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Mass balance analysis of mineralization in talc deposits from different origin

서로 다른 기원의 활석광상 내 활석 광화작용에 대한 물질수지 분석

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Abstract

Mass balance analysis of mineralization in talc deposits from different origin

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Typically, the talc is subdivided into two types of deposit: 1) dolomite type deposits, 2) ultramafic type deposits. In South Korea, the first type deposits are mainly founded in near Chungju area and the other type deposits are mainly founded in Yesan area. In the processes of forming talc deposits from original rock, the gain and loss of element is occurred. In this study, the isocon mass-balance method is applied to determine the differences of elemental behavior between talc orebodies of different origin and to investigate the usefulness of mass-balance method for tracing the origin of host rock. For researching the behavior of major and trace element in the talc deposit and comparing the elemental behavior between each type of talc deposits, four talc deposits (Gapyeong and Yoogoo deposit – serpentinite type, Dongyang and Poongjeon deposit – dolomite type) are studied in this paper. The isocon diagram and calculated concentration changes of each talc deposits indicate that the elemental behavior is mainly affected by mineral assemblages of each alteration stage and tremolite, phlogopite, diopside, and chlorite are generally composed of mineral assemblage as accessory minerals. In case of comparing two different type deposits derived from end-member data, the total mass change and behavior of SiO_2, CaO, and Sr show the distinct differences during overall alteration stage and Co and Ni are considered as immobile element in almost alteration stage.

Keywords : talc deposit, mass balance, elemental behavior, isocon diagram, concentration change, alteration stage

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Table of Contents

List of Figures

List of Tables

1. Introduction

The talc is commonly formed from parent rocks which have abundant magnesium and generally subdivided into two types of deposit based on the parent rocks as following: 1) dolomite type deposits, 2) ultramafic type deposits (Prochaska, 1989; Woo et al., 1991; Shin and Lee, 2003; Lee et al., 2007). Due to its abundance in South Korea, the importance of talc deposit has been emphasized from many researchers (e.g., Lee et al., 2007). In South Korea, both talc deposit types are well developed. The dolomite type deposit is mainly distributed in Okcheon Belt located in the central part of South Korea, where several complex metamorphisms have occurred through geological time scale (Park et al., 1995; Park et al., 1997; Shin and Lee, 2003; Shin and Lee, 2004; Lee et al., 2007). Another type of talc deposits, serpentinite type deposit, is usually found in Yesan area, Chungnam province (Woo et al., 1991; Kim and Kim 1997; Woo and Lee, 2001). These two different types of talc deposits have been already studied by several researchers. For example, Park et al. (1995) studied talc mineralization and stable isotopes of Dongyang deposit. Shin and Lee (2003) researched geochemistry, phase relationships and stable isotopes compositions of sulfide and sulfate minerals of Hwanggangri mineralized zone in South Korea. Kim and Kim (1997) and Woo and Lee (2001) argued origin and formation processes of serpentinite and talc mineralization of ultramafic rocks in Yoogoo dicstrict, Chungnam area. In order to grasp the talc mineralization in detail, it is so important to understand the elemental behavior between original rocks and products during formation of talc deposit, which are leading to elucidate the origin and formation processes of ore deposits. However, most studies have dealt with movement of only a few elements during the formation of talc deposits in South Korea except the paper of Shin and Lee (2003), and Kim and Kim (1997). Therefore, four talc deposits which are two serpentinite type (Gapyeong and Yoogoo deposit) and two dolomite type deposits (Dongyang and Poongjeon deposit) are studied in this paper. The main purposes of this study focus on 1) researching the behavior of major and trace element in talc deposits, 2) comparing the differences of elemental behavior between two type talc deposits formed from different origin and 3) investigating the usefulness of mass-balance method for tracing the origin of host rock. The chemical data measured in the previous studies (Shin and Lee, 2003) were used in this study for comparison among different types of deposits with the data analyzed in this study.

2. Geological Setting

2.1. Local geology of Gapyeong talc deposit

The Gapyeong talc deposit is located in the middle part of the Gyeonggi massif. The deposit area, from bottom to top, consists of banded gneiss, calc-schist, banded gneiss intercalated with amphibolite, biotite schist, serpentinite and alluvium (Fig. 1). Felsic intrusion also partly appeared near the ultramafic body. The serpentinite is broadly distributed along the sampling site showing greenish black color. The black colored part is largely composed of amphibolite containing this plagioclase layer. The talc ores generally occurred between the serpentinite body and the felsic intrusion, but their amounts are small. The ore mainly contains talc, tremolite, phlogopite, chlorite and some opaque minerals. And as minerals reported from many serpentinite type talc deposits, diopside, calcite, quartz, spinel and other accessory minerals also could be occur (Woo et al., 1991; Kim and Kim 1997; Woo and Lee, 2001). Three mineral assemblages were identified: 1) serpentinite, 2) talc + serpentine + phlogopite and 3) tremolite + talc.

The detailed description of each assemblage are:

1) Serpentinite : this was mainly composed of serpentine minerals. It has dark green color and massive texture.

2) Talc + serpentine + phlogopite assemblage : this assemblage consistsed of mainly talc, serpentine, phlogopite and few tremolite. Some tremolite was altered to talc and some serpentine minerals were mixed with talc. Phlogopite were observed with talc and some serpentine minerals showed layering (Fig. 2A).

3) Tremolite + Talc assemblage : this assemblage zone was composed of tremolite and talc. Talc minerals usually occurred between the tremolite and form fine-grained aggregates. Some platy shaped tremolite have been partly altered by talc (Fig. 2B).

2.2. Local geology of Dongyang talc deposit

The Dongyang talc deposits in Chungju area is located in the north-east part of Okchen belt. From bottom to top, the deposit area consists of biotite-quartz gneiss included in Kyemyeongsan Formation, dolomite, quartzite, chlorite schist included in Munjuri Formation and phyllitic rock included in Hwanggangri Formation shown in Fig. 3 (Choi et al., 2012). Cretaceous Bulguksa granite also occurred near the sampling site. The talc ores originated both from the dolomite and the chlorite schist, and talc ore from former were evaluated as major orebody in Chungju area showing more economic importance (Park et al., 1995). The ore body is mainly composed of talc, dolomite, calcite and quartz. Although some impurities including tremolite and anhydrite are also reported in previous studies (Park et al., 1995; Shin et al., 2004), the main talc ore of Dongyang deposit represents high purity and negligible impurity. Sharp and clear alteration boundary between dolomite and talc was well observed in thin section (Fig. 4).

2.3. Local geology of Poongjeon talc deposit

The Poongjeon talc deposit is located in Hwanggangri Mineralized Zone. The deposit area consists of sedimentary rocks including of Samtaesan, amphibolite, Muamsa granite, and ultramafic dyke (Park et al., 1997, Shin and Lee, 2003). Dolomitic marble, which was considered to be the original rock of talc, occurred in uppermost part of the Samtaesam formation intruded by Muamsa granite (Park et al., 1997, Shin and Lee, 2003). Talc ore is observed in lithologic contact between dolomitic marble and amphibolite (Park et al., 1997, Shin and Lee, 2003).

2.4. Local geology of Yoogoo talc deposit

The Yoogoo talc deposits are distributed in Yesan talc ore deposits area. The deposit is mainly composed of serpentinite with unknown age (Woo et al., 1991, Woo and Lee 2001). The major components of serpentinite include serpentine, olivine and talc. Clinochlore, phlogopite, tremolite, and enstatite are also observed as a minor constituent (Woo et al., 1991, Woo and Lee 2001). Serpentinite body intrudes the Precambrian Yoogoo gneiss and is intruded by Jurassic granite. Talc ore principally occurred in lithologic contact between serpentinite and gneiss (Woo and Lee, 2001).

3. Method

The isocon method is devised by Grant (1986) based on the Gresens' equation (1967). It can be used to illustrate the compositional change from unaltered rock to altered rock and be treated as useful tool for analyzing the relative gains or losses of components. Elements with no or little gain or loss during alteration processes are plotted on the straight line (called "Isocon") crossing the origin representing their immobility. Elements plotted above or below area from the Isocon indicate gain or loss of mass respectively during alteration.

On the basis of this method, the whole-rock data from four talc deposits (Gapyeong, Dongyang, Poogjeon, Yoogoo) are applied to discuss elemental behavior. Chemical analyses whole rocks from Gapyeong and Dongyang were conducted by the whole-rock samples using X-ray Fluorescence (XRF) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) analysis for major and trace element analysis respectively at NCIRF in Seoul National University (Table 1, 2). Raman spectroscopy was used to identify the uncertain minerals at Tectonophysics Lab in Seoul National University.

The data of Poongjeon and Yoogoo was obtained from previous studies (Shin and Lee, 2003; Woo and Lee, 2001). Major elements of Poongjeon and Yoogoo were measured by XRF spectrometer and trace elements were measured by ICP-MS (Woo and Lee, 2001; Shin and Lee, 2003).

4. Result and Discussion

4.1 Gapyeong talc deposit

The Gapyeong talc deposit was considered to be formed during alteration of serpentinite. The rock samples of the deposit show two stages alteration sequences: Stage 1 (serpentinite → talc + serpentine + phlogopite) and Stage 2 (talc + phlogopite + tremolite → talc + tremolite) (Fig. 2). Fig. 5 shows elemental behaviors of stage 1 and 2 respectively in Gapyeong talc deposit and Table 3 represents the concentration changes of each elements.

The diagram for Stage 1 alteration (Fig. 5A) indicates the increase of approximately 8% mass. Fe_2O_3, MgO, Na_2O, Co, and Ni were plotted near the solid line implying that these elements were relatively immobile. SiO_2, Al_2O_3, K_2O, and Rb were increased. For production of the talc from serpentinite, influx of hydrothermal solution including enormous silica is essential (Turner, 1948). The formation of phlogopite seems to be main cause for the gain of Al_2O_3 and K_2O in this stage (Shin and Lee 2003). Although MgO is considered to be relatively immobile element, slightly decrease (approximately 24%) of MgO observed in this study means that a little amount of MgO were removed during the alteration through hydrothermal solution (Turner, 1948). As a main alteration reaction of this stage, the formation of talc from serpentine and removal of MgO could be expressed by following reaction (1) (Turner, 1948).

$$\underset{\text{(serpentine)}}{Mg_3Si_2O_5(OH)_4} + 1.16SiO_2 \rightarrow \underset{\text{(talc)}}{0.79Mg_3Si_4O_{10}(OH)_2} + \underset{\text{(removed in solution)}}{\underline{0.63MgO + 1.21H_2O}} \quad (1)$$

The diagram for Stage 2 alteration (Fig. 5B) shows the increase of about 100% of mass. Al_2O_3, TiO_2, Co, and Ni are plotted near the isocon. During alteration Stage 2, SiO_2, Fe_2O_3, MgO, CaO, Na_2O, MnO, Sr, Zr, and Cr were increased, whereas Rb and K_2O were decreased. In this stage, lots of tremolite were observed. It seems that the tremolite was formed by introduction of huge amount of SiO_2 and CaO from hydrothermal solution. The decrease of K_2O seems to be affected by breakdown of phlogopite. Because phlogopite is Al-bearing mineral, Al_2O_3 should be decreased similar with K_2O during breakdown of phlogopite. The observed smaller decrease of Al_2O_3 is considered to be related to the production of chlorite. The formation of chlorite seems to explain Fe_2O_3 increase in this study as well. The detailed concentration changes of all elements in this deposit are shown in Table 3.

4.2 Yoogoo Talc Deposit

The talc ore in Yoogoo was formed from the alteration of serpentinite like Gapyeong talc deposit. Fig. 6 shows elemental behaviors from serpentinite to talc ore in Yoogoo deposit. The isocon diagram suggests that the 18% of mass have been increased. Fe_2O_3, Co, and Ni are considered to be relatively immobile whereas SiO_2 and CaO was increased significantly. Introduction of substantial hydrothermal solution is necessary to produce huge amount of talc deposits and it seems to play an important role for supplying amount of silica (Turner, 1948). The CaO is also thought to be transported by solution contributing to tremolite formation. MgO and

Al_2O are calculated to be lost about 11% and 27% respectively during alteration. Turner (1948) insisted that formation of talc from serpentinite could be accompanied by removing of slight MgO, which are expressed by following reaction;

$$\underset{\text{(serpentine)}}{Mg_3Si_2O_5(OH)_4} + 1.16SiO_2 \rightarrow \underset{\text{(talc)}}{0.79Mg_3Si_4O_{10}(OH)_2} + \underbrace{0.63MgO + 1.21H_2O}_{\text{(removed in solution)}} \quad (1)$$

Turner (1948) also showed that the hydrothermal alteration of clinochlore results in the formation of talc as below reaction.

$$\underset{\text{(clinochlore)}}{4Mg_5Al_2Si_3O_{10}(OH)_8} + 13.2SiO_2 \rightarrow \underset{\text{(talc)}}{7.3Mg_3Si_4O_{10}(OH)_2} + \underbrace{4.1MgO + 4Al_2O_3 + 12.7H_2O}_{\text{(removed in solution)}} \quad (2)$$

The existence of clinochlore was already reported by Woo et al., (1991). Decreasing of MgO and Al_2O_3 during the talc mineralization in the system is corresponding to removal of MgO and Al_2O_3 in the reaction. The detailed concentration changes of all elements in this deposit are shown in Table 4.

4.3 Dongyang talc deposit

The Dongyang talc deposit showing high quality was originated from hydrothermal alteration of dolomite. Fig. 7 and table 5 show elemental behaviors and concentration changes of the Dongyang talc deposit. Isocon diagram shows that the mass have been lost about 41% during alteration from dolomite to talc. Al_2O_3, TiO_2, MgO, Na_2O, K_2O, and Co are considered to be relatively immobile element. SiO_2 and Fe_2O_3 are increased whereas CaO, MnO, Sr, Rb, and Ni were decreased during alteration. The introduction of hydrothermal solution involving the input of sufficient silica is critical to form talc deposit from dolomite (Shin and Lee, 2003). Decrease of CaO and MgO are thought to be attributed to the decarbonation reaction during alteration process (Shin and Lee, 2003). Main talc ores in Dongyang talc deposits are very famous for its high purity. In addition, the talc ores which has low impurities are usually produced by alteration of dolomite. The reaction of formation of talc from dolomite could be expressed by following reaction (3) (Cooper, 1957).

$$\underset{\text{(dolomite)}}{3CaMg(CO_3)_2} + 4SiO_2 + H_2O \rightarrow \underset{\text{(talc)}}{Mg_3Si_4O_{10}(OH)_2} + 3CaCO_3 + 3CO_2 \quad (3)$$

4.4 Poongjeon Talc Deposit

The talc ore in Poongjeon was formed through two alteration stage: Stage 1 (dolomite → calc-silicate rock) and Stage 2 (calc-silicate rock → talc ore) (Shin and Lee, 2003). The talc ore body has high impurity such as tremolite, phlogopite, and diopside in contrast to high purity of Dongyang talc deposits as mentioned above. Because of the impurities, the Poongjeon deposit shows different elemental behaviors from Dongyang. Fig. 8 and Table 6 indicate the isocon diagram and detailed concentration changes of

Poongjeon respectively. For isocon diagram, whole rock and trace element data was from Shin and Lee (2003). Co, Ni, and Cr are considered as relatively immobile elements during all alteration processes. Fig. 8A representing elemental behaviors from dolomite to calc-silicate rock shows that about 37% of mass have been lost. SiO_2, Al_2O_3, Fe_2O_3, TiO_2, Na_2O, K_2O, and Rb were increased, whereas CaO and MgO were decreased. During the first stage, the formation of phlogopite, tremolite and diopside are thought to be the main cause for the increase of those elements (Shin and Lee, 2003). Among them, the significant increase of K_2O and Na_2O is derived from very low in the dolomite (Shin and Lee, 2003). The decrease of CaO and MgO is thought to be caused by decarbonation reaction (Shin and Lee, 2003). Shin and Lee (2003) suggested following reaction (4) and (5) about the formation of calc-silicate rock from dolomite based on the mineral assemblages.

$$\underset{\text{(dolomite)}}{5CaMg(CO_3)_2} + 8SiO_2 + H_2O = \underset{\text{(tremolite)}}{Ca_2Mg_5Si_8O_{22}(OH)_2} + 3CaCO_3 + 7CO_2 \quad (4)$$

$$Ca_2Mg_5Si_8O_{22}(OH)_2 + 3CaCO_3 + 7CO_2 = 5MgCaSi_2O_6 + 3CO_2 + H_2O \quad (5)$$

(tremolite) (diopside)

Fig. 8B representing elemental behaviors from calc-silicate rock to talc ore shows about 8% of rock mass have been lost. Except the immobile elements and CaO, all other elements were increased during second alteration stage. This stage is characterized by increase of MgO. In order to form talc from calc-silicate rock consisting of tremolite, phlogopite and diopside, external source of MgO is must be involved (Shin and Lee, 2003). Introduction of MgO in the system for forming talc resulted in increase of MgO during second stage (Shin and Lee, 2003).

Generally, major elements, except the immobile element, tend to behave in accordance with the mineral assemblage which is produced or removed during each alteration stage. In case of trace element, it seems behave with substitutable element. For instance, though there are some exception, K and Rb, Ca and Sr show very similar behavior at most of alteration stages.

4.5 Comparisons of talc deposits

The talc minerals in Gapyeong and Yoogoo are produced by alteration of serpentinite rocks (Woo and Lee, 2001), while Dongyang and Poongjeon are from alteration of dolomite (Shin and Lee, 2003; Shin et al., 2004; Shin and Lee, 2005). In case of the same type deposit, although the overall produced minerals are similar, the degree of elemental behavior varies depending on mineral assemblages of each alteration stage. Especially in dolomite type, some elements such as Al_2O_3, MgO, and CaO show somewhat different behavior in accordance with mineral assemblages of each alteration stage. Comparing two different types of talc deposit, serpentinite type and dolomite type, represents considerably different mineral assemblages. Many kinds of accessory minerals such as tremolite, phlogopite, and diopside are observed at serpentinite type talc deposit. These accessory minerals also occur at some dolomite type talc deposit as impurities. However, because the amount of impurities are relatively small compared those of with serpentinite type, the differences of elemental behavior could be observed. Fig. 9 and Table 7 shows the graphical elemental concentrations and calculated elemental concentrations respectively, which are derived from end-member (serpentinite, dolomite and talc) data of each talc deposits indicating the elemental behaviors of overall alteration stage in each deposits. The diagram shows that SiO_2 was more increased in dolomite type deposits than serpentinite type. The CaO behaves differently according to the deposit types, which increased at serpentinite type but was decreased at dolomite type alteration. During overall alteration, the total mass in serpentinite type was increased because serpentinite became altered rock, while dolomite type showed decreased. This is the most evident characteristics during alteration between each type talc deposits. The Co, and Ni represented immobile behavior similar to the consideration as immobile element in the previous studies. In addition to elemental behaviors during alteration processes, concentration of specific elements can help distinguish the types of talc deposits. For example, W. Prochaska (1989) suggest that ultramafic type talc has more high Ni and Cr values than carbonate-hosted type. In this study, Ni and Cr concentration of

Gapyeong and Yoogoo deposit are distinctly higher than those of the other two deposits which are subdivided into dolomite types.

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5. Conclusion

1) The Gapyeong talc deposit show two stages alteration sequences: Stage 1 (serpentinite → talc + serpentine + phlogopite) and Stage 2 (talc + serpentine + phlogopite → talc + tremolite). Increase of SiO_2, Al_2O_3 and K_2O caused formation of talc and phlogopite during Stage 1, whereas increase of SiO_2, Fe_2O_3, MgO and CaO caused production of talc, tremolite and chlorite during Stage 2. The decrease of K_2O in Stage 2 seems to be affected by breakdown of phlogopite.

2) The talc ore in Yoogoo was mainly formed from the alteration of serpentinite and the alteration of clinochlore seem to have an effect on the forming talc adjunctively. From these reaction, SiO_2 and CaO were increased significantly, whereas MgO and Al_2O_3 were decreased by hydrothermal solution.

3) The Dongyang talc deposit which is representative dolomite type talc deposit is characterized by increase of SiO_2 and

decrease of CaO during alteration. This alteration could be expressed as following reaction which is the typical for forming talc from dolomite.

$$3CaMg(CO_3)_2 + 4SiO_2 + H_2O \rightarrow Mg_3Si_4O_{10}(OH)_2 + 3CaCO_3 + 3CO_2$$

(dolomite) (talc)

4) The talc ore in Poongjeon was produced by two alteration stage: Stage 1 (dolomite → calc-silicate rock) and Stage 2 (calc-silicate rock → talc ore). At the Stage 1, the impurity such as tremolite, phlogopite, and diopside were produced. The talc ore was formed during Stage 2 and in this stage, the introduction of MgO by hydrothermal fluid cause the formation of talc.

5) The elemental behaviors of overall alteration stage in each deposits shows that SiO_2 was more increased in dolomite type deposits than serpentinite type. The CaO behaves oppositely according to the deposit types, which increased at serpentinite type but was decreased at dolomite type alteration. In case of

total mass, the serpentinite type was increased, while dolomite type showed decreased during overall alteration. This is the most evident characteristics during alteration between each type talc deposits. Co, and Ni are generally considered as immobile element.

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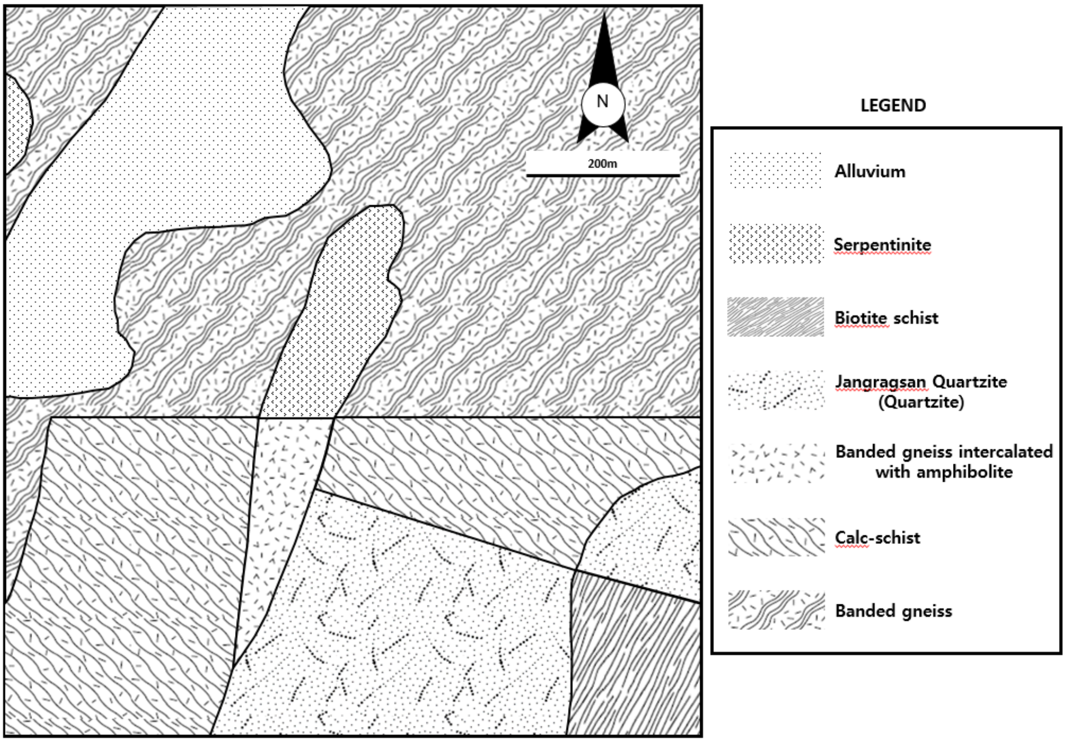

Fig. 1. Geological map of the Gapyeong talc deposit (after Kim et al., 1974 and Lee et al., 1974)

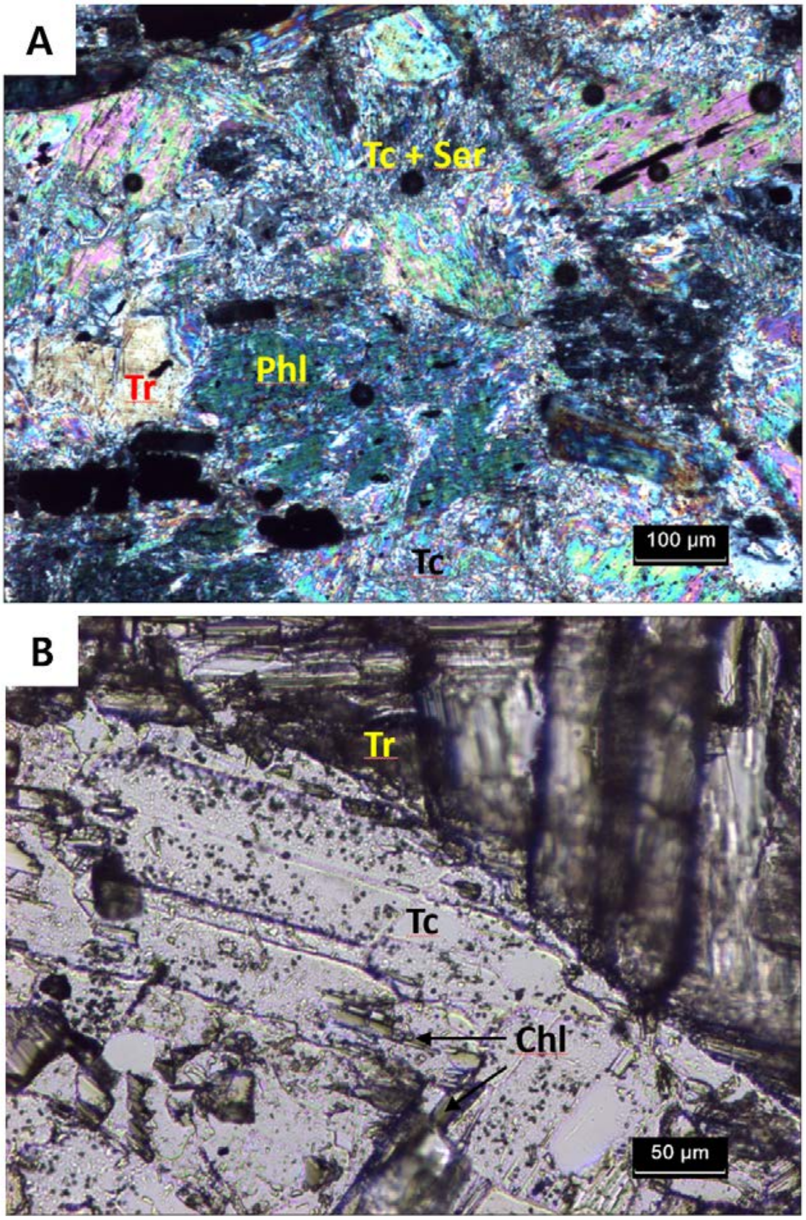

Fig. 2. Microphotographs of Gapyeong talc ore deposits. (A) Talc – serpentine – phlogopite assemblages occurred after first alteration. (B) Tremolite – Talc assemblages occurred after second alteration (Ser = serpentine, Phl = phlogopite, Tr = tremolite, Tc = talc, Chl = chlorite).

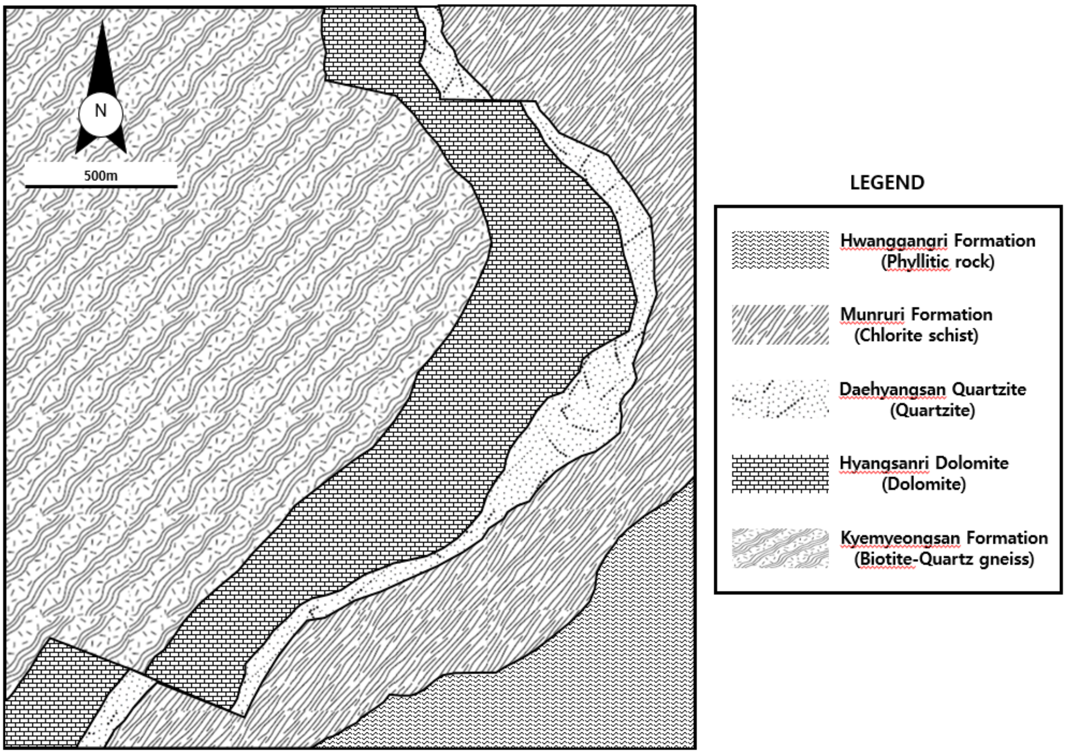

Fig. 3. Geological map of the Dongyang talc deposit (after Shin and Lee, 2005)

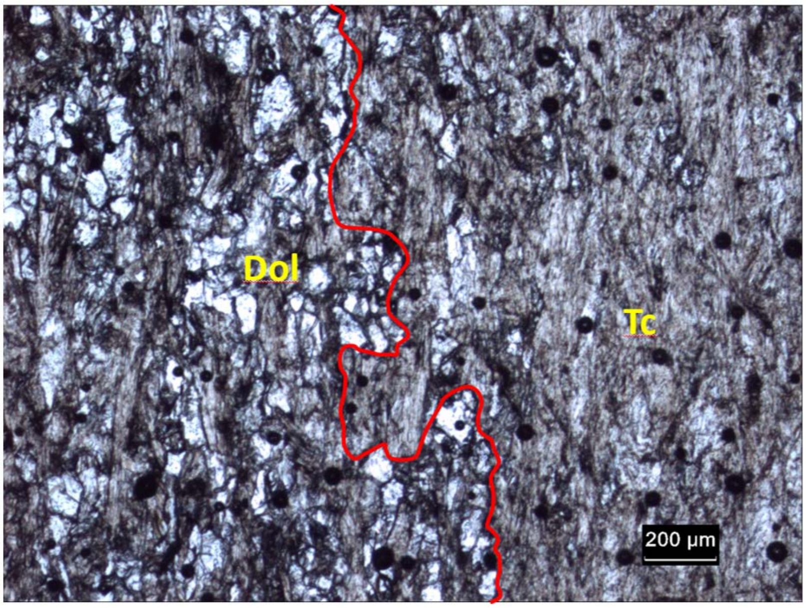

Fig. 4. Microphotographs of sharp alteration boundary in Dongyang talc deposits. The photograph takes under the plane-polarized light (Dol = dolomite, Tc = talc).

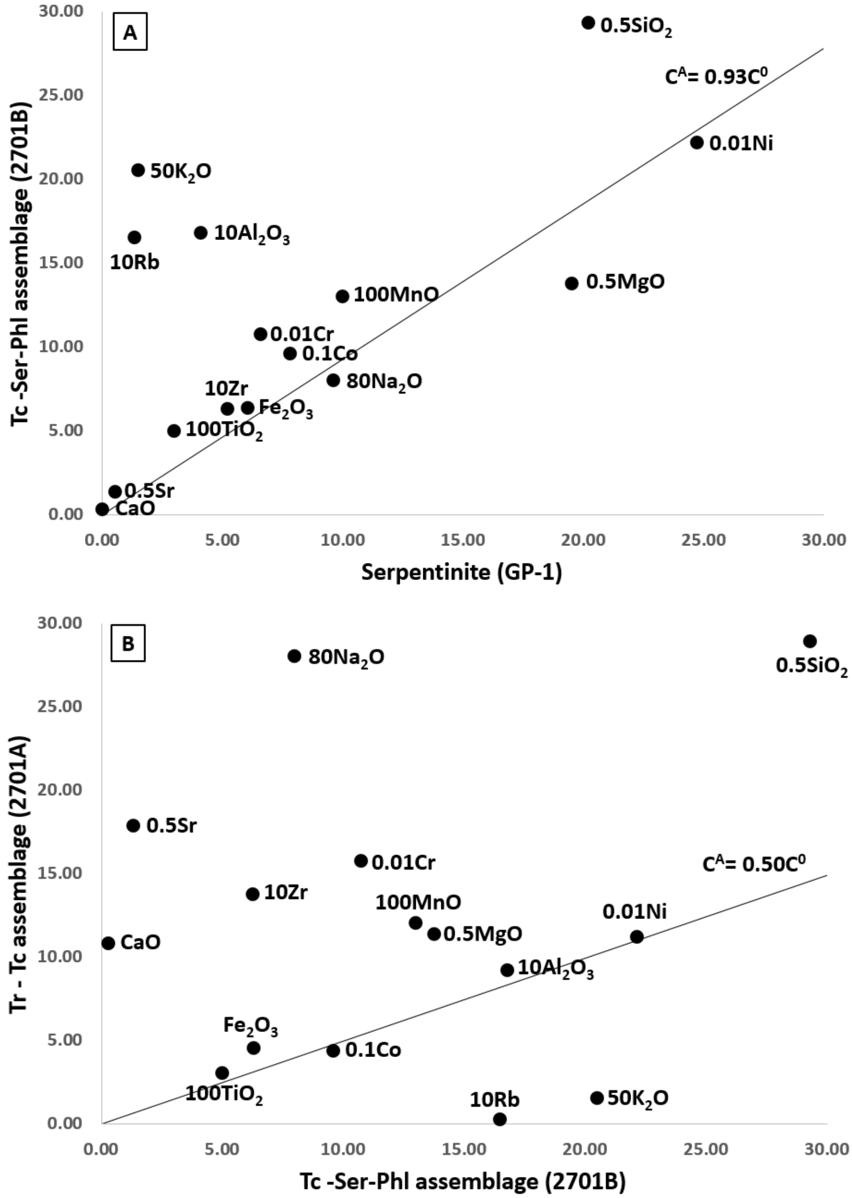

Fig. 5. Isocon diagrams of Gapyeong talc deposits for stage 1 (A: from serpentinite to Tc – Ser – Phl assemblage) and stage 2 (B: from Tc – Ser – Phl assemblage to Tr – Tc assemblage). The all data of components are scaled. The solid line indicates the isocon line. (Ser = serpentine, Phl = phlogopite, Tr = tremolite, Tc = talc, Chl = chlorite).

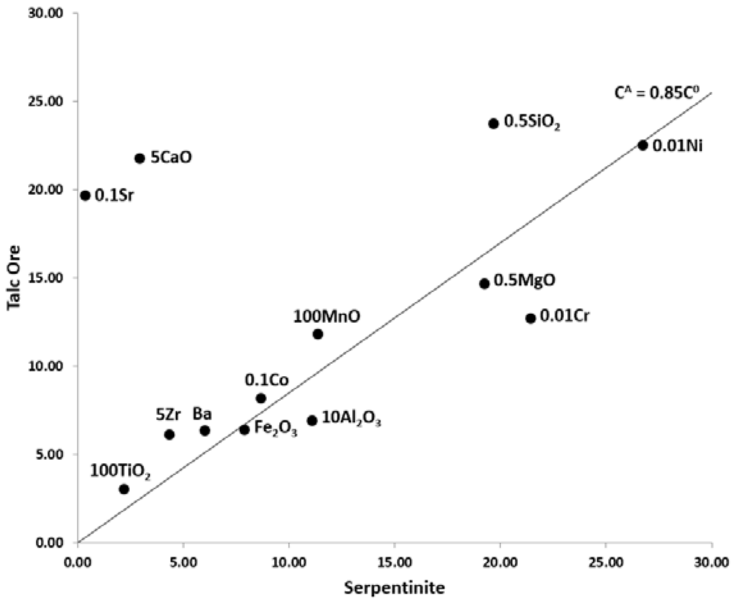

Fig. 6. Isocon diagrams of Yoogoo talc deposits. The all data of components are scaled. The solid line indicates the isocon line. The geochemical data was obtained from Woo and Lee, 2001.

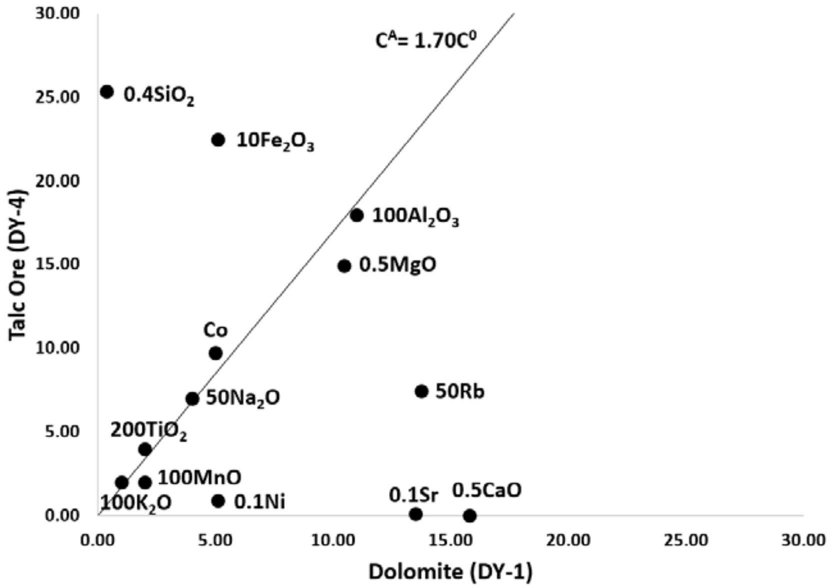

Fig. 7. Isocon diagrams of Dongyang talc deposits. The all data of components are scaled. The solid line indicates the isocon line.

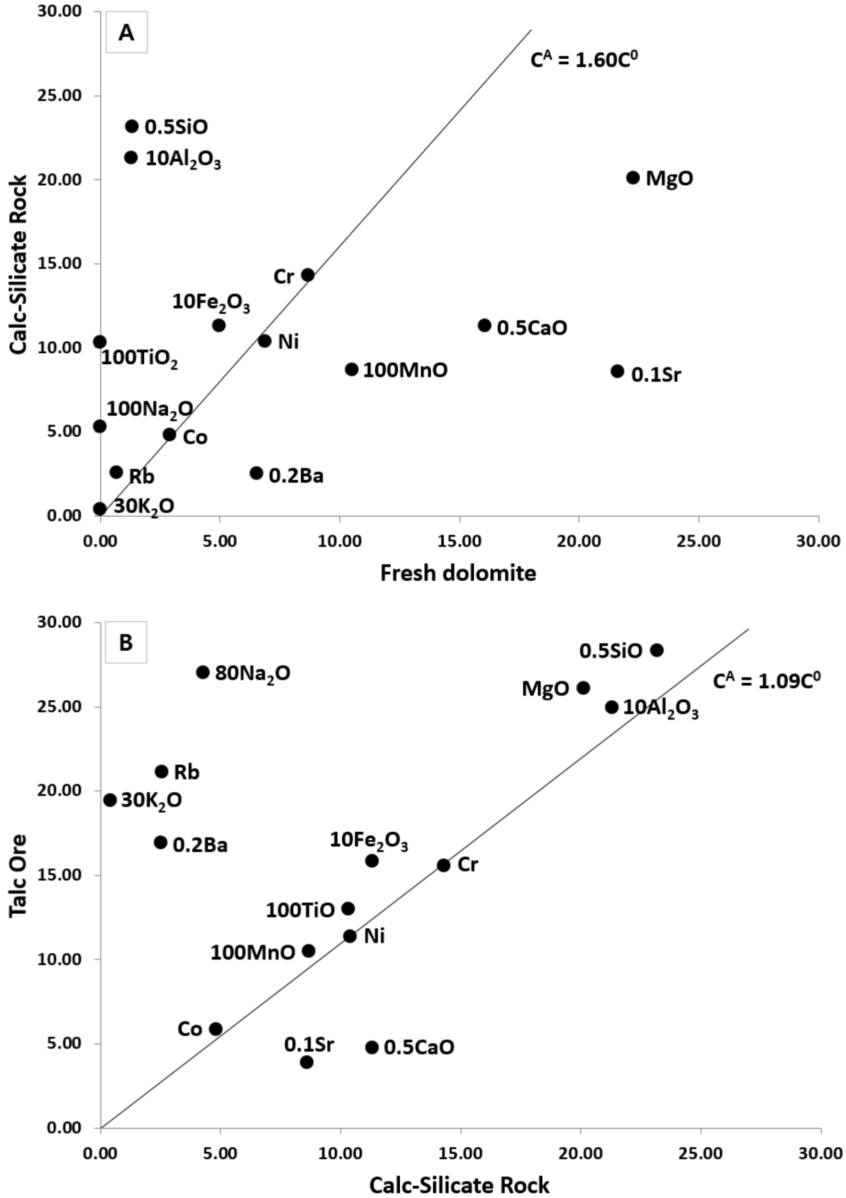

Fig. 8. Isocon diagrams of Poongjeon talc deposits for prograde stage (A) and retrograde stage (B). The all data of components are scaled. The solid line indicates the isocon line. The geochemical data was obtained from Shin and Lee, 2003.

Fig. 9. Graphical concentration changes derived from end-member (serpentinite, dolomite and talc) data of each talc deposits and indicate the elemental behaviors of overall alteration stage in each deposits corresponding to best-fit isocon of immobile elements.

GP - Gapyeong YG - Yoogoo DY - Dongyang PJ - Poongjeon ▲ - Increased ▼ - Decreased ■ - Immobile

	SiO_2	Al_2O_3	Fe_2O_3(t)	TiO_2	MgO	CaO	Na_2O	K_2O	MnO	Sr	Ba	Rb	Cr	Co	Ni	Zr
GP (Serpentinite)	▲	▲	▲	▲	▲	▲▲▲	▲▲	▲	▲	▲▲▲	-	▼	▲	■	■	▲
YG (Serpentinite)	▲	▼	■	▲	▼	▲▲	-	-	▲	▲▲▲	▲	-	▼	■	■	▲
DY (Dolomite)	▲▲▲	■	▲	■	■	▼	■	■	▼	▼	-	▼	-	■	▼	-
PJ (Dolomite)	▲▲▲	▲▲	▲	▲▲▲	▼	▼	▲▲▲	▲▲▲	▼	▼	▲	▲▲▲	■	■	■	-

▲ / ▼ - **1 to 5 fold increase / decrease** ▲▲ / ▼▼ - **5 to 10 fold increase / decrease** ▲▲▲ / ▼▼▼ - **10 to more fold increase / decrease**

Table 1. The whole-rock major element and trace element analyses of Gapyeong talc deposits (major elements in wt% and trace element in ppm) (Tr = tremolite, Tc = talc, Ser = serpentine, and Phl = phlogopite).

	Gapyeong						
	Tr - Tc assemblage	Partly altered	Tc - Ser - Phl assemblage	Partly altered	Fresh serpentinite	Amphibolite	Granite intrusion
Sample	2701A	2701A-1	2701B	2701C	GP-1	GP-2	GP-3
SiO_2	57.82	37.75	58.58	46.79	40.41	45.67	71.54
Al_2O_3	0.92	0.44	1.68	6.34	0.41	11.03	14.39
TiO_2	0.03	0.03	0.05	0.09	0.03	2.18	0.04
Fe_2O_3*	4.52	6.99	6.33	5.41	6.06	13.11	0.37
MgO	22.73	39.46	27.51	28.42	39.07	12.47	0.25
CaO	10.82	0.02	0.31	4.80	0.03	10.59	0.92
Na_2O	0.35	0.15	0.10	0.10	0.12	1.32	6.28
K_2O	0.03	0.01	0.41	0.06	0.03	1.45	4.71
MnO	0.12	0.10	0.13	0.12	0.10	0.20	0.02
P_2O_5	0.01	0.01	0.04	0.01	0.01	0.28	0.01
LOI	2.46	14.71	4.78	7.82	13.53	1.67	1.14
Total	99.81	99.67	99.92	99.95	99.80	99.98	99.66
La	0.95	0.19	0.37	0.54	0.11	22.79	1.11
Ce	2.15	0.21	0.67	0.53	0.27	46.36	1.99
Pr	0.41	nd	nd	nd	nd	6.87	0.25
Sm	0.59	nd	nd	nd	nd	6.04	0.74
Eu	0.25	nd	nd	nd	nd	2.03	0.50
Gd	0.92	nd	0.13	nd	nd	6.61	0.28
Tb	0.19	nd	nd	nd	nd	0.87	0.04
Dy	1.48	nd	0.13	nd	nd	4.71	0.20

Table 1. continued

Ho	0.34	nd	nd	nd	nd	0.84	0.04
Er	1.17	nd	nd	nd	nd	2.34	0.14
Tm	0.19	nd	nd	nd	nd	0.30	0.03
Lu	0.19	nd	nd	nd	nd	0.29	0.07
Y	12.48	nd	1.03	0.57	nd	25.81	1.25
Nd	1.77	nd	0.33	0.26	nd	30.98	0.97
Yb	1.33	nd	0.13	nd	nd	1.91	0.26
Sr	35.67	0.21	2.70	5.58	1.06	163.18	707.94
Ba	nd	nd	20.23	6.27	nd	384.64	2304.59
Rb	0.23	nd	16.49	2.41	1.37	45.89	85.47
Cr	1573.35	686.24	1075.54	2807.93	660.44	1225.81	1.93
Co	43.41	99.39	95.93	64.80	78.17	75.22	0.85
Ni	1120.42	2587.01	2216.66	1883.18	2471.76	514.44	3.28
Cu	31.64	15.92	69.13	151.77	17.78	5252.99	64.73
Zn	128.63	166.90	259.72	174.60	157.88	881.21	47.80
Zr	1.38	nd	0.63	0.91	0.52	15.28	57.07

Table 2. The whole-rock major element and trace element analyses of Dongyang talc deposits (major elements in wt% and trace element in ppm).

	Dongyang						
	Dolomite	Dolomite	Partly altered	Talc ore	Amphibolite	Granite intrusion	Quartzite
Sample	DY-1	DY-2	DY-3	DY-4	DY-6	DY-7	DY-8
SiO_2	0.97	2.69	14.03	63.43	33.05	71.74	94.83
Al_2O_3	0.11	0.15	1.42	0.18	16.21	14.58	2.90
TiO_2	0.01	0.01	0.05	0.02	3.46	0.27	0.09
Fe_2O_3*	0.51	0.36	2.13	2.25	9.32	2.19	0.21
MgO	20.97	19.82	10.81	29.94	26.89	0.65	0.10
CaO	31.62	32.59	34.16	0.03	0.67	0.57	0.02
Na_2O	0.08	0.03	0.07	0.14	0.11	3.80	0.09
K_2O	0.01	0.01	0.01	0.02	0.01	4.85	0.87
MnO	0.02	0.03	0.19	0.02	0.05	0.07	0.01
P_2O_5	0.01	0.01	0.02	0.00	0.40	0.08	0.01
LOI	45.55	44.00	37.05	3.94	9.73	1.09	0.61
Total	99.86	99.70	99.92	99.97	99.90	99.90	99.74
La	0.76	1.20	7.48	nd	0.47	35.25	4.00
Ce	0.97	2.05	14.48	nd	1.08	61.57	8.51
Pr	0.16	0.30	1.75	nd	0.17	7.58	0.92
Sm	nd	0.24	1.35	nd	0.44	4.64	0.73
Eu	nd	0.10	0.32	nd	nd	1.00	0.19
Gd	0.11	0.35	1.71	nd	0.91	4.79	0.49
Tb	nd	nd	0.25	nd	0.17	0.57	nd
Dy	nd	0.33	1.49	nd	1.41	3.01	0.26

Table 2. continued

Ho	nd	nd	0.30	nd	0.25	0.55	nd
Er	nd	0.19	0.91	nd	0.72	1.69	0.17
Tm	nd	nd	0.13	nd	nd	0.23	nd
Lu	nd	nd	0.13	nd	nd	0.24	nd
Y	0.57	2.56	9.13	nd	7.07	13.31	1.02
Nd	0.39	1.00	6.15	nd	0.94	28.08	3.18
Yb	nd	0.14	0.87	nd	0.88	1.57	0.19
Sr	135.03	87.11	548.00	1.08	5.10	229.30	21.89
Ba	1.78	7.14	6.00	nd	nd	1234.87	714.89
Rb	0.28	0.04	0.10	0.15	0.40	203.39	19.98
Cr	0.16	1.35	7.34	nd	133.97	3.79	17.91
Co	5.01	4.60	6.16	9.76	21.10	3.67	2.39
Ni	51.19	50.53	56.52	9.00	71.81	7.69	4.06
Cu	10.54	5.42	100.96	29.89	1575.06	581.20	163.91
Zn	112.63	66.06	127.10	314.79	802.38	149.32	58.52
Zr	nd	0.33	14.46	1.04	10.69	58.07	13.49

Table 3. Concentration changes of Gapyeong talc deposits corresponding to best-fit isocon of immobile elements.

	Stage1	**Stage2**
	$C^A=0.93C^0$	$C^A=0.50C^0$
Mobility	$\Delta C_i/C_i^0$	
SiO_2	0.56	0.99
Al_2O_3	3.42	0.10
TiO_2	0.80	0.21
Fe_2O_3*	0.13	0.44
MgO	-0.24	0.66
CaO	10.15	69.21
Na_2O	-0.10	6.04
K_2O	13.75	-0.85
MnO	0.40	0.86
Sr	1.74	25.53
Ba	-	-
Rb	12.00	-0.97
Cr	0.76	1.94
Co	0.32	-0.09
Ni	-0.03	0.02
Zr	0.30	3.41
M_A/M_O	1.079	2.012

Table 4. Concentration changes of Yoogoo talc deposits corresponding to best-fit isocon of immobile elements. The geochemical data was obtained from Woo and Lee, 2001.

	$C^A=0.85C^0$
Mobility	$\Delta C_i/C_i^0$
SiO_2	0.42
Al_2O_3	-0.27
TiO_2	0.60
Fe_2O_3*	-0.06
MgO	-0.11
CaO	7.62
Na_2O	-
K_2O	-
MnO	0.22
Sr	59.35
Ba	0.23
Rb	-
Cr	-0.30
Co	0.10
Ni	-0.01
Zr	0.64
M_A/M_O	1.18

Table 5. Concentration changes of Dongyang talc deposits corresponding to best-fit isocon of immobile elements.

	$C^A=1.70C^0$
Mobility	$\Delta C_i/C_i^0$
SiO_2	37.51
Al_2O_3	-0.04
TiO_2	0.18
Fe_2O_3*	1.60
MgO	-0.16
CaO	-1.00
Na_2O	0.03
K_2O	0.18
MnO	-0.41
Sr	-1.00
Ba	-
Rb	-0.68
Cr	-
Co	0.15
Ni	-0.90
Zr	-
M_A/M_O	0.59

Table 6. Concentration changes of Poongjeon talc deposits corresponding to best-fit isocon of immobile elements. The geochemical data was obtained from Shin and Lee, 2003.

	Prograde	**Retrograde**
	$C^A=1.60C^0$	$C^A=1.09C^0$
Mobility	$\Delta C_i/C_i^0$	
SiO_2	10.02	0.12
Al_2O_3	9.24	0.07
TiO_2	16.23	0.15
Fe_2O_3*	0.43	0.28
MgO	-0.44	0.19
CaO	-0.56	-0.61
Na_2O	>100	4.81
K_2O	>100	43.55
MnO	-0.48	0.11
Sr	-0.75	-0.58
Ba	-0.76	5.17
Rb	1.34	6.56
Cr	0.03	0.00
Co	0.03	0.12
Ni	-0.06	0.00
Zr	-	-
M_A/M_O	0.63	0.92

Table 7. Calculated concentration changes derived from end-member (serpentinite, dolomite and talc) data of each talc deposits and indicate the elemental behaviors of overall alteration stage in each deposits corresponding to best-fit isocon of immobile elements.

	Gapyeong	**Yoogoo**	**Dongyang**	**Poongjeon**
	$C^A=0.46C^0$	$C^A=0.85C^0$	$C^A=1.70C^0$	$C^A=1.75C^0$
Mobility	$\Delta C_i/C_i^0$	$\Delta C_i/C_i^0$	$\Delta C_i/C_i^0$	$\Delta C_i/C_i^0$
SiO_2	2.09	0.42	37.51	11.31
Al_2O_3	3.85	-0.27	-0.04	9.97
TiO_2	1.16	0.60	0.18	>100
Fe_2O_3*	0.61	-0.06	1.60	0.83
MgO	0.26	-0.11	-0.16	-0.33
CaO	778.04	7.62	-1.00	-0.83
Na_2O	5.30	-	0.03	>100
K_2O	1.16	-	0.18	>100
MnO	1.59	0.22	-0.41	-0.43
Sr	71.46	59.35	-1.00	-0.90
Ba	-	0.23	-	0.49
Rb	-0.63	-	-0.68	16.64
Cr	4.15	-0.30	-	0.02
Co	0.20	0.10	0.15	0.15
Ni	-0.02	-0.01	-0.90	-0.06
Zr	4.70	0.64	-	-
M_A/M_O	2.16	1.18	0.59	0.57

국문 초록

서로 다른 기원의 활석광상 내 활석 광화작용에 대한 물질수지 분석

일반적으로, 활석은 두 가지 광상 타입: 1) 돌로마이트 타입, 2) 초염기성 타입으로 세분화 할 수 있다. 우리나라에서 첫 번째 타입은 주로 충주지역 일대에서 산출되고, 두 번째 타입은 주로 예산지역 일대에서 산출된다. 원암으로부터 활석광상이 형성되는 과정에서 원소의 증가와 감소가 나타나게 된다. 본 연구에서는, 다른 기원의 활석광상간 원소의 거동 차이를 알아보고, 모암의 기원을 추적하는데 물질 수지를 이용한 방법의 유용성을 조사하기 위해 아이소콘 물질수지 방법 (isocon mass-balance method)을 적용하였다. 활석광상의 주원소 및 미량원소의 거동을 조사하고, 각 타입간 원소의 거동을 비교하기 위해 본 연구에서는 네 지역 (가평, 유구 광상 - 사문암 타입 (초염기성 타입), 동양 풍전 광상 - 돌로마이트 타입)의 활석 광상에 대해 연구하였다. 각 광상의 아이소콘 도표와

계산된 농도변화는 원소의 거동이 주로 각 변질 단계의 광물 조합에 영향을 받는 것으로 나타났으며, 투각섬석, 금운모, 투휘석, 녹니석이 부수광물로 광물 조합을 주로 구성하고 있다. 끝성분 자료를 이용하여 두 다른 타입간 비교를 한 경우, 전반적인 변질 단계 동안 총 질량의 변화, 그리고 SiO_2, CaO, Sr의 거동이 뚜렷한 차이를 보이며, Co와 Ni은 거의 모든 변성 단계에서 비거동원소로 나타났다.

주요어 : 활석광상, 물질 수지, 원소의 거동, 아이소콘 도표, 농도변화, 변질 단계

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