韓國鑛物學會誌 第3卷 第1號(1990)
J. Miner. Soc. Korea, 3, 44−57(1990)

Mineralogy and Genesis of Hydrothermal Deposits in the Southeastern Part of Korean Peninsula : (1) "Napseok" Deposits in Yangsan Area

우리나라 東南部 地域의 熱水鑛床에 對한 鑛物學的 및 鑛床學的 研究 : (1) 梁山地域의 "납석" 鑛床

Soo Jin Kim(金洙鎭)*, Yeong Kyoo Kim(金瑛圭)*, and Jin Hwan Noh(魯振煥)**

*Department of Geological Sciences, Seoul National University, Seoul 151-742, Korea
(서울大學校 地質科學科)

**Department of Geology, Kangwon National University, Chuncheon 200-701, Korea
(江原大學校 地質學科)

ABSTRACT: Mineralogy of clay(Napseok) deposits in Yangsan area has been studied by the methods of field investigation and laboratory works including the polarizing microscopy, X-ray diffraction, infrared spectroscopy, thermal analysis, chemical analysis by electron microprobe and atomic absorption spectrophotometer, and electron microscopy (SEM and TEM).

The Napseok ores in both the Cheonbulsan and Yongcheon deposits consist mainly of sericite, pyrophyllite and quartz, with more or less tourmaline. The high temperatrue minerals such as corundum and dumortierite are found in the Cheonbulsan deposit, but not in the Yongcheon deposits. Dickite, nacrite, and halloysite are found in the Yongcheon deposit, but not in the Cheonbulsan deposit. The Napseok ores of the Yukwang deposit consist of sericite and quartz with no pyrophyllite, suggesting its formation at lower temperature than other deposits in the Yangsan area.

Occurrence, chemistry and structural features of important minerals are described. Mineralogical data of sericite such as intensity ratios and chemistry also support that the Napseok deposits of both the Cheonbulsan and Yongcheon mines were formed at the higher temperature than those of the Yukwang mine. Presence of sericite-dickite-pyrophyllite ores in the Yongcheon deposit also suggests the lower temperature than in the Cheonbulsan deposit.

요약 : 경남 양산지역의 납석광산을 야외조사 및 실내연구 (편광현미경 연구, X선회절분석, 적외선 분광분석, 열분석, 전자현미분석, 원자흡광분석)에 의하여 연구하였다.

천불산광산과 용천광산의 납석광석은 주로 견운모, 엽납석 및 석영과 그리고 다소의 전기석(buergerite)으로 구성되어 있다. 두 광상의 광물학적 차이점은 천불산광상에는 고온 광물인 강옥과 듀모티에라이트가 산출되고 용천광상에는 이들 광물이 산출되지 않으며 딕카이트, 나크라이트, 할로이사이트가 용천광상에는 산출되지만 천불산광상에는 산출되지 않는다는 점이다. 유광광상의 납석광석은 견운모와 석영으로만 구성되어 있어서 천불산광상 및 용천광상보다 저온에서 생성되었다는 것을 지시해준다. 중요 수반광물에 대하여 산출상태, 화학조성 및 구조적 특성이 자세히 연구되었다. 견운모의 구조 및 화학조성은 천불산광상과 용천광상이 고온에서 그리고 유광광상은 저온에서 생성되었음을 지시해 준다. 또한 용천광상에 있어서 견운모−딕카이트−엽납석광석의 산출은 이것이 없는 천불산광상의 광석보다 저온에서 생성되었음을 지시해 준다.

INTRODUCTION

Yangsan area is one of three most important so-called "Napseok" mineralization in Korea. There are three clay mines in the area; Cheonbulsan, Yongcheon, and Yukwang mines. They are all located in the Yangsan-gun, Kyeongsangnam-do, Korea(Lat. 35°21′−35°27′, Long. 129°07′−129°14′).

"Napseok" ores consists mainly of pyrophyllite and sericite in the Cheonbulsan and Yongcheon mines, but sericite only in the Yukwang mine. They are used as the important ceramic raw materials in Korea. The annual production of the ores is about 10,000 tons.

Geology of the Yangsan area has been studied by Lee and Kang (1964), Cha et al. (1972, 1984), Lee (1986) and Kim (1987). Lee(1986) and Kim (1987) studied the genesis of these deposits. But detailed mineralogy has not yet been made for these deposits.

The purpose of this paper is to study the mineralogy of "Napseok" ores and their genesis in the hydrothermal alteration system.

EXPERIMENTAL METHODS

Geological mapping was done to know the geological environment of "Napseok" mineralization. Mineralization was studied by systematic sampling of ores of various mineralogy, texture and color after detailed field observation, and laboratory works including polished thin section microscopy, mineral separation, X-ray diffraction, infrared spectroscopy, thermal analysis, electron microscopic (SEM, TEM) observation, intercalation experiment, and chemical analysis using electron microprobe and atomic absorption spectrophotometer.

Mineral separation of clay minerals by centrifuge was not successful because the size of sericites was so large ($> 10\mu$) that other clays are also easily associated with centrifuging. Pyrite and quartz were separated by hand-picking under the stereomicroscope. In some cases, gravity separation was used for sulfide or oxide minerals. Pure clay mineral samples were prepared by hand-picking under the stereomicroscope.

Pure samples of sericite and smectite were fused at 1400-1450℃ and quenched to prepare the polished section for electron-microprobe analysis. X-ray study was made using the X-ray diffractometer, JEOL JDX-5P with Cu or Co target. Slit condition was 1°-0.1-2° and the scanning speed was adjusted to the purpose. X-ray diffraction was made for accurate identification and characterization of clay minerals.

Chemical analyses of minerals were carried out using electron-microprobe JEOL Model JXA-733.

Morphology and textures of minerals were studied using the scanning electron microscope JEOL Model JSM-35 and transmission electron microscope JEOL Model JEM 200 CX.

GEOLOGY OF "NAPSEOK" DEPOSITS

Geology of the area consists mainly of the sedimentary and volcanic rocks of the Silla Series and granitic rocks of the Bulgugsa Series of Mesozoic age (Fig. 1).

Sedimentary rocks consist of the Daeyangdong Formation which forms the basement of the area, and the Palyongsan Formation which is composed of volcanic tuffs. The Daeyangdong Formation is correlated with the Haman Formation (Lee and Kang, 1964). Hornfelsization is observed near the contact with granitic rocks.

Volcanic rocks consist of andesite, welded tuff and rhyolitic rocks. They are intruded by granite porphyry, hornblende-biotite granite, granodiorite and biotite granite.

Host rocks of "Napseok" ores were previously assumed to be andesite and volcanic breccia by Lee and Kang (1964), rhyolitic tuff by Cha et al. (1972) and Kim(1987), rhyodacite by Cha et al. (1984), and rhyolite by Lee (1986). However, the present study suggests that host rocks of "Napseok" ores are rhyolitic rocks, although they are extensively altered to white rocks by hydrothermal alteration.

"Napseok" deposits are found mainly in the rhyolitic rocks near the Dongrae fault trending N30E. Many small-scaled faults and joints normal to the Dongrae fault are found in the rhyolitic rocks. High-grade ores are mainly found along

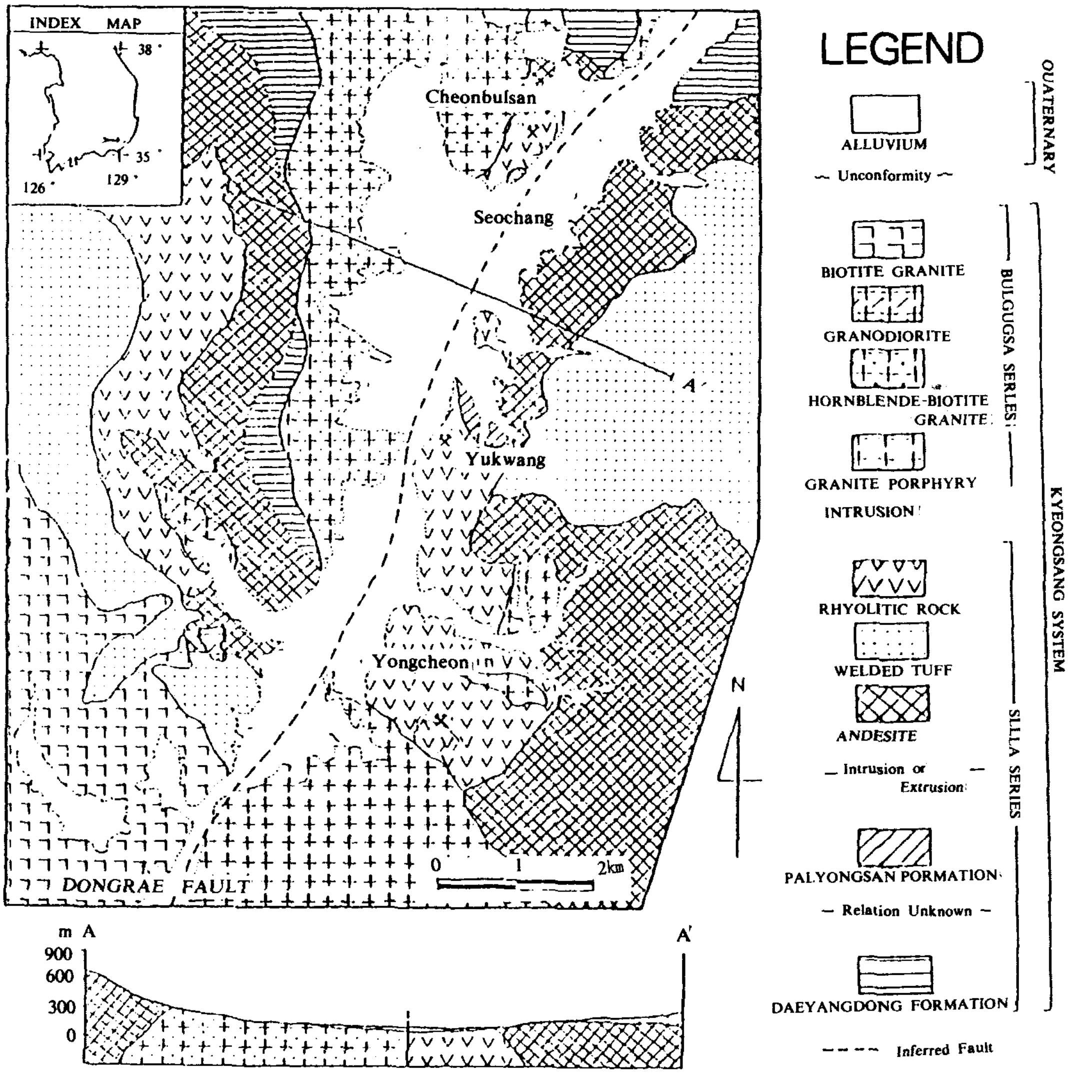

Fig. 1. Geological map of Yangsan area.

or near the minor faults or joints.

NATURE OF MINERALIZATION

"Napseok" ores in the Yangsan area occur as two mineralogical types; pyrophyllite-sericite and sericite types. Pyrophyllite and sericite (muscovite) are the major consituent minerals of "Napseok" ores in the Yangsan area. But many other minor minerals are also associated with them. The mineral species identified from Napseok deposits are listed in Table 1.

"Napseok" ores are generally massive in outcrops and working faces. They give soft and waxy feeling, and white, grey, yellowish or greenish in color depending on their mineralogy.

Quartz occurs widely in "Napseok" ores. Dark sports in "Napseok" in the Cheonbulsan deposit are due to dissemination of tourmaline (buergerite) (Fig. 2A, B, C). Tourmaline occurs as disseminated columns, rediating cluster or ring aggregates in the "Napseok" ore. Bluish spots are

Table 1. Clay minerals and their associated minerals from "Napseok" deposits in Yangsan area

Classification	Mineral	Cheonbulsan	Yukwang	Yongcheon
Silicate	Sericite	***	***	***
	Pyrophyllite	***	–	***
	Dickite	*	–	**
	Nacrite	–	–	*
	Hallosite (10Å)	–	–	*
	Hallosite (7Å)	–	–	*
	Smectite	–	–	*
	Tourmaline	**	–	*
	Dumortierite	*	–	–
	Rectorite	*	–	–
	Quartz	***	***	***
	Feldspar	*	*	*
Sulfide	Pyrite	**	**	**
	Galena	–	–	*
	Sphalerite	–	–	*
Oxide	Goethite	*	*	*
	Hematite	*	*	**
	Anatase	–	*	–
	Corundum	*	–	–
Sulfate	Beaverite	–	–	*
Hydroxide	Diaspore	*	–	–
Carbonate	Calcite	–	*	–

*** Major, ** Minor, * Accessory

due to dumortierite. Greenish or bluish acicular tourmaline (rubellite) is found in geodes within "Napseok" in the Yongcheon deposit. Grey color is due to dissemination of fine-grained pyrite. Pyrite patches or veinlets are occasionally found in "Napseok" (Fig 2D). Galena and sphalerite are associated with smectite in the Yongcheon deposit. The brownish color is due to the iron hydroxide (goethite). It is significant to mention that corundum and diaspore occur in the Cheonbulsan deposit.

It is hard to distinguish pyrophyllite from sericite in the pyrophyllite-sericite ores in the field. Zonal distribution of minerals could be recognized only by X-ray diffraction of samples which were collected systematically from ore bodies. The results show that pyrophyllite is present in the central part and sericite is in the outer zone.

CLAY MINERALOGY

Sericite

Sericite is a petrographic term used to indicate highly birefringent, fine-grained, and micaceous material that is viewed under the optical microscope (Eberl et al., 1987). It is one of the most common alteration products found in rocks surrounding hydrothermal ore deposits. The term sericite has actually been used to indicate the fine-grained and micaceous material such as muscovite, phengite, illite, hydromica or mixed layer I/S (Beaufort and Meuniter, 1983; Parry et al., 1984; Bishop and Bird. 1987) with fixed interlayer cation contents that usually are less than the structural limit of 1.0 equivalent per $O_{10}(OH)_2$. Sericite in the Yangsan area corresponds to dioctahedral muscovite of $2M_1$ or 1M polytype.

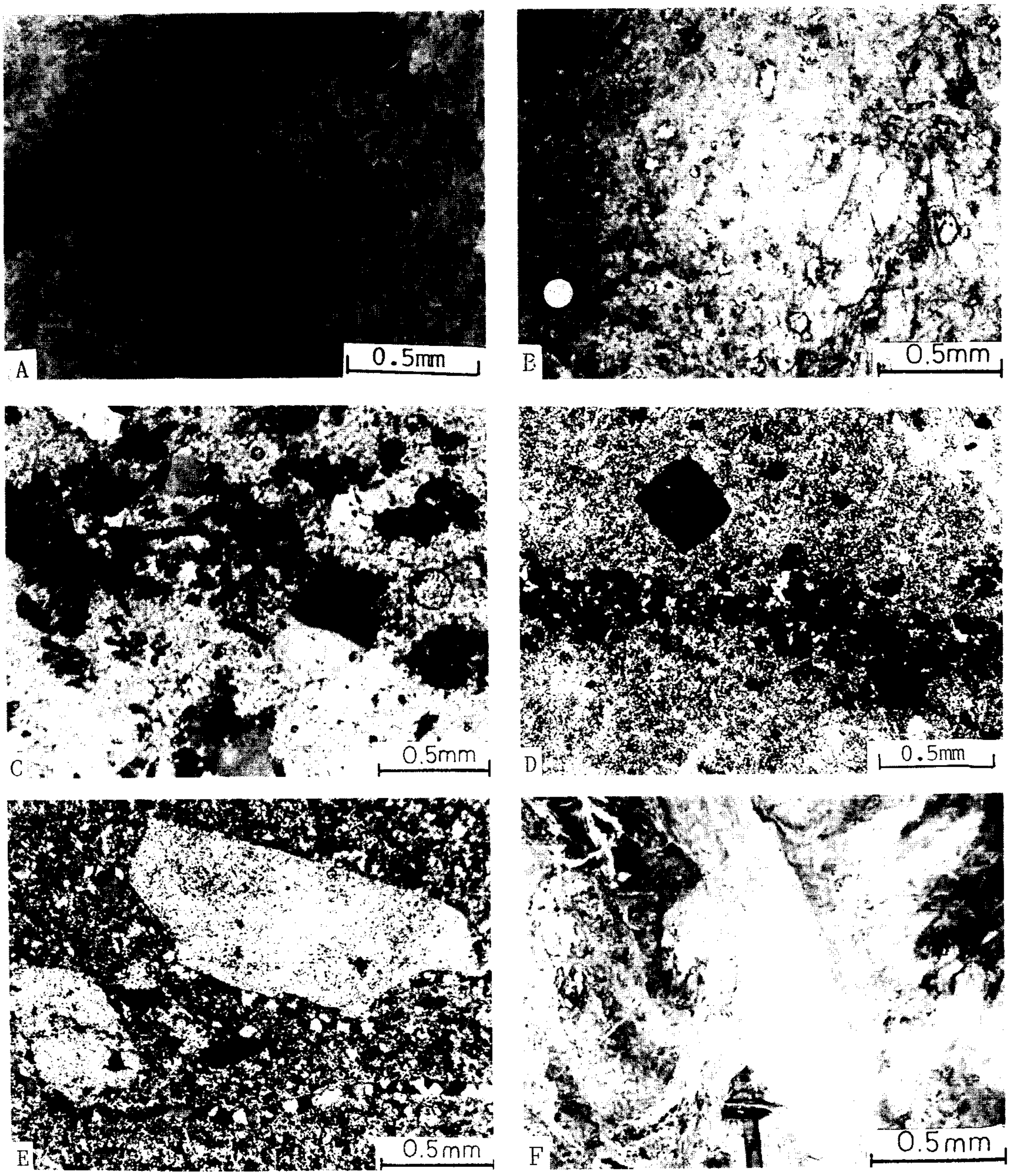

Fig. 2. (A) (B) Tourmaline (buergerite) in the sericitic Napseok ore in the Cheonbulsan deposit. Dark spots are tourmaline. Rectorite is found inside the dark tourmaline ring (B). (C) Tourmaline (columnar) in the sericitized rhyolitic groundmass in the Cheonbulsan deposit. Note the quartz phenocrysts not severely altered. Thin section. (D) Pyrite dissemination in vein-like fashion in the sericitic matrix in the Yukwang deposit. Thin section. (E) Feldspar phenocrysts and groundmass in the Cheonbulsan deposit which have been nearly completely altered to sericite. Thin section. (F) Smectite veins in the pyrophyllitic Napseok in the Yongcheon deposit.

Fig. 3. (A-D) SEM photographs. (A) Sericite (muscovite) (S) on feldspar (F). (B) Flaky sericite. (C) Dickite in book-form. (D) Flaky pyrophyllite. (E-H) TEM photographs. (E) Long tubular form of 10Å-halloysite. (G) (H) Spherulitic forms of 10Å-halloysite.

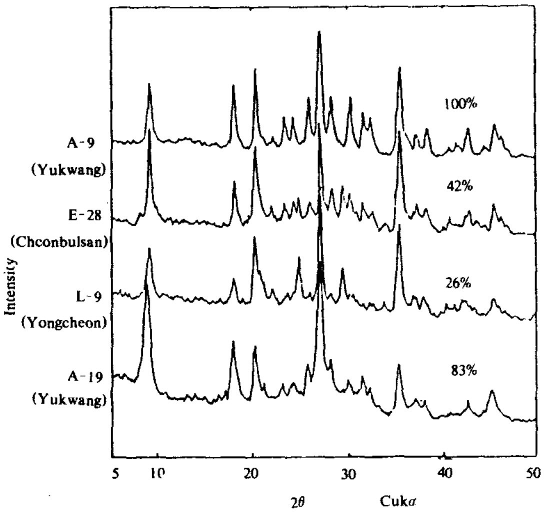

Fig. 4. X-ray diffraction patterns of sericites of various $2M_1$%. A-19 is from feldspar phenocryst.

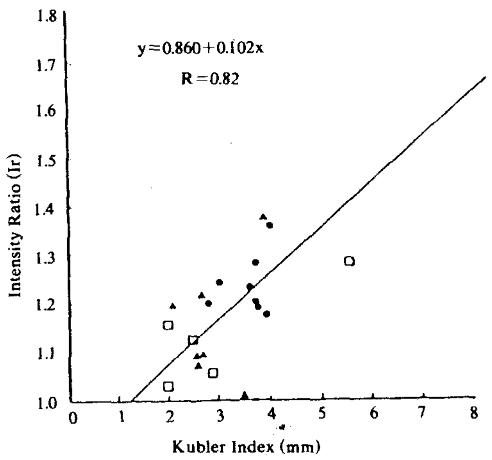

Fig. 5. Relation between Kubler Index and intensity ratio (Ir). ▲ Cheonbulsan, ● Yukwang, □ Yongcheon

Sericite occurs as hard, massive aggregates in both the Cheonbulsan and Yongcheon deposits, whereas it occurs as powders in the Yukwang deposit. It is generally greenish or whitish in color but rarely violet or reddish in places. However, sericite in the Yukwang deposit is always white. It has somewhat lower birefringence than pyrophyllite, but both have the same textural features. Distinction between two minerals is possible only by X-ray diffraction.

It is often found that feldspar phenocrysts are completely replaced by sericite (Figs. 2E and 3A). Sericite replaces quartz along the grain border or fissures. However, later quartz veinlets crossing the sericite ores are also found (Fig. 2E).

Sericite from the Yangsan area consists of muscovite of 1M and $2M_1$ polytypes. Nearly all the samples are mixture of 1M and $2M_1$, although pure $2M_1$ sample is identified in rare case. Any definite distribution pattern of these polytypes is not found. The percentages of $2M_1$ dioctahedral muscovite relative to total dioctahedral muscovite were calculated from the curve by Maxwell and Hower (1967). 2.8Å and 2.58Å peaks were used for calculation. The results show that the percentage of $2M_1$ to total mica vary from 16 to 91% in the studied samples. X-ray diffraction patterns of various percentages of $2M_1$ polytype are shown in Fig. 4.

Intensity ratio (Ir) (Srodon, 1984) and Kubler index (KI) (the width at half height in millimeters of the illite (001) XRD reflection) which is called the illite crystallinity index (Kubler, 1964) have linear relation for sericites from Yangsan area (Fig. 5). (001) peak breadth is mostly a function of the amount and composition of the I/S component of the sample (Srodon, 1979, 1984; Weaver and Broekstra, 1984). Eberl et al. (1987) showed that Ir and Kubler index have close relation to expandability. Because peak shifts after glycol intercalation are small and difficult to detect, expandabilities have been calculated based on Eberl's equation which is related to intensity ratio.

Intensity ratios of some samples from Cheonbulsan and Yongcheon deposits are nearly 1, which means that they are non-expandable, whereas those of samples of the Yukwang deposit are relatively high. This phenomenon is justified by the fact that high-temperature minerals are not found in the Yukwang deposit.

The largest value of expandability is recorded for the sample A-19 which was collected from the sericite pseudomorph after feldspar grain in the border zone of sericite ore body in the Yukwang deposit. Calculation shows that expandability increases in its value from the center to the margin of the hydrothermal alteration. It

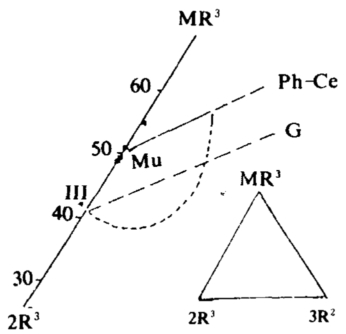

Fig. 6 (A) Compositions of sericites in Yangsan area in the MR^3-$2R^3$-$3R^2$ coordinates. $MR^3 = Na + K + 2Ca$, $3R^2 = (Mg + Fe^{3+})/3$, $2R^3 = (Al + Fe^{3+} - MR^3)/2$. Mu = muscovite, Ph-Ce = phengite-celadonite compositions, G = glauconite-type composition, Ill = illite.

suggests that expandability of sericite decreases with advancing sericitization.

Chemical analyses of sericites (Table 2) show that interlayer charges arise mainly from tetrahedral layers. The total interlayer charges are nearly 1 per 10 $(OH)_2$. Chemical compositions of sericites are nearly the same as dioctahedral muscovite as shown in compositional diagram by Velde (1985) (Fig. 5). Fig. 6 shows that the composition corresponds to the magmatic muscovite.

Pyrophyllite

Pyrophyllite occurs in the inner zone of hydrothermal alteration in both the Cheonbulsan and Yongcheon deposits. It is similar to sericite in its occurrence and physical properties. It is yellowish green to yellow or white in the Cheonbulsan deposit, whereas white in the Yongcheon deposit. Sericite, dickite and quartz are generally associated with pyrophyllite.

Pyrophyllite has 3 polytypes; 2M, 1Tc and a disordered form (Brindley and Wardle, 1979). Crystal structure of pyrophyllite was studied by Lee and Guggenheim (1981). Pyrophyllite is of 1Tc or 2M polytype in Yangsan area(Fig 7) and mainly 1Tc-pyrophyllite in Yongcheon deposit. Intensities of (110) and (002) peaks of 1Tc and (004) peak of 2M are indicators in distinguishing two polytypes (Table 3). Also the difference is found in the peaks at 4.24-4.07Å. The difference in X-ray diffraction patterns between sample G-6 and N-3 might be caused by different crystallinity. Chemical analysis of pyrophyllite was not made because of difficulty in preparing the pure sample.

Table 2. Electron-microprobe analyses of sericites in Yangsan area

	A-9	A-19	E-29	K-14
SiO_2	45.88	47.50	45.27	51.79
Al_2O_3	37.52	34.48	39.94	33.61
Fe_2O_3	0.15	0.31	0.91	0.40
MgO	0.15	0.10	0.07	0.73
MnO	0.16	0.10	0.16	0.00
SrO	0.17	0.00	0.00	0.14
BaO	0.17	0.00	1.16	0.57
CaO	0.08	0.67	0.00	0.08
Na_2O	0.18	0.48	1.22	0.29
K_2O	10.66	9.36	10.18	11.19
Total	95.12	93.00	98.91	98.80
Structural formulas of sericite (per $O_{10}(OH)_2$)				
Octahedral				
Al	1.97	1.92	1.96	1.84
Fe^{3+}	0.01	0.02	0.04	0.02
Mg	0.01	0.01	0.01	0.07
Mn	0.01	0.01	0.01	-
Tetrahedral				
Al	0.96	0.81	1.08	0.69
Si	3.04	3.19	2.92	3.31
Interlayer				
Ca/2	0.01	0.10	-	0.01
Na	0.02	0.06	0.15	0.04
K	0.91	0.80	0.84	0.91
Sr/2	0.01	-	-	0.01
Ba/2	0.01	-	0.06	0.03
Charge				
Octahedral	−0.02	−0.14	+0.04	−0.28
Tetrahedral	−0.96	−0.81	−1.08	−0.69
Interlayer	+0.96	+0.96	+1.05	+1.00

Smectite

Smectite occurs as massive veins in restricted area in the pyrophyllitic Napseok in the Yongcheon depsosit (Fig. 2F). Dickite, halloysite,

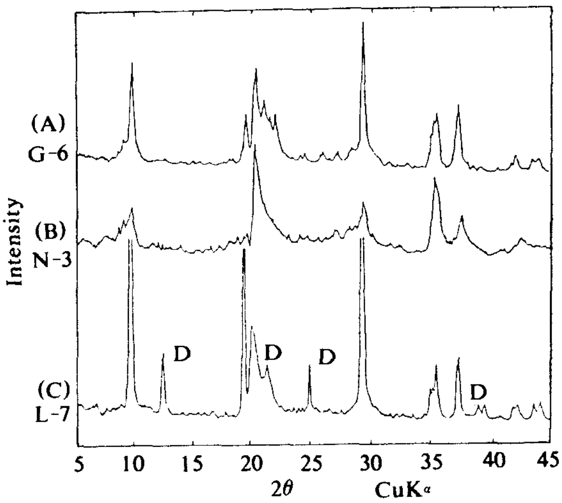

Fig. 7. X-ray diffraction patterns of two polytypes of pyrophyllite. (A) (B) 1Tc (C) 2M D: dickite

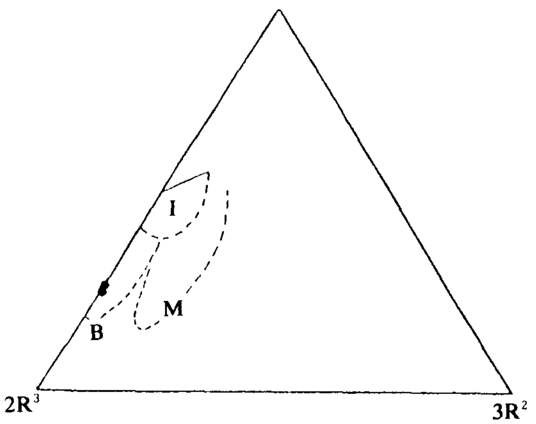

Fig. 8 Smectite (p-6) in the MR^3-$2R^3$-$3R^2$ coordinates. B = beidellite, M = montmorillonite, I = illite

Table 3. X-ray diffraction data of pyrophyllite polytypes; 1Tc and 2M

1Tc			2M		
d(Å)	I/I	hkl	d(Å)	I/I	hkl
9.20	65	001	9.17	90	002
4.60	35	002	4.59	35	004
4.42	65	110, $1\bar{1}0$	4.42	15	110
4.24	35	$11\bar{1}$, $1\bar{1}\bar{1}$	4.16	10	$11\bar{2}$, 111
4.07	30	$02\bar{1}$	3.06	100	006
3.73	2	$1\bar{1}1$, 111	2.550	10	$\bar{2}02$, 130
3.47	3	$11\bar{2}$, $1\bar{1}\bar{2}$	2.423	10	210, $\bar{1}33$
3.20	5	022	2.323	2	008
3.07	100	003	2.151	3	$\bar{1}18$, 042
2.569	25	$1\bar{3}0$, $20\bar{1}$	2.085	3	043
2.549	30	$13\bar{1}$, $02\bar{3}$	1.841	8	0010, 029
2.532	35	200, $1\bar{3}\bar{1}$			
2.416	35	$20\bar{2}$, 131			
2.148	10	$20\bar{3}$, 132			
2.086	8	$13\bar{3}$, $2\bar{2}1$			
2.067	10	221, 202			
1.844	5	005			

galena, and sphalerite are associated with smectite. Beaverite, an alteration product of galena is rarely associated. Smectite vein shows white or reddish color. White part consists of smectite, dickite and halloysite, whereas the reddish part of only smectite.

X-ray diffraction was done for the samples before and after organic intercalation as well as heating at 550℃ for exact identification. d(060) (1.491 Å) suggests that it is dioctahedral (Warshaw and Roy, 1961: Douglas et al., 1980: Brown and Brindley, 1980).

Chemical analyses of smectites (Table 4) show that the interlayer charges, about 0.33 per 10 $(OH)_2$ arise from tetrahedral layer, suggesting that it is beidellite (Green-Kelly, 1955; Velde, 1985). The octahedral cation is mainly Al, and the main interlayer cation is Mg. Chemical analyses are also plotted on the beidellite area in the MR^3 $-2R^3-3R^2$ coordinates(Fig. 8).

Dickite and Nacrite

Dickite and nacrite are each polymorph of kaolinite. The only difference is the stacking sequence of basic layers.

Dickite occurs as veinlets in the pyrophyllite-sericite ores in the Cheonbulsan deposit. It is associated with sericite and /or pyrophyllite in the Yongcheon deposit. Smectite is also associated with dickite in rare case. It is white in color.

Nacrite is found in association with sericite and pyrophyllite in the Yongcheon deposit. It is also white in color.

Table 4. Electron-microprobe analyses of smectite in Yongcheon mine

	P-6-1	P-6-2	P-6-3	Average
SiO_2	57.22	59.18	60.38	58.93
Al_2O_3	29.04	31.99	31.86	30.96
Fe_2O_3	0.50	0.77	0.90	0.72
TiO_2	0.12	0.23	0.15	0.17
MgO	1.56	1.58	1.44	1.53
MnO	0.25	0.25	0.20	0.23
SrO	0.16	0.32	0.27	0.25
BaO	0.00	0.22	0.00	0.07
CaO	0.05	0.01	0.07	0.04
Na_2O	0.00	0.05	0.23	0.09
K_2O	0.09	0.20	0.18	0.16
Total	88.99	94.80	95.68	93.15
Structural formulas of smectite (per $O_{10}(OH)_2$)				
Octahedral				
Al	1.95	1.94	1.94	1.95
Fe^{3+}	0.02	0.04	0.04	0.03
Ti	0.01	0.02	0.01	0.01
Mn	0.01	0.01	0.01	0.01
Tetrahedral				
Si	3.72	3.64	3.66	3.68
Al	0.28	0.36	0.34	0.32
Interlayer				
Mg/2	0.30	0.29	0.26	0.28
Ca/2	0.01	–	0.01	0.01
Na	–	0.01	0.03	0.01
K	0.01	0.02	0.01	0.01
Sr/2	0.01	0.02	0.02	0.02
Ba/2	–	0.01	–	–
Charge				
Octahedral	−0.03	+0.04	0.00	0.00
Tetrahedral	−0.28	−0.36	−0.34	−0.32
Interlayer	+0.33	+0.35	+0.33	+0.33

X-ray diffraction patterns of dickite and nacrite are shown in Fig. 9. Brindley and Porter (1978) found that dickite occurs in various order and disorder forms. Dickite in the Yangsan area also shows different order-disorder forms. Dickite of the Yongcheon deposit is better ordered than that of the Cheonbulsan deposit. The former corresponds to B and the latter to D (the most disordered form) based on Brindley and Porter's (1978) scheme.

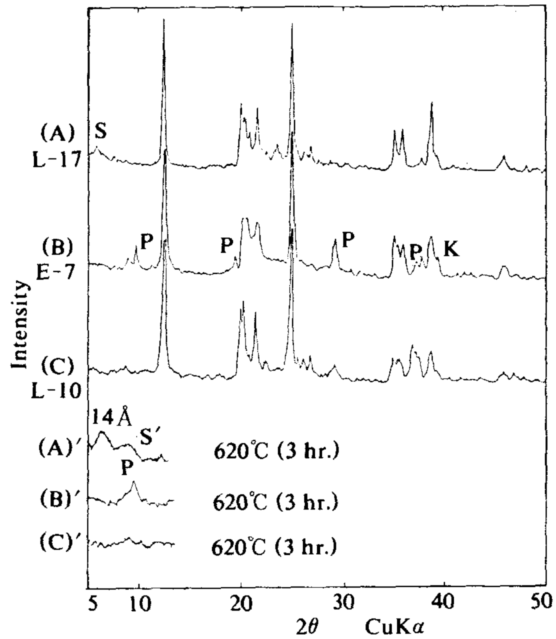

Fig. 9. X-ray diffraction patterns of untreated (A, B, C) and heat-treated (A', B', C') dickite and nacrite. (A) Structurally ordered dickite in Yongcheon Mine. (B) Structurally disordered dickite in Cheonbulsan Mine. (C) Nacrite in Yongcheon Mine. S = smectite S' = dehydrated smectite, P = pyrophyllite, K = kaolinite type peak.

Brindley and Wan (1979) show that dickite with well-ordered crystal sturcture and with relatively high dehydration temperature develops a 14Å phase when heated to temperature in the range of 550-800℃. Dickite from the Yongcheon deposit shows 14Å phase when heated to 620℃ ((A)' in Fig. 9). But disordered dickite (B)' and nacrite (C)' from the Yongcheon deposit do not show 14Å phase. Survival of X-ray diffraction peaks at 470℃ suggests that dickite from the Yongcheon deposit is well-ordered.

Halloysite

Halloysite occurs in association with smectite only in the Yongcheon deposit. Both the 10Å- and 7Å-halloysites are found. Both are white in color. X-ray powder diffraction patterns of untreated 7Å-and 10Å-halloysites as well as heat-

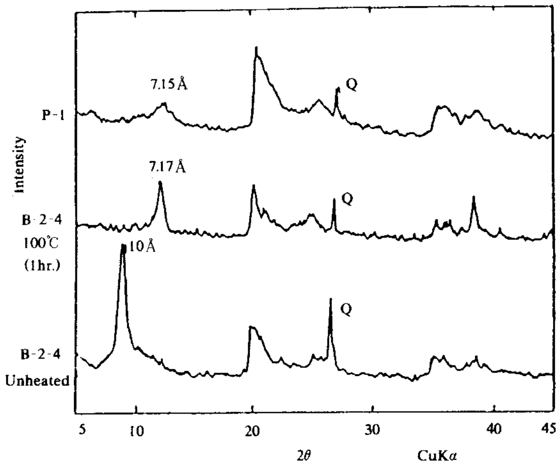

Fig. 10 X-ray diffraction patterns of halloysites in Yongcheon Mine. B-2-4 is untreated 10Å halloysite and P-1 is untreated 7Å halloysite. Q = quartz

treated 10Å-Halloysite are shown in Fig. 10.

Halloysite shows various morphology; tubular, spherical, crinkly and scroll forms (Fig. 3E-H). Among these, spherical and tubular forms are most common.

Morphology of halloysite has been studied by Beutelspacher and Van der Marel (1968), Dixon and Mckee (1974), Nagasawa and Miyazaki (1976), Sudo and Yotsumoto (1977), Tazaki (1980), and Sudo et al. (1981). Nagasawa and Miyazaki (1976) studied many halloysite samples and concluded that the morphology of halloysite varies with its origin, that is, short tubular and spherical form in hydrothermal origin, and long tubular form in weathering origin.

Halloysite from the Yongcheon deposit has characteristic features. Halloysite studied shows characteristic forms distinguishable depending on the hydration states. The 10Å-halloysite shows long tubular (Fig. 3E) and rarely spherical forms (Fig. 3G, H). The spherical forms include nearly perfect spherules, rings and scroll forms. The 7Å-halloysite shows short tubular form (Fig. 3F). Nagasawa and Miyazaki's study is not applicable to the halloysite from the Yongcheon deposit.

Rectorite

Rectorite is the regular interstratified mineral of illite and smectite. It occurs inside of tourmaline ring (Fig. 2B) in the pyrophyllite-sericite ore. It has the same characters as sericite or pyrophyllite in color, surface feeling and hardness.

The mineral has d(001) (23.9Å) and d(002) (12Å). d(001) (23.9Å) shifts to 9.7Å after heating at 500℃ and to 26.3Å when ethylene glycol-treated (Fig. 11).

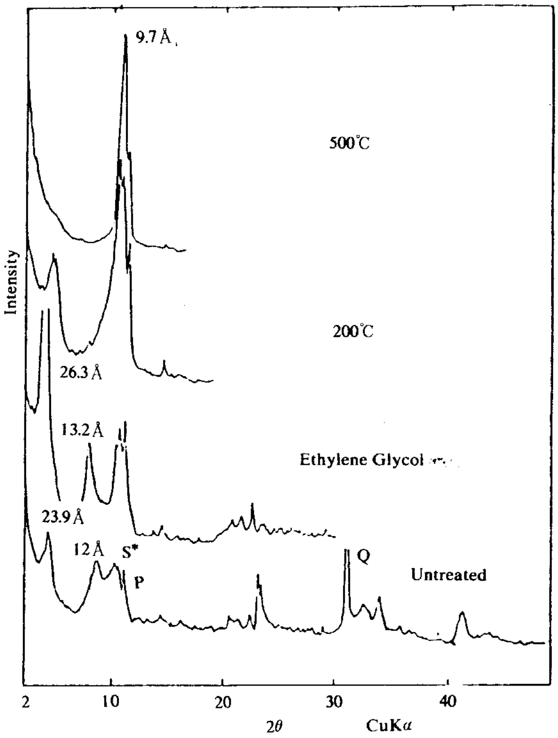

Fig. 11 X-ray diffraction patterns of rectorite in Yongcheon mine. S* = sericite, P = pyrophyllite, Q = quartz

DISCUSSION

In order to know the mineral distribution in the deposits, samples collected systematically across the pyrite-enriched zone along the fault in the Yongcheon deposit, were analyzed by X-ray diffraction. The result shows that pyrophyllite occurs in the inner zone and sericite in the outer zone. Dickite is associated with pyrophyllite (Table 5). According to Meyer and Hemley's (1967) classification, the pyrophyllite-dickite corresponds to the advanced argillic zone, sericite to

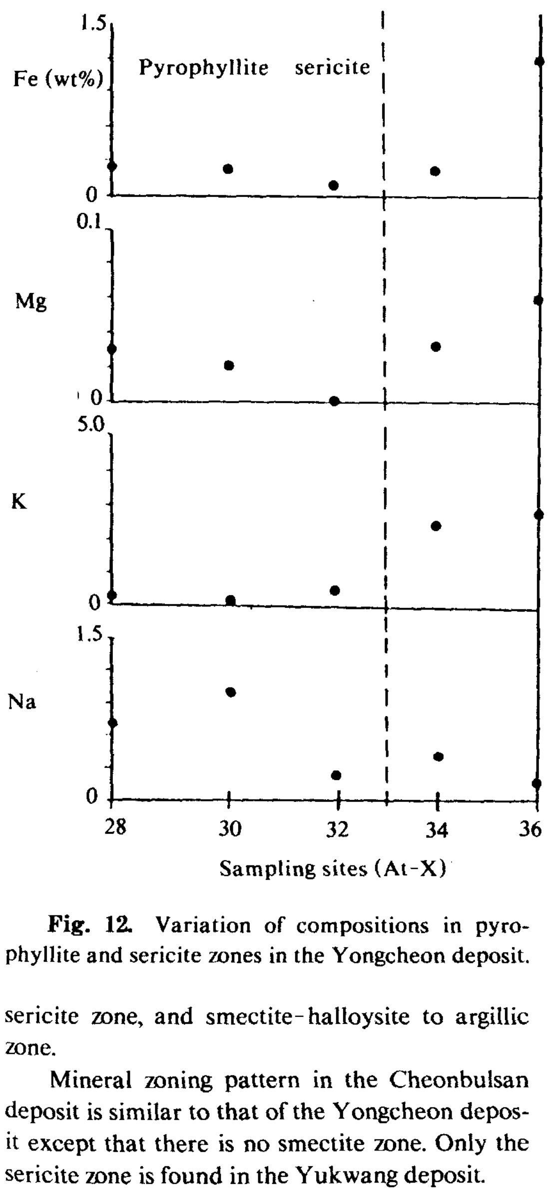

Fig. 12. Variation of compositions in pyrophyllite and sericite zones in the Yongcheon deposit.

sericite zone, and smectite-halloysite to argillic zone.

Mineral zoning pattern in the Cheonbulsan deposit is similar to that of the Yongcheon deposit except that there is no smectite zone. Only the sericite zone is found in the Yukwang deposit.

Samples representing each zone were analyzed using atomic abosrption spectrophotometer to know the chemical distribution pattern. The results are shown in Fig. 12. Nearly all the elements analyzed show the tendency to increase from the inner zone (pyrophyllite) to the outer zone (sericite). Among them, K shows typical increasing tendency.

Pyrophyllitization of rhyolitic rocks has been studied by Tsyzuki and Mizutani (1971). They gave the following processes of formation of minerals which are applicable to the clay minerals in the Yangsan area.

Table 5. Distribution of phyllosilicate minerals from At-21 to At-36 in Yongcheon deposit.

Sample No.	Sericite	Pyrophyllite	Dickite
At-21	***		
At-22	***		
At-23	***		**
At-24	***		
At-25	***		
At-26	***		
At-27	**	***	
At-28		***	**
At-29	***	*	
At-30	***	***	*
At-31		***	**
At-32		***	
At-33	***		
At-34	***		*
At-35	***		
At-36	***		

*** Major ** Minor * Accessory

1. $5KAlSi_3O_8 + H^+ — 0.5KAl_3Si_3O_{10}(OH)_2 + 3SiO_2 + K^+ \cdots (1)$
K-feldspar muscovite

$2KAl_3Si_3O_{10}(OH)_2 + 3H_2O + 2H^+ — 3Al_2Si_2O_5(OH)_4 + 2K^+ \cdots (2)$
muscovite dickite

$Al_2Si_2O_5(OH)_4 + 2H_4SiO_4 — Al_2Si_4O_{10}(OH)_2 + 5H_2O \cdots\cdots (3)$
dickite pyrophyllite

As the alteration proceeds, SiO_2 and alkali ions are removing, that is, aquous solution is leaching Si, Mg and alkali ions, and firstly forming the sericite, then dickite and finally pyrophyllite. The decrease of K in the inner zone is well correlated with above equations.

According to Hemley and Johns (1964), above (1) and (2) reactions limit the stability of K-feldspar and muscovite at temperature below about 300°C, and pyrophyllite is the stable product at higher temperatures instead of dickite as in the following equation (3)'.

$KAl_3Si_3O_{10}(OH)_2 + 3SiO_2 — 1.5Al_2Si_4O_{10}(OH)_2 + K^+ \cdots (3)'$
muscovite pyrophyllite

Pyrophyllite-dickite ores can be explained by reaction (3), but pyrophyllite-sericite ores containing no dickite suggests the formation of pyrophyllite from sericite as shown in the reaction (3)′.

Temperature is a major controlling factor for the formation of pyrophyllite. According to Eberl's(1979) synthetic study, pyrophyllite-1Tc is formed at 375℃ and above, whereas pyrophyllite-$2M_1$ at lower temperature. Association of high temperature minerals such as corundum and dumortierite with pyrophyllite in the Cheonbulsan deposit suggests a high temperature condition for the formation of pyrophyllite.

Absence of pyrophyllite and high temperature minerals as well as the high expandability of sericite in the Yukwang deposit suggests the lower temperature than other deposits in the Yangsan area.

Acknowledgments: The present studies were supported by the Basic Science Research Institute Program (1989) by the Ministry of Education, Korea

REFERENCES

Beaufort, D. and Meunier, A. (1983) A petrographic study of phyllic alteration superimposed on potassic alteration: The Silbert porphyry deposit (Phone, France). Econ. Geol. 78, 1514-1527.

Beutelspacher, H. and Van der Marel, H. W. (1968) Atlas of Electron Microscopy of Clay Minerals and their Admixtures.

Bishop, B. P. and Bird, D. K. (1987) Variation in sericite compositions from fracture zones within the Coso Hot Springs Geothermal System. Geochim. et Cosmochim. Acta. 51, 1245-1256.

Brindley, G. W. and Porter, A. R. d. (1978) Occurrence of dickite in Jamaica — order and disordered varieties. Am. Miner. 63, 554-562.

Brindley, G. W. and Wan, H. (1978) The 14Å phase developed in heated dickites. Clay Miner. 13, 17-23.

Brindley, G. W. and Wardle, R. (1970) Monoclinic and triclinic forms of pyrophyllite and pyrophyllite anhydride. Am. Miner. 55, 1259-1272.

Brown, G. and Brindley, G. W. (1980) X-ray diffraction procedures for clay mineral identification. In: Brindley, G. W. and Brown, G. (Eds.) Crystal Structures of Clay Minerals and their X-ray Identification. Miner. Soc. London, 305-359.

Cha, M. S., Kim, J. J. and Yun, S. (1972) Study on the igneous activity and mineralization in the vicinity of the Tongnae-Eonyang, Pusan. Jour. Korean Inst. Mining Geol. 5, 151-162.

Cha, M. S., Yun, S. H. and Hwang, I. H. (1984) Daeun-san Cauldron, Yangsan-gun, Kyeongsang Nam-do, Korea. Pusan National Univ. 265-275.

Dixon, J. B., and Mckee, T. R. (1974) Internal and external morphology of tubular and spheroidal halloysite particles. Clays Clay Miner. 22, 127-137.

Douglas, M., MacEwan, C. and Wilson, M. J. (1980) Interlayer and intercalation complexes of clay minerals. In: Brindley, G. W. and Brown, G. (Eds.) Crystal Structures of Clay Minerals and their X-ray Identification. Miner. Soc. London, 197-248.

Eberl, D., Srodon, J., Nadeau, P. H. and Northop, H. R. (1987) Sericite from the Silverton Caldera, Colorado: Correlation among structure, composition, origin and particle thickness. Am. Miner. 72, 914-834.

Greene-Kelly, R. (1955) Dehydration of the montmorillonite minerals. Miner. Mag. 30, 604-615.

Hemley, J. J. and Jones, W. R. (1964) Chemical aspects of hydrothermal alteration with emphasis on hydrogen metasomatism, Econ. Geol. 64, 599-612.

Kim, Y. H. (1987) Genesis of Cheonbulsan Pyrophyllite deposits in Yangsan, Kyeongnam. M. S. Thesis, Pusan National Univ.

Kubler, B. (1964) Les argiles, indicateurs de metamorphisme, Rev. Inst. Franc. Petrole 19, 1093-1112.

Lee, C. S. (1986) Genesis of Yukwang Pyrophyllite Deposits in Yangsan, Kyeongnam. M. S. Thesis, Pusan National Univ.

Lee, J. H. and Guggenheim, S. (1981) Single crystal X-ray refinement of pyrophyllite-1Tc. Am. Miner. 66, 350-357.

Lee, M. S. and Kang, P. J. (1964) Geological map of Yangsan sheet, scale 1:50,000, Geological Survey of Korea.

Maxwell, D. T. and Hower, J. (1967) High-grade diagenesis and low-grade metamorphism of illite in the Precambrian Belt Series. Am. Miner. 52, 843-857.

Meyer, C. and Hemly, J. J. (1967) Wall rock alteration. In: Barnes, H. L. (1967) (Ed.) Geochemistry of hydrothermal Ore Deposits. Holt, Rinehart and Winston, 166-235.

Nagasawa, K and Miyazaki, S. (1976) Mineralogical porperties of halloysite as related to its genesis. Proc. Int. Clay Conf. Mexico City, 1975, 257-265.

Parry, W. T., Ballantyne, J. M. and Jacobs, D. C. (1984) Geochemisty of hydrothermal sericite from Roosevelt hot springs and the Tintic and Santa Rite porphyry copper systems. Econ. Geol. 79, 72-86.

Srodon, J. (1984) X-ray powder diffraction identification of illitic materials. Clays Clay Miner. 32, 337-349.

Srodon, J. and Eberl, D. D. (1984) Illite. In: Bailey, S. W. (Ed.) Micas. Miner. Soc. America, 495-544.

Sudo, T., Shimoda, S., Yotsumoto, H. and Aita, S. (1981) Electron Micrographs of Clay Minerals. Elsevier.

Sudo, J. and Yotsumoto, H. (1977) The formation of halloysite tubes from spherulitic halloysite. Clays Clay Miner. 25, 155-159.

Tazaki, D. (1980) Micromorphology and chemical composition of kaoline minerals – Observation with aid of analytical electron microscopy (in Japanese). Clay Sci. 20, 83-90.

Velde, B. (1965) Experimental determination of muscovite polymorph stabilities. Am. Miner. 50, 436-499.

Velde, B. (1985) Clay Minerals: A Physico-Chemical Explanation of their Occurrence. Elsevier.

Weaver, C. E. and Broekstra, B. R. (1984) Illite-mica. In: Weaver at al. (Ed.) Shale Slate Metamorphism in the Southern Appalachians. Elsevier, New York, 67-199.