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The compositions of biotite and muscovite in the Yuksipryong two-mica granite and its petrological meaning

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ABSTRACT: The Yuksipryong granite is a medium- to coarse-grained leucocratic granite, which contains two micas. It belongs to peraluminous granite and has primary muscovite as aluminous minerals. Biotite of the Yuksipryong granite has an average FeO^*/MgO ratio of 3.7 and 6–7 wt% MgO, which is in accordance with those from the other peraluminous granite. However, biotite has low Mg/(Fe+Mg) ratio with an average of 0.37 and low aluminum content as compared to siderophyllitic biotites occurring in the typical peraluminous two mica suites. It contains substantial octahedral site vacancy probably due to the substitution of $3M^{2+VI} \Leftrightarrow 2Al^{VI}, \square^{VI}$, suggesting lower temperature crystallization compared with ideal trioctahedral biotite–eastonite compositions.

On the basis of petrographic observation, the muscovite in Yuksipryong two-mica granite can be classified into six types on the basis of textural criteria: (1) occurring as intergrowth with or across biotite filling the interstices or as overgrowth of other minerals, (2) as euhedral crystals including small biotite, (3) as single euhedral to subhedral crystals without inclusions, (4) as subhedral crystal within plagioclase, (5) as lath-shaped crystals, and (6) in pegmatitic dyke, occurring as a single large subhedral crystal. According to the textural evidence and chemical compositions of muscovite, types 1, 2, 3, and 4 belong to primary muscovite. Thus, muscovite in Yuksipryong granite is considered to be mostly primary muscovite formed at the magmatic stage. Primary muscovite contains significant magmatic muscovite, however, sodium and silicon contents show wide variations in all types. Muscovite shows celadonite or tschermark subsitutions: $R^{3+}+Al^{IV}=Si+R^{2+}$ ($R^{3+}=Al$, Fe and $R^{2+}=Mg$, Mn).

Considering the composition of micas together with the experimental results of many workers, the biotite and the primary muscovite of Yuksipryong granite are considered to have been crystallized at pressures higher than 3.5 kbar and temperatures between 700–750°C.

Key words: two-mica, peraluminous granite, octahedral site vacancy, primary muscovite, tschermark substitutions

1. INTRODUCTON

Peraluminous two-mica granite is a small but genetically important component of the granitic complex in most orogenic belts. Its petrogenetic significance has been the focus of recent discussion (Lee et al., 1981; White, 1989; Zen, 1989; Oretega and Gil-Ibarguchi, 1990). It is generally thought that the granitic magmas containing muscovite and biotite have relatively high volatile contents, mainly water and fluorine (White, 1989; Zen, 1989). Relatively dry but geochemically equivalent granites contain garnet, cordierite and/or biotite (with or without Al-silicate) (White and Chappell, 1988). The term "peraluminous" granite is used for rock having a molar ratio of $Al_2O_3/(K_2O+Na_2O+CaO)$ higher than 1. This means that peraluminous granite contains more aluminum than those incorporated into feldspar. Pealuminous granite exhibits distinctively different petrographic, mineralogical, and chemical charateristics compared to the metaluminous calc-alkaline or peralkaline granites (Barbarin, 1990). Mineralogically the excess alumina in magma is demonstrated by the presence of aluminous minerals such as cordierite, garnet, muscovite, and aluminum silicate (Clarke, 1981).

It has been considered that Jurassic S-type granitic rocks distributed in the Yeongnam Massif were originated from continental crust, and thus studying their origin is essential for understanding the evolution of the crust. Since the 1980's, many studies have been carried out on Jurassic S-type granitic rocks (Kim et al., 1989a, Kim et al., 1989b, Kim et al., 1991; Kim and Kim, 1990; Kwon and Hong, 1993; Park et al., 1990, Park et al., 1996), but there is only one study for two-mica granite (Jwa, 1997).

Few petrographical and mineralogical studies have been done on the Yuksipryong peraluminous two-mica granite in the central part of Yongnam Massif. Recently, in this granite, two-micas, biotite and primary muscovite have been discovered (Koh and Yun, 1997). The mineral compositions of biotite and muscovite (especially primary muscovite) in the Yuksipryong two-mica granite may provide informations about the genesis and nature of Yuksipryong two-mica granite.

The principal aims of this paper are: (1) to describe the petrographic characteristics of the Yuksipryong two-mica granite, (2) to reveal the nature of biotite in the Yuksipryong granite, (3) to microscopically examine the petrographic criteria between primary and secondary muscovite, (4) to elucidate the nature of muscovite in the Yuksipryong peraluminous granite, and (5) to determine the pressure and temperature conditions at which coexisting biotite and muscovite were crystallized.

2. OUTLINE OF GEOLOGY

The southwestern part of the Sobaeksan metamorphic complex in the Yongnam Massif is largely occupied by the gneissic terranes with metasedimentary rocks and granites. The Precambrian gneisses are generally thought to have been formed during the early Proterozoic (Choo, 1986).

The granites in the study area can be divided into Triassic and Jurassic granites (Hong and Yun, 1993). The Hamyang foliated granite is distributed mainly in the southeastern part of the study area. It consists of quartz, alkali feldspar, plagioclase, biotite, and opaque minerals, and its Rb–Sr whole rock age is 200±5 Ma (Kim et al., 1989a). Along the western boundary of the Hamyang foliated granite, Yuksipryong two-mica granite intruded. The Jangsu granite is fine- to medium-grained equigranular biotite granite, but locally porphyritic. It is distributed in the southwestern part of the study area. Constituting minerals of the Jangsu granite are quartz, alkali feldspar, plagioclase, biotite, epidote, and allanite. Because of no outcrops in the boundary area between Yuksipryong granite and Jangsu granite, it is difficult to find the boundary between two granites. The hornblende biotite granite is distributed in the northwestern part of the area and commonly contains mafic inclusions. This granite generally shows equigranular texture, is predominantly medium-grained, and has a foliation trending northeast. Constituting minerals are quartz, alkali feldspar, plagioclase, hornblende, biotite, epidote, and allanite.

The Yuksipryong two-mica granite is widely distributed around Sosang-myon of Hamyang-gun, the central part of the study area (Fig. 1). The granite intruded into all neigh-

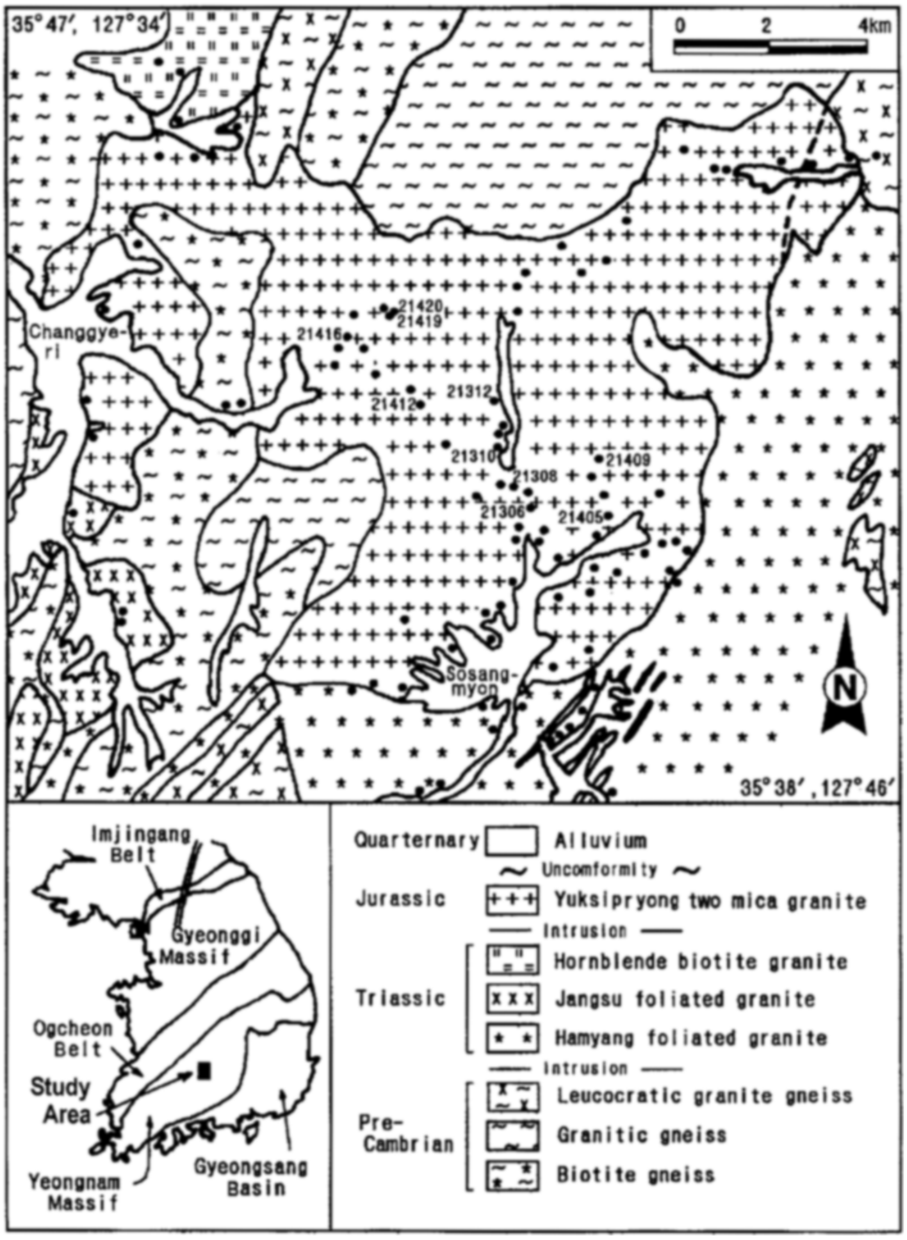

Fig. 1. Geological map of the study area. Solid dots indicate sampling sites.

boring granites and gneisses of the study area. The age of Yuksipryong two-mica granite is believed to be early Jurassic, because it does not show noticeable foliated fabric. Constituting minerals are quartz, perthite, microcline, plagioclase, biotite, muscovite, and opaque minerals.

3. PETROGRAPHY OF THE YUKSIPRYONG TWO-MICA GRANITE

The Yuksipryong granite is generally medium- to coarse-grained leucocratic granite (Koh and Yun, 1997). In the southern and northeastern margin, it is typically porphyritic but the porphyritic texture gradually disappears towards the center. They are locally intruded by pegmatitic and aplitic dykes, especially in the southern part.

The constituting major minerals are quartz (21–45%), perthite (9–27%), microcline (4–15%), plagioclase (21–41%), muscovite (1–7%), and biotite (3–7%). Accessory minerals are zircon, apatite, epidote, and opaque minerals (Table 1). Subhedral quartz commonly shows undulatory extinction and has incipient subgrains due to ductile deformation (Hibbard, 1995). The plagioclase is euhedral to subhedral and its composition is oligoclase (An_{22-13}). It shows albite and carlsbad–albite twins with a zonal texture. The core of plagioclase is partly altered, and sometimes has a small piece of bladed muscovite. The blade-shape muscovite occurs along the two directions of plagioclase cleavage. In the contact zone with alkali feldspar, myrmekitic texture is commonly observed in a sodic plagioclase margin. Alkali feldspar phenocrysts are mainly perthitic microcline and their Xor are 0.90–0.94. They show poikilitic texture in which muscovite, biotite, plagioclase, and quartz are enclosed. The completely enclosed minerals are subhedral to anhedral and randomly oriented. Some subhedral enclosed minerals across the boundary, which is similar to ophitic texture. This feature is related to the nucleation and growth rates of minerals. Swanson (1977) investigated the effects of varying nucleation and growth rates in a granitic melt, and reported that the growth rate of alkali feldspar is much higher than that of plagioclase and quartz. Thus alkali feldspar seems to form larger crystals than enclosed minerals because of its higher growth rate.

Biotite is subhedral to anhedral and usually contains inclusions of apatite, zircon, and opaque minerals. Some biotites are altered to chlorite. Pleochroism of biotite is yellowish brown to dark brown. It occurs as a subhedral grain, intergrown with or parallel to muscovite, or as a interstitial phase with muscovite. Some biotites show kink bands.

One of the important questions about the origin of muscovite in igneous rock is whether it is a primary igneous mineral or not. Various criteria have been used to recognize an igneous muscovite but they are not definite (Speer, 1984). Recently, this question has intensified because a mineral's peraluminous nature may indicate whether the granitic rocks' origin was aluminous or sedimentary. Microscopic textural evidence is the most important criteria for recognizing magmatic muscovite.

Moscovites in the Yuksipryong two-mica granite and pegmatitic dyke can be classified into six types: occurring (1) as intergrowth with or across biotite filling the interstices (Fig. 2a, b) or as overgrowth of other minerals; (2) as euhedral crystals including small biotite and opaque minerals (Fig. 2c); (3) as single euhedral to subhedral crystals without inclusions (Fig. 2d) (Its grain size is comparable to the other magmatic minerals and has a narrow reaction rim, and it shows kink bands suggesting that it has been deformed concurrently with biotite); (4) as subhedral crystal within plagioclase (Fig. 2e) (It does not show altered features and have a narrow reaction rim); (5) as lath-shaped muscovite within plagioclase (Fig. 2e) (It often has marginal alteration); and (6) as a single large subhedral crystal (Fig. 2f) occurring in the pegmatitic dyke. The modal compositions for muscovite

Table 1. Representative modal compositions of the Yuksipryong two-mica granites.

	Granite										Pegmatitic dyke	
Sample no.	21306	21308	21310	21312	21314	21405	21409	21412	21422	21426	21419	21420
Quartz	26.4	21.0	28.2	28.1	32.4	44.5	34.5	24.6	29.0	37.0	52.7	45.3
Perthite	14.6	27.4	19.6	16.3	21.9	16.3	8.5	21.1	16.5	13.7	3.3	9.8
Microcline	15.4	3.7	10.0	4.8	1.9	4.4	4.0	4.9	7.3	3.8	2.7	2.8
Plagioclase	36.7	40.9	31.9	37.0	39.5	20.9	36.5	40.0	39.4	37.3	29.3	32.0
Muscovite	3.0	2.1	(6.1)	5.0	1.4	(6.3)	(7.0)	(4.3)	2.3	2.0	11.4	8.3
Biotite	3.1	3.7	4.2	6.1	2.6	6.3	6.8	3.8	4.9	5.4	tr	–
Zircon	tr	tr	tr	tr	tr	0.1	tr	tr	tr	tr	–	–
Apatite	tr	tr	tr	tr	tr	0.5	0.6	0.1	0.1	0.1	0.2	0.2
Opaque minerals	0.2	0.3	tr	0.1	0.1	0.1	0.3	0.1	tr	0.2	tr	0.1
Chlorite	0.3	0.4	–	tr	tr	tr	0.5	–	0.1	0.2	0.1	1.2
Epidote	0.1	0.1	tr	0.1	0.1	0.5	0.8	0.8	0.2	tr	–	–

( )=muscovite recalculated to 100% in according to the types 1, 2, 3, 4, and 5 (21310=19%, 37%, 27%, 9%, 8%; 21405=74%, 0%, 1% 11%, 14%; 21409=41%, 0%, 20%,18%, 19%; 21412=13%, 52%, 22%, 1%, 12%).

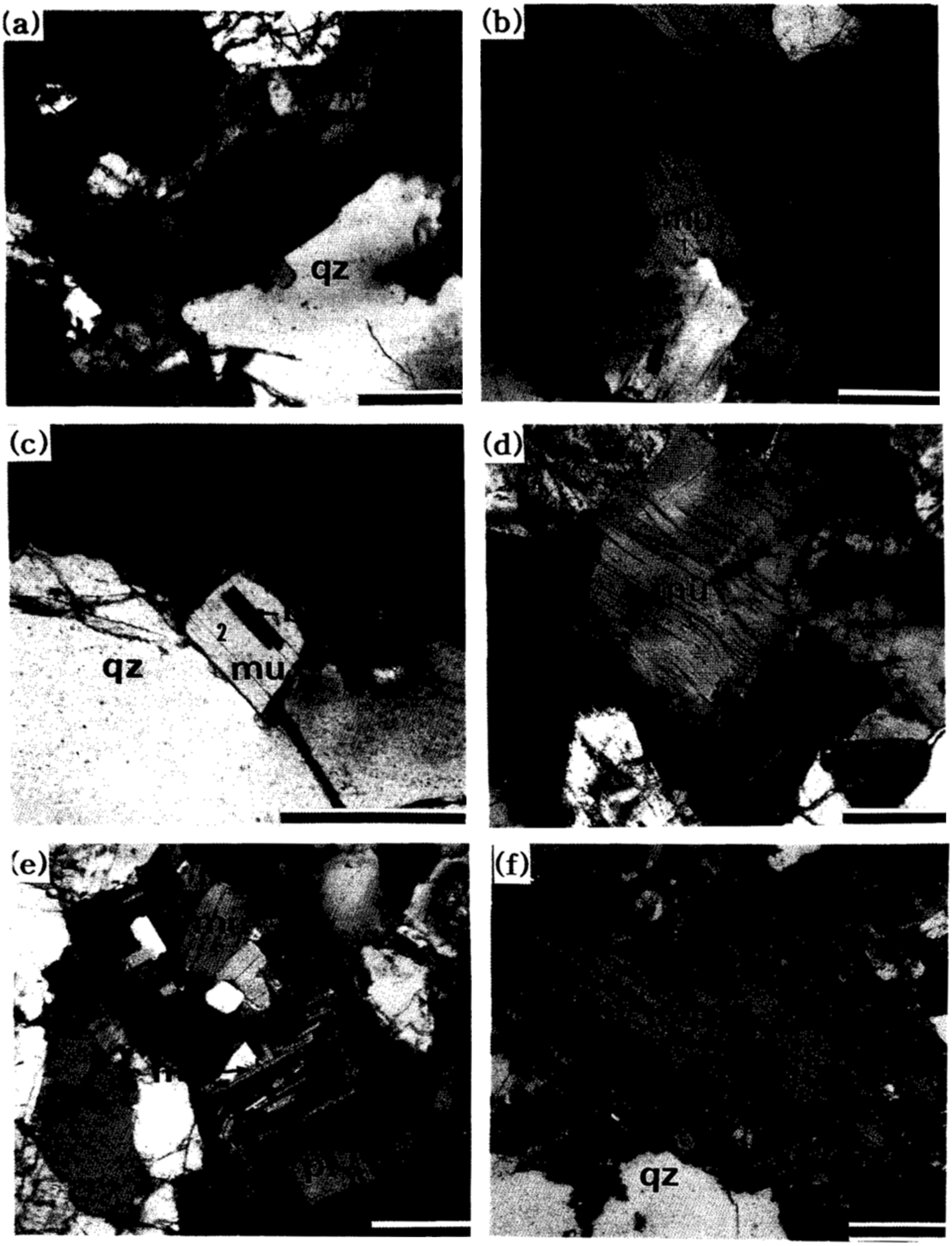

Fig. 2. Textural criteria of the muscovite in the Yuksipryong granite. **(a)** and **(b)** type 1 muscovite occurring as intergrowth with or across to biotite. **(c)** type 2 muscovite as euhedral crystals including small biotite. **(d)** type 3 muscovite as a large single muscovite euhedral to subhedral crystals showing kink band. **(e)** types 4 and 5 muscovite as small lath-shaped within plagioclase, respectively. **(f)** type 6 muscovite as single large subhedral crystal in pegmatitic dyke. The scale bar is 0.35 mm. bt=biotite, mu=muscovite, qz=quartz, pl=plagioclase.

are recalculated to 100% in accordance with the type and listed in Table 1.

4. MINERAL CHEMISTRY OF MICAS

4.1. Analytical Method

The chemical compositions of biotite and muscovite in the Yuksipryong granite were analyzed by an electron microprobe analyzer (JEOL Superprobe JXA-86600SX) at the Center for Mineral Resources Research, Korea University. The settings used for the acceleration voltage, the beam diameter, and the beam current were 15 kV, 2–3 μm, and 3.0 μA, respectively. The ZAF method was used to reduce the analytical data. The standards used were as follows: quartz for Si, corundum for Al, rutile for Ti, hematite for Fe, periclase for Mg, manganese metal for Mn, jadeite for Na, and orthoclase for K.

4.2. Chemistry of Biotite

The chemical composition of the biotite of the Yuksipryong granite are listed in Table 2. The composition of the unaltered biotites are uniform throughout the rock. Biotite has 6.1–7.6 wt% MgO, 21.4–24.2 wt% FeO, 2.1–2.9 wt% TiO_2, and 15.0–16.5 wt% Al_2O_3, respectively. It contains approximately 2.4–2.5 atoms per formular unit (a.p.f.u.) of tetrahedral Al (Al^{IV}) and 0.5–0.6 a.p.f.u. octahedral Al (Al^{VI}) (Fig. 3). The Fe/(Fe+Mg) ratio in biotite is 0.62–0.69, with an average of 0.63.

Abdel-Raham (1994, 1996) suggested MgO–Al_2O_3 diagram of biotite chemistry for discriminating between alkaline magma (A), peraluminous magma (P) (including S-type), and calc-alkaline magma (C). Biotite in the Yuksipryong granite belongs to peraluminous granite (P) suites (Fig. 4). This is consistent with the the aluminum saturation index of granite (1.15–1.20) (Koh and Yun, 1997).

Although biotites in igneous rocks commonly host the excess aluminum, making the rocks peraluminous, their composition vary according to the coexisting mineral assemblage. The aluminum content as well as Fe/(Fe+Mg) content in biotites generally increases in the sequence of hornblende, muscovite, and alumino-silicate+muscovite (de Albuquerque, 1973). But the tetrahedral aluminum content of Yuksipryong granite is lower than those of two-mica granites studied by Speer (1984) with a range of 2.6–2.8. According to experimental data, aluminum content decreases and Mg increases, with an increase in temperature, because of the lower solubility of Al in biotite with increasing temperature (Monier and Robert, 1986; Puziewicz and Johannes, 1988; Patino Douce, 1993). When we consider the relationship between Al and Mg/(Fe+Mg) in this study, low aluminum

Table 2. Representative chemical compositions and structural formulas of biotites.

	Biotite														
Sample no.	140502	140510	140509	140515	140520	140525	140527	140529	140537	140546	140547	140549	140550	140964	140967
SiO_2	35.254	35.323	35.470	35.488	35.254	35.094	35.226	35.071	35.694	35.015	34.922	35.786	36.278	34.892	35.563
$Al2O_3$	15.887	15.596	15.508	16.592	15.735	15.049	16.253	15.765	15.585	15.615	15.534	16.104	15.581	16.109	16.031
TiO_2	2.199	2.478	2.128	3.041	2.591	2.292	2.426	2.617	2.610	2.797	2.598	2.354	2.604	2.488	2.882
FeO*	23.590	23.139	22.732	21.419	22.450	23.878	23.506	23.518	22.090	22.871	23.850	23.466	22.517	23.776	23.569
MgO	7.228	7.328	7.629	7.328	7.489	7.144	7.299	7.135	7.273	6.914	7.578	7.609	7.594	6.645	6.508
MnO	0.512	0.460	0.457	0.352	0.340	0.466	0.386	0.453	0.470	0.471	0.619	0.307	0.610	0.441	0.825
Na_2O	0.533	0.515	0.464	0.487	0.419	0.463	0.519	0.609	0.529	0.352	0.549	0.472	0.484	0.361	0.399
K_2O	10.141	10.017	9.999	10.220	9.880	9.802	9.937	9.962	10.072	9.963	9.488	9.941	10.046	10.119	9.784
NiO	0	0	0	0	0	0	0	0	0	0.562	0	0	0	0	0
Total	95.344	94.856	94.387	94.927	94.158	94.188	95.552	95.130	94.323	94.560	95.138	96.039	95.714	94.831	95.561
FeO*/MgO	3.264	3.158	2.980	2.923	2.998	3.342	3.220	3.296	3.037	3.308	3.147	3.084	2.965	3.578	3.622
	Recalculated on 22 oxygen														
Si	5.547	5.570	5.607	5.536	5.573	5.596	5.514	5.527	5.628	5.549	5.505	5.559	5.638	5.523	5.567
Al^{IV}	2.453	2.430	2.393	2.464	2.427	2.404	2.486	2.473	2.372	2.451	2.495	2.441	2.362	2.477	2.433
Al^{VI}	0.491	0.466	0.494	0.584	0.502	0.422	0.510	0.453	0.522	0.463	0.389	0.505	0.489	0.526	0.522
Ti	0.260	0.294	0.253	0.357	0.308	0.275	0.286	0.310	0.310	0.333	0.308	0.275	0.304	0.296	0.339
Fe	3.104	3.052	3.005	2.795	2.968	3.184	3.077	3.100	2.913	3.031	3.144	3.049	2.926	3.148	3.085
Mg	1.695	1.723	1.798	1.704	1.765	1.698	1.703	1.676	1.710	1.633	1.781	1.762	1.759	1.568	1.519
Mn	0.068	0.061	0.061	0.047	0.046	0.063	0.051	0.060	0.063	0.063	0.083	0.040	0.080	0.059	0.109
Na	0.163	0.157	0.142	0.147	0.128	0.143	0.158	0.186	0.162	0.108	0.168	0.142	0.146	0.111	0.121
K	2.035	2.015	2.017	2.034	1.993	1.994	1.984	2.003	2.026	2.014	1.908	1.970	1.992	2.043	1.954
$Mg^{\#}$	0.35	0.36	0.37	0.38	0.37	0.35	0.36	0.35	0.37	0.35	0.36	0.37	0.38	0.33	0.33

FeO*=total Fe as FeO, $Mg^{\#}$=Mg/(Mg+Fe).

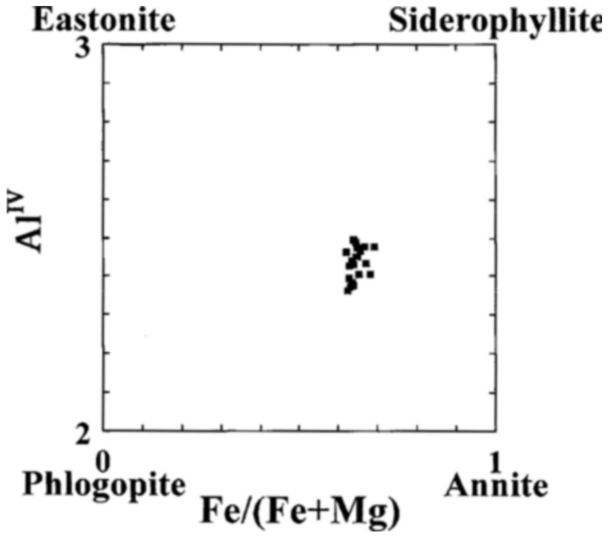

Fig. 3. Al^{IV} plotted against Fe/(Fe+Mg) of biotite.

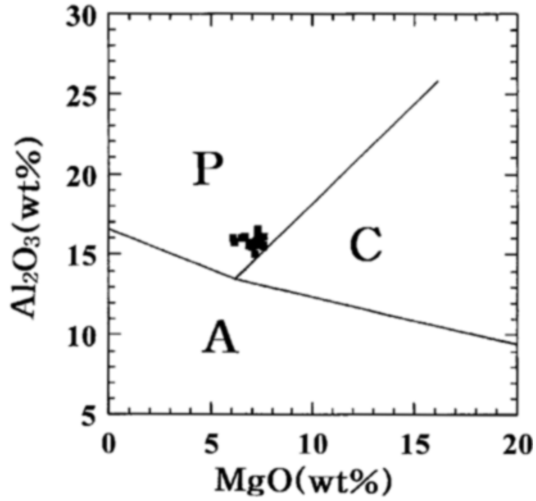

Fig. 4. Biotite compositions plotted in MgO-Al_2O_3 biotite discriminant diagram (Abdel-Raham, 1994, 1996). A=biotite in anorogenic alkaline suits, P=biotite in peraluminous (including S-type) suites, C=biotite in calc-alkaline orogenic suites. In general, biotites in the calc-alkaline orogenic granite suites (field C) are moderately enriched in Mg with an average FeO*/MgO ratio of 3.48 and Al-rich siderophyllitic composition. This is an important feature with petrogenetic significance; most peraluminous magmas are relatively highly felsic, generally anatectic (i.e. low MgO) melt, and commonly of crustal sedimentary source origin.

content seems to be related to a lower ratio of Mg/(Fe+Mg) of the biotite. As proposed by Stussi and Cuney (1996), the substitution of Mg⇔Fe (phlogopite–annite subsitution) is specific for biotites in peraluminous granites; coupled with the substitution of $3M^{2+VI} \Leftrightarrow 2Al^{VI}, \square^{VI}$.

Biotite compositions are plotted in Fig. 5, which illustrates octahedral site occupancy vs. total Al content. The plot is far from the ideal trioctahedral biotite composition. Biotites contain substantial octahedral site vacancies (so called, annite/phogophite–muscovite subtitution suggested by Monier and Robert (1986)). Thus the aluminum content of the biotite in the study is controlled by the primary substitution mechanism as follows: $3M^{2+VI} \Leftrightarrow 2Al^{VI}, \square^{VI}$.

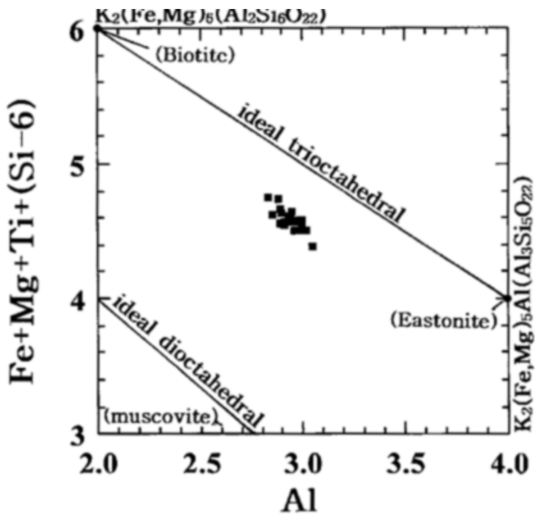

Fig. 5. Biotite compositions in terms of octahedral-site occupancy vs. total Al cation (Tracy, 1978). Substitutions within ideal trioctahedral- and dioctahedral-mica compositions are projected as parallel lines.

Conrad et al. (1988) give important information about determining the stability of biotite. According to their crystallization experiment at lower temperatures (675–750°C), biotites contain substantial octahedral site vacancies. It is thus likely that biotites in this study have low thermal stability compared to the ideal trioctahedral biotite–eastonite compostion.

4.3. Chemistry of Muscovite

Muscovite coexisting with biotite is the most common mineralogical indicator of highly peraluminous composition of plutonic rock. The identification of primary muscovite is important because it is commonly a good indicator of both magma composition and the depth of crystallization.

In this study, we first utilized textural criteria to identify the primary muscovite, and then investigated the mineral chemistry of primary and late to post magmatic muscovite (including secondary muscovite), to see whether the compositional variations were sufficient to distinguish between primary and the other muscovites. The most important textural criteria for recognizing primary muscovites are as follows: (1) primary muscovites have relatively coarse, comparable to the other primary phases and they should occur as a major phase comparable to biotite; (2) they must be clearly terminated, ideally with subhedral or euhedral form; (3) they should not be enclosed by other minerals, or raggedly enclosed; (4) they should have no reaction texture with other minerals; and (5) it should be present in an unaltered, fresh igneous rock (Miller et al., 1981; Speer, 1984; Barbarin, 1996).

Table 3 shows the chemical compositions and structural

Table 3. Representative chemical compositions and structure formulas of muscovites.

Sample	Type 1 Intergrowth with biotite			Type 2 Including biotite, opaque mineral		Type 3 Single euhedral crystal		Type 4 Plate shape within plagioclase			Type 5 Lath (or altered) shape within plagioclase			Type 6 Single large crystal in pegmatite	
no.	140503	140505	140968	141262	140519	140540	140541#	140516	141253	140970	140543	141255	141256	141974	141976
SiO_2	45.233	45.417	45.733	45.319	44.972	46.163	46.137	46.227	45.078	44.937	47.009	45.955	45.496	45.595	46.201
Al_2O_3	30.640	29.964	30.005	31.463	29.978	28.981	27.552	28.366	31.697	31.582	28.040	32.822	32.741	32.783	31.868
TiO_2	0.996	0.787	0.751	0.826	0.900	0.935	0	0.908	0.945	0.834	0.266	0	0.215	0.254	0.248
FeO*	4.691	4.962	4.571	3.695	5.268	4.756	6.016	6.086	3.730	3.857	5.711	3.661	3.341	3.580	3.630
MgO	0.733	0.960	0.969	0.645	0.908	1.058	1.669	1.485	0.653	0.700	1.571	0.460	0.560	0.411	0.612
Na_2O	0.315	0.480	0.433	0.638	0.425	0.494	0.337	0.413	0.705	0.614	0.346	0.445	0.510	0.276	0.692
K_2O	10.658	10.596	10.347	10.517	10.490	10.560	10.469	10.566	10.504	10.394	10.874	10.714	10.946	10.851	10.209
Total	93.306	93.164	92.808	93.104	92.941	92.946	92.220	94.051	93.312	92.918	93.817	94.058	93.809	93.750	93.461
	Recaculated on 22 oxygen														
Si	6.288	6.332	6.370	6.275	6.295	6.438	6.527	6.420	6.233	6.239	6.529	6.281	6.243	6.256	6.342
Al^{IV}	1.712	1.668	1.630	1.725	1.705	1.562	1.473	1.580	1.767	1.761	1.471	1.719	1.757	1.744	1.658
Al^{VI}	3.304	3.251	3.292	3.405	3.237	3.198	3.117	3.059	3.395	3.402	3.116	3.564	3.534	3.553	3.494
Ti	0.104	0.083	0.079	0.086	0.095	0.098	0	0.095	0.098	0.087	0.028	0	0.022	0.026	0.026
Fe	0.545	0.579	0.532	0.428	0.617	0.555	0.712	0.707	0.431	0.448	0.663	0.418	0.383	0.411	0.417
Mg	0.152	0.200	0.201	0.133	0.189	0.220	0.352	0.307	0.135	0.145	0.325	0.094	0.115	0.084	0.125
Na	0.085	0.130	0.117	0.171	0.115	0.134	0.092	0.111	0.189	0.165	0.093	0.118	0.136	0.073	0.184
K	1.890	1.885	1.839	1.858	1.873	1.879	1.889	1.872	1.853	1.841	1.927	1.868	1.916	1.899	1.788
$Mg^{\#}$	0.22	0.26	0.27	0.24	0.23	0.28	0.33	0.30	0.24	0.24	0.33	0.18	0.23	0.17	0.23

FeO*=total Fe as FeO, $Mg^{\#}$=Mg/(Mg+Fe), sample of #=altered muscovite.

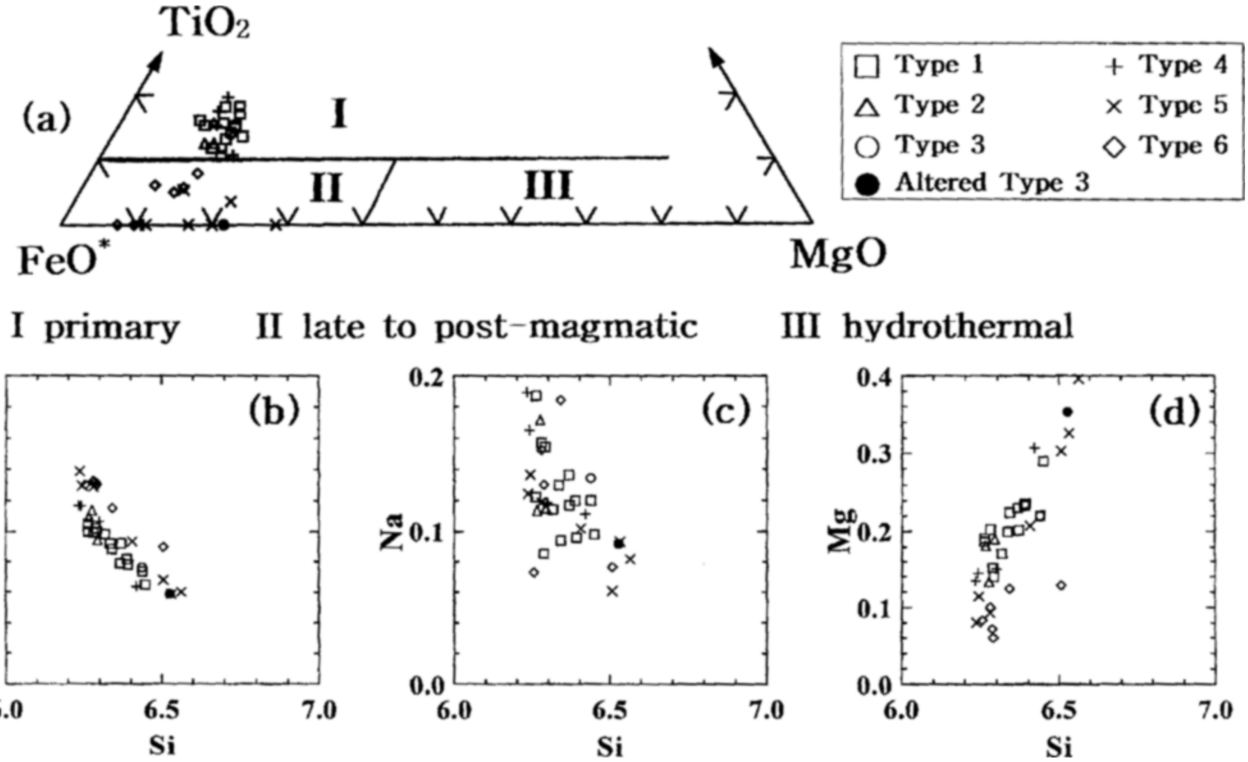

Fig. 6. Compositional variations in muscovite. **(a)** TiO_2–FeO*–MgO diagram (Speer, 1984). **(b)**, **(c)** and **(d)** Al, Na, and Mg plotted against Si, respectively.

formulas of muscovites. Primary muscovites are richer in Ti, Al, and Na and poorer in Mg and Si than secondary muscovites (Miller et al., 1981). The types 1, 2, 3, and 4 muscovites of Yuksipryong granite have significantly higher Ti

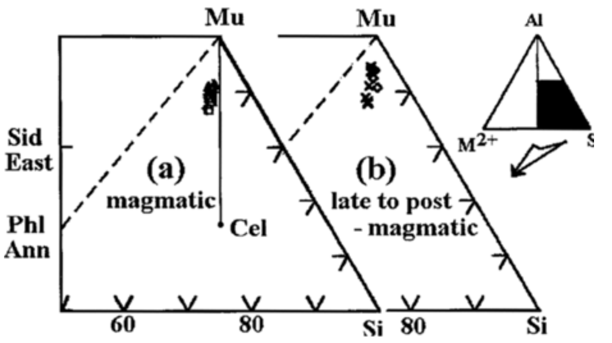

Fig. 7. Al(Al+Fe^{3+}−2Ti)–M^{2+}(Fe^{2+}+Mg+Mn+Ti)–Si(Si+2Ti) diagram (Monier and Robert, 1986) showing compositional variation of micas. Mica compositions are calculated assuming Fe^{3+}=10 mole% total Fe. **(a)** biotite and muscovite of type 1, 2, 3, and 4. **(b)** muscovite of type 5 and 6. Mu=muscovite, Cel=celadonite, Phl=phlogopite, Ann=annite, Sid=siderophyllite, East=eastonite. Symbols are same as Fig. 6.

than types 5 and 6 muscovites (Fig. 6). Na, Al, Mg, and Si show a wide variation in all types (Fig. 6). It seems that the relationship depends on the individual situation, which results from three major substitutions (Na, K, H_2O) in the interlayer site of muscovite (Speer, 1984). According to Speer (1984), primary muscovite contains higher TiO_2 than late to post-magmatic muscovite. This suggests that types 1, 2, 3, and 4 are possibly primary muscovites, and types 5 and 6 are late to post-magmatic muscovites, which is in agreement with our microscopic textural observation. Thus primary muscovite forms 70–80% of the total muscovite (Table 1).

Although we do not fully understand the nature of Ti substitution, we can consider the following substitutions in the primary muscovite: (1) (Mg, Fe)+Ti⇔$2Al^{VI}$; (2) Ti+Al^{IV} ⇔Al^{VI}+Si; (3) Ti+□⇔2(Mg, Fe). Guidotti (1978) considers substitution (1) to be the most important in muscovite. All the analyzed muscovites are notably enriched in FeO* and MgO representing solid solution between muscovite and celadonite, and belong to phengitic mica (Table 3). On the M^{2+}–Al–Si diagram (Fig. 7), all six types of muscovites are plotted along the muscovite–celadonite line, indicating the celadonite or tschermark substitution. The celadonite or tschermark substitution can be defined as R^{3+}+Al^{IV}=Si+R^{2+} (R^{3+}=Al, Fe^{+3} and R^{2+}=Mg, Fe^{+2}, Mn).

This substitution is dependent on temperature and pressure. It has been shown that relatively high pressure and low temperature favor an increase of the phengitic component in muscovite (Veld, 1967). Anderson and Rowley (1981) propose, on the basis of thermodynamic considerations that celadonitic muscovite should be stable at higher temperature than pure muscovite. Since Fe or Mg preferentially enter muscovite, the addition of Fe or Mg must increase the stability field of muscovite until saturation, which corresponds to crystallization of the biotite and plagioclase substitution, depending on the pressure (Thomson 1982; Vielzeuf and Holloway, 1988). All types of muscovite show this substitution. Although all types of muscovite are phengitic, we should note that the texture criteria and the amount of TiO_2 between primary and late to post-magmatic muscovite are significantly different (Table 3 and Fig. 6).

The determination of the stability field of the phases of peraluminous granite has been a subject of many investigations. Kerrick (1972) investigated the stability of muscovite+quartz and established the equilibrium curve of dehydration reaction as muscovite+quartz=Al_2SiO_5+K-feldspar+H_2O under fixed X_{H_2O}. The minimum melting curve of ideal granite under X_{H_2O}=1 intersects the dehydration reaction curve of muscovite+quartz at approximately 3.5 kbar and 650°C. This means that primary muscovite can be crystallized from a liquid of granite composition above 3.5 kbar. This is similar to the result of 3 kbar by Miller et al. (1981) and 3.5 kbar, 700°C by Deer et al. (1992). As the solubility of Ti in biotite increases with increasing temperature (Puziewicz and Johannes, 1988), natural biotite containing Ti increases in thermal stability and will tend to displace the biotite dehydration reaction to a much higher pressure (Pantino Douce, 1993). As biotite in Yuksipryong granite has high amounts of TiO_2 (Table 2) than common biotite in the typical peraluminous two mica granite suite (Deer et al., 1992) and annite/phogophite–muscovite substitution, micas are stable at temperatures higher than 700°C, probably about 750°C.

5. CONCLUSIONS

The study on the petrography, mineralogy and chemistry of micas in the Yuksipryong granite leads to the following conclusions.

(1) The Yuksipryong granite contains both muscovite and biotite. It belongs to leucocratic granite. The constituting minerals are mainly quartz, plagioclase, K-feldspar, muscovite, and biotite. The microscopic observation indicates that the granite has undergone more or less ductile deformation. The following microscopic texture are observed: the undulatory extinction of quartz, the myrmekitic texture of plagioclase, the undulatory extinction and a kink band of biotite and muscovite.

(2) The Fe/(Fe+Mg) ratio and Al^{IV} content of biotite is 0.62–0.69 and 2.4–2.5, respectively. The biotite of the Yuksipryong granite has lower Al content than siderophyllitic biotite in typical peraluminous suites. but it has an average FeO^*/MgO ratio of 3.7 and 6–7 wt% of MgO. The relatively lower ratio of Mg/(Fe+Mg), an average of 0.37, and substantial octahedral site vacancies in biotite seem to suggest that biotite was crystallized in lower temperatures than compared to the ideal trioctahedral biotite–eastonite composition.

(3) Muscovite of the Yuksipryong two-mica granite can be divided into six types on the basis of textural criteria: occurring (i) as intergrowth with or across biotite; (ii) as euhedral crystals including small biotite; (iii) as single euhedral to

subhedral crystals without inclusion; (iv) as subhedral crystal within plagioclase; (v) as lath-shaped muscovite within plagioclase; and (vi) in the pegmatitic dyke, occurring as a single large subhedral crystal.

(4) Types 1, 2, 3, and 4 muscovites are of magmatic origin (primary muscovite) and types 5 and 6 are of late to post magmatic muscovite. Primary muscovites of the Yuksipryong granite show significantly higher Ti than late to post magmatic muscovites. But Na and Si show wide variation in all types.

(5) Muscovite compositions suggest that the celadonite or tschermark substitutions govern the muscovite composition: $R^{3+}+Al^{IV}=Si+R^{2+}$ (R^{3+}=Al, Fe and R^{2+}=Mg, Mn).

(6) Considering the composition of micas together with experimental results of many workers, the biotite and the primary muscovite of Yuksipryong granite are considered to have been crystallized at pressures higher than 3.5 kbar and temperatures higher than 700°C, probably about 750°C.

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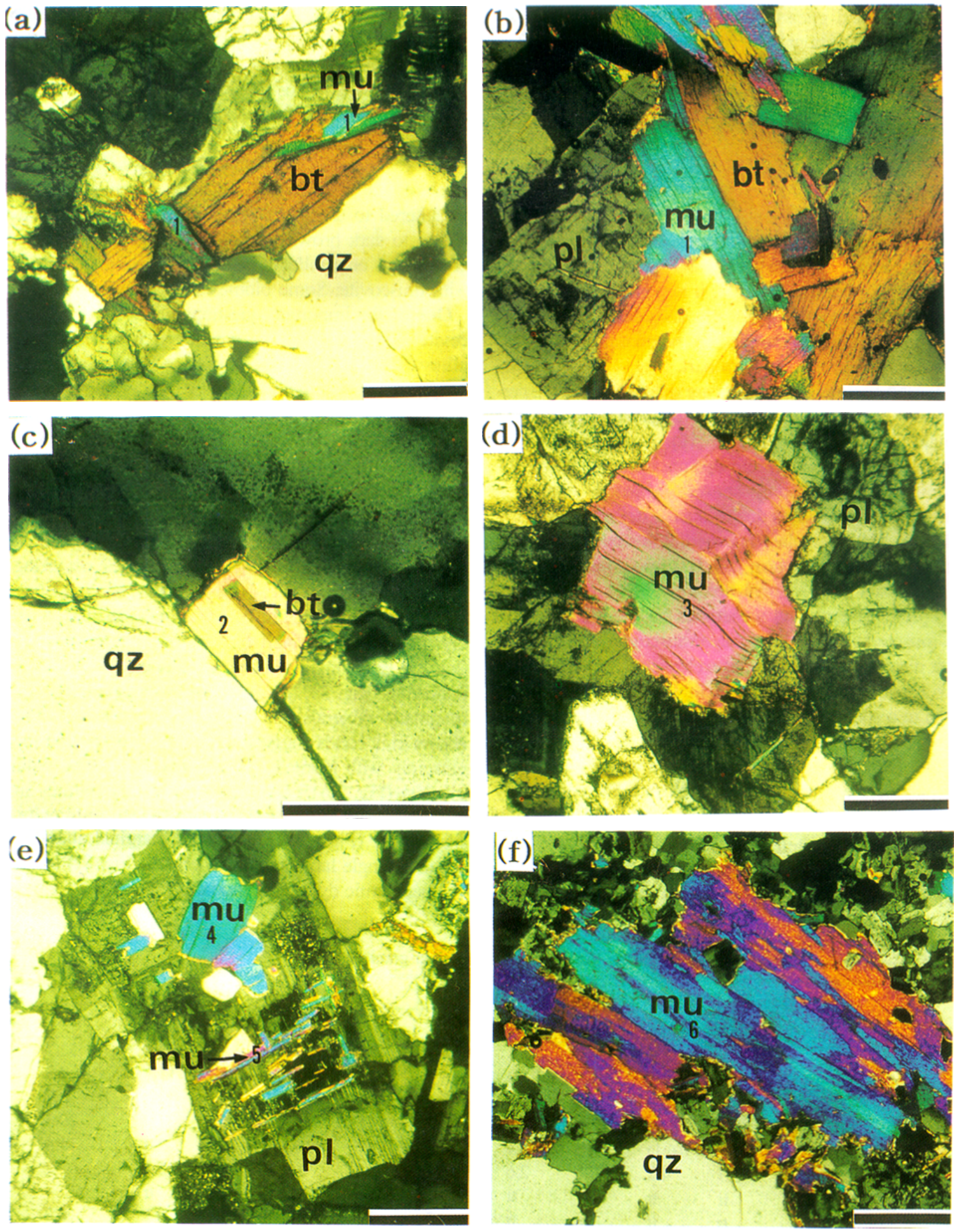

Fig. 2. Textural criteria of the muscovite in the Yuksipryong granite. **(a)** and **(b)** type 1 muscovite occurring as intergrowth with or across to biotite. **(c)** type 2 muscovite as euhedral crystals including small biotite. **(d)** type 3 muscovite as a large single muscovite euhedral to subhedral crystals showing kink band. **(e)** types 4 and 5 muscovite as small lath-shaped within plagioclase, respectively. **(f)** type 6 muscovite as single large subhedral crystal in pegmatitic dyke. The scale bar is 0.35 mm. bt=biotite, mu=muscovite, qz=quartz, pl=plagioclase.