of primary spinel.

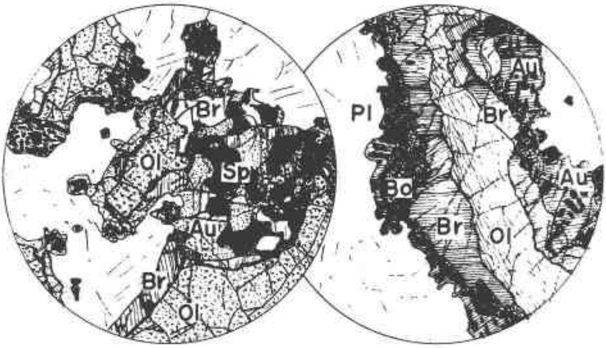

FIG. 1. Sketch showing pyroxene-spinel symplectite between olivine and plagioclase in gabbro inclusion. O1, olivine, P1, plagioclase, Au, aluminous augite, Br, aluminous bronzite, Sp, spinel, Bo, olivine after bronzite. X 11.

Magnetite-bearing inclusions (*Group 2*). Gabbro and anorthosite have a granular texture and homogeneous appearance in hand specimen, although some specimens have a banded structure. Both rock types are gradational into one another, according to the amount of plagioclase. They consist of three essential minerals, plagioclase, augite, and magnetite with or without accessory olivine. Plagioclase, all of which shows polysynthetic twinning, forms subhedral to anhedral prismatic crystals up to 5 mm in length. Zonal structure is developed at the margin of each crystal. The margins are always more or less sodic. Inclusions of magnetite and augite are common. Augite forms subhedral to anhedral prisms less than 2 mm in length. It is pale brownish green in color, but is not pleochroic. Irregular magnetite grains up to 0.3 mm across occur interstitially. Most of the olivine is anhedral in form and is always intergrown with magnetite.

WHOLE ROCK AND MINERAL CHEMISTRY OF THE INCLUSIONS

Chemical compositions of the inclusions and their constituent minerals are given in Tables 3 to 7 together with their normative compositions and atomic ratios.

TABLE 3. CHEMICAL ANALYSES AND NORMS OF ULTRABASIC AND BASIC INCLUSIONS

	1	9	10		1	9	10
SiO_2	44.57	39.40	44.09	Or	0.61	0.95	0.95
TiO_2	0.70	3.14	0.78	Ab	5.40	5.97	11.74
Al_2O_3	8.57	15.34	28.91	An	20.18	36.67	72.09
Fe_2O_3	2.18	8.10	2.66	Ne		1.53	
FeO	8.92	10.24	2.91	Wo	17.21	14.82	3.21
MnO	0.17	0.10	0.03	En	11.08	9.70	2.10
MgO	21.07	6.79	1.82	Fs	2.88	4.07	0.88
CaO	12.33	14.60	16.13	Fo	29.11	5.09	1.72
Na_2O	0.64	1.04	1.39	Fa	8.37	2.35	0.80
K_2O	0.10	0.16	0.16	Mt	3.16	11.74	3.85
H_2O^+	0.61	1.10	0.66	Il	1.32	5.96	1.47
H_2O^-	0.09	0.30	0.40	Ap		0.10	0.10
P_2O_5		0.04	0.04				
Total	99.95	100.35	99.98				

Key to Tables 3–7

1\. Plagioclase spinel wehrlite
1p. Plagioclase
1o. Olivine
1c. Aluminous titanaugite (Aoki, 1964)
2\. Spinel olivine gabbro
2p. Plagioclase
2o. Olivine
2r. Bronzite in pyroxene-spinel symplectite
2s. Spinel
3\. Spinel olivine gabbro
3p. Plagioclase
3o. Olivine
3c. Aluminous titanaugite
4\. Spinel olivine gabbro
4p. Plagioclase
4o. Olivine
4c. Aluminous titanaugite (Aoki, 1964)
5\. Spinel olivine pyroxenite
5o. Olivine
5c. Aluminous titanaugite (Aoki, 1964)
6\. Spinel olivine pyroxenite
6o. Olivine
6c. Aluminous titanaugite (single crystal) (Aoki, 1964)
7\. Spinel wehrlite
7o. Olivine
7c. Aluminous augite (Aoki, 1959)
8\. Spinel olivine pyroxenite
8c. Aluminous augite (Aoki, 1964)
9\. Magnetite olivine gabbro
9p. Plagioclase
9o. Olivine
9c. Titanaugite
10\. Magnetite augite anorthosite
10p. Plagioclase

Locality: 1–7, 9, and 10, Komaki, Numazu, Iki Island 8, Yokouchi, Numazu, Iki Island
Analyst, 1. H. Onuki and the others K. Aoki

Table 4. Chemical Analyses of Plagioclase Feldspars

	1p	2p	3p	4p	9p	10p
SiO_2	48.31	48.70	48.95	51.24	47.01	45.93
TiO_2	0.06	0.05	0.05	0.08	0.06	0.04
Al_2O_3	32.74	32.35	32.69	30.72	33.51	34.32
Fe_2O_3	0.42	0.50	0.66	0.52	0.92	0.56
FeO	0.20	0.00	0.02	0.17	0.00	0.02
MnO	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.10	0.10	0.01	0.12	0.05	0.04
CaO	15.41	14.79	15.12	13.22	16.58	17.12
Na_2O	2.40	2.63	2.59	3.61	1.75	1.46
K_2O	0.27	0.24	0.19	0.52	0.09	0.13
H_2O		0.35				0.24
Total	99.91	99.71	100.28	100.20	99.97	99.82
Si	8.872	8.969	8.941	9.334	8.653	8.497
Al	7.074	7.010	7.025	6.584	7.256	7.470
Ti	0.008	0.007	0.007	0.011	0.008	0.006
Fe^{3+}	0.055	0.069	0.060	0.072	0.126	0.078
Fe^{2+}	0.031	0.000	0.003	0.026	0.000	0.003
Mn	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.028	0.028	0.002	0.033	0.013	0.011
Ca	3.030	2.918	2.959	2.581	3.270	3.393
Na	0.853	0.937	0.916	1.272	0.623	0.522
K	0.064	0.057	0.044	0.120	0.022	0.031
Z	16.009	16.055	16.063	16.001	16.043	16.048
XY	4.006	3.940	3.924	4.032	3.928	3.964
mol %						
Or	1.6	1.4	1.1	3.1	0.6	0.8
Ab	20.6	22.9	22.3	30.7	15.1	12.5
An	77.8	75.7	76.6	66.2	84.3	86.7

Whole Rocks. The wehrlite inclusions from Iki Island is characterized by high Al_2O_3, CaO and alkalis and low MgO. High Al_2O_3 wehrlites are not found as inclusions in alkali basalts nor as Alpine-type ultrabasic intrusions or even as cumulus phase of basic layered intrusions. Similarly, magnetite-bearing gabbro and anorthosite inclusions have unusual compositions in that they are low in SiO_2 and alkalis and rich in total iron and CaO. Such rocks have not been reported from igneous intrusions.

Plagioclase. Plagioclase has a compositional range of An_{87-66}. The Or content increases from 0.6 to 3.1 with increase of the Ab content. Plagioclase

Table 5. Chemical Analyses of Olivines, Bronzite and Spinel

	1o		2o		2r		2s*	
SiO_2	38.95		38.76		51.78		0.03	
TiO_2	0.13		0.15		0.23		0.34	
Al_2O_3	0.00		0.00		6.22		59.87	
Fe_2O_3	0.00		0.00		0.30		6.98	
Cr_2O_3	0.00				0.01		0.17	
FeO	18.44		18.65		11.78		14.22	
MnO	0.22		0.22		0.16		0.11	
MgO	41.78		41.97		27.49		17.48	
CaO	0.04		0.42		1.30		0.00	
Na_2O					0.12			
K_2O					0.00			
H_2O	0.21						0.45	
Total	99.77		100.17		99.74		99.65	
	O=4.000				O=6.000		O=32.000	
Si	0.997		0.988		1.850		0.006	15.979
Al	0.000		0.000		0.150		14.792	
Al	0.000	2.004	0.000	2.020	0.112	2.014		
Ti	0.002		0.003		0.006		0.054	
Fe^{3+}	0.000		0.000		0.008		1.099	
Cr	0.000				0.000		0.028	
Fe^{3+}	0.393		0.396		0.351		2.489	8.014
Mn	0.005		0.005		0.005		0.019	
Mg	1.603		1.605		1.474		5.506	
Ca	0.001		0.011		0.050		0.000	
Na					0.008			
K					0.000			
atomic %								
Ca					2.6			
Mg	80.1		80.0		78.1		60.4	
Fe	19.9		20.0		19.3		39.6	

* Refractive index $n=1.794$, and unit cell $a=8.123$ Å.

Table 6. Refractive Indexes and Estimated Compositions of Olivines

	1o	2o	3o	4o	5o	6o	7o	9o
β	1.692	1.693	1.702	1.695	1.693	1.693	1.692	1.692
Fa mol %	19	20	24	21	20	20	19	19

TABLE 7. CHEMICAL ANALYSES OF AUGITES

	1c	2c	3c	4c	5c	6c	7c	8c	9c
SiO_2	49.78	48.84	48.74	47.46	48.42	48.07	48.11	48.43	50.19
TiO_2	1.19	1.05	1.41	1.67	1.33	1.48	1.14	1.15	1.30
Al_2O_3	7.66	7.65	6.76	8.19	7.49	7.93	7.26	8.02	3.94
Fe_2O_3	1.91	2.59	3.23	3.14	2.50	2.66	3.13	2.68	3.33
Cr_2O_3	0.18	0.08	0.13	0.05	0.13	0.11		0.10	0.00
FeO	4.18	4.09	4.86	4.76	4.50	4.51	4.86	4.78	5.62
MnO	0.16	0.14	0.16	0.17	0.15	0.15	0.11	0.15	0.21
MgO	14.27	14.18	13.60	13.58	14.05	14.22	14.04	13.60	13.78
CaO	20.23	20.46	20.52	19.90	20.35	20.15	20.46	20.46	21.19
Na_2O	0.73	0.83	0.58	0.74	0.65	0.61	0.66	0.84	0.32
K_2O	0.07	0.04	0.02	0.03	0.05	0.02	0.04	0.04	0.06
H_2O				0.21	0.31		0.43		
Total	100.36	99.95	100.01	99.90	99.93	99.91	100.24	100.25	99.94
Si	1.814	1.794	1.800	1.758	1.788	1.771	1.782	1.781	1.864
Al	0.186	0.206	0.200	0.242	0.212	0.229	0.218	0.219	0.136
Al	0.142	0.125	0.094	0.115	0.113	0.114	0.099	0.128	0.036
Ti	0.033	0.029	0.039	0.046	0.037	0.041	0.032	0.032	0.036
Fe^{3+}	0.052	0.071	0.090	0.087	0.069	0.073	0.087	0.074	0.093
Cr	0.005	0.002	0.004	0.001	0.004	0.003		0.003	0.000
Fe^{2+}	0.127	0.125	0.150	0.147	0.139	0.138	0.150	0.147	0.174
Mn	0.005	0.004	0.005	0.005	0.005	0.005	0.003	0.003	0.007
Mg	0.780	0.781	0.753	0.755	0.778	0.786	0.775	0.750	0.768
Ca	0.790	0.805	0.753	0.790	0.805	0.795	0.812	0.806	0.843
Na	0.052	0.059	0.042	0.053	0.047	0.043	0.047	0.060	0.023
K	0.003	0.002	0.001	0.001	0.002	0.001	0.002	0.002	0.003
WXY	1.989	2.003	1.990	2.000	1.999	1.999	2.007	2.005	1.983
atomic %									
Ca	45.0	45.1	44.9	44.3	44.8	44.2	44.3	45.3	44.7
Mg	44.5	43.7	41.6	42.3	43.3	43.7	42.6	42.1	40.8
Fe	10.5	11.2	13.5	13.4	11.9	12.0	13.1	12.6	14.5
mol % *									
$CaAlFeSiO_6$		1.0	4.7	3.3	2.0	2.9	3.8	1.2	6.8
$CaAl_2SiO_6$	13.3	13.8	8.8	11.7	11.8	11.8	10.7	13.6	1.7
$NaAlSi_2O_6$	0.3								

* Calculated by Kushiro's method (Kushiro, 1962).

from spinel-bearing inclusions is clearly more sodic and different from that of magnetite-bearing inclusions (An_{78-66} and An_{87-84}, respectively). The compositions of calcic cores of plagioclase which occur as precipitated phenocrysts at an early stage from the alkali basalts, were estimated from optical properties to range from An_{75} to An_{58}. Thus the cores of the plagioclase phenocryst have essentially the same composition as the plagioclase in wehrlite and gabbro inclusions. The Iki plagioclase has up to 0.9 percent of total iron, but MgO, TiO_2 and MnO are negligible. It seems likely, therefore, that these components may be present both as impurities and/or, in the case of Fe^{3+} and Ti, as Al substitutions.

Olivine. The composition of olivine varies from Fa_{19} to Fa_{24} (Tables 5 and 6). The range of values for the cores of phenocrystic olivine in alkali basalts nearly the same (Fa_{14-24}). In contrast, olivine from dunite and peridotite inclusions in alkali basalts of Karatsu near Iki Island has a compositional range from Fa_8 to Fa_{17}. It falls within the range of variation of olivines from lherzolite inclusions in basalts throughout the world (Ross, et al., 1954) and is clearly more MgO-rich than that of the wehrlite-pyroxenite-gabbro inclusions and phenocrysts of alkali basalts.

Bronzite. Separation of bronzite is extremely difficult owing to its smallness in size and quantity and its alteration to olivine. Only one sample has been carefully purified from symplectite. No chemical analysis of bronzite in symplectite has previously been reported.

The most important feature of the bronzite is its high Al_2O_3 content which contrasts with the much lower Al_2O_3 contents of orthopyroxenes of igneous origin. Such highly aluminous orthopyroxenes occur only in ultrabasic and basic inclusions in nepheline or alkali basalt and allied rocks, eclogite or some granulite facies rocks formed under high pressure and low temperature conditions (Kuno, 1964, White, 1966, Eskola, 1952). Chemically, the bronzite closely resembles that found in Taka-sima near Iki (Kuno, 1964) and some websterite and clinopyroxenite inclusions of Hawaii (White, 1966). In addition, these orthopyroxenes from Iki, Taka-sima and Hawaii tend to have higher FeO content than those of the lherzolite inclusions.

Augite. As shown in Table 7, the augites from spinel-bearing inclusions have exceptionally high Al_2O_3, TiO_2 and Na_2O contents, despite the small range of values for FeO, MgO and CaO. The cation ratio Ca:Mg:Fe is 45:44.5 to 41.6:10.5 to 14.5, and the augites fall in a narrow field of the pyroxene system. Except for their Al_2O_3 and Na_2O contents the augites have compositions similar to those of phenocrystic augites in alkali basalts of Japan (Aoki, 1964, Uchimizu, 1966). There are also conspicuous differences between the clinopyroxenes of Iki inclusions and those of lherzolite inclusions in basalts; the former have higher TiO_2 and FeO and lower SiO_2, MgO, Na_2O and Cr_2O_3. Such augites have been reported from many localities, e.g. Karatsu near Iki (Kuno, 1964, Ishibashi, 1964, Yamaguchi, 1964), Oki, Japan (Uchimizu, 1966), Hawaii (White, 1966), Galápagos (McBirney and Aoki, 1966), Australia (Wilshire and Binns, 1963). It seems likely that they have a composition typical of augites in wehrlite, pyroxenite and gabbro inclusions.

The composition of augite from magnetite-bearing gabbro is similar to that of phenocrysts in alkali basalts.

Spinel. Spinel minerals form one of the most important group of accessory minerals in a wide range of ultrabasic and basic rocks. Spinel is a useful indicator of the stability relations of such rocks. Although chromian spinel and chromite have been studied by many investigators, the spinel-hercynite series has received little information in inclusions in alkali basalts. The $MgAl_2O_4$-$FeAl_2O_4$ spinel series seems to have a limited occurrence, being found only in certain wehrlite, pyroxenite and gabbro inclusions. Such spinels have been found not only in Iki Island, but in the other localities such as Karatsu (Yamaguchi, 1964), Galápagos (McBirney and Aoki, 1966), New South Wales (Wilshire and Binns, 1961) and Kerguelen (Talbot, *et al.*, 1963, McBirney and Aoki, unpublished).

As ferrous iron is not determined directly in the present spinel analyses, the composition is calculated assuming a partition of iron as FeO and Fe_2O_3 that results in a value of 1.0 for the ratio of $RO:R_2O_3$. As shown in Table 5, the spinel from gabbro inclusions of Iki Island is characterized by a high content of Fe_2O_3, placing it clearly in the spinel ($MgAl_2O_4$)—hercynite ($FeAl_2O_4$) series with a small amount of magnetite (Fe_3O_4) in solid solution. When calculated according to the end members, the Iki spinel is spinel ($MgAl_2O_4$) 68.5, hercynite ($FeAl_2O_4$) 23.8, picrochromite ($MgCr_2O_4$) 0.2, and magnetite ($FeFe_2O_4$) 7.5 mol per cent and has a ratio of spinel to hercynite of 74.2:25.8.

PETROGENESIS

Ultrabasic and basic inclusions in basaltic lavas have been reported from more than two hundred localities throughout the oceanic, orogenic, and continental regions of the world. Ultrabasic types are invariably found in alkali basalt and related rocks and never in silica-saturated lavas. The more common gabbroic types occur in both alkali basalt and silica-saturated lavas (Forbes and Kuno, 1965). In Hawaii there are two distinct types of inclusions which are distinguished by their mineralogy: 1) the lherzolite group and, 2) a group that includes dunite, wehrlite, feldspathic peridotite, and pyroxenite (White, 1966). The lherzolite group occurs preferentially in nepheline basalt and allied rocks, while the second group is found principally in alkali basalt and allied rocks, but also in nepheline basalt. Both types may be associated with subordinate gabbro. The Iki rocks are alkali basalts and related rocks and their ultrabasic and basic inclusions correspond to the second types of Hawaiian inclusions. Gabbro is the predominant rock type, however, and differs from the gabbro of Hawaii. White (1966) has suggested that the dunite-wehrlite-gabbro suite is produced at a shallower depth than that at which lherzolite inclusions originated. Less attention has been given to the petrogenesis of the wehrlite-gabbro group than to that of lherzolites. The former is characterized by a diverse mineral assemblage, variable modal composition, broad compositional changes of each essential constituent, and complex equilibrium relations. It is especially difficult, therefore, to interpret their origin.

Spinel-bearing inclusions are of especial petrologic interest. In this group are found symplectite intergrowths of aluminous augite, aluminous bronzite and spinel; these are thought to be produced by reaction of Mg-rich olivine and calcic plagioclase under high pressure conditions. Recent experimental work at high pressures and temperatures on the systems $CaAl_2Si_2O_8+Mg_2SiO_4$, and $CaAl_2Si_2O_8+MgSiO_3$ (Kushiro and Yoder, 1966) and on rock compositions (Ringwood and Green, 1966), however, offer data that helps interpretation of wehrlite-gabbro inclusions.

This experimental data, together with mineralogic and petrographic relations of spinel-bearing inclusions indicate that the inclusions are derived from their enclosing alkali basalts, and are cumulus phases or clots of phenocrysts concentrated by gravity settling at a depth of 25 to 35 km below the surface. The basis for this conclusion will now be described in detail.

One of the most important facts is the chemical similarity of the three essential constituents, olivine, augite and plagioclase of the inclusions to phenocrysts in alkali basalts of the Iki area. The only exception is augite, which is more aluminous in inclusions. TiO_2 contents of the Iki augites from both inclusions and basalts, which can be calculated as $CaTiAl_2O_6$, are clearly higher than those of tholeiitic pyroxenes. The proportion of $CaTiAl_2O_6$ appears to be related to the chemical environment of crystallization (Kushiro, 1960, Le Bas, 1962). According to the synthetic study on titanaugites (Yagi and Onuma, 1966), the extent of solid solution in diopside is up to 11 weight percent $CaTiAl_2O_6$ at 1 bar, but that is very low at higher than 10 kb. They have concluded that the titanaugite would not be produced at high pressure condition. It suggests that the augites of the Iki inclusions probably crystallized at less than 35 km. The concentration of the $CaAl_2SiO_6$ and $NaAlSi_2O_6$ components, however, seem to be related to physical conditions, as has already been pointed out by many petrologists. It is probable that the solubility of $CaAl_2SiO_6$ component in diopsidic clinopyroxenes is higher at high pressures. If the $CaAl_2SiO_6$ component is calculated by Kushiro's method (1962), augites from the Iki inclusions contain 8.8 to 13.8 mol percent and those of phenocrysts from basalts 0 to 10 percent. Averages are 11.9 and 2.7 percent respectively (Aoki, 1964 and this paper). Despite considerable overlap of values, the average percentages are clearly different. The only analysed clinopyroxene that contains a $NaAlSi_2O_6$ component is the augite of column No. 1, Table 4 the composition of which includes only 0.3 percent $NaAlSi_2O_6$.

Huge augite crystals (up to 3 cm in size) with well developed crystal faces occur in alkali basalt from Karatsu. They are assoicated with bronzite and andesine crystals and inclusions of the dunite-wehrlite-gabbro group (Kuno, 1964). These augites have from 6.9 to 17.8 percent $CaAl_2SiO_6$ and an average of 11.2 percent or about the same as those of Iki Island. One contains 1.3 percent of $NaAlSi_2O_6$ as well.

Kuno (1964) has suggested that on the basis of experimental data that Karatsu augites crystallized from an alkali basalt magma in the lower crust or upper mantle at a depth of as much as 70 km. The thickness of the crust of the Iki area is about 35 km (Kanamori, 1963). The augites consequently formed in the upper mantle.

More recent experimental work by Lindsley (1966) has shown that calcic plagioclase begins to melt incongruently to corundum+liquid at pressure near 10 kb and the region of congruent melting is confined to successively more sodic compositions with increasing pressure. Therefore, the Iki inclusions containing calcic plagioclase such as gabbro and plagioclase bearing wehrlite would be produced at less than 35 km also.

It seems reasonable to conclude, therefore, that the spinel-bearing wehrlite-pyroxenite-gabbro inclusions of Iki Island were formed directly from an alkali basalt magma in the lower part of the crust at depths of the order of less than 35 km.

The pyroxene-spinel symplectite relation to olivine and plagioclase holds the key to interpreting the depth of origin of spinel-bearing inclusions, because the reaction is very sensitive to P-T conditions. Forsterite +anorthite changes with increasing pressure first to an intermediate assemblage of aluminous diopside+aluminous enstatite+spinel and secondly to a garnet-bearing assemblage (Kushiro and Yoder, 1966). Although inclusions with coexisting olivine and plagioclase occur in alkali basalt and related rocks throughout the world, pyroxene-spinel symplectites found in lavas derived from more deep-seated conditions are only known from Iki and Kerguelen Islands (McBirney and Aoki, unpublished).

Kushiro and Yoder (1966) have shown that the reaction between forsterite and anorthite is given by the equation:

Low pressure High pressure

$$\underset{\text{forsterite}}{Mg_2SiO_4}+\underset{\text{anorthite}}{CaAl_2Si_2O_8}\rightarrow\underset{\text{aluminous diopside}}{CaMgSi_2O_6\cdot nCaAl_2SiO_6}+\underset{\text{aluminous enstatite}}{MgSiO_3\cdot nMgAl_2SiO_6}+\underset{\text{spinel}}{(1\text{-}n)MgAl_2O_4}$$

where n is estimated to be between 0.3 and 0.46 depending on pressure and temperature and the molecular ratio of forsterite to anorthite. The chemical formula of the bronzite in the Iki symplectite can be presented as $85.3(Mg,Fe)_2Si_2O_6\cdot 2.2Ca_2Si_2O_6\cdot 12.5MgAl_2SiO_6$. Its most notable feature is its high content of $MgAl_2SiO_6$ (12.5%), which is the highest value so far reported for an orthopyroxene from an inclusion. There is, however, a remarkable difference between the n values of synthetic and natural bronzite, namely 0.3 to 0.46 and 0.125, respectively. It is not clear why there is such a discrepancy in yield.

According to Kushiro and Yoder (1966), reaction between forsterite and anorthite takes place at 9 kb at 1300°C and at 8 kb at 1100°C. The fact that the plagioclase (An_{77-66}) is not pure anorthite and the olivine (Fa_{19-24}) is not pure forsterite requires that there reaction products include Fe and Na. The presence of albite and fayalite components will also result in a shift of the field boundary to a lower pressure range side (Kushiro, oral communication), but an accurate evaluation of this effect is not yet possible. Experimental melting of natural basalts at various pressures indicate that the temperature of an alkali basalt magma is about 1100°C to 1300°C at 1 bar. Solid-state reaction between plagioclase and olivine to produce pyroxene-spinel symplectite probably took place at less than 8kb or a depth less than about 25 km.

The reaction of bronzite with the basalt magma already described shows that the alkali basalt magma cannot precipitate orthopyroxene as ordinary phenocrysts under low pressure conditions.

Summary Model for the Origin of the Spinel-bearing Inclusions

Spinel-bearing wehrlite, clinopyroxenite and gabbro inclusions of Iki Island were precipitated from the host alkali olivine basalt magma at pressures near 8 kb. Inclusions containing plagioclase+olivine+spinel +augite formed near 8 kb, and those lacking plagioclase possibly also formed at the nearly same condition with the former from their mineralogy and petrography. At a depth of about 25 km, the magma crystallized phenocrysts of olivine, aluminous augite, calcic plagioclase, and spinel. The phenocrysts and glomerocrysts were segregated as crystal cumulates.

At this depth, which corresponds to the lower part of the crust in this region, and at igneous temperatures (1100° to 1300°C) the pressure is approximately that at which forsteritic olivine and anorthitic plagioclase may react to form aluminous augite+aluminous bronzite+spinel. With moderate decline in temperature, (or slight increase in pressure) the inclusions passed from the olivine+plagioclase field into the pyroxenes +spinel field, and the original assemblage was partially transformed to symplectite by solid reaction, Subsequently, the inclusions were carried to the surface by the enclosing magmas.

The rarity of plagioclase-bearing wehrlite, clinopyroxenite and gabbro inclusions which contain pyroxene-spinel symplectite may be due to the fact that the univariant curve has a very steep $\Delta P/\Delta T$ and only under very special conditions may the assemblage both pass from the low-pressure field to the high pressure one with falling temperature, and remain available for transport to the surface.

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