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SPINELS IN BASALTIC LAVAS AND ULTRAMAFIC INCLUSIONS OF OSHIMA-OSHIMA VOLCANO, NORTH JAPAN

by

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(with 4 tables and 4 text-figures)

Abstract

Spinel and olivines in the alkali basalts and in the ultramafic inclusions cognate with the basalts of Oshima-Ōshima volcanic island, north Japan, were analysed. When the compositions of spinels in olivine phenocryst in the basalts plot in terms of Cr-Al-Fe³⁺ ratio, the crystallization trend proceeds from Cr-rich corner towards Fe³⁺ corner associated with an increase in Al/(Cr+Al) ratio. The spinels in the wehrlite and olivine-clinopyroxene inclusions have the same trend, while those in the dunite inclusions which are the most aluminous among inclusions have a different trend.

The olivine phenocrysts in the basalts and the olivines in the inclusions are clearly classified in terms of CaO contents considered to be controlled by pressure. The data obtained in this study show that the compositions of spinels in wehrlite and olivine-clinopyroxene inclusions and in the olivine phenocryst of basalts, are mainly controlled by the chemistry of host magma. The petrography and chemistry indicate that the magma crystallizing dunite inclusions is lower in Al₂O₃ content than that crystallizing other inclusions, and that the dunite inclusions are formed at a deeper place than the other inclusions. Therefore, the enrichment of aluminum in the spinels of the dunite is probably due to high pressure rather than the chemistry of host rock.

Introduction

Composition of spinel is controlled by various factors (bulk chemistry, pressure, temperature and oxygen fugacity) of the magma crystallizing spinel (Irvine, 1965, 1967; Thompson, 1973; Hill and Roeder, 1974; Haggerty, 1979; Shiraki et al., 1979), it is therefore important to decide the main factor that controls the chemistry of spinel.

Nagao et al., (1980) who investigated the spinels in the Misasa alkali basalts and the Chōkai calc-alkali andesites suggested a possibility that chemistry of spinel is governed by the chemical composition of host magma as well as pressure. In a comment on this conclusion, Shiraki et al., (1981) stated that excess Al₂O₃ in spinel is effected by pressure rather than chemical composition of host rock. In a reply to this comment Nagao et al. (1981) pointed out the necessity to set up the standard in judging "the excess Al₂O₃" and stated that normalizing the host rock chemistry by the SiO₂, Al₂O₃ and Cr₂O₃ contents is an effective method, when spinel chemistries are compared with each other.

From this point of view, it is interesting to investigate the composition of spinels which occur in basalts and in ultramafic inclusions cognate with basalts. In this paper the petrochemical data of the basalts and the mineralogical data of spinels in the basalts and the ultramafic inclusions of Oshima-Ōshima volcano are presented and their crystallization trends are discussed.

Geological and Petrological Background

Oshima-Ōshima volcanic island is situated about 50km west to the Japan Sea coast, southwestern Hokkaido, and composed of a triple stratovolcano, i.e. Higashi-yama somma, Nishi-yama somma, and Central cone. Although the Central cone is made up of only alkali olivine basalts, the others are alkali olivine basalts and calc-alkali andesites. Ultramafic and mafic inclusions occur in the andesites and rarely in the basalts.

In major element chemistry of the volcanic rocks from Oshima-Ōshima, almost continuous variation curves can be traced from basalt to andesite without notable break. The ultramafic and mafic inclusions were formed as cognate cumulates in the basalts and the andesites, judging from their textures, gradual variation of modal composition, and dependence of K_2O in hornblende and TiO_2 in spinel on the chemistries of the basalts and andesites in this volcano (Yamamoto et al., 1977, Yamamoto, 1978).

Table 1 Chemical analyses of basalts.

	1	2	3	4	5
SiO_2	47.75	48.71	49.60	50.92	52.31
TiO_2	0.79	0.99	0.95	0.93	0.95
Al_2O_3	13.26	16.16	17.06	18.26	17.54
Fe_2O_3	3.01	6.09	2.36	1.89	4.83
FeO	6.57	4.18	6.88	5.79	5.02
MnO	0.08	0.13	0.09	0.12	0.10
MgO	15.13	8.78	5.96	5.53	4.03
CaO	9.70	11.06	11.05	9.98	8.42
Na_2O	2.04	2.16	2.70	3.13	3.63
K_2O	1.07	1.32	1.54	1.91	2.40
P_2O_5	0.31	0.38	0.42	0.42	0.53
$H_2O(+)$	0.64	0.78	0.45	0.56	0.25
$H_2O(-)$	0.02	0.02	0.13	0.06	0.08
Total	100.37	100.76	99.19	99.50	100.09

1: augite olivine basalt, Nishi-yama upper lava (Nu-104) 2: olivine augite basalt, the scoria of Nishi-yama ejecta (Ne-56) 3: olivine augite basalt, Higashi-yama upper lava (Hu-100) 4: olivine augite basalt, Central cone lava (Cl-119) 5: olivine augite basaltic andesite, Nishi-yama lower lava (Nl-14)

analysis from Yamamoto (1977)

Mineralogy

Chemical analyses were carried out using the electron microprobe, JSM-50A at Government Industrial Laboratory, Hokkaido and the correction was made by the method of Bence and Albee (1968).

Spinel in basalts

The host rocks of the present spinels are Higashi-yama upper lava (Hu-100), Nishi-yama

lower lava (Nl-14), Nishi-yama upper lava (Nu-104), Central cone lava (Cl-119), and the scoria of Nishi-yama ejecta (Ne-56). Their bulk composition are given in Table 1. Most spinels are included in the olivine phenocrysts, but some spinels in Nu-104 occur as large phenocryst with thin magnetite rim. The selected chemical analyses by microprobe are listed in Table 2.

Table 2 Selected microprobe analyses of the spinels in the basalts

	1	2	3	4	5	6	7	8	9	10
TiO ₂	0.25	0.54	0.55	0.51	1.58	10.34	0.58	2.01	10.71	11.64
Al ₂ O ₃	6.94	10.77	15.85	16.85	8.71	4.45	15.64	12.75	6.08	5.89
Cr ₂ O ₃	56.15	48.40	42.48	40.56	33.29	3.91	32.90	26.44	0.56	0.38
Fe ₂ O ₃	6.50	8.75	10.40	10.44	24.58	39.71	19.31	27.05	42.16	40.56
FeO	22.66	24.84	21.03	20.55	25.67	35.71	21.34	26.04	36.84	37.72
MnO	0.54	0.56	0.36	0.33	0.37	0.37	0.32	0.46	0.48	0.51
MgO	6.51	5.59	8.71	8.85	5.46	3.01	8.21	6.04	3.06	2.96
Total	99.55	99.45	99.38	98.09	99.66	97.50	98.30	100.79	99.89	99.66
Cr/(Cr+Al)	0.844	0.751	0.643	0.618	0.719	0.371	0.585	0.582	0.058	0.041
Fe ³⁺ /(Cr+Al+Fe ³⁺)	0.085	0.114	0.130	0.131	0.336	0.782	0.441	0.362	0.807	0.808
Mg/(Mg+Fe ²⁺)	0.339	0.286	0.425	0.434	0.275	0.131	0.407	0.293	0.129	0.123

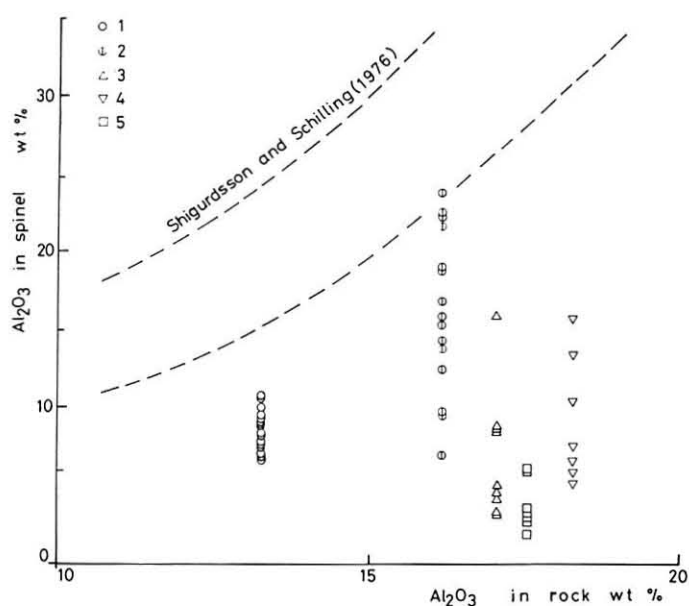
1 – 2: augite olivine basalt (Nu-104) 7 – 8: olivine augite basalt (Cl-119)

3 – 4: olivine augite basalt (Ne-56) 9 – 10: olivine augite basaltic andesite (Nl-14)

5 – 6: olivine augite basalt (Hu-100) Fe₂O₃ were calculated assuming stoichiometry

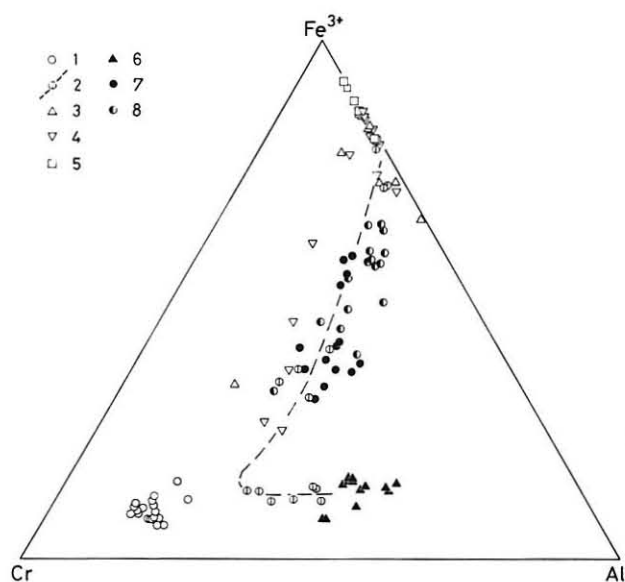
The relationship of the Al₂O₃ contents of bulk composition of basalts and those of spinels in the basalts are shown in Text-fig. 1. Since the separation of plagioclase from basaltic magma is delayed under the hydrous condition, the Al₂O₃ content increases as differentiation of basaltic magma proceeds (Yamamoto et al., 1977). The Al₂O₃ contents of the spinels in Nu-104 and Ne-56 seem dependent on the variation of the Al₂O₃ contents in the host basalts caused by differentiation. This is consistent with the observation of Sigurdsson and Schilling (1976) that the chemistry of spinels in MAR basalts depends on the chemistry of host rock. The Al₂O₃ contents of spinels rich in magnetite component are low; the spinels in Hu-100, Nl-14, and Cl-119 are lower in Al₂O₃ content than in Nu-104 and Ne-56.

Text-fig. 2 shows the plots of spinels in the Cr-Al-Fe³⁺ diagram. The spinels in Nu-104 have the highest Cr content, whereas the others are higher in the Fe³⁺/Cr+Al+Fe³⁺ and Al/Cr+Al ratios. Since the Mg/Mg+Fe²⁺ ratios of spinels decrease and the Fe³⁺/Cr+Al+Fe³⁺ ratios increase as crystallization of basalts proceeds, a trend in Text-fig. 2 which shows a compositional variation of spinels from Cr to Fe³⁺ corner associated with an increase in the Al/Cr+Al ratio, represents a crystallization course of spinel in the basalt. However, it is worthy of notice that some spinels in Ne-56 which are low in Fe³⁺ have a strange trend that reaches the area shown by the spinels in the dunite.



Text-fig. 1 Plot of Al_2O_3 content in spinels versus Al_2O_3 content of whole rock.

1: augite olivine basalt (Nu-104), 2: olivine augite basalt (Ne-56), 3: olivine augite basalt (Hu-100), 4: olivine augite basalt (Cl-119), 5: olivine augite basaltic andesite (Nt-14)



Text-fig. 2 Cr-Al- Fe^{3+} diagram of spinels.

1-5: same as Text-fig. 1, 6: dunite, 7: wehrlite 8: olivine-clinopyroxenite

Spinels in ultramafic inclusions

The host rocks of this spinels are dunite, wehrlite and olivine-clinopyroxenite. Spinels in the dunite occur in the grain boundaries between olivines in some cases and are included in the olivines in other cases. Spinels in the wehrlite and olivine-clinopyroxenite are included in the olivines. The selected chemical analyses are listed in Table 3. As shown in Text-fig. 2,

two trends of spinels are clearly distinguished each other in terms of their host, dunite and wehrlite—olivine-clinopyroxenite. The spinels in the wehrlite and olivine-clinopyroxenite are scattered in the wide range of Fe^{3+} , whereas those in the dunite plot in a narrow area. Although spinels in the wehrlite and the olivine-clinopyroxenite have the ratios of $\text{Fe}^{3+}/\text{Cr}+\text{Al}+\text{Fe}^{3+}$ more than 0.3, a trend in Cr-Al- Fe^{3+} diagram proceeds towards the Fe^{3+} corner with a decrease in the Cr/Cr+Al ratio. On the other hand, there is an area of spinels in the dunite plotted apart from the trend of spinels in the wehrlite and olivine-clinopyroxenite. The compositions of spinels in the dunite are higher in the Al/Cr+Al ratio than the others and they seem to show a trend along which the Cr/Cr+Al ratio decreases with an increase of Fe^{3+} .

Table 3 Selected microprobe analyses of the spinels in the inclusions

	1	2	3	4	5	6	7	8	9	10	11	12
TiO ₂	0.48	0.49	0.53	0.42	0.65	0.58	1.14	3.61	0.56	1.24	1.04	5.08
Al ₂ O ₃	28.97	27.88	30.93	26.43	17.20	15.74	19.31	11.67	12.83	15.37	13.23	10.92
Cr ₂ O ₃	32.92	29.11	26.54	30.61	24.34	23.81	18.48	10.09	30.90	17.80	19.63	6.47
Fe ₂ O ₃	8.93	12.08	12.25	12.43	25.72	28.55	29.87	40.53	24.96	33.83	34.70	43.23
FeO	14.38	15.72	16.11	16.68	22.65	23.96	23.85	28.44	22.92	24.29	24.46	29.00
MnO	0.18	0.29	0.27	0.19	0.29	0.27	0.32	0.27	0.43	0.39	0.34	0.37
MgO	14.75	13.30	13.70	12.66	7.53	6.73	7.66	5.05	7.03	6.74	6.33	5.59
Total	100.61	98.87	100.33	99.42	98.38	99.64	100.63	99.66	99.63	99.66	99.73	100.66
Cr/(Cr+Al)	0.433	0.412	0.365	0.437	0.487	0.504	0.391	0.367	0.618	0.437	0.499	0.284
$\text{Fe}^{3+}/(\text{Cr}+\text{Al}+\text{Fe}^{3+})$	0.100	0.140	0.138	0.145	0.329	0.365	0.376	0.584	0.322	0.442	0.456	0.644
Mg/(Mg+Fe ²⁺)	0.646	0.601	0.603	0.575	0.372	0.334	0.364	0.240	0.354	0.331	0.316	0.256

1 – 4: dunite 5 – 8: wehrlite 9 – 12: olivine-clinopyroxenite

Fe₂O₃ were calculated assuming stoichiometry

Olivine in basalts and ultramafic inclusions

The Fo contents of olivine phenocrysts in the basalts range as follows: 92.1-72.7 (Nu-104), 88.7-76.2 (Ne-56), 72.8-67.8 (Cl-119) and 69.3-60.0 (Ni-14). The cores, rims and contact parts with spinels were analysed by microprobe. The selected chemical analyses are listed in Table 4. The highest value of Fo contents of each basalt increases with increasing MgO/MgO+FeO ratio of bulk chemistry of their host rocks. Taking FeO-MgO distribution between host rock and the olivine with the highest Fo content into account, KD ($(\text{FeO}/\text{MgO})^{\text{ol}}/(\text{FeO}/\text{MgO})^{\text{liq}}$, Roeder and Emslie, 1970) are obtained with the following results: 0.33 (Nu-104), 0.28 (Ne-56), 0.65 (Cl-119), and 0.46 (Ni-14). Since the KD values of Cl-119 and Ni-14 are too high, it is unlikely that the liquid which have such bulk compositions as Cl-119 and Ni-14 produce these olivines as liquidus mineral. The high KD values probably caused by the deficiency of the number of points analysed. Furthermore, the points analysed are confined to the contact parts with spinel in Cl-119 and Ni-14. This is the reason why the liquidus olivines in Cl-119 and Ni-14 could not be found yet. Therefore, most olivines crystallize at liquidus temperatures or from residual liquid. However, it is interesting to note that KD of Ne-56 is lower than 0.34 (Hermes and Schilling, 1975) and 0.3 and that, as mentioned earlier, the trend of the spinels starts at the area where the spinels

Table 4 Selected microprobe analyses of the olivines in the basalts and inclusions

	1	2	3	4	5	6	7	8	9	10
SiO ₂	40.77	39.91	38.93	37.29	40.23	40.09	41.09	37.91	37.47	38.58
TiO ₂	0.07	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al ₂ O ₃	0.04	n.d.	n.d.	n.d.	0.03	0.06	0.00	0.01	0.02	0.02
FeO	7.89	13.88	24.44	27.48	13.61	13.90	19.43	21.81	21.16	22.81
MnO	0.15	0.17	0.50	0.57	0.26	0.28	0.32	0.40	0.93	0.46
MgO	50.86	45.41	37.37	34.75	45.75	46.25	40.09	39.10	39.49	38.52
NiO	0.33	0.16	0.09	0.00	0.26	0.23	0.30	0.15	n.d.	n.d.
CaO	0.15	0.17	0.18	0.29	0.03	0.04	0.14	0.14	0.11	0.10
Total	100.27	99.70	101.51	100.38	100.17	100.86	101.68	99.38	99.18	100.49
Mg/Mg+Fe	0.919	0.854	0.728	0.693	0.855	0.853	0.785	0.758	0.761	0.747

1: augite olivine basalt (Nu-104)

5 – 6: dunite

2: olivine augite basalt (Ne-56)

7 – 8: wehrlite

3: olivine augite basalt (Cl-119)

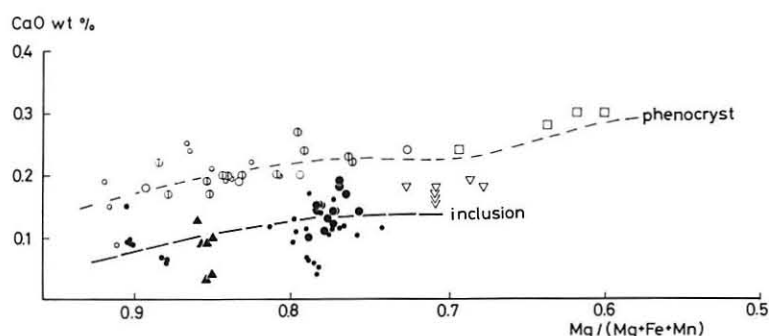
9 – 10: olivine-clinopyroxenite

4: olivine augite basaltic andesite (NI-14)

in dunites plot.

The Fo contents of olivines contacting with spinels have the following ranges: 86.2-85.2 (dunite), 79.1-75.8 (wehrlite). These data plot in Text-fig. 3 with olivines in other specimens (dunite, wehrlite and olivine-clinopyroxenite).

The relationship the ratio of Mg/(Mg+Fe+Mn) and CaO content of olivines in the basalts and the ultramafic inclusions are illustrated in Text-fig.3. The CaO contents of olivines in the ultramafic inclusions are lower than those of the olivine phenocrysts in the basalts, and they are hardly overlapped. According to Simkin and Smith (1970), the former can be classified into "inclusion and plutonic olivine" and the latter "extrusive and hypabyssal olivine".



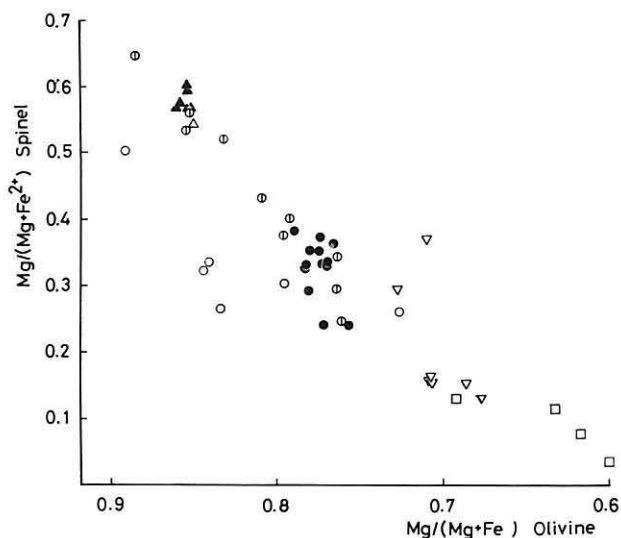
Text-fig. 3 CaO-Mg/(Mg+Fe+Mn) diagram of olivines in contact with spinels.

symbols, the same as Text-fig. 1 and 2, small open circle: other olivine phenocryst in basalt (Nu-104 and Ne-56), small solid circle: other olivines in ultramafic inclusions (dunite, wehrlite and olivine-clinopyroxenite)

Discussion

Simkin and Smith (1970) suggested a dependence of CaO content in olivine on pressure from their data on minor elements in olivine from various rock types. Stormer (1973) investigated the CaO zoning of olivine phenocrysts from volcanic rocks and stated that the pressure release during crystallization causes an increase of the CaO content in olivine and the stable pressure conditions do not lead an increase of CaO content with increasing of FeO content. These authors pointed the pressure dependence of CaO content in olivine. However, Takahashi (1979) interpreted that the CaO content is controlled by temperature.

In Oshima-Oshima, as mentioned earlier, since the inclusions are cognate cumulates, if CaO content of olivine depends only on chemistry of magma, only one trend must be present in the CaO-Fo diagram of phenocryst and inclusion olivines. Two trends, however, are observed in Text-fig. 3, suggesting that the pressure and/or temperature effect on the CaO content of olivines. The relationship of the $Mg/(Mg+Fe^{2+})$ ratio of olivines and spinels being contact with each other is illustrated in Text-fig. 4. It shows a positive correlation. The spinels in Nu-104 have low $Mg/(Mg+Fe^{2+})$ ratio, indicating that the spinels suffer the strong effect of cooling. The relationship between the temperature calculated by olivine-spinel geothermometer (Roeder et al., 1979) and Fo content of the olivines except Nu-104 has a positive correlation and both phenocrysts and inclusions have the same trend. Therefore, the CaO content seems to be independent on temperature, and the difference of CaO content between phenocrysts and inclusions may be due to the difference of the pressure at which they are crystallized.



Text-fig. 4 Correlation between $Mg/(Mg+Fe^{2+})$ in spinels and olivines being contact with the spinels. Symbols same as Text-fig.1 and 2.

Nevertheless, no distinct difference in the chemistry of spinels is observed, and the trends of spinels both in the basalts and inclusions except dunite are overlapped in the Cr-Al-Fe³⁺ diagram (Text-fig. 2). Therefore, it is more likely that spinel chemistry is controlled by the composition of host magma in the pressure range in which the phenocrysts

and the wehrlite —olivine-clinopyroxenite inclusions are formed.

In the Oshima-Ōshima volcano, the fractionated olivine-clinopyroxenite and hornblende gabbro inclusions, which played an important role on the differentiation of basaltic magma to andesitic magma, would be formed at the shallow place in the crust (Yamamoto et al., 1977). However, as stated before, spinels in the inclusions formed such a low pressure have similar Al_2O_3 content to those in olivine phenocrysts formed near the surface from the magma that ascends after the suffuring the fractionation.

According to the experimental study on the Appollo 14 rock by Green et al., (1973) Al_2O_3 content of spinel increases only about 7 wt% with an increase of pressure from 5 kb to 7 kb. Jaques and Green (1980) investigated the chemistry of the spinels produced as residual phase of the partial melting of the peridotites, and stated that chrome spinels near the solidus at low pressure (2–5 kb) were distinctly more chrome-rich than those at higher pressure (10–15 kb). Their experimental data showed that the variations of Cr/Cr+Al ratio of the spinels at the pressure difference of 3 kb (2 kb–5 kb) at 1300°C are constant or weak.

In Oshima-Ōshima, the dunite inclusions are found in small amounts and they are small in size ($2 \times 3\text{cm}$) and angular, while the olivines in other two inclusions do not. The olivines included in this rock have always kinkbands. Therefore, the dunite inclusions would have formed as fractionation products from magma at deeper place than the other two inclusions. Al_2O_3 contents of spinels in the dunite are 12 to 20 wt% higher than those in the wehrlite and the olivine-clinopyroxenite inclusions.

Judging from the experimental result of Jaques and Green (1980), this difference in Al_2O_3 content of spinel is due to the pressure rather than bulk composition of host liquid. The discussion stated above leads a conclusion that the enrichment of aluminium depends mainly on the high pressure rather than the chemistry of host magma. Some olivine phenocrysts in the basalts may be transported from the dunite inclusion: for example Ne-56 which has more aluminous trend of spinels (Text-fig. 2) and less KD.

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