

## Chemistry of Talc Ores in Relation to the Mineral Assemblages in the Yesan-Gongju-Cheongyang Area, Korea

충남 예산-공주-청양지역 활석광석의 광물조합에 따른 화학적 특징

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**ABSTRACT :** The talc of the Daeheung, Pyeongan, and Cheongdang (Shinyang) talc deposits in the Yesan-Gongju-Cheongyang area is a hydrothermal alteration product of serpentinite originated from ultramafic rocks. The mineral assemblages in alteration zones are : serpentinite, serpentine-talc, talc, talc-chlorite, talc-phlogopite-chlorite, and talc-tremolite-chlorite. Chemical distributions in both the  $Al_2O_3$ -FeO-MgO system and the immobile elements suggest that the serpentine-talc and talc rocks are the reaction product of ultramafic rocks and silicic hydrothermal solution without addition of other granitic components, whereas chlorite-, phlogopite-, and tremolite-bearing rocks are the metasomatic alteration product of serpentinite by hydrothermal solution affected by granitic gneiss. Discontinuities in the immobile element ratios of mineral assemblages are due to changes in their mineralogy. The relative contents of  $Al_2O_3$ ,  $TiO_2$ , Zr in the talc-phlogopite-chlorite and talc-tremolite-chlorite rocks increase irregularly with increasing phlogopite, tremolite, and/or chlorite contents in contrast to other ore types. But the relative contents of Cr, Ni, and Co are uniform in all the mineral assemblages. Chemistry of each mineral assemblage formed by steatitization of serpentinite suggests that Cr, Co, Ni, MgO, and  $Fe_2O_3$  are relatively immobile during the alteration, whereas  $SiO_2$ ,  $Al_2O_3$ , CaO, and  $K_2O$  are highly increased. The contents of chlorite, phlogopite, and tremolite in each mineral assemblage might be controlled by addition of  $Al_2O_3$ ,  $K_2O$ , and CaO, respectively. The high contents of other elements than immobile elements in the altered rocks as compared with unaltered rocks indicate that a large amount of elements were introduced from hydrothermal solution up to about 8~41% in total mass showing maximum value in the talc-phlogopite-chlorite rock.

**요약 :** 충남 예산-공주-청양지역의 대흥-평안-신양 (청당)광산을 잇는 활석광체는 초염기성암기원의 사문암이 열수변질작용을 받아 생성되었으며, 산출되는 활석광석은 광물조성과 그 상대적 함량에 따라 사문석, 활석, 사문석-활석, 활석-녹니석, 활석-금운모-녹니석, 활석-투각섬석-녹니석, 등의 6가지로 나뉘어 질 수 있다.  $Al_2O_3$ -FeO-MgO 계에 도시한 결과와 비유동성 원소들의 상대비율 및 화학적 계산결과는 사문석-활석 및 활석 암상이 다른 이질기원의 성분들의 첨가없이 규질 열수 용액과의 반응에 의해 형성되었으며, 반면에, 녹니석, 금운모, 투각섬석을 함유한 암상들은 사문암이 주변암에 의해 영향을 받은 열수용액과의 반응에 의한 산물이다. 암상들간의 비유동성 원소들의 상대비율의 불연속성은 각 암상의 광물조성에서의 변화와 일치한다. 활석-금운모-녹니석과 활석-투각섬석-녹니석 광물조합에 있어서 금운모, 투각섬석, 녹니석의 양이 증가함에 따라  $Al_2O_3$ ,  $TiO_2$ , Zr의 상대적 함량이 다른 광물조합에 비해 불연속적으로 증가하며, Cr, Ni, Co 원소의 상대적 거동은 광물조합 유형에 관계없이 일정하다. 사문암이 활석화 작용을 받아 여러 광물조합을 가진 암상을 형성시키는데 필요한 원소들의 상대적 증감을

계산한 결과 Cr, Co, Ni, MgO, Fe<sub>2</sub>O<sub>3</sub> 등의 원소들은 상대적으로 immobile하며 SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, K<sub>2</sub>O는 생성된 광물조합에 따라 농도 변화가 큼을 보여준다. 이밖에 immobile한 원소들을 제외한 대부분의 원소들이 모암에 비해 증가한 양상을 보여 활석화 작용 중 외부로부터 다량의 원소들이 광화용액과 함께 첨가되었음을 알 수 있으며 특정 원소의 첨가에 따라 투각섬석, 금운모, 녹니석의 상대적 함량이 결정되었음을 알 수 있다. 전체적으로는 광물조합에 따라 8~41wt%의 질량증가가 있었고 이 중 활석-금운모-녹니석 암상의 형성시 가장 큰 질량증가가 있었다.

## INTRODUCTION

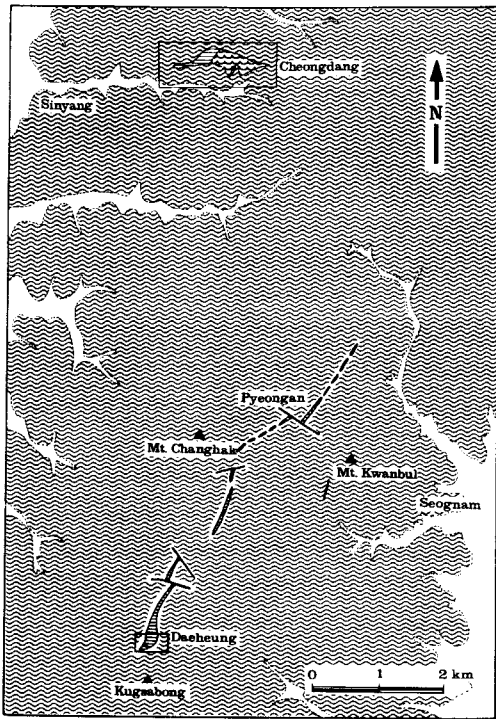
It is reported that most of talc deposits in Korea are originated from either the alteration of ultramafic rocks or magnesian carbonates. Talc ores in the Yesan-Gongju-Cheongyang area are products of hydrothermal alteration of serpentinite originated from ultramafic rocks (Chi and Kim, 1977; Woo et al., 1991; Yun et al., 1994; Kim and Kim, 1995). The talc deposits originated from ultramafics or serpentinites are formed by alteration involving only slight chemical transfer since the chemical composition of the primary rocks is relatively similar to that of talc or talc-chlorite mixtures, and the talc ores of ultramafic origin are thus characterized by the assemblage talc±serpentinite±chlorite±tremolite±carbonates (Moine et al., 1989). The talc ores of three representative talc mines (Daeheung, Pyeongan, and Cheongdang) in the study area contain a lot of impurity minerals such as chlorite, phlogopite, amphiboles, carbonates, and serpentine. Mineralogy of talc ores and their characteristics are similar to that of Moine et al (1989).

Mineralogy of talc ores and their distribution and chemistry suggest two different processes of alteration for the formation of talc deposits. They are serpentinitization and steatitization (Kim and Kim, 1995). Serpentinitization of ultramafic protolith consisting of olivine and some enstatite produced serpentine minerals and to a lesser extent talc, chlorite, and magnesite. Steatitization of serpentinite results in mainly talc and chlorite. The alteration history of these rocks involves retrogressive recrystallization

from the original ultramafic assemblage and chemical mass transfer between the country rock and the ultramafic intrusive. Lithological units of the talc deposits are composed of variable amounts of talc, chlorite, phlogopite, amphibole, carbonates, serpentine with minor olivine, pyroxene, epidote, spinel, chromite and other opaque minerals and expandable clay minerals such as smectite and regularly interstratified chlorite/smectite (corrensite). The complex nodular talc ores have the black wall zone along the contact with the country rock. Although the talc deposits has been formed by hydrothermal alteration of serpentinite, it alone cannot account for the complex mineral assemblage of the talc ores and its associated complex black-wall zoning. It is possible that the protolith was characterized by complex chemical variability, compositionally layered, tectonically intermixed with the enclosing country rock or sediments, or simply altered by external hydrothermal solution during the serpentinitization or steatitization. Mineralogy and chemical behaviour of talc ores and their occurrence show that talc ores have been formed mainly by simple hydrothermal alteration, but their chemistry has been affected by country rock in the limited region. This paper is focussed on the chemical behaviours in relation to the formation of talc deposits from the ultramafic rock.

## GEOLOGY AND ORE DEPOSITS

The Yesan-Gongju-Cheongyang talc mining area consists almost entirely of Precambrian



**LEGEND**

Quaternary		ALLUVIUM
		Unconformity
Jurassic		TALC MINERALIZED ZONE
		Intrusion
Age Unknown		HORNBLLENDE GNEISS
Pre-Cambrian		GRANITIC GNEISS

Fig. 1. Geologic map of the Yesan-Gongju-Cheongyang area.

granitic gneisses (Woo et al., 1991) with minor hornblende gneiss, tremolite schist, serpentinite, talc-chlorite schist, and dike rocks in the restricted mining area (Figs. 1 and 2). The granitic gneisses belong to Gyeonggi gneiss complex (Woo et al., 1991; Yun et al., 1994; Lee and Choi, 1994) and are locally gradational to banded or biotite gneiss. They were formed by regional metamorphism of both epidote-amphibolite and later greenschist facies and granitization (Lee and Choi, 1994).

The talc zones are generally developed as elongate or lens-shaped bodies in the Precam-

brian granitic gneiss. The Daeheung, Pyeongan, and Shinyang talc mines are three representative mines in the northeast trending mineralized zone which developed over the area of about 6 to 7 km in length and 10 to 100 m in width. Not a large differences in mineralogy and occurrence of the talc ores are found among three talc mines. Talc ores are mined in the open pits in the Daeheung mine, whereas in underground in the Pyeongan and Shinyang mines.

The major constituent minerals of the talc ores are talc, chlorite, phlogopite, amphibole, antigorite, and carbonates and the minor minerals are olivine, pyroxene, chromite, smectite, and some other expandable clay minerals such as regularly interstratified smectite/chlorite (corrensite). Chlorite is widely and abundantly distributed in the deposits. Aggregates of phlogopite and radiating acicular crystals of tremolite-actinolite in talc ore bodies are found near the contact zones between the talc-chlorite rock and granitic gneiss. Quartz and feldspar coexisting with talc are found only in the blackwall-type zone or in the contact zone between talc ore body and granitic gneiss. The color of the talc ores is generally dark gray to greenish gray due to their high chlorite content.

Detailed geologic map of the Daeheung mines was prepared from the open pits cover a wide area (Fig. 2). Tremolite schist and hornblende gneiss are found along the margin of the talc ore bodies. Unaltered serpentinite relicts are also present within talc ore bodies. Many acidic or basic dikes, which seem to be not directly related to steatitization, are found in the area.

Joints and small faults are abundant in the rocks and the talc ore bodies. Such high stress condition might promote open-system conditions. These joint and fault surfaces are typically coated with thin selvages of black mine-

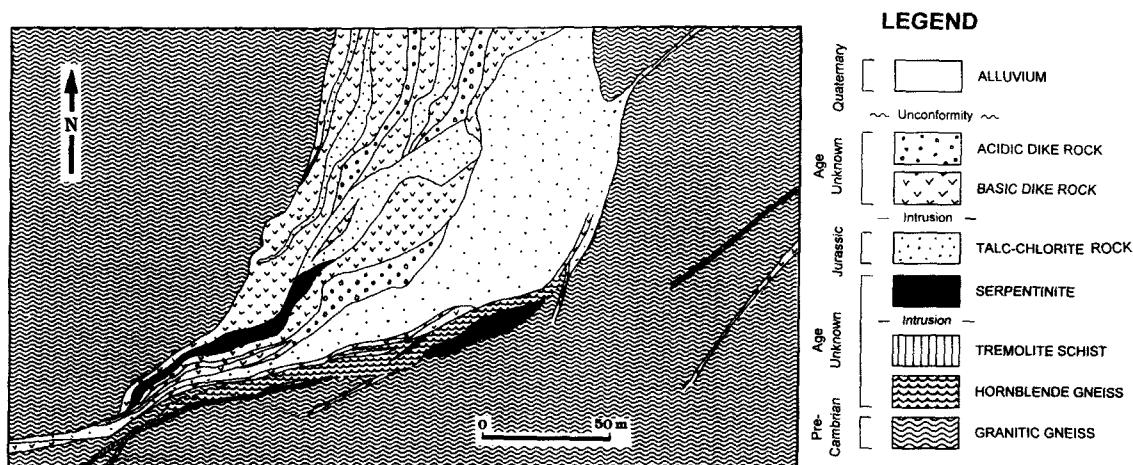


Fig. 2. Detailed geologic map of the open pit of the Daeheung mine.

ral aggregate usually consisting of chlorite and/or talc. Especially, the nodular ore bodies are widely distributed in the contact zone between talc-chlorite rock and granitic gneiss. Each nodular ore bodies or lenses are surrounded by two or three layers of platy and acicular minerals. The inner layer consists of radiating acicular chlorite and the next consists of brown phlogopite and/or tremolite. Xenolith of gneiss of several centimeters to 10s centimeters scale are also formed in the nodular talc ore bodies. Smectite, corrensite, and other expandable clay minerals often occur in the fracture zones.

A K-Ar dating of phlogopite coexisting with talc from the talc ore body yielded a K-Ar date of  $153 \pm 3$  M. Y., indicating that the formation of main talc ore body is late Jurassic, possibly in association with Daebo orogeny. Generally, structural line of Daebo orogeny is Sinian direction. This direction is in accordance with direction of talc ore body of study area and the talc ores of good quality are occurred along the fault plane in the talc ore body.

## EXPERIMENTAL

X-ray powder diffraction (XRD) patterns of samples, which were collected systematically by their color, texture, and the degree of alteration, were obtained using a Rigaku Geigerflex with Ni-filtered  $\text{CuK}\alpha$  radiation. Samples were examined on random or oriented mounts at 40kV/30mA in a continuous scan mode. The samples for X-ray quantitative analysis were washed in distilled water and crushed in an iron mortar. They were powdered in an agate mortar without grinding. XRD patterns for X-ray quantitative analysis were recorded between  $2$  and  $90^\circ 2\theta$  with  $0.02$  steps and  $2s$  counts. Quantitative mineral analyses were done using SIROQUANT software of SIETRONICS.

41 samples from talc deposits were selected for geochemical study. One gneiss sample was selected also for comparison to the talc-related samples. The samples for XRF and ICP analysis were ground in a tungsten carbide ball mill. Philips/PW 1480 X-ray fluorescence spectrometer at Korea Basic Science Institute was used to analyze of major elements. Rare earth

**Table 1.** Descriptions of six ore types having various mineral assemblages.

Lithology	Mineralogy	*Symbol
Serpentine	talc < 10%	△
Serpentine-Talc	talc > 10%	○
Talc	tremolite + phlogopite < 5% and chlorite < 10%	□
Talc-Chlorite	chlorite > 10%	■
Talc-Phlogopite-Chlorite	phlogopite > chlorite > 10%	●
Talc-Tremolite-Chlorite	tremolite > chlorite > 10%	▲

\* Symbol is used for graphic presentation in this paper.

elements (REE) and selected trace elements were analyzed by inductively coupled plasma mass spectrometer (VG Elemental-PQ2 Turbo) at Inter-University Center for Natural Science Research Facilities. The precision and accuracy of the analytical data were judged from the results on the replicate analysed of the standard rock DST-1, W-2, and BIR-1 furnished by USGS.

Scanning electron microscope (SEM) was used for the textural study. JEOL JSM 840A fitted with a Link energy-dispersive X-ray (EDS) detector at Inter-University Center for Natural Science Research Facilities and CA-MECA SX50 at Korea Basic Science Institute were used. K-Ar dating was performed at the Krueger Enterprise, Inc., U.S.A.

## RESULTS AND DISCUSSION

### Occurrence of Talc

Six typical mineral assemblages of the talc ores, which have the characteristic color and mineral composition, were also distinguished on the basis of XRD quantitative analysis using SIROQUANT program. They are: 1) serpentine, 2) serpentine-talc, 3) talc, 4) talc-chlorite, 5) talc-phlogopite-chlorite, and 6) talc-tremolite-chlorite rocks (Table 1).

1. Serpentine rock: This rock is composed of serpentine mineral with less than 10 percent talc and trace amounts of chlorite and phlogo-

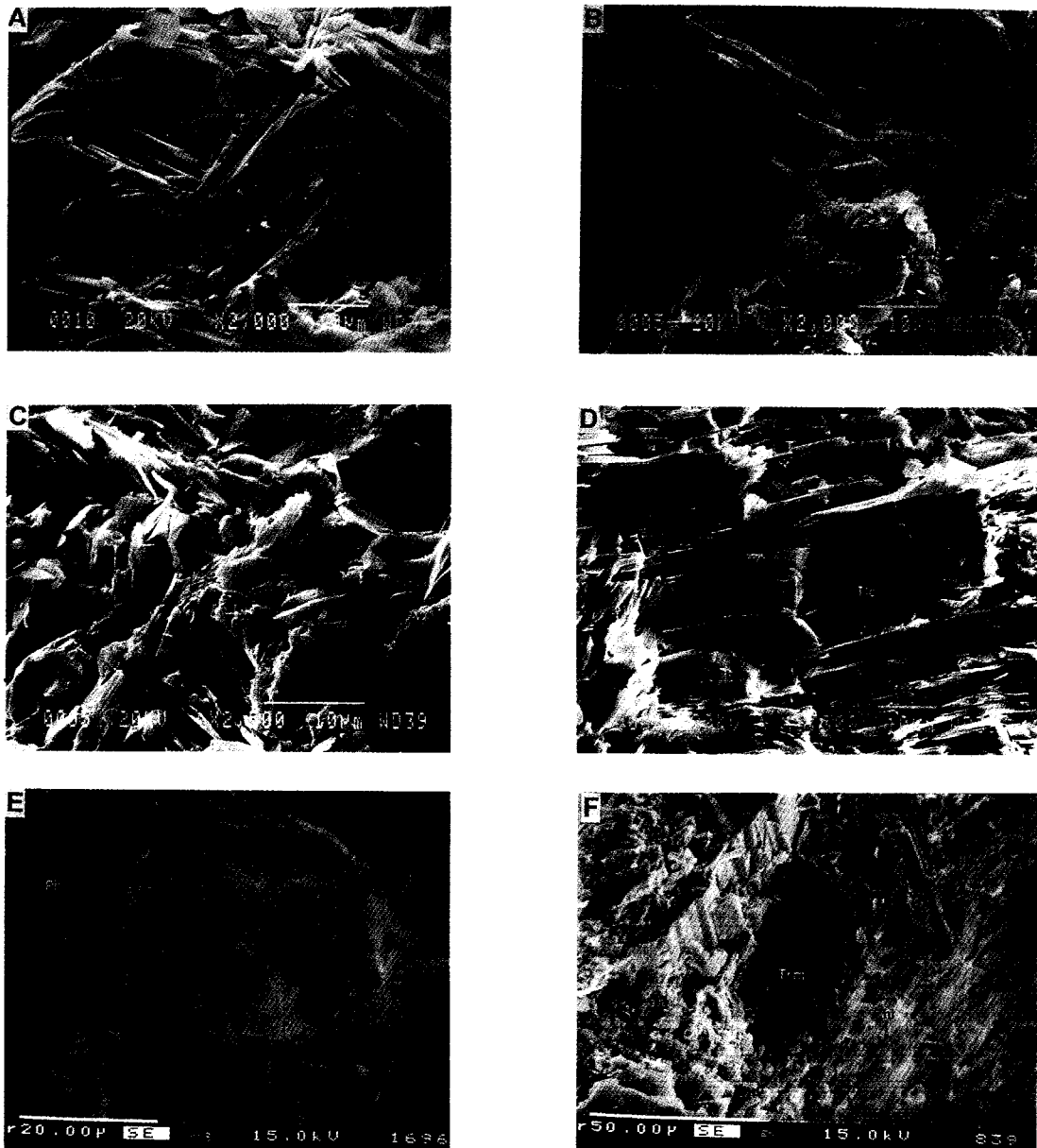
pite. It is green to dark green in color and the texture is massive. Under the scanning electron microscope, serpentine minerals show the flaky morphology rather than fibrous one (Fig. 3A).

2. Serpentine-talc rock: This rock consists mainly of serpentine minerals of less than 80 percent and talc and chlorite of more than 10 percent. This rock is distinguished from the serpentine rock by its light color and soft character. It is easily observed that talc is formed from the serpentine under the electron microscope (Fig. 3B).

3. Talc rock: The talc rock is white to pale green in color and more soft than serpentine-talc rock. Tabular morphology under the electron microscope is characteristic of talc (Fig. 3C).

4. Talc-chlorite rock: This is a dark green rock composed mainly of talc with less amounts of chlorite. The talc-chlorite rock can be distinguished from the talc or serpentine-talc rocks by wt. percent  $Al_2O_3$  from chlorite on the basis of XRF analysis. Most of talc ores contain either fine- or coarse-grained chlorite closely associated with talc. Both fine- or coarse-grained chlorites are often finely interleaved with talc or phlogopite. The interleaved texture can be easily observed under the electron microscope (Fig. 3D).

5. Talc-phlogopite-chlorite rock: This rock is pale to dark brown in color. In some specimens, phlogopite is partially altered to chlorite and closely associated with talc and/or chlorite



**Fig. 3.** Scanning electron micrographs of six ore types. A. Serpentine, showing flaky morphology of antigorite. B. Serpentine-talc, showing poorly crystalline talc, which is formed from serpentine. C. Talc, showing well crystallized tabular morphology of talc. D. Talc-chlorite, showing interleaved coarse-grained chlorite and talc. E. Talc-phlogopite-chlorite, showing closed associated talc, phlogopite, and chlorite. F. Talc-tremolite-chlorite rock, showing prismatic tremolite having well-developed cleavage.

(Fig. 3E).

6. Talc-tremolite-chlorite rock : This rock is pale to dark green in color. Tremolite occurs in acicular or fibrous form. Occasionally, pris-

matic tremolite having well-developed cleavage is observed (Fig. 3F).

The above ore types usually contain euhedral rhombs of magnesite or dolomite. The carbonates make up as much as 46 percents of the rock. Some specimens are composed of talc, chlorite, phlogopite, tremolite, and carbonates in various proportions.

### Chemistry of Talc Ores

Fig. 4 shows the chemical variation of talc ores together with one gneiss in the  $Al_2O_3$ -FeO-MgO diagram. Samples of six ore types are plotted on a limited range of  $Al_2O_3$  content and very narrow range in  $MgO/(MgO+FeO)$ . Serpentine, serpentine-talc, and talc rocks are grouped within a very narrow range of chemical variation. Gneiss sample, which was sampled near the talc ore body, shows very low  $MgO/(MgO+FeO)$  ratio and high  $Al_2O_3$  content in contrast to the talc ores. However, the chemistry reveals that chemical compositions of talc ores show a tendency approaching toward that of gneiss with increasing of chlorite, phlogopite, and tremolite contents. Such chemical trend of talc ores indicates that the formation of chlorite, phlogopite, and tremolite has been related to gneiss and the chemistry of talc ores containing chlorite, phlogopite, and tremolite might have been affected by other environment as well as ultramafic protolith.

Rare earth element (REE) patterns for the serpentine, serpentine-talc, and talc rocks are presented in Fig. 5. Other rock types containing much amount of chlorite, phlogopite, or tremolite were excluded from this figure. Rare earth element concentrations were normalized to the values based upon average CI chondrite (Boynnton, 1984). The rare earth elements are relatively immobile during low-grade metamorphism, weathering and hydrothermal alteration (Rollinson, 1993 ; Michard, 1989). There-

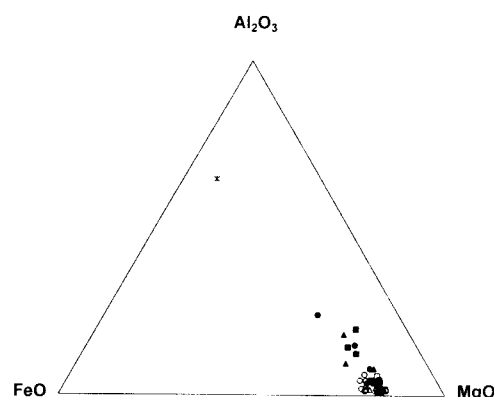


Fig. 4. Chemical variation of talc ores in  $Al_2O_3$ -CaO-(FeO+MgO) (wt%) system. Symbols are the same as in Table 1.

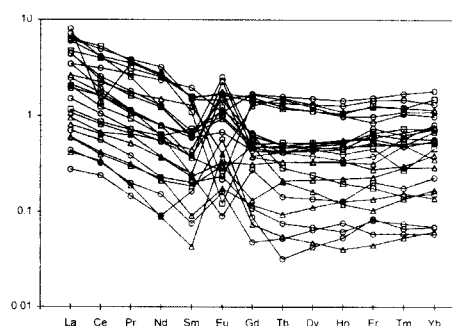


Fig. 5. Chondrite-normalized REE patterns for the serpentine ( $\Delta$ ), serpentine-talc ( $\circ$ ), and talc ( $\square$ ) rock.

fore, they can faithfully represent the original composition of the unaltered parent materials and a fair degree of confidence can be placed in the significance of peaks and troughs and the slope of an REE pattern. However, the REEs are not totally immobile, and there should be cautions in interpreting the REE patterns of heavily altered or highly metamorphosed rocks (Humphries, 1984). As shown in Fig. 5, the REE patterns of three ore types with respect to the alteration from the serpentine to talc ores show the similar trend, suggesting that the REE contents are not affected

Chemistry of Talc Ores in Relation to the Mineral Assemblages

**Table 2.** Mean elemental ratios and standard deviations of six ore types and one gneiss.

Lithology	analyses	1000Al <sub>2</sub> O <sub>3</sub> /Cr	1000Al <sub>2</sub> O <sub>3</sub> /Ni	1000Al <sub>2</sub> O <sub>3</sub> /Co	1000TiO <sub>2</sub> /Cr	1000TiO <sub>2</sub> /Ni	1000TiO <sub>2</sub> /Co	1000Zr/Cr	1000Zr/Ni	Zr/Co	Cr/Ni	Ni/Co
srp	9	0.440 (0.241)	38.6 (18.5)	10.6 (5.3)	0.011 (0.007)	0.013 (0.008)	0.278 (0.167)	0.389 (0.358)	0.419 (0.326)	0.009 (0.007)	1.343 (0.627)	21.3 (1.3)
srp-tlc	12	0.658 (0.365)	52.7 (28.3)	15.4 (8.7)	0.011 (0.010)	0.013 (0.013)	0.254 (0.231)	0.618 (0.648)	0.700 (0.784)	0.014 (0.015)	1.124 (0.172)	21.1 (1.9)
talc	7	1.029 (0.441)	43.1 (30.2)	14.4 (10.7)	0.016 (0.010)	0.009 (0.003)	0.191 (0.077)	1.302 (1.366)	0.689 (0.612)	0.015 (0.014)	0.778 (0.489)	20.9 (1.5)
talc-chl	8	1.015 (0.195)	60.7 (6.9)	19.8 (5.2)	0.017 (0.012)	0.016 (0.012)	0.335 (0.231)	0.815 (0.493)	0.760 (0.490)	0.017 (0.012)	0.904 (0.095)	21.5 (2.3)
talc-phl-c	3	4.693 (4.841)	261.7 (217.4)	90.3 (77.4)	0.106 (0.115)	0.131 (0.147)	2.016 (1.881)	4.661 (6.197)	5.839 (7.819)	0.085 (0.109)	1.183 (0.105)	19.7 (7.8)
talc-trm-c	3	2.883 (2.342)	193.6 (107.9)	58.0 (20.8)	0.033 (0.026)	0.037 (0.029)	0.857 (0.642)	1.008 (0.377)	1.149 (0.617)	0.027 (0.015)	1.094 (0.419)	23.0 (2.3)
gneiss	1	231.4	646.1	816.1	13.98	19.5	49.3	9067.2	12656.3	32.0	1.396	2.5

Standard deviations are in parentheses

by hydrothermal alteration for the talc formation. The most interesting characteristic feature of the REE patterns of the talc ores is their LREE enrichment pattern. Wee et al. (1994) suggested that the LREE enrichment characteristic of the ultramafic rocks from the Chungnam province including this study area is resulted from the mixture of two geochemically distinct components; one is depleted residual mantle material and the other is for the abundant incompatible elements and LREE enrichment.

Curtis and Brown (1971) and Sanford (1982) showed that elements Cr, Ti, and Zr were essentially immobile during the alteration of serpentinite to talc and sharp discontinuities in Cr/Ti, Cr/Zr, Cr/(Fe+Mg), and Ni/(Fe+Mg) were observed at the boundary between the ultramafic protolith and country rock even though extensive migration of Mg, Ca, and Si had taken place producing characteristic black-wall metasomatic zones. In addition, they showed that concentration discontinuities of Al<sub>2</sub>O<sub>3</sub> and Ni corresponded to those of Cr, Ti, and Zr. Using the immobile element ratios of Al<sub>2</sub>O<sub>3</sub>/Cr, Zr/Cr, Ti/Cr, and Al<sub>2</sub>O<sub>3</sub>/Ni in the blackwall-type zones, Linder et al. (1992) concluded that

these zones resulted from mixing of pelitic and serpentinite-bearing material, with later modifying metasomatism. In the present study, the ratios among these immobile elements were used to compare the chemistry of six mineral assemblages and the granitic country rock. Although the volumetric concentration of immobile elements may change during metamorphism and/or hydrothermal alteration, the ratio of any two immobile elements will not change and will, therefore, reflect the ratio of the immobile elements in the protolith. Eleven independent immobile element ratios have been calculated for each of the six mineral assemblages as well as for the unaltered granitic gneiss. The elements were selected by their known immobile characteristic; Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, and Zr for the granitic rocks and Cr, Ni, and Co for the ultramafic rocks. Table 2 gives the mean and standard deviation of the measurements of these ratios for the mineral assemblages. The data in Table 2 show that serpentinite, serpentinite-talc, talc, and talc-chlorite rocks have similar immobile element ratios, whereas talc-tremolite-chlorite and talc-phlogopite-chlorite rocks have immobile element ra-



tios distinctly different from other ore types especially in the ratios related to  $Al_2O_3$ , Zr, and  $TiO_2$ . Discontinuities in element ratios coincide with changes in mineralogy. Ratios related to  $Al_2O_3$ ,  $TiO_2$ , and Zr are distinctly higher in assemblages that contain tremolite, phlogopite and/or chlorite. Because the concentrations of Ti,  $Al_2O_3$ , and Zr are higher in the country rock (granitic gneiss) and Cr, Ni, and Co are higher in the serpentinite, it can be concluded that the composition of the hydro-thermal solution related to the formation of tremolite, phlogopite, and some chlorite might be affected by granitic gneiss, which surrounds the talc ore body. The large standard deviations associated with their mean ratios reflect the wide range in the ratios and the non-normal distribution of their values.

### The isocon diagram method

Gresens' (1967) basic equation and method of graphical solution for the composition-volume relations in metasomatic alteration have been widely applied in many studies of hydrothermal alteration (Appleyard, 1980; Gibson et al., 1983; Morton and Nebel, 1984). His equation is for the calculation of gains and losses from chemical analyses and specific gravities of altered and unaltered equivalents, both minerals and rocks. Grant (1986) rearranged Gresens' equation into a linear relationship between the concentration of a component in the altered rock and that in the original (equation ①). This is a simple solution for analyzing changes in mass and concentrations during metasomatism.

$$C_i^A = \left( \frac{M^O}{M^A} \right) \cdot C_i^O \quad \text{①}$$

$C_i^A$  and  $C_i^O$ : concentrations of component i in the altered rock sample and the parent rock sample

$M^A$  and  $M^O$ : mass of altered rock sample and parent rock sample

Simultaneous solution of such equations for immobile components generate an isocon, which is a straight line through the origin on a plot of concentrations in the altered rock against those in the protolith. The isocon is readily determined by calculating the best fit line through a series of points. This implies that the components used to define an isocon have been relatively immobile during alteration. The equation of the best-fit isocon is:

$$C^A = \left( \frac{M^O}{M^A} \right) \cdot C^O \quad \text{②}$$

The slope ( $M^O/M^A$ ) of the isocon defines the mass change in the alteration, with a slope greater than one indicating an addition of mass during metasomatism and a slope less than one indicating loss. Deviations of data points for all other components from the reference isocon define the concentration changes for the corresponding components. Immobile components during metasomatism construct an isocon and the relative gains and losses of mobile components are then read from the graph.

Fig. 6 shows the isocon diagrams for the talc ores having various mineral assemblages where the fresh serpentinite (serpentine ore type) is taken as the protolith. The data for all components are scaled as shown and plotted as weight percent of oxides for major elements or as ppm for trace elements. The isocons in Fig. 6 are the best fit lines for the relatively immobile elements which show a linear relationship through the origin on the diagram. As shown in Fig. 6, all the slopes of the isocons are less than one, therefore 8~41% masses have been added during the alteration for the talc formation. On the basis of this isocon method, concentration changes of various elements for the five ore types are shown in

Chemistry of Talc Ores in Relation to the Mineral Assemblages

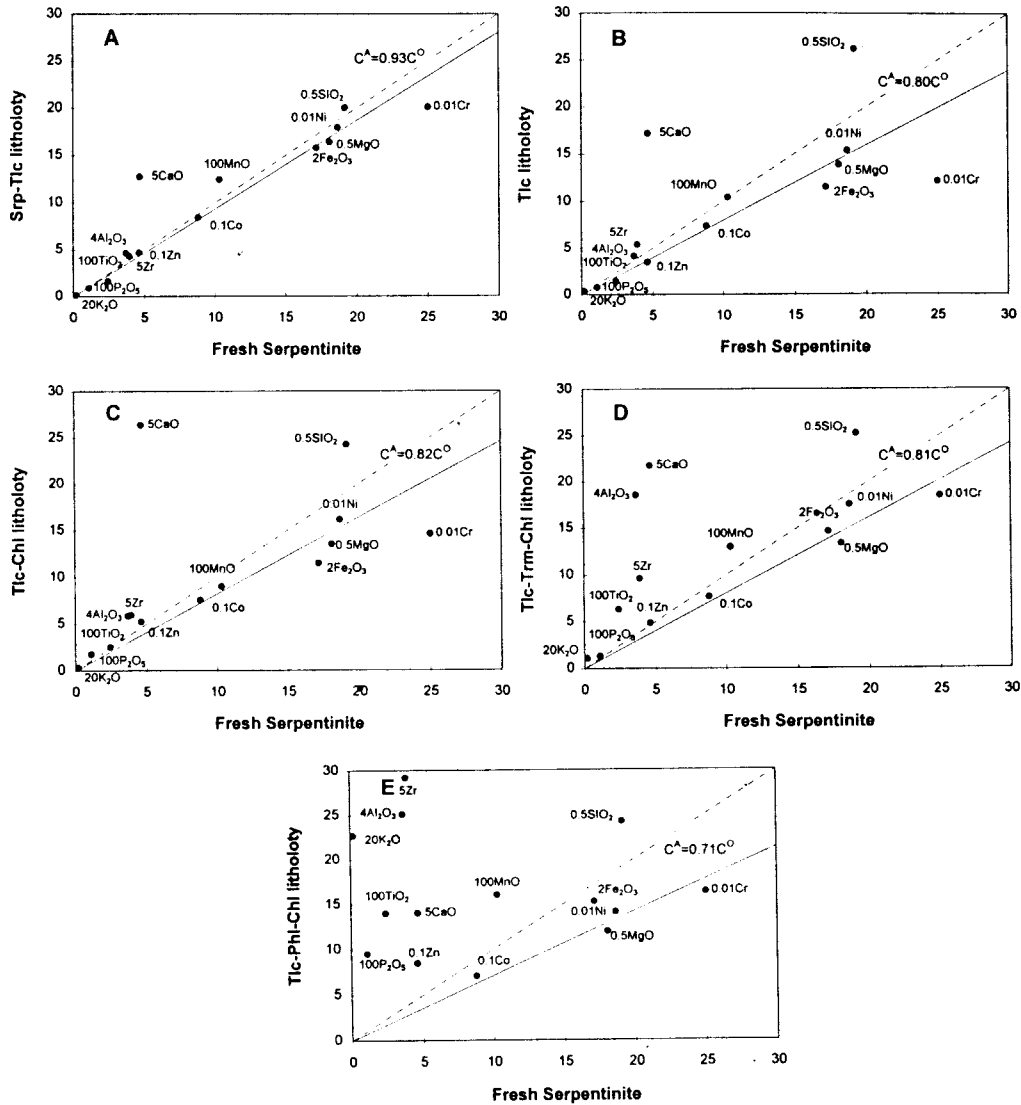


Fig. 6. Isocon diagrams for the talc ores having various mineral assemblages in the study area. The protolith is the fresh serpentinite. The data for all components are scaled as shown. The solid lines are the best fit for the relatively immobile elements. The dashed lines show equal abundances in protolith and metasomatic products. A. serpentine-talc B. talc C. talc-chlorite D. talc-tremolite-chlorite E. talc-phlogopite-chlorite.

Table 4 and graphically displayed in Fig. 7. The gain of  $\text{SiO}_2$  is between 12 and 78 percent and those of  $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$ , and  $\text{K}_2\text{O}$  are drastically changed according to the mineral assemblages. The gain of  $\text{K}_2\text{O}$  in talc-phlogopite-chlorite rock is very high because  $\text{K}_2\text{O}$  contents of non-phlogopite-bearing rocks are too

low. Especially, the gains of the granitic components such as  $\text{K}_2\text{O}$ ,  $\text{P}_2\text{O}_5$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Zr}$  increase according to the addition of chlorite, tremolite, and phlogopite into the protolith, but the gains of  $\text{SiO}_2$  are not affected by mineral assemblages. It means that the vast amount of  $\text{SiO}_2$  was mostly from the hydrothermal solution origi-

**Table 3.** Averaged mineral contents\* of six ore types.

Ore types [No. of analysis]	**Srp [9]	Srp-Talc [12]	Talc [7]	Talc-Chl [8]	Talc-Trm-Chl [3]	Talc-Phl-Chl [3]
Lizardite	87.9	53.2	3.9	0.0	0.0	0.0
Talc	3.9	27.1	81.2	70.8	29.2	54.2
Chlorite	0.1	3.6	4.9	14.3	31.4	21.5
Phlogopite	0.0	0.0	0.1	0.2	0.4	14.8
Tremolite	0.0	0.0	0.0	0.0	39.1	0.0
Magnesite	5.8	9.1	0.0	0.0	0.0	0.0
Dolomite	2.3	6.5	6.4	13.0	0.0	7.4
Calcite	0.0	0.5	3.5	1.7	0.0	0.0
Albite	0.0	0.0	0.0	0.0	0.0	2.2

\* These were analysed by X-ray quantitative analysis using SIROQUANT program.

\*\* fresh serpentinite selected as parent rock

**Table 4.** Concentration changes of various elements for the five ore types corresponding to best-fit isocon of immobile elements.

Ore types [No. of analysis]	Srp-Talc [12]	Talc [7]	Talc-Chl [8]	Talc-Trm-Chl [3]	Talc-Phl-Chl [3]
Slope of isocon	$C^1=0.93C^0$	$C^1=0.80C^0$	$C^1=0.82C^0$	$C^1=0.81C^0$	$C^1=0.71C^0$
Components	$\Delta C/C^0$				
SiO <sub>2</sub>	0.12	0.71	0.54	0.63	0.78
Al <sub>2</sub> O <sub>3</sub>	0.35	0.40	0.92	5.23	8.55
Fe <sub>2</sub> O <sub>3</sub>	-0.01	-0.16	-0.18	0.06	0.25
TiO <sub>2</sub>	-0.28	-0.28	0.25	2.21	7.06
MnO	0.29	0.26	0.06	0.56	1.18
CaO	1.92	3.61	5.87	4.76	3.21
MgO	-0.03	-0.04	-0.09	-0.09	-0.07
K <sub>2</sub> O	-0.22	1.26	0.83	5.62	158.72
P <sub>2</sub> O <sub>5</sub>	-0.12	-0.10	0.92	0.49	11.03
Cr	-0.14	-0.39	-0.29	-0.08	-0.08
Co	0.03	0.05	0.05	0.09	0.13
Ni	0.03	0.03	0.05	0.16	0.06
Zn	0.08	-0.05	0.38	0.31	1.57
Zr	0.18	0.72	0.85	2.04	9.46
M <sup>1</sup> /M <sup>0</sup>	1.08	1.25	1.22	1.23	1.41

nally and the composition of hydrothermal solution for the formation of other minerals was locally affected by granitic gneiss. The addition of granitic components into the hydrothermal solution was probably occurred mainly in the contact zone between serpentinite and granitic rock. It is evidenced by the fact that black

talc ores containing a large amount of chlorite, phlogopite, and tremolite are mainly found at the boundary between talc ore body and surrounding metamorphosed granitic rocks. Mineral contents of the five lithological groups are shown in Table 3, also. The talc-phlogopite-chlorite rock contains albite (Table 3) and the

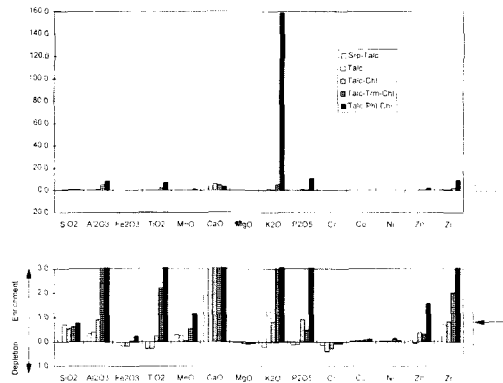


Fig. 7. Enrichment-depletion diagram showing the enrichment factors for the selected elements of the talc ores against the fresh serpentinite.

gains of  $\text{Al}_2\text{O}_3$  and Zr in that rock are much higher than any other types (Table 4), which are also good evidences of external introduction of granitic material for the formation of phlogopite. Therefore,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , CaO, and K<sub>2</sub>O were gained from the hydrothermal solution or granitic rocks surrounding the protolith. The main talc ore body which consists of talc and some chlorite was formed by the reaction between serpentinite and silicic hydrothermal solution, and at the border zone, the addition of  $\text{Al}_2\text{O}_3$ , CaO, and K<sub>2</sub>O from the granitic rock resulted in the formation of chlorite, tremolite, and phlogopite, respectively. Ni, Co, and MgO remain essentially immobile during metasomatism and form a linear array through the origin with defining a best-fit isocon in Fig. 6, and  $\text{Fe}_2\text{O}_3$  also fall on the isocon except the phlogopite-bearing rock. This suggests that MgO and  $\text{Fe}_2\text{O}_3$  were not lost or gained and Mg/Fe ratio of protolith have been preserved during steatitization. Therefore, the vast amount of MgO needed for the formation of the large talc deposit in the study area did not come from the external source such as hydrothermal solution, but existed originally in high magnesian protolith, ultramafic rock. Because of the high MgO condition of protolith, chlorite, mica,

and amphibole having Mg-end member chemistry have formed with talc by addition of  $\text{Al}_2\text{O}_3$ , K<sub>2</sub>O, and CaO, respectively, from the external environment to the parent rock, so the chemistry of these minerals shows two types: talc-related type having very high Mg/Fe ratio and talc-unrelated type having wide range of Mg/Fe ratio (Kim and Kim, 1995). Through the steatitization of serpentinites, the extraneous hydrothermal solutions often became partially more siliceous because of accompanying chloritization and carbonatization, thereby promoting steatitization. Where these processes were assisted by corresponding metasomatic addition of  $\text{Al}_2\text{O}_3$ , CaO, K<sub>2</sub>O and iron from the external environment, mainly at the border zone of the main talc ore body, the chlorite, chlorite-tremolite, and tremolite-phlogopite containing rocks were formed together with talc during the late stage of steatitization.

## CONCLUSIONS

The mineral assemblages of the alteration zone in the Yesan-Gongju-Cheongyang talc deposits are the serpentine, serpentine-talc, talc, talc-chlorite, talc-phlogopite-chlorite, talc-tremolite-chlorite rocks.

The REE patterns for the serpentine, serpentine-talc, and talc rocks, which are related to the main formation of talc from the serpentine, show the similar LREE enrichment trend, suggesting that the REE patterns are not affected by hydrothermal alteration for the talc formation. For the formation of talc ore from serpentinite, some addition of granitic components to the serpentinite took place. Data of immobile and trace elements ratios and the result of the chemical calculation using isocon method with relation to the mineral assemblages support the hypothesis that these talc ore bodies resulted from the simple metasomatic alteration by hydrothermal solution. But the hydro-

thermal solution was affected by granitic rock in the limited region, as the most likely explanation for the mineralogical and chemical variability in the study area. Therefore, talc ores containing large amount of chlorite, phlogopite, and tremolite are largely localized along the margin of the talc ore body. It is because  $Al_2O_3$ ,  $K_2O$ , and  $CaO$  necessary to form chlorite, phlogopite, and tremolite, respectively, are available there either from the granitic rock or incoming solutions.

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