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Geochemistry of the Kwanaksan alkali feldspar granite: A-type granite?

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ABSTRACT : The Jurassic Kwanaksan stock, so far known to be composed of biotite granite only, has the mineral assemblage of quartz + K-feldspar + plagioclase + biotite ± garnet. The lithology of the stock is classified as alkali feldspar granite by their mode and plagioclase compositions (An<5). Subsolvus feldspars, rather early crystallization of biotite, and shallow emplacement depth estimated from Q-Ab-Or diagram suggest hydrous nature of the magma, which contrasts with anhydrous A-type like geochemistry described below. Major and trace element compositions of the Kwanaksan stock are distinct from those of the adjacent Seoul batholith, suggesting a genetic difference between the two. The Kwanaksan stock shows geochemical characteristics similar to A-type granite in contrast to most other Mesozoic granites in Korea, in that it has high SiO_2 (73~78 wt%), Na_2O+K_2O, Ga (27~47 ppm), Nb (22~40 ppm), Y (48~95 ppm), Fe/Mg and Ga/Al, and low CaO (<0.51 wt%), Ba (8~75 ppm) and Sr (2~23 ppm). However, it has lower Zr and LREE and higher Rb (384~796 ppm) than typical A-type granite. LREE-depleted rare earth element pattern with strong negative Eu anomaly of previous studies is reinterpreted as representing source magma characteristics. The residual material during partial melting is not compatible with pyroxenes, amphibole or garnet, while significant amount of plagioclase is required. Similarity of geochemistry of the Kwanaksan stock to A-type granite suggests the origin of the stock has a close relationship with that of A-type granite. These observations lead us to propose that the Kwanaksan stock was formed by partial melting of felsic source rock.

Key word : Kwanaksan stock, alkali feldspar granite, A-type granite, felsic source

INTRODUCTION

A-type granite has been defined traditionally as alkaline, anhydrous, and anorogenic one (e.g., Collins *et al.*, 1982). It is geochemically distinct from other granites, in that it has high SiO_2, K_2O+Na_2O, Fe/Mg, Ga/Al, Ga, Nb, Zn and REE, and low CaO, Ba, and Sr. It has been commonly considered that A-type granite forms by anhydrous partial melting of residual material from which I-type melt has been extracted previously.

Recently petrogenesis and tectonic setting of A-type granite are being reexamined. Whalen *et al.* (1987) stated that the setting of A-type granite needs not to be restricted to anorogenic. Creaser *et al.* (1991) argued that A-type granite can form by direct partial melting of tonalite to granodiorite. Moreover, Clark (1992) has suggested to discard the term 'A-type' because it does not refer to source characteristics, while I- or S-type does.

The Kwanaksan granite is a small pluon of Mesozoic age intruding the Kyonggi massif. The pluton has been usually thought as differentiation product of the Seoul granitic batholith to the north because of geographic proximity of the two (Hong, 1984; Park and Chi, 1994). For example, Hong (1984) suggested from geochemical consideration that the Kwanaksan granite was formed from differentiation of the Seoul granite by fractionation of feldspar. However, we noted from reported geochemical data (Hong, 1984; Park and Chi, 1994) that the geochemistry of the Kwanaksan granite appears to be quite distinct from common Mesozoic granites in Korea. And we suspected that the Kwanaksan pluton could be anther example of A-type granite. So far, several A-type gra-

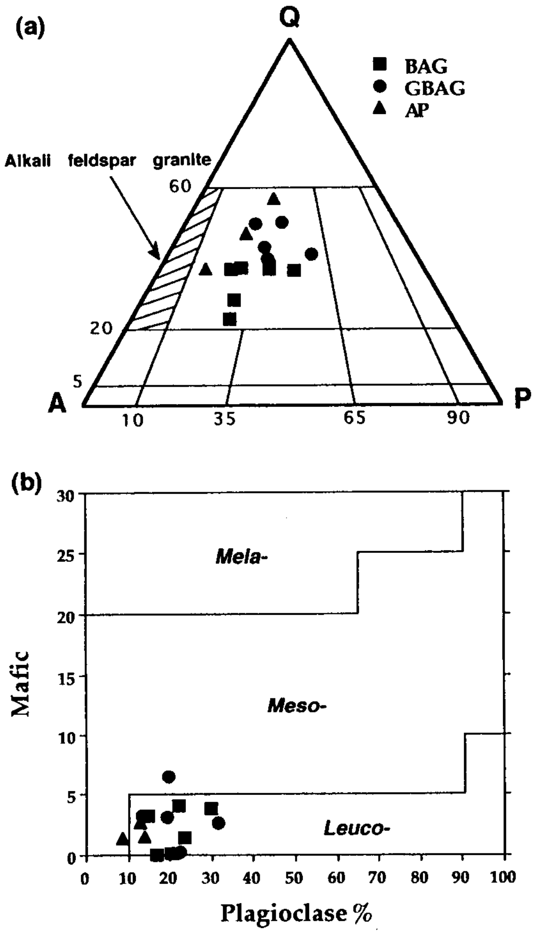

Fig. 2. Q-A-P (a) and Plagioclase%-Mafic (b) diagrams from mode data. Although the data plot in granite field, they should plot in the alkali feldspar granite field according to IUGS classification, since An contents of plagioclases are less than 5. Abbreviations: BAG, biotite alkali feldspar granite; GBAG, garnet biotite alkali feldspar granite; AP, aplite.

solvus monzogranite of typical S-type. Recently Park and Chi (1994) reported detailed petrography and geochemistry for the granites associated with the Anyang feldspar mine. Kim (1971) reported a K-Ar muscovite age of 171 Ma, which is similar to the emplacement age(~160 Ma) of the Seoul batholith.

PETROGRAPHY

Overall, the Kwanaksan stock has a mineral assemblage of quartz + K-feldspar + plagioclase + biotite ± garnet with secondary muscovite and chlorite. Although some muscovites appear primary, their chemical compositions with low TiO$_2$ content (0~0.34 wt%) are similar to those of the secondary ones which occur ubiquitously. Mode data for the Kwanaksan stock are listed in Table 1 and are plotted in QAP (Fig. 2a) and plagioclase %-mafic diagrams (Fig. 2b) of IUGS classification (Streckeisen, 1976). All the samples analyzed in this study have lower plagioclase/K-feldspar than the two samples reported by Hong (1984), and can be regarded as leucogranite due to low content of mafic phases when considered with mode data only (Fig. 2b). However, they are classified as alkali feldspar granite because plagioclase compositions are less than An$_{34}$. In the following, we describe the lithology of the stock into biotite granite and garnet biotite granite for simplicity.

Biotite Granite

Biotite granite is medium-grained and shows equigranular texture. It consists of quartz, K-feldspar, plagioclase, biotite, zircon, muscovite and chlorite. Muscovite occurs as the secondary phase inside plagioclase and K-feldspar, and secondary chlorites often replace biotite.

Plagioclase (An$_{0\sim1.4}$) is subhedral to anhedral and 2~4 mm in diameter, and sometimes occurs as inclusion in quartz, in K-feldspar, and rarely in biotite. Secondary muscovite grows in most plagioclases. Myrmekite is often observed. Some grains are bent.

K-feldspar consists of microcline and orthoclase. Perthitic textures are well developed as patchy- or string-type. Microcline grains sometimes have inclusions of quartz and plagioclase. Some orthoclase grains have subhedral plagioclase inclusions and some form graphic textures in contact with quartz. Sericite is developed in some grains.

Quartz grains are anhedral and 0.5~6 mm in diameter. Many show wavy extinction and sutu-

Table 2. Major and trace element data of the Kwanaksan alkali feldspar granite

Rock type	Biotite alkali granite								Garnet-biotite alkali granite							Aplite			Korea standard	
Sample No.	122707	62002	51603	41803	51601	50504	122805	41101	52301-1	50502	53003	53001	53002	122712	122713	52301	62009	51602	KG1	KG2
Lattitude	37.25.26	37.26.08	37.27.01	37.28.02	37.26.32	37.27.20	37.25.56	37.24.05	37.27.54	37.26.52	37.24.30	37.45.05	37.24.23	37.25.11	37.25.00	37.27.54	37.26.40	37.26.33		
Longitude	126.56.30	126.55.03	126.57.13	126.58.46	126.57.57	126.56.30	126.58.20	126.55.42	126.58.15	126.55.25	126.56.16	126.55.53	126.56.03	126.56.52	126.55.34	126.58.15	126.55.29	126.57.53		
SiO_2	75.81	74.83	74.63	77.94	75.29	76.06	75.9	75.59	74	73.05	75.21	75.93	75.91	76.78	76.55	76.21	76.4	76.26	76.45	75.56
TiO_2	0.03	0.01	0.03	0.01	0.04	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.09	0.13
Al_2O_3	13.58	13.77	13.54	12.48	13.68	13.46	13.23	13.13	14.58	15.59	13.31	13.22	13.25	12.89	13.00	13.24	13.45	13.28	12.7	13.47
Fe_2O_3	0.15	0.18	0.32	0.04	0.29	0.14	0.27	0.36	0.14	0.09	0.18	0.27	0.27	0.13	0.22	0.14	0.18	0.24	0.45	0.38
FeO	0.21	0.28	0.51	0.02	0.48	0.26	0.23	0.19	0.12	0.1	0.39	0.24	0.18	0.15	0.27	0.18	0.19	0.27	0.56	0.53
MnO	0.02	0.09	0.03	0.01	0.03	0.04	0.02	0.12	0.02	0.02	0.06	0.05	0.04	0.04	0.04	0.05	0.06	0.03	0.05	0.06
MgO	0.04	0.03	0.06	0.03	0.07	0.03	0.04	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.12	0.22
CaO	0.15	0.37	0.47	0.31	0.51	0.34	0.37	0.36	0.28	0.13	0.41	0.31	0.34	0.31	0.29	0.37	0.2	0.25	0.69	1.11
Na_2O	4.4	5.35	4.47	4.21	4.38	4.58	4.43	4.13	4.82	6.56	4.74	4.74	4.99	4.68	4.82	5.74	5.45	4.41	3.66	3.81
K_2O	4.36	3.8	4.39	4.12	4.41	4.12	4.4	4.58	5.16	3.81	4.13	4.03	3.88	4.03	3.72	2.73	2.99	4.15	4.82	4.56
P_2O_5	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03
L.O.I.	1.3	1.56	1.1	0.9	1.19	1.05	0.84	1.35	1.22	0.77	1.13	1.27	0.97	0.85	0.86	0.81	1.26	1.1	0.39	0.48
Total	100.07	100.28	99.57	100.08	100.39	100.1	99.76	99.86	100.39	100.17	99.6	100.11	99.88	99.91	99.82	99.52	100.24	100.05	100	100.34
Q(%)	33.19	28.11	30.43	37.14	31.29	32.68	32.29	33.01	25.45	19.81	30.75	32.01	31.09	33.36	33.42	31.58	32.64	33.95	33.78	32.13
C	1.38	0.17	0.60	0.53	0.79	0.83	0.51	0.71	0.55	0.42	0.29	0.48	0.21	0.25	0.51	0.17	0.88	1.08	0.21	0.28
Zc	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02
Or	26.30	23.02	26.55	24.75	26.45	24.89	26.46	27.78	30.98	22.92	25.05	24.37	23.43	24.29	22.44	16.49	18.10	25.02	28.79	27.12
Ab	37.69	45.85	38.41	35.91	37.36	39.12	37.89	35.47	41.12	55.84	40.73	40.58	42.69	39.97	41.21	49.20	46.59	37.72	30.97	32.17
An	0.64	1.80	2.26	1.49	2.45	1.64	1.80	1.75	1.34	0.59	2.00	1.50	1.64	1.49	1.39	1.80	0.94	1.19	3.30	5.31
Hy	0.76	1.80	1.70	0.19	1.59	0.87	1.03	1.31	0.58	0.45	1.21	1.10	0.97	0.65	1.04	0.75	0.88	1.08	2.84	2.74
Hm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Il	0.06	0.02	0.06	0.02	0.08	0.02	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.00	0.17	0.25
Apt	0.05	0.02	0.05	0.02	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.05	0.07
Total	100.08	100.09	100.08	100.07	100.08	100.10	100.07	100.10	100.08	100.09	100.09	100.09	100.08	100.08	100.08	100.06	100.08	100.08	100.12	100.08

Table 2. continued.

Rock type	Biotite alkali granite								Garnet-biotite alkali granite							Aplite			Korea standard	
Sample No.	122707	62002	51603	41803	51601	50504	122805	41101	52301-1	50502	53003	53001	53002	122712	122713	52301	62009	51602	KG1	KG2
Be	3.5	2.8	3.2	2.1	4.4	2.6	3.7	2.6	2.6	3.5	4.5	2.3	3.7	3.2	3.2	2.8	3.9	4.7	4.5	2.3
Sc	3	3.1	3.6	3	3	3.3	1.1	4.5	4.2	2.7	3.1	3.7	2.6	3.2	3.6	3.8	3.3	3.9	2.3	2.7
V	1	2	1	3.4	3	2	2	3	3	<1	4	3	1	2	<1	1	1	2	4	9
Cr	18	15	15	12	13	12	8.5	10	9	13	12	9.2	5	10	13	9	13	11	5.4	6.5
Ni	2.4	5.7	3.5	3	3.5	5.3	2.5	5.3	3.3	4.1	7.1	2	1.9	1.8	2.3	3.1	2.2	3.4	0.3	<0.2
Co*																			<1	<1
Cu	<1	<1	<1	<1	1.2	<1	<1	<1	4.5	<1	<1	<1	<1	<1	<1	<1	<1	<1	5.4	2.2
Zn	40	82	104	12	34	57	52	140	5.2	115	147	141	124	42	103	82	123	48	26	29
Ga	29.8	39.1	28.5	29.7	27.1	35.4	26.8	36.8	40.7	47.4	32.3	35.9	36.3	33.2	33.9	34.5	39.3	32	15.4	16.4
Rb	544	688	520	523	449	796	448	790	582	690	664	716	637	644	584	384	652	591	271	169
Sr	14	16	17	4.2	23	5.8	6	4.2	6.5	16	4.7	4.8	1.5	4	2.8	4.8	5.7	3.7	41	159
Ba	48	20	70	31	75	21	27	10	18	22	8	18	17	12	17	12	12	14	144	572
Y	54	130	78	60	89	113	105	137	63	8.4	271	66	143	85	88	137	33	51	42	6.2
Zr	78	68	77	74	86	60	81	66	55	48	95	61	66	65	72	115	29	82	105	87
Nb	33.5	34.2	38.9	23.9	39.6	30.7	31.8	21.8	35.6	28.2	24	29.9	27.4	22.7	35.4	33.4	31.6	35	15.7	11.1
Th	23.7	20.9	30.3	19.4	33.3	18.5	22.9	17.3	12.3	14.7	24.7	16.2	19.6	18.5	24.4	28.3	7.4	23.3	27.5	15.5
U	8.6	18.5	12.9	10	7.3	8.7	8.3	11.8	13.8	9.4	20.8	11.3	13.9	7.7	11.3	20.8	7.7	14.2	6.1	1.8
La	5	12	13	8	14	11	8	7	8	7	8	6	7	5	9	14	5	4	34	29
Ce	13	23	30	17	34	17	15	16	18	16	20	17	16	12	19	31	13	9	69	56
Yb	6.2	18.9	7.9	10.8	7.8	14.9	7.8	14.6	11.5	4.6	20.7	10.8	18.3	12.6	10.7	16.6	5.5	10.4	4.7	0.6

*Our Co data were excluded here since samples appear to be contaminated in Co from the tungsten carbide ballmill.

red boundary with adjacent quartz. Inclusions of K-feldspar, plagioclase and rare biotite are observed.

Biotite is euhedral to subhedral or anhedral and often has quartz inclusion. Most biotites are nearly colorless, so they can easily be misidentified as muscovite. Occasionally they show pale brown to pale green pleochroism. Some are replaced by chlorite or secondary muscovite. Rarely biotite is rimmed by muscovite of possibly magmatic origin. Zircon occurs as inclusion in biotite with pleochroic halo. Biotite has composition of Fe/(Fe+Mg)=0.93 and Al(T)=3.8 (22 oxygen basis) corresponding to near siderophyllite-annite solid solution, which is typical of A-type granite.

Garnet Biotite Granite

The mineral assemblage and texture of the garnet biotite granite are very similar to those of the biotite granite except the presence of garnet. This rock has plagioclase compostion of $An_{0-2.5}$ and biotite composition of Fe/(Fe+Mg)=0.99 and Al(T)=4.0. Garnet is euhedral and 0.3~1 mm in diameter. Garnet appears to be pure without any inclusions. Garnet has little pyrope and small grossular components (average $Pyr_{0.1}Alm_{42.6}Grs_{1.4}Sps_{55.9}$) and thus approximates almandine-spessartine solid solution. It shows normal zoning, that is, higher Mn and lower Fe contents in core than in margin. Because of its euhedral form and high Mn contents, the garnet is thus considered to be of magmatic origin.

Aplite

Aplite consists of K-feldspar quartz plagioclase ($An_{2.0-3.4}$)± rare biotite (Fe/(Fe+Mg)=0.99; Al(T)=3.9)± garnet (average $Pyr_{0.1}Alm_{45.2}Grs_{1.4}Sps_{53.3}$) and accessory zircon.

WHOLE ROCK GEOCHEMISTRY

Eighteen samples of biotite granite, garnet biotite granite and aplite were analyzed for major and trace elements, using the method described in Kwon *et al.* (1994). Sample locations are shown in Fig. 1. The results of major and trace elements analyses and calculated CIPW norm values are listed in Table 2. Also reported in the Table 2 are the data for two Korean standard samples of KG1 and KG2, which will be useful to interlaboratory comparison. In the following we compare the chemical data of the Kwanaksan stock with those (Kwon *et al.*, 1994) of the Seoul batholith to test genetic relationship between the two.

Major Elements

Harker diagrams for major elements are shown in Fig. 3. The Kwanaksan alkali granite is highly felsic (SiO_2 73~78 wt%) and has very low contents of TiO_2 (<0.1 wt%), MgO (<0.07 wt%), total FeO (<0.51 wt%), P_2O_5 (0.02 wt%) and CaO (0.51 wt%), and high Na_2O (4.1~6.6 wt%), which is similar to major element characteristics of A-type granite. Most oxides in the Harker diagrams for the Kwanaksan granite show no obvious trends except Al_2O_3 which decreases with increasing SiO_2, indicating feldspar fractionation. Neither a there any apparent relationships between lith logy and major element chemistry. Compared with the Seoul granite, the stock has higher Na_2O, distinctly lower CaO, MgO, total FeO and TiO_2, and somewhat lower K_2O contents for given SiO_2, suggesting that the Kwanaksan stock has no simple genetic relationships with the Seoul batholith.

A/CNK vs. A/NK diagram is shown in Fig. 4. All the samples of the Kwanaksan stock are slightly peraluminous with A/CNK values between 1.00 and 1.15. In TAS (total alkali - silica) diagram (Fig. 5), the Kwanaksan stock belongs to alkaline granite according to the dividing curve of Irvine and Baragar (1971).

Normative quartz, albite and orthoclase are plotted in Fig. 6. Since the Kwanaksan stock has simple and leucocratic mineral assemblages, and very low concentrations of normative anorthite,

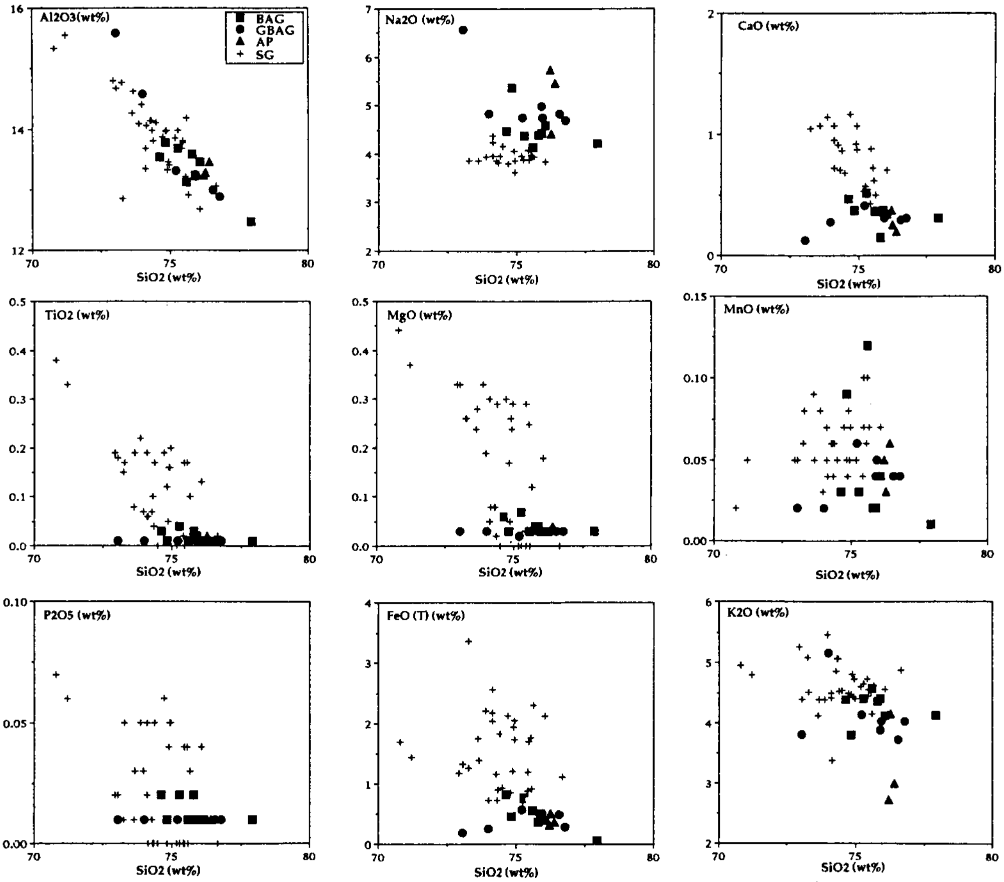

Fig. 3. Harker diagrams for major elements. Abbreviations are the same as in Fig. 2 except SG which is for Seoul granite (Kwon *et al.*, 1994).

which is similar to the haplogranitic composition, the estimation of emplacement pressure using this diagram of Tuttle and Bowen (1958) might be justified. The emplacement pressure for the Kwanaksan stock can be estimated to 2~3 kbars (Fig. 6), although the data appear scattered. However, the addition of volatiles such as F and B to the haplogranitic system can shift the ternary minimum toward the albite-rich corner because the volatiles tend to form complexes mainly with Na and thus increase its solubility (Manning, 1981; Burnham and Nekvasil, 1986). Fluorite in the Anyang feldspar mine reported by Park and Chi (1994) may suggest the presence of fluorine in the Kwanaksan magma. Moreover, significant amount of F in the magma might be conjectured

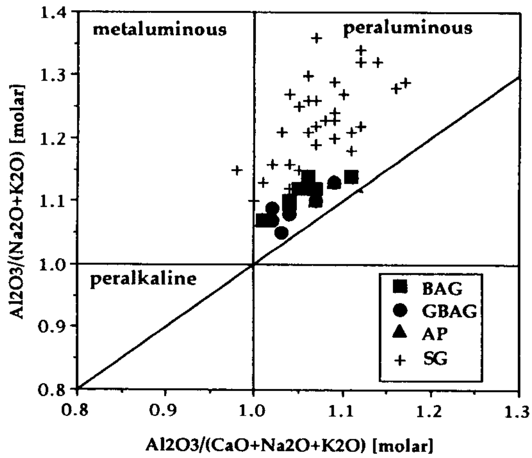

Fig. 4. Molar $Al_2O_3/(CaO+Na_2O+K_2O)$ [A/CNK] vs. $Al_2O_3/(Na_2O+K_2O)$ [A/NK] diagram. Abbreviations are the same as Fig. 3.

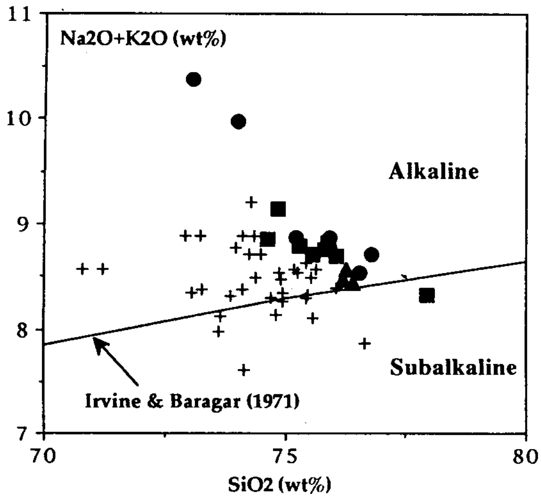

Fig. 5. Total alkali - silica diagram. Abbreviations are the same as Fig. 3.

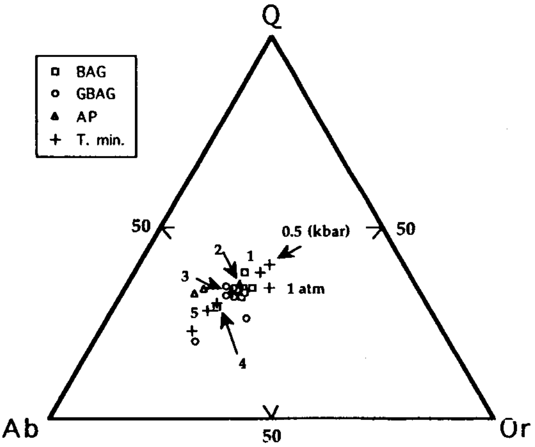

Fig. 6. Q-Ab-Or diagram. Temperature Minima (T. min.) and eutectics (+) for 1 and 0.5 to 5 kbars are from Tuttle and Bowen (1958). Abbreviations are the same as Fig. 3.

from exceptionally high contents of Ga, as discussed below. These observations suggest that the emplacement depth of the Kwanaksan stock could be rather shallow (i.e. less than 2~3 kbars).

Trace Elements

Harker diagrams for trace elements of the Kwanaksan stock are given in Fig. 7. As is the case for major elements, trace elements do not show appreciable trend with increasing SiO_2. For given SiO_2, Rb (384~796 ppm), Ga (27~47 ppm), Zn (5~147 ppm), Nb (22~40 ppm), Y (48~95 ppm), Yb (5~21 ppm) and U (7~21 ppm) contents are distinctively higher in the Kwanaksan stock than in the Seoul batholith, while Sr (3~23 ppm), Ba (8~75 ppm), V (1~4 ppm), La (5~14 ppm) and Ce (12~34 ppm) are lower in the former. Other elements, such as Be, Sc, Ni, Zr, and Th show abundances similar to those of the Seoul batholith. These diagrams indicate that the Kwanaksan stock has trace element compositions distinct from the Seoul batholith, suggesting a genetic difference between the two. We note that the high abundances of Ga, Zn, Nb, Yb and Y, and low abundances of Sr and Ba are characteristics of A-type granite. When the data for the Kwanaksan stock are plotted in Ga/Al-based discrimination diagrams (Fig. 8) proposed by Whalen *et al.* (1987), they (Ga/Al=3.5~5.8) belong to the A-type granite. However, features such as strong enrichment of Rb, normal Zr and depletion of LREE (esp., La and Ce) are different from typical A-type granite.

Rare Earth Elements

Our data for the REE are limited to La, Ce and Yb. However, Hong (1984) gave REE data for two samples and Park and Chi (1994) for nine samples. The average values for each of these data are shown in a chondrite-normalized diagram (Fig. 9). Average CI values suggested by Talor and McLennan (1985) were used for normalization.

The Kwanaksan stock shows LREE-depleted pattern with large negative Eu anomaly. This pattern is distinctly different not only from those of the Seoul batholith and most other Mesozoic granites in South Korea (Hong, 1983; Tsusue *et al.*, 1987), but also from typical A-type granites (Collins *et al.*, 1982). Hong (1984) and Park and Chi (1994) interpreted the REE pattern resulting from fractionation of feldspars, although they did

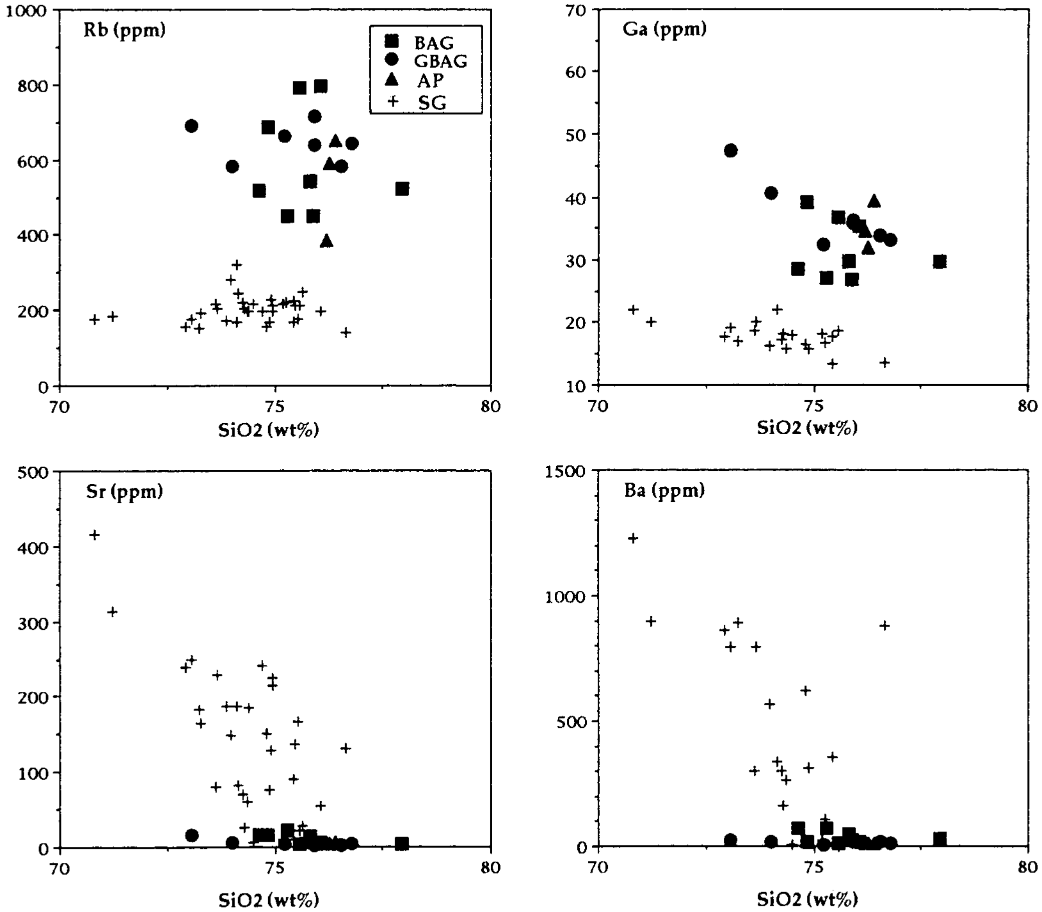

Fig. 7. Harker diagrams trace elements. Abbreviations are the same as Fig. 3.

not explain how it is possible. However, we do not agree with this interpretation for the following reasons.

The REE pattern for the Kwanaksan stock could be interpreted either as a result of extreme fractionation from LREE-enriched magma, e.g., the Seoul granite, or as representing a source magma. However, we do not think that the former interpretation is applicable in this case, since REE patterns of the Seoul granite and the Kwanaksan granite for similar SiO_2 content, i.e., similar degree of fractionation, are clearly different. Although the LREE depletion could be the result of fractionation of accessary phase such as monazite which is extremely enriched in LREE relative to HREE (Mariano, 1989), or possibly by loss of F- and/or Cl-rich fluids concentrated in LREE from magma (Flynn and Burnham,1978), the strong enrichment of HREE (about 50 times the chondritic value for the Kwanaksan stock vs. 5 times for the Seoul batholith) is hard to explain by the same mechanisms. The HREE enrichment might result from accumulation of zircon or xenotime (e.g., Watson and Harrison, 1983 and 1984), but this mechanism conflicts with relatively low Zr contents of the Kwanaksan Stock. Garnet might contribute to the HREE enrichment in part. However, the fact that the garnet-bearing granite from the Seoul batholith has still lower contents of HREE indicates that the role of garnet is limited. These observations suggest that the Kwanaksan granite was formed from a 'parent magma'

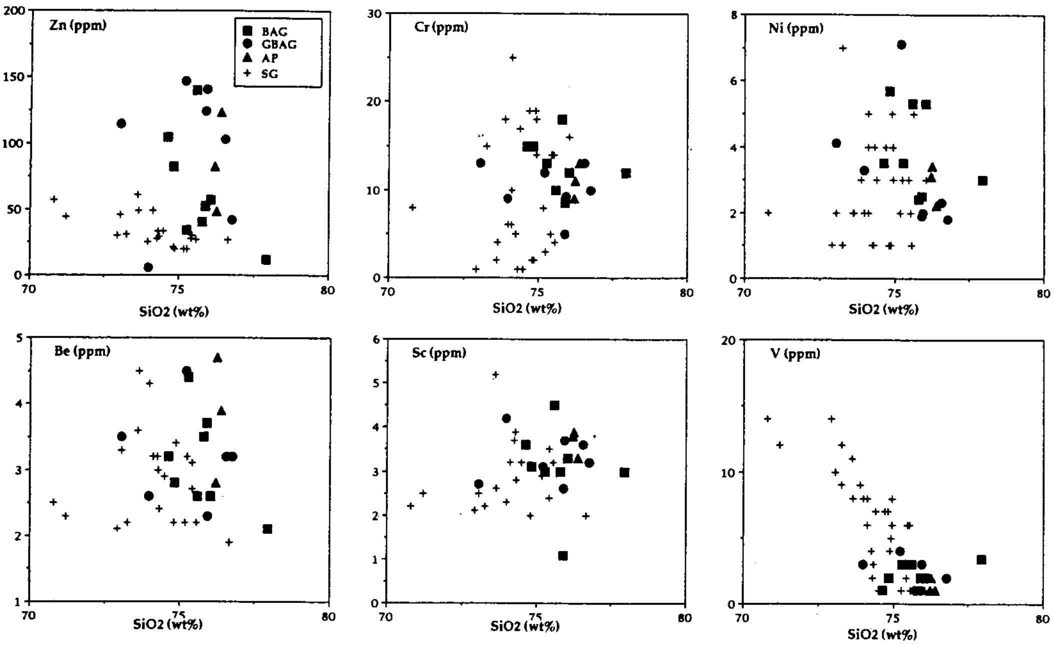

Fig. 7. (continued).

richer in HREE (and Y) than the one that formed the Seoul batholith, as McKenzie *et al.* (1988) explained the HREE-enriched pattern and low Zr content of the Lottah granite, northeastern Tasmania, Australia. Therefore, we think that the REE pattern shows the source magma characteristics.

If this interpretation is true, we may speculate the nature of source materials. In order to produce a magma with LREE-depleted pattern during partial melting, phases with HREE-enriched pattern such as garnet, pyroxene or amphibole should not be present appreciably in the residue. It suggests that the source composition might be felsic. Also, strong negative anomaly of Eu and extremely low Sr indicates plagioclase in the residue, which further strengthens felsic source composition.

Tectonic Discrimination

Since the first systematic study of the trace element geochemistry of granites from known tectonic settings by Pearce *et al.* (1984), several attempts have been made to discriminate the tectonic settings of granitoid rocks using major and trace element geochemistry. (Batchelor and Bowden, 1985; Harris et al., 1986; Maniar and Piccoli, 1989).

Y-Nb and Rb-(Y+Nb) diagrams of Pearce *et al.* (1984) are shown in Fig. 10. In Y-Nb variation diagram, the data from the Kwanaksan stock belong to within-plate granite, while in Rb-(Y+Nb) diagram, they plot to both syn-collisional granite and within-plate granite fields. This might be related to anomalously high contents of Rb.

In the multicationic diagram (Fig. 11) of Batchelor and Bowden (1985), the Kwanaksan granite belongs to anorogenic to post-orogenic granite, which agrees in general with the discrimination shown by diagrams of Pearce *et al.* (1984). Major element discrimination diagrams proposed by Maniar and Piccoli (1989) are shown in Fig. 12. In these diagrams tectonic discrimination is dubious: orogenic granite in SiO_2-Al_2O_3, MgO-FeO, and CaO-(FeO+MgO) diagrams, but anorogenic

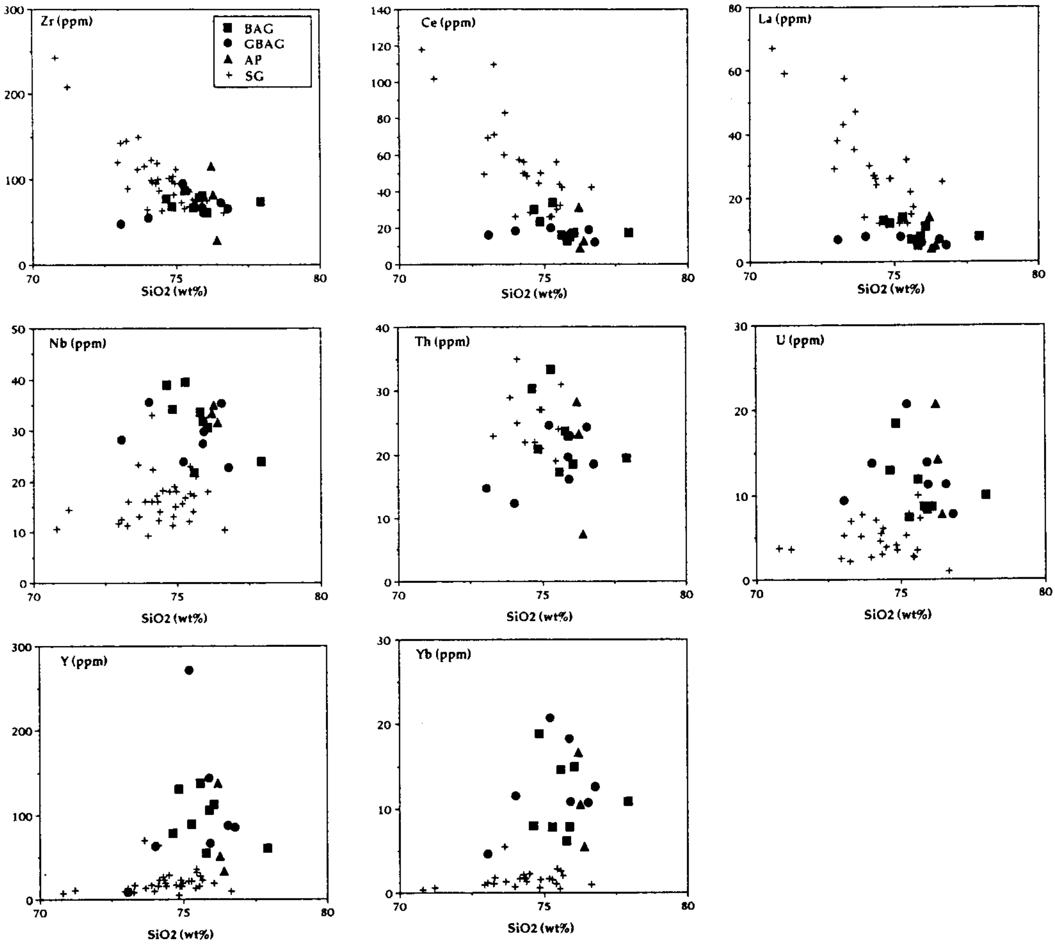

Fig. 7. (continued).

or post-orogenic granite in SiO_2-FeO/(FeO+MgO) diagram. Contradictory discriminations shown by the above diagrams suggest that one should be careful in using geochemical discrimination diagrams. The inconsistency might have resulted partially from the absence of granite database from the East Asian continent in constructing the discrimination diagrams, which merits further study.

Kwon *et al.* (1994) have suggested subduction-related continental magmatic arc for the tectonic setting of the Seoul batholith from regional geology and geochemical tectonic discriminations. Since the Kwanaksan stock appears to be closely associated with the Seoul batholith spatially and temporally, we consider the tectonic setting of the Kwanaksan stock should be similar to that of the Seoul batholith regardless of its geochemistry.

Is the Kwanaksan granite A-type?

The Kwanaksan granite has geochemisty very similar to A-type granite: highly felsic, high Na_2O, K_2O, Fe/Mg, Nb, Y, U, Ga and Ga/Al, and low CaO, Sr and Ba (White and Chappell, 1983; Whalen *et al.*, 1987). However, LREE and Zr contents are lower than those of typical A-type granite, while Rb contents are much higher. Table 3 su-

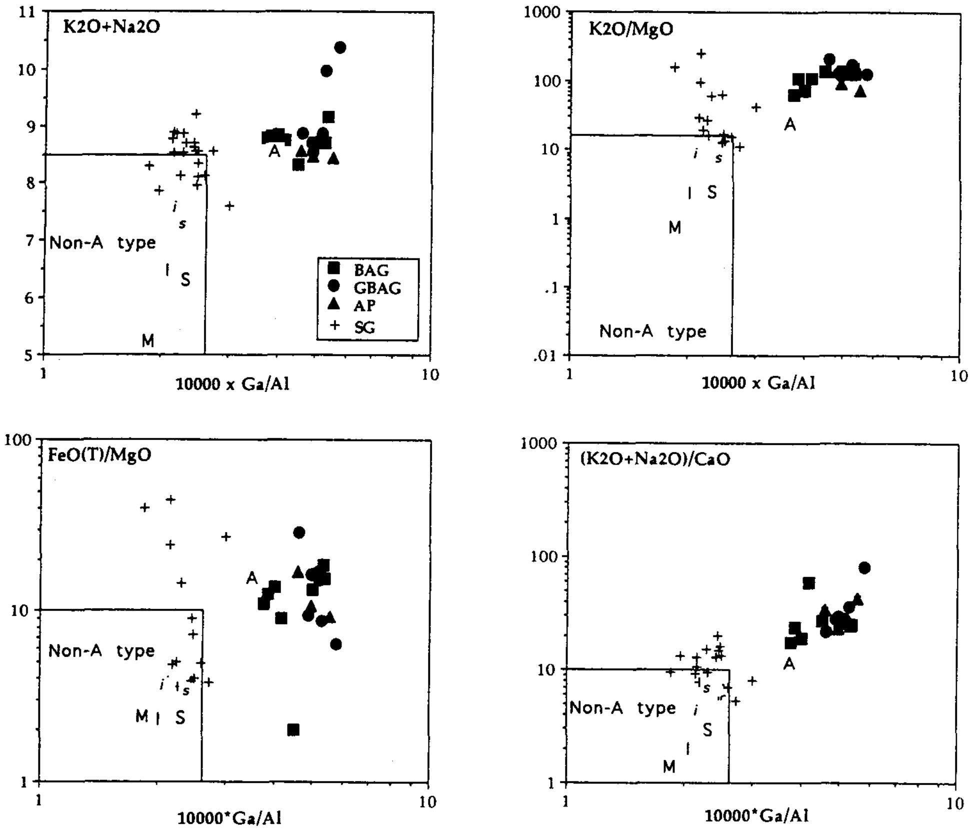

Fig. 8. Division of A-type vs. other granites after Whalen *et al.* (1987). The capital letters A, M, S and I represent average composition of A-, M-, S- and I-type granites respectively, and small italic letters s and i are average composition of felsic I- and S-type granites respectively. Abbreviations are the same as Fig. 3.

mmarizes comparison of geochemistry, petrography and field relationships between A-type granite and the Kwanaksan granite. Although the geochemistry appears similar, petrography and field relationships are quite different.

Petrographically, subsolvus nature and early crystallization of biotite observed in the Kwanaksan granite is different from hypersolvus and late crystallization of biotite in typical A-type granite. This petrographic difference appears to be related to hydrous nature of the Kwanaksan granite. Solvus curve of alkali feldspars can be intersected by increasing total pressure, and/or increasing H_2O, and/or addition of anorthite component (see summary in Hyndman, 1985). High total pressure and influence of anorthite component can be discarded from the Q-Ab-Or diagram (Fig. 6) and very low contents of Ca in the Kwanaksan stock respectively. Therefore, high H_2O content remains as the only possible mechanism to have two alkali feldspars, which also explains relatively early crystallization of biotite.

The Kwanaksan granite is probably not related to tensional environment. No volcanic equivalents have been reported yet around the pluton.

In the following we review origin of geochemical characteristics of A-type granite and discuss if it can be applied to the Kwanaksan granite.

A-type melts have large amounts of halogens, F and/or Cl, which distort the aluminosilicate framework and create various highly-ordered sites. High-field cations are stabilized as high-field

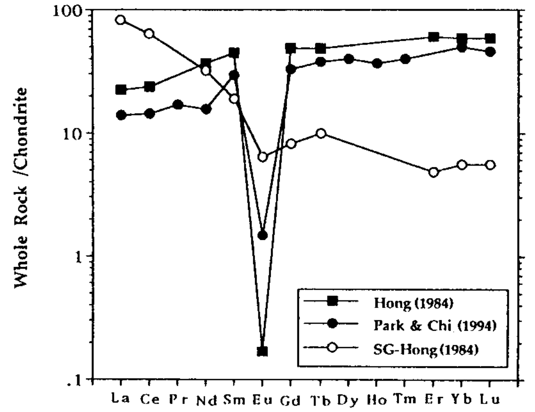

Fig. 9. Average chondrite-normalized REE patterns for the Kwanaksan granite (solid symbols) and the Seoul granite (open symbol).

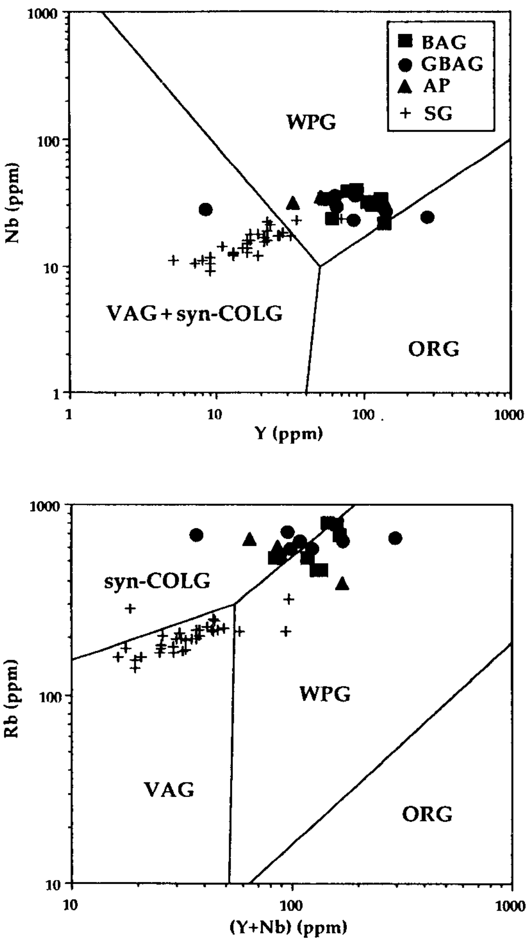

Fig. 10. Tectonic discrimination diagrams of Pearce, *et al.* (1984). Abbreviations are the same as Fig. 3.

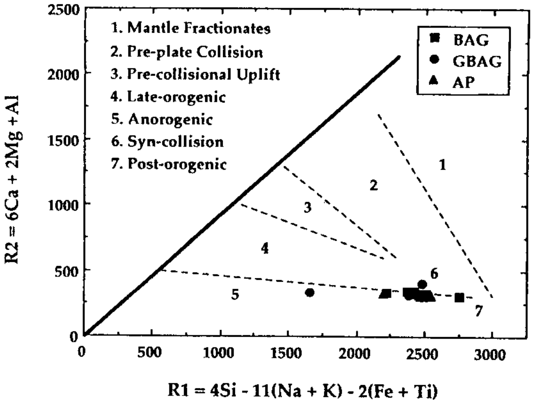

Fig. 11. Tectonic discrimination diagrams of Batchelor and Bowden (1985). Abbreviations are the same as Fig. 3.

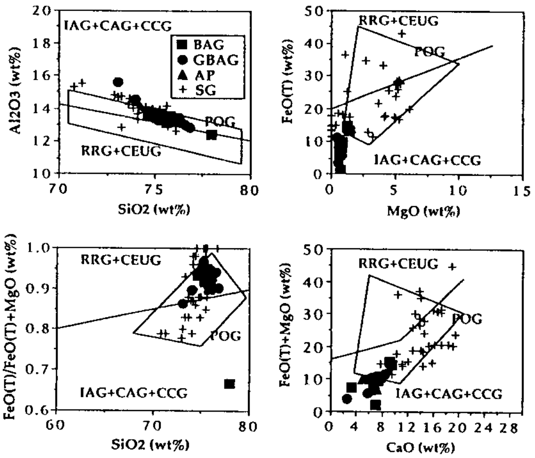

Fig. 12. Tectonic discrimination diagrams of Maniar and Piccoli (1989). Abbreviations are the same as Fig. 3.

metal complexes in melts (Clemens *et al.*, 1986; Anderson and Thomas, 1985). Therefore, the melts become enriched in Zr, Nb, Ga, Sn, Y, and REEs (not Eu). Meanwhile, it has somewhat low contents of some transition metals: Ni, Co, V, and Cr. Because their high crystal field stabilization energy and proper size to octahedral M1 site of pyroxene, they are rather accommodated to residual pyroxene or possibly to amphibole, although there exist many highly-ordered coordinates created by F and/or Cl in the A-type melts (Burns, 1970). However, Zn, Pb, and Cu can be

Table 3. Comparison of the Kwanaksan alkali feldspar granite with A-type granite

Chemical composition			Mineralogy	
low	CaO, Al_2O_3	Yes	hypersolvus	No
high	FeO(T)/MgO	Yes	fayalite	No
	K_2O+Na_2O	Yes	ferrohastingsite	No
	SiO_2	Yes	annite-rich biotite	Yes
high	Ga, Ga/Al	Yes	alkali amphibole	No
	Zr	No	sodic pyroxene	No
	Nb	Yes	fluorite	partly yes
	Y	Yes	interstitial nature of hydrous minerals	No
	Zn	Yes		
	LREE(not Eu)	No		
	HREE	Yes		
low	Ba, Sr	Yes		
Field relationships				
tensional environment			Probably No	
emplacement at high level			Probably Yes	
associated with volcanic equivalents			Probably No	

enriched in the melts because they are not suitable for pyroxene and amphibole structure (Collins *et al.*, 1982). Although residual amphibole and/or pyroxene are not compatible with REE interpretation described previously, halogen-rich melt can generally explain the geochemistry of the Kwanaksan stock.

Ga-enrichment of the Kwanaksan stock is very significant because Ga, especially Ga/Al, can be the 'key element' to discriminating A-type granite from others. Although both Ga and Al are of group IIIB, Ga is rather enriched in A-type melts than Al, because Ga is preferentially excluded from plagioclase structure relative to Al during partial melting involving preferential retention of plagioclase (Goodman, 1972), as evidenced by strong negative Eu anomaly. Of more fundamental significance is the effect of F upon Ga retention in aluminosilicate melt. The stability of the octahedral GaF_6^{3-} in wide temperature range is well established (Cotton and Wilkinson, 1980), but AlF_6^{3-} structures are stable only water-saturated or near-saturated alumonosilicate melts at magmatic temperatures (Manning *et al.*, 1980). Thus, Ga/Al values are generally high in A-type granites.

Zr content can be low at high-SiO_2 and peraluminous melts. Alkali cations are strongly bound to feldspar structure in alumina-rich melts. Therefore, they cannot act as counter-ions which can form alkali zirconofluoride complexes (e.g., Na_2ZrF_6 and Na_3ZrF_7) or zircon-polymer (e.g., $(Na,K)_2ZrSiO_5$) disturbing precipitation of zircon (Collins *et al.*, 1982). This process can explain low Zr content in peraluminous A-type granite, e.g., Membulla granite in southeastern Australia (Collins *et al.*, 1982), and can be applied to our case. However, low LREE (La and Ce) and high Rb contents of the Kwanaksan stock are enigmatic, requiring further study.

In summary, we conclude that geochemistry of the Kwanaksan granite is very similar, though not typical, to that of A-type granite. Hydrous nature of the A-type-like Kwanaksan magma remains to be solved.

PETROGENESIS

The origin of highly felsic granites with exteme enrichment of certain elements and depletion of others, such as the Kwanaksan granite, has long been controversial. Petrogenetic models for these granites are varied about possible source rocks or about the processes which led to their felsic nature. Suggested models can be summarized into four categories: (1) metasomatism of the pre-existing granites (Taylor *et al.*, 1980), (2) fractional crystallization from I- or S-type melts (McKenzie et al., 1988; Champion and Chappell, 1992), (3) partial melting of residual source materials (Barker *et al.*, 1975; Collins *et al.*, 1982; Clemens *et al.*, 1986; Whalen *et al.*, 1987), and (4) direct partial melting of tonalitic sources (Creaser *et al.* 1991). We discuss adequacy of these models to explain the origin of the Kwanaksan granite.

Metasomatism

Park and Chi (1994) suggested albitization of granite by local hydrothermal solution to explain the origin of Anyang feldspar mine in southwestern margin of the Kwanaksan stock. Metasomatism could have been beneficial in forming the albite orebody, but is not expected to have affected the Kwanaksan stock entirely. Even if the Kwanaksan granite formed by metasomatism of a granite similar to the Seoul batholith, concentrations of immobile elements, such as Nb, Y, and REE etc., are not expected to change significantly, since they generally have very low solubility in fluids associated with metasomatism. Distinctive differences in immobile element contents between the Kwanaksan and Seoul granites exclude this possibility (Fig. 7).

Fractional Crystallization

As we have shown previously (Fig. 3 and 7), distinct differences in major and trace element variations between the Kwanaksan and the Seoul granites suggest that the former cannot be product of fractional crystallization from the latter.

Partial melting

Since the above two possiblities can be excluded, we are left with source processes. We noted already that the geochemistry of the Kwanaksan granite is very similar to that of A-type granite. Therefore, petrogenetic mechanisms proposed for A-type granite could be applied to the origin of the Kwanaksan granite.

It has been the most popular idea that A-type granites are formed by anhydrous partial melting of depleted residual source materials such as granulite from which I-type melts had previously been extracted (Collins *et al.*, 1982; Clemens *et al.*, 1986; Whalen *et al.*, 1987). These residual source models, however, have been questioned in mineralogical and geochemical aspects. Rutter and Wyllie (1988) reported that K-feldspar and biotite are entirely eliminated after 8% and 15% partial melting of tonalite respectively. Rudnick and Taylor (1987) reported the residual assemblage of plagioclase+clinopyroxene+subsolidus garnet for basaltic to tonalitic sources after extracting I-type melts. Partial melts from the residual source without alkali feldspar and biotite but with plagioclase and clinopyroxene would have high Ca, Al, Mg and Fe, and low K and Si, which is not consistent with the characteristics of A-type granites (Creaser *et al.*, 1991). As an alternative model for generation of A-type granites, Creaser *et al.* (1991) have suggested the 'direct' vapor-absent partial melting of tonalitic or granodioritic source. This model suits well with the criteria of typical metaluminous A-type granites. However, the model cannot be applied to the Kwanaksan stock without modifications, since the stock is peraluminous and hydrous. According to Creaser *et al.* (1991), unusually high F contents are not always required from the source for enrichment in high field strength elements. During partial melting of tonalite and granodiorite, essentially all F will be partitioned into the melt with modally minor apatite ± titanite in the residue which can accept F. The amount of F would increase with the degree of partial melting (Creaser *et al.*, 1991).

The above discussion suggests that the Kwanaksan granite is thought to have been produced by partial melting of felsic source, although it is not clear if the source is igneous or sedimentary.

Genetic relationship between the Kwanaksan stock and the Seoul batholith

Park (1994) reported whole rock Nd isotope data for an alkali feldspar granite from the Kwanaksan stock and for a biotite granite from the Seoul batholith in Pocheon area. Using 170 Ma for the emplacement age of the stock (Kim, 1971) and the batholith (Kwon and Lan, 1995), the two samples have essentially identical εNd(T) values of -16.6 and -16.7 respectively, indicating common source for the two granites. The oxygen isotope data reported by Kim (1992) also indicate similar sources for the two granites. The $\delta^{18}O$ values of the whole rock and quartz are +8.7 and +9.8 for the Kwanaksan granite and +8.4 and +9.7 for the Seoul batholith. The geochemical data in this study, along with the isotope data, suggest that the Kwanaksan stock and the Seoul batholith have isotopically similar source material but different mineral assemblages.

CONCLUSION

(1) The Kwanaksan stock is defined as subsolvus alkali feldspar granite according to its mode data.

(2) Geochemistry of the Kwanaksan stock is very similar to that of A-type granite except lower LREE and higher Rb contents.

(3) From the consideration of the geochemistry, the Kwanaksan granite formed by partial melting of felsic source rock.

(4) The origin of the Kwanaksan stock might be explained by that of A-type granite, although hydrous nature of magma remains to be solved.

(5) Although limited isotope data suggest isotopically common source for the Kwanaksan stock and the Seoul batholith, geochemical variations suggest that the former is not directly related to the latter by fractional crystallization or metasomatism. Rather, there appear to be differences in source lithology and process.

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관악산 알칼리 장석 화강암의 지구화학 : A-형 화강암 ?

권성택 · 신광복 · 박현근 · S.A. 머츠만

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요　약 : 관악산 암주는 지금까지 단순히 흑운모 화강암으로만 구성된 것으로 알려져 왔으나 실제로는 석영＋K-장석＋사장석＋흑운모±석류석의 광물군을 보인다. 모드자료와 An_5미만의 사장석 성분을 고려하면 이 암주는 알칼리 장석화강암으로 명명된다. 서브솔버스 장석, 비교적 초기의 흑운모 정출, Q-Ab-Or 그림에서 유추된 얕은 관입깊이 등은 관악산 암주를 만든 마그마가 물을 함유하고 있었음을 지시하는데, 이는 아래에 설명하는 무수의 A-형 화강암과 유사한 지화학 성분을 가지는 것과는 대조된다. 관악산 암주의 주성분과 미량성분원소는 서울 화강암질 저반의 것과 뚜렷이 구분되며 이는 두 암체간의 성인적 차이를 시사한다. 관악산 암주의 주성분 및 미량원소 함량은 우리나라의 대부분 중생대 화강암과는 달리 A-형 화강암 특징을 보인다. 즉, SiO_2(73～78 wt%), Na_2O+K_2O, Ga (27～47 ppm), Nb (22～40 ppm), Y (48～95 ppm) 함량과, Fe/Mg and Ga/Al 비는 높은 반면, CaO (<0.51 wt%), Ba (8～75 ppm) 과 Sr (2～23 ppm) 함량은 낮다. 그러나, 전형적인 A-형 화강암과 비교했을때, Zr과 LREE는 낮은 함량을 Rb (386～796 ppm)은 높은 함량을 갖는 차이점을 보인다. 이 연구에서는 기존의 연구에서 보고되었던 LREE가 결핍되고 큰 부의 Eu이상을 가지는 희토류 원소 패턴이 근원 마그마의 특성을 가지는 것으로 재해석하였다. 즉 부분용융동안의 잔류물질로 다량의 사장석이 남아야 하는 반면, 휘석, 각섬석, 석류석은 남을 수 없다. 관악산 암주와 A-형 화강암의 지구화학적 유사성은 이 암주의 기원이 A-형 화강암의 기원과 밀접한 관련이 있음을 시사한다. 이러한 해석은 관악산 암주가 산성 근원물질의 부분용융으로 생성되었음을 시사한다.

핵심어 : 관악산 암주, 알칼리 장석 화강암, A-형 화강암, 산성근원