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Petrology and Amphibolites (Meta-Dolerite sill) in the Mungyong Area, Korea

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문경지역에 분포하는 각섬암(변성조립현무암)에 대한 암석학적연구

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요 약: 옥천습곡대 중앙부에 해당하는 문경지역에 분포하는 각섬암에 대하여 정밀한 산상, 조직 및 지화학적 성질을 조사하고, 지구조적 환경을 추적했다. 본역의 상내리층(옥천층군)과 석회암층(조선누층군)에 분포하는 각섬암은 변성된 조립현무암질 암상이며 주변암과 조화적로 분포함을 확인했다. 본 연구를 통하여 본 암석의 분포를 이전의 그것에 비해 크게 대선하였다. 상내리 지역을 중심으로 관찰한 암상을 최소한 4매 이상이다. 그 하나는 석회암층 내에 분포하며(Ls Sill, 두께 약 3 m), 나머지는 상내리층 내에 분포한다. 상내리층 내에 분포한 암상들을 하부로부터 각각 First Sill(두께 약 40 m), Second Sill(두께 약 100 m), Third Sill(두께 약 40 m)로 명명했다. 두꺼운 암상은 후기에 관입한 소규모의 암상을 포함하며, Third Sill은 2매의 주 암상과 2매의 소규모 암상으로 구성된다. 각 암상은 주변암과의 접촉부에서 세립질의 냉각대를 가지며, 내측으로 갈수록 입자의 크기가 증가한다. 두꺼운 암상은 다양한 암맥과 중심부에서 힌색의 단편을 가지며, 접촉부에서 중앙부로 감에 따라 화학적 성질도 규칙적으로 변한다. SiO_2, Na_2O, K_2O, P_2O_5는 증가하며, TiO_2, FeO*, Al_2O_3, CaO는 감소하는 경향을 보인다. 각섬암의 산상과 화학적 특징을 고려하여, 초기에 관입한 마그마로 생각되는 대표적인 10개의 화학조성을 선택하여 그들의 주성분 및 부성분 변화를 조사하였다. 그들이 보여주는 조성변화는 단일 마그마의 분별결정작용으로 설명할 수 없다. 본 역의 각섬암에 관한 지질분포, 지화학적 특성 및 과거 연구자들의 자료는 각섬암의 원암(현무암질마그마)이 intracontinental rift 환경에서 암상형태로 관입하였음을 지시한다.
주요어: 각섬암, 조립현무암질 암상, 문경지역, 옥천습곡대

Abstract: With respect to the amphibolites in the Mungyong area of the central part of the Ogcheon Fold Belt, detail field occurrence, texture and geochemical properties within each sills and petrogenetic environment are presented. We confirmed that the amphibolites in the Sangnaeri Formation (Ogcheon Supergroup) and limestone (Cambro-Ordovician Chosun Supergroup) sequences are metamorphosed dolerite sills which are roughly concordant to bedding of country rocks. Geologic distribution of the rocks is distinctly improved compared with those of previous investigations. There are four main sills so far observed in the study area. One is emplaced in limestone (Ls Sill, about 3 m thick) and the others are emplaced in Sangnaeri Formation, which are named First Sill (about 40 m thick), Second Sill (about 100 m thick) and Third Sill (about 40 m thick) from lower to upper horizons of the meta-pelitic sequences. The thick sills are intruded by minor sills and the Third Sill is a composite sill consisting of two main and two minor sills. Each sill has fine grained chilled marginal zones and grain size increases inwards from both contacts. The Second Sill has various vein and white patch in central part and the rock compositions vary systematically from margin to central part. SiO_2, Na_2O, K_2O and P_2O_5 increase, whereas TiO_2, FeO, Al_2O_3 and CaO decrease toward the centert. We investigate the major and trace element variations of ten selected rock compositions as intruding initial magma take occurrence and chemical properties into consideration. The compositional variations of them can not be explained by fractionation crystallization of single magma. Geologic distribution, geochemical properties and previous data suggest that amphibolite precursors (basaltic magma) of the study area were intrusive as sill-like in an intracontinental rift environment.
Key words: amphibolite, dolerite sill, Mungyong area, Ogcheon fold belt

INTRODUCTION

The Korean peninsular is situated on the eastern margin of the Eurasian plate close to boundary with the Pacific plate. The southern part of the peninsular is composed of five structural provinces including Kyonggi massif, Ryongnam massif, Ogcheon Fold Belt, Kyongsang basin and Pohang basin (Fig. 1a). The NE-SW trending Ogcheon Fold Belt, which separates the Kyonggi massif

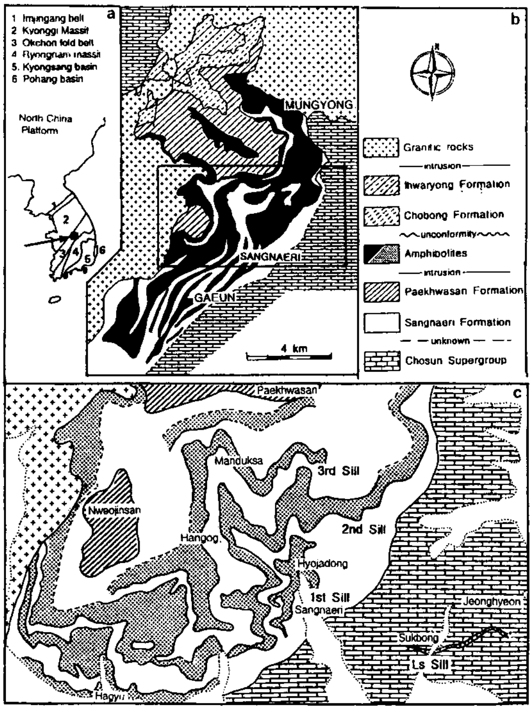

Fig. 1. (a) General sketch map of the Korean peninsula showing major tectonic provinces. (b) Simplified geologic map of Mungyong area (combination of Kim *et al.*, 1967 and Lee and Kim, 1968) (c) Distribution of amphibolites in Sangnaeri area.

from Ryongnam massif, is divided into two zones: the southeastern metamorphic Ogcheon and the northeastern non-metamorphic Taebaeksan zones (Kobayashi, 1953). The Ogcheon zone is composed mainly of the metasedimentary Ogcheon Supergroup and the Taebaeksan zone is composed mainly of Chosun Supergroup of Cambro-Ordovician age. The age and stratigraphy of the Ogcheon Supergroup still remains in question because of the paucity of fossils and lack of primary structures (Lee, 1987).

In the Ogcheon Fold Belt, amphibolites mainly occur in the Chungju, Mungyong and Boeun areas. The age, occurrence and magmatism of the rocks are very important to understanding tectonic environment of the Ogcheon Fold Belt. According to previous studies, the amphibolites are parts of ophiolites (Lee, D. S. 1980, Lee, S. M. *et al.* 1982) resulting from the collision with Gyeonggi and Ryongnam Precambrian massifs, island arc basalt (Park and So, 1972) and products of continental rift-related environments (Cluzel and Cadet, 1989; Kwon and Lan, 1991, Cluzel, 1992; Kwon and Lee, 1992). Cluzel and Cadet (1989) and Cluzel (1992) described this rocks as metadoleritic intrusive complexes (dykes, sills and laccoliths) and volcano-sedimentary formations (basic tuffs, lava flows) and as closely related to the crustal thinning and subsequent rifting and tilting, although detailed geologic map and descriptions were not made. The age of amphibolites is still a matter of debate. Several investigators have tried to date the amphibolites occurring within Ogcheon zone (Lee, 1988; Kwon and Lan, 1991; Kwon *et al.*, 1994; Min *et al.*, 1995; Lee and Chang, 1996). Obtained some isotopic data are most likely the age of metamorphism and some Sm-Nd isotopic data may be not a true but a apparent age.

No detailed descriptions of amphibolites have been carried out, although many petrological and geochemical features have been study (Lee and Woo, 1970; So and Kim, 1975; Kim and Kim, 1976; Lee *et al.*, 1980; Lee, 1980; Ahn, 1985; Ahn *et al.*, 1993; Lee, 1988; Lee and Chang, 1996). With respect to the amphibolites in the Mungyong area, geological observations were made by Kim *et al.* (1967), Lee and Kim (1968) and Lee and Chang (1996). Their distribution and mode of emplacement, of course, has been poorly understood so far. The bulk chemistry of amphibolites in the area have been accumulated by previous authors with wet chemical and XRF analyses. The previous analyzed samples were collected randomly because they had no concept of sill-like intrusions. This study is occurrence, major and trace elemnent chemistry within each sills and magma source of the amphibolites in the Mungyong area of the central part of the Ogcheon Fold Belt.

GEOLOGIC SETTING

The rocks of Mungyong area in the central part of Ogcheon Fold Belt consists of the Ogcheon Supergroup (amphibolites and metapelites), Chosun Supergroup (mainly of limestone) and Cretaceous granite (Kim *et al.*, 1967; Lee and Kim, 1968).

The Chosun Supergroup is composed of the Great Limestone Group and the Kurangni Formation. The Kurangni Formation consists mainly of reddish and bluish gray shales, gray phyllitic shales and sandstones, and is generally well bedded. Lee and Lee (1985) confirmed that the Kurangni Formation is of Early Cambrian in age by the rediscovery of the triobite Redlichia nobilis Walcott. The Great Limestone Group is widely distributed in the northern part of Kurangni town and its small exposure is also enclosed in the Kurangni Formation. The group is composed mainly of bluish gray limestones associated with thinly bedded calcareous or non-calcareous shales, showing predominant banded structures.

The Ogcheon Supergroup of the area is composed of the Sangnaeri Formation, the Paekhwasan Formation, the Chobong Formation and the Ihwaryong Formation in the ascending order. The amphibolites occur as sill-like bodies within the Sangnaeri Formation and Limestone formation of Chosun Supergroup. The amphibolites intrude the Paekhwasan Formation as well (Lee and Chang, 1996). The Ogcheon Supergroup apparently overlies Chosun Supergroup, but relationships are not known. These two Supergroups are intruded by Cretaceous granitic rocks and acidic dykes in the northern part of the area. Simplified geologic map based on the previous geologic sheets by Kim *et al.* (1967) and Lee and Kim (1968) is shown in Fig. 1b.

The Sangnaeri Formation is lowermost sequence of Ogcheon Supergroup in the study area. Lower part of the Formation is mainly composed of black slate and shale with two or three intercalated layers of gray limestone and with a thin layer of gray to black, medium to coarse sandstone about 7 m thick. They include lenticular seam of low grade anthracite and coally shale. Upper part consists of phyllite and grayish to greenish slate intercalating with two or three thin layers of milky, white medium to coarse sandstone. The uppermost part, which is distributed around Mt. Nweojinsan and Mt. Paekhwasan, consists of phyllite with intercalated conglomeratic phyllite. Pebbles of conglomeratic phyllite are mainly composed of shales and schists and up to 10 cm in diameter.

The Paekhwasan Formation consists of the light-colored compact pebble-bearing silicic phyllitic rock. It is well exposed in Nweojinsan and Paekhwasan. The pebbles of the Formation are largely quartzite and limestone of about 2 cm in diameter and associated with small amounts of granitic rocks. The pebbles are usually stretched by deFormation. The matrix consists mainly of quartz grains associated with biotite, muscovite, chlorite and pyrites. The quartz grains are also found as micro-pebble and a few polycrystalline quartz aggregates are present as pebbles. The Chobong and Ihwaryong Formation are well exposed in the road-cut from Kakseori to Yeonpung, which is intruded by Cretaceous granite. This Formation consists of light or dark gray chlorite schist intercalated frequently with massive sandy rock.

Granitic rocks including biotite granite, quartz porphyry and acidic dyke are widely exposed in the northern and western part of the study area. The biotite granite is predominant rock type of late Cretaceous age (83~90 Ma, Kim, O. J., 1971) in this area. The rock is in contact with Ogcheon Supergroup at the north and west. It also intrudes into Chosun Supergroup at north. The quartz porphyry also intrudes into Sangnaeri Formation.

OCCURRENCE OF AMPHIBOLITES

The amphibolites, which are metamorposed dolerite, occur in the Ogcheon Supergroup and Cambro-Ordovician Chosun Supergroup, forming intusive sill. They are best exposed from the town of Sangnaeri to the temple of Manduksa in the Sangnaeri Formation. The thin dolerite sills (amphibolites) are distributed in the limestone sequences in the Jeonghyeon and Sukbong area. Many of them are roughly concordant to strikes of country rocks. Kim *et al.* (1967) has considered the rock to be the Cretaceous mafic dyke, but Lee and Kim (1968) has interpreted it as the equivalent of amphibolite in the Sangnaeri Formation. The thickness, extension and petrographic characters of sills are variable. The outline of each sills are roughly concordant to the general structural trend of country rocks and their distribution is shown in Fig. 1c.

Petrological investigation in this study is concentrated on four sills of the Mungyong area. One is exposed in the Chosun Supergroup, consisting of impure limestones, and is named Ls Sill. The others are exposed in the Sangnaeri Formation, and are named the First Sill, the Second Sill, the Third Sill from lower to higher horizons of pelitic succession. Fig. 2 shows schematic columnar section for above four sills. The thick sills are well differentiated, and include various rock facies within them. The Second Sill is a good example of the well-differentiated one. The thick sills are intruded by small minor sills. Considering the present mineral assemblage, which are largely made up hornblende, actinolite, plagioclase, chlorite and opaque minerals, dolerite sills were more and less recrystallized due to the subsequent metamorphism.

The Ls Sill

The Ls Sill intrudes flat lying, thinly bedded siltstone and limestone of the Chosun Supergroup at the Jeonghyeon area. The contact plane is concordant with the bedding plane of the limestone, which shows no disturbance. Its thickness is less than 3 m. The chilled margin is 5 cm wide, gradually changing to medium grained dolerite. It is homogeneous on the whole in rock facies, except for the fine-grained chilled zones.

This sill is exposed in the lowest-grade part of the contact metamorphic zone. Therefore their texture is relatively well preserved although most of mineral constituents are metamorposed. The chilled contact is porphyritic with conspicuous phenocrysts of subhedral clinopyroxene (augite) and

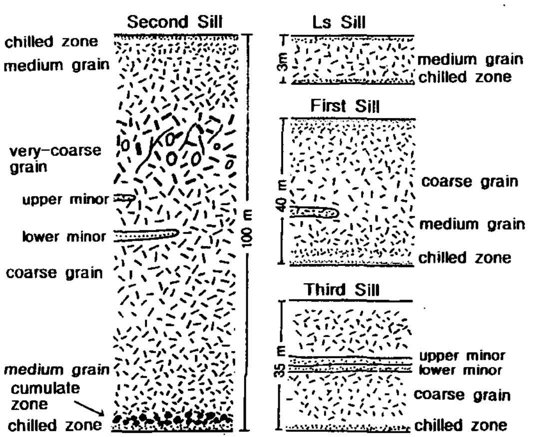

Fig. 2. Schematic columnar sections of the amphibolites in Sangnaeri area.

prismatic plagioclase. Phenocrysts make up 15% of the chilled contact. Groundmass is a dense aphanitic of closely packed microlites of slender plagioclase laths, opaque minerals and indeterminable mesostasis. The porphyritic chill phase passes rapidly into a coarser ones. More even-grained dolerite is composed of a subophitic intergrowth of plagiclase and clinopyroxene. Subophitic dolerite, with a uniform average grain size of 1.5 mm, makes up about 90% of the sill. In both of the lower and upper chilled margins, numerous small white veins, composed mostly of quartz, calcite and chlorite, occur.

The First Sill

This sill is broadly exposed around the town of Sangnaeri and Hyojadong. The thickness of the sill is about 40 meters. The First Sill is concordant to the strike and dips of country rocks. The contact plane of the two rock types is parallel to the strikes of limestone sequence.

The lower and/or upper contacts can be seen in several places. Grain size gradually increases from chilled marginal zone to central part of the sill. Large grain is up to 2~3 mm in central zone of the sill. This sill is differentiated, but its differentiation is not so conspicuous as in the Second Sill. Very coarse grained rock and cumulated zone as seen the Second Sill is not found in this sill. This sill has a minor sill at 15 m high from the lower contact in Hyojadong valley. The thickness of the minor sill is about 2 m and it can be confirmed by fine-grained rock at the contact with the main body.

Rocks of upper chilled zone (ie. sample B72) have euhedral phenocrysts of olivine pseudomorphs (up to 1.5 mm) associated with small amount of plagioclase lath and pyroxene but opaque mineral is rare. Phenocrysts make up to only about 5 percents of the chilled margin rocks. The matrix consist of slender plagioclase lath and irregular forms of pyroxene pseudomorphs, opaque minerals and indeterminable mesostasis. Chlorite aggregates may be replaced products of olivine. The rest of the sill is made up of a relatively coarse grained subophitic intergrowth of pyroxene and plagioclase pseudomorphs.

The Second Sill

It is emplaced into Sangnaeri pelitic rocks at an upper horizon of the First Sill. The Second Sill, one of the well-differentiated sill in this area, exposed from valley of Hyojadong- Manduksa, through Hangog and Sangnaeri valley, to Minori town. The thickness of the sill is about 100 meters. It is in contact with phyllites at the base and the top. One of the lower contact is exposed at point about 500 meters northwest of Sangnaeri town along the valley and its contact plane has strike N 30°E, dip 60°NW in spite of somewhat disturbance by small scale faults. The lower contact at the valley of Hyojadong- Manduksa is very sharp but rocks of marginal zone have week schistosity.

The grain size of the constituent minerals except for cumulate zone increases inwards from both contacts. The largest crystals are observed in 2/3 part from the lower contact. The Second Sill can be divided into four parts based on grain size and rock facies. The four are chilled marginal zone, cumulate zone, medium-coarse grained zone and very coarse grain zone. Their relations are schematically illustrated in the columnar section.

The chilled marginal zones range in thickness from 30 cm to 60 cm. The rocks of marginal zone are composed of fine grained rocks with irregular whitish veins. The rocks show porphyritic texture but phenocrysts are replaced by metamorphic minerals. The original phenocryst would have been pyroxene and plagioclase. The thickness of the cumulate zone is less than three meters. This part is enriched in pseudomorphs of olivine, clinopyroxene and plagioclase, which would have accumulated by gravitational sinking. The grain sizes of the constituent minerals are larger than rocks of its lower and upper zone.

The medium-coarse grained zone is the main constituent of the Second Sill and is common rock type in this area. The grain size ranges from 1 mm to 4 mm. It consists mainly of plagioclase and pyroxene pseudomorphs. Almost all plagioclase is replaced to saussuritic aggregate, which is tabular and often attains 5 mm, and some are recrystallized to albite. The pyroxene is also replaced by actinolite and hornblende aggregate but some relics are rarely observed (eg. sample 247 and 250). The rocks are more abundant in opaque minerals than those of the chilled zone.

The very coarse grained zone is characterized by very coarse grain size (up to 1 cm) and various rock facies. The rock is well exposed as 30 meters cliff at point about 2 km north of Sangnaeri. The occurrences of thin vein, two to three centimeters in thickness, and white colored oval patches are common. The white patch, up to 30 centimeters in diameter, consists mainly of plagiclase. This sill has two minor sills in normal dolerite zone at the Sangnaeri valley. The lower minor sill and the upper minor sill are 3 m and 30 cm thick respectively. The lower contact of the lower minor sill is sharp and it has fine grained marginal zone but the upper contact is obscure. The grain size increases gradually from margin to central part in the minor sills. Texture and mineral constituents of central part of the lower minor sill are similar to those of the normal dolerite of main body. The upper minor sill has distinct contacts. Texture and mineral constituents of central part of the upper minor sill is similar to those of chilled marginal zone of the main sill.

The Third Sill

This sill is also emplaced into Sangnaeri pelitic rocks. It is the uppermost sill among the four sills. The rocks are well exposed near the temple of Manduksa and Samjeonri. This area belongs to the highest grade part of the contact metamorphic zone in the study area.

Its thickness is about 40 meters. The lower contact is visible near the temple of Manduksa. Although upper contact could not observed, it may be between sample A254 and overlying pelitic rocks, the distance between the two being about 5 meters.

The Third Sill is a composite sill consisting of two main sills and two small-scale sills. The main two sills are the lower and the middle parts of the sill, respectively, although the very contact between them can not be seen. The lower one is fine-grained rock and contact with pelitic rock. The thickness of this sill now exposed is about 5 meters. This lower sill may be an independent sill, because it is difficult to regard this lower part as chilled marginal zone of the middle and upper parts of the Third Sill. The main middle sill consists of medium to coarse grained rocks and its observable thickness is about 35 meters. Mineral constituents and texture of the middle one is similar to those of the normal dolerite of the Second Sill. The two minor sills are exposed in the middle part with clear contact.

The lower minor sill, 1 m in thickness, is composed of fine-grained rock. Sample A252 in this minor sill is characterized by absence of phenocrysts. The upper contact of the upper minor sill is obscure due to covered by other rock fragments, and exposed thickness is about 2 meters. The grain size of the upper minor sill is coarser than the lower minor sill but finer than the main middle sill.

ANALYTICAL METHODS

Because the bulk composition of rocks changes not only for different sills but also for different positions in a single sill, 20 to 60 pieces of hand specimen were systematically collected from the lower to the upper contact in each sill. These rock-samples have been metamorposed, so that their compositions may be modified from original ones. However, We assumed that metamorphisms have occurred essentially closed chemical system except for H_2O and CO_2.

About 62 XRF analyses of major and trace elements were performed. Fresh rocks were selected based on microscopic observations on thin sections and were crushed into cm-sized pieces from which veins were eliminated. These samples were crushed into coarse powder (smaller than 1 mm, about 100 g) in a WC mill and ground into fine powder in a WC ball mill. For the analyses, dried rock powder of 0.4 g was used. The mixture of sample and flux (lithium tetraborate) was made into glass bead. The sample-flux ratio was 1:10. Major element analyses were carried out by Prof. Aramaki and Fujii with the Rigaku System 3080ES XRF of the Earthquake Research Institute, University of Tokyo. The sample of about 5 g was made into the pressed pellet with a plastic ring for analyze of trace elements. Analyses for Rb, Sr, Ba, Y, Zr, Nb, Ce, Sm, and Th of about 100 samples have been determined with the same XRF. JB-1 and/or JB-2 (rock reference samples from Geological Survey of Japan) were repeatedly analyzed with unknown samples in order to maintain the reliability of the analyses.

VERTICAL VARIATION OF THE SILLS

Various number of specimens were selected for understanding chemical properties and variation in each sill. All oxide data have been recalculated to 100% on a volatile-free basis and their values are represented in Table 1. In diagram of major element variations versus height, the ordinate is height from the lower contact in meter and the abscissa is weight percentage.

The Ls Sill

Seven specimens were selected in a vertical section of the sill which include the both upper and lower chilled marginal zones (Table 1). Fig. 3 shows major element variations versus height of the sill. This sill is uniform in chemical composition except for the upper chilled margin, although the central part shows slightly higher SiO_2 and lower MgO contents. Fig. 7 shows the major element variations versus SiO_2. The points are concentrated at almost one point compared with those of Second Sill. Furthermore, they plot out of variation trends of the first and Second Sills.

The initial rock composition of the Ls Sill differ from those of other sills. The composition of the lower chilled margin is assumed as the initial intrusive rock compositions, because the upper one suffered much alteration that the analysis would not represent the composition of the original.

The First Sill

Twenty specimens was selected in a vertical section. They include the both upper and lower chilled marginal zone, which are obtained from the sample at the road-cut toward Manduksa temple and at Sangnae-bridge respectively. The compositions of inner zone are obtained from the sample at Sangnaeri valley and from those at the cliff near the Hyojadong. The major element are plotted against

Table 1. Major element data of the meta-dolerite sills in the Sangnaeri area, Mungyong-Gun

	The Le Sill							The First Sill								
	B100a	B100b	B100c	B100d	B100e	B100f	B100g	B70	A193	A176	A194	A180	A182	A188	A302	A304
SiO_2	51.41	52.57	52.64	51.34	51.98	50.75	53.25	47.96	50.40	47.98	53.67	48.60	50.84	51.54	54.26	51.79
TiO_2	2.45	2.41	2.28	2.43	2.16	2.07	2.37	2.45	2.88	2.75	1.43	3.39	2.95	3.85	2.49	3.34
Al_2O_3	14.80	13.08	13.66	13.07	12.97	13.47	13.94	14.30	13.98	14.04	18.81	13.98	14.15	13.81	13.88	13.80
FeO*	11.87	10.88	11.35	11.91	11.94	11.76	10.67	15.54	13.87	14.83	8.79	14.22	14.58	14.41	13.18	14.21
MnO	0.12	0.18	0.16	0.19	0.19	0.17	0.17	0.24	0.20	0.24	0.17	0.18	0.20	0.29	0.25	0.29
MgO	9.41	6.25	5.96	6.20	6.89	6.95	7.06	5.40	6.67	6.54	5.21	4.86	5.57	3.64	2.79	03.11
CaO	4.73	9.14	8.79	9.58	8.82	10.29	6.74	10.26	7.66	9.07	7.86	10.30	5.89	5.94	6.13	6.77
Na_2O	4.16	3.23	2.77	3.30	3.12	3.43	4.61	3.50	3.22	3.65	3.21	3.70	4.56	4.94	5.84	05.11
K_2O	0.78	2.01	2.16	1.72	1.69	0.88	0.94	0.07	0.68	0.54	1.38	0.51	0.95	0.94	0.54	0.97
P_2O_5	0.27	0.25	0.24	0.26	0.24	0.23	0.25	0.28	0.44	0.36	0.47	0.26	0.31	0.64	0.64	0.71
Sum	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

	The First Sill											The Second Sill				
	A305	A306	A307	A308	A309	A311	A312	A165	A164	A163	A162	B761	A248	A247	B767	A246
SiO_2	52.51	53.37	49.50	50.69	52.43	51.14	51.73	47.75	50.59	48.73	49.06	47.99	46.48	46.29	47.42	49.07
TiO_2	3.07	1.82	4.31	2.44	3.83	2.82	2.79	2.70	2.85	2.56	2.81	3.52	4.30	3.37	3.78	3.60
Al_2O_3	13.39	14.25	12.51	17.21	13.66	14.34	12.81	14.96	15.01	14.30	13.95	14.90	11.83	13.00	13.61	14.16
FeO*	14.51	13.43	16.99	12.21	14.15	13.71	13.44	14.63	13.73	13.45	15.03	15.03	17.54	15.94	16.00	14.16
MnO	0.26	0.23	0.31	0.17	0.28	0.24	0.25	0.20	0.22	0.19	0.26	0.20	0.27	0.23	0.23	0.21
MgO	3.50	2.39	3.87	3.53	2.94	6.07	5.87	7.32	6.34	7.12	6.13	4.87	5.59	5.48	5.82	5.18
CaO	5.99	6.85	7.07	8.34	6.27	6.90	8.25	8.82	6.68	9.76	8.22	9.19	10.13	12.07	8.91	8.55
Na_2O	5.09	5.78	4.11	4.83	5.41	4.19	4.30	3.20	4.11	3.44	4.03	3.72	2.67	2.49	3.58	4.08
K_2O	1.29	0.66	0.91	0.20	0.49	0.21	0.21	0.13	0.15	0.18	0.18	0.16	0.62	0.59	0.15	0.76
P_2O_5	0.39	1.22	0.42	0.38	0.54	0.38	0.36	0.30	0.32	0.27	0.33	0.42	0.57	0.54	0.50	0.23
Sum	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

	The Second Sill															
	A245	A233	A230	A236	A352	A234	A232	A322	A320	A353	A349	A348	A347	A242	A213	A212
SiO_2	49.99	49.97	56.02	49.96	50.87	46.90	47.11	50.94	48.77	48.87	47.03	46.13	46.66	45.34	46.65	47.03
TiO_2	2.81	2.71	2.44	2.83	4.18	4.65	4.29	2.80	3.03	3.21	3.88	3.87	3.81	0.99	1.06	1.08
Al_2O_3	11.94	13.52	16.59	14.89	12.97	10.80	12.66	13.54	15.80	13.40	13.37	13.61	13.50	12.24	14.61	16.03
FeO*	12.30	13.73	6.38	13.25	11.85	17.76	16.95	14.88	13.26	14.71	17.80	16.72	17.29	10.08	10.42	9.33
MnO	0.19	0.20	0.17	0.17	0.26	0.25	0.23	0.24	0.15	0.25	0.24	0.21	0.25	0.19	0.19	0.19
MgO	4.43	3.74	0.86	5.83	4.52	5.50	5.45	3.58	3.98	4.74	7.21	6.81	6.69	19.81	14.89	11.98
CaO	15.25	11.73	10.25	8.08	10.07	10.70	8.61	7.53	10.33	10.70	6.64	8.63	8.03	10.05	10.08	11.64
Na_2O	2.64	3.49	5.90	4.37	4.25	2.70	3.49	3.82	3.49	2.94	3.24	3.44	3.16	0.29	1.86	2.47
K_2O	0.21	0.56	0.98	0.33	0.50	0.57	0.86	1.83	0.89	0.63	0.16	0.13	0.15	0.91	0.13	0.14
P_2O_5	0.24	0.35	0.41	0.29	0.53	0.17	0.35	0.85	0.30	0.56	0.43	0.45	0.45	0.10	0.11	0.11
Sum	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

		Minor 1 of 2nd sill			Minor 2 of 2nd sill			The Third Sill						
	A346	B90a	B90b	B90c	A356	A355	A354	A261	A262	A250	A251	A254	A252	A253
SiO_2	46.20	51.41	50.76	50.01	50.04	49.78	49.07	55.50	56.03	47.09	45.75	48.65	51.63	44.24
TiO_2	3.79	3.16	2.84	3.15	2.64	2.63	2.85	1.17	1.21	3.66	4.29	3.21	1.21	3.65
Al_2O_3	13.75	15.65	13.89	16.12	14.16	14.17	14.10	13.98	14.74	14.40	15.15	15.71	15.07	15.46
FeO*	17.52	13.94	14.56	15.46	13.52	13.80	14.70	7.54	7.44	16.47	15.86	14.56	8.95	16.58
MnO	0.25	0.13	0.15	0.13	0.18	0.18	0.18	0.13	0.15	0.19	0.20	0.26	0.13	0.22
MgO	7.06	3.95	4.83	4.32	5.64	5.68	5.40	8.29	7.26	4.92	4.65	6.03	9.94	4.99
CaO	7.46	5.06	6.78	4.23	9.69	9.59	7.80	6.27	7.40	9.42	9.66	6.55	6.58	11.09
Na_2O	2.91	5.43	4.31	5.30	3.50	3.40	3.52	4.01	3.51	2.89	2.84	3.75	2.78	2.40
K_2O	0.61	0.86	1.51	0.89	0.31	0.43	2.01	2.74	1.89	0.66	0.65	0.56	3.32	0.60
P_2O_5	0.45	0.41	0.37	0.39	0.32	0.34	0.37	0.37	0.37	0.30	0.95	0.72	0.39	0.77
Sum	100	100	100	100	100	100	100		100	100	100	100	100	100

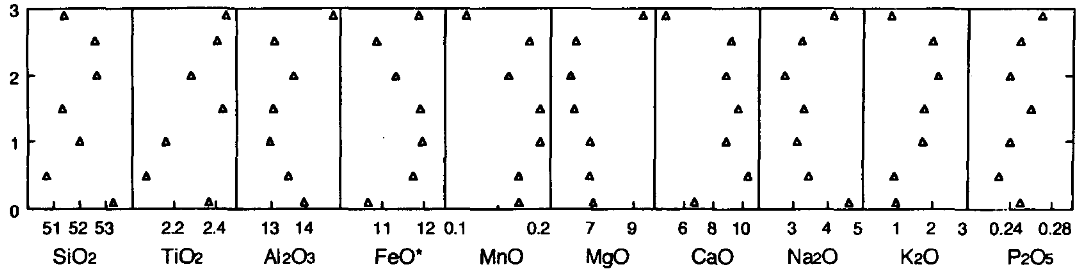

Fig. 3. Major elements variation with height of the Ls Sill.

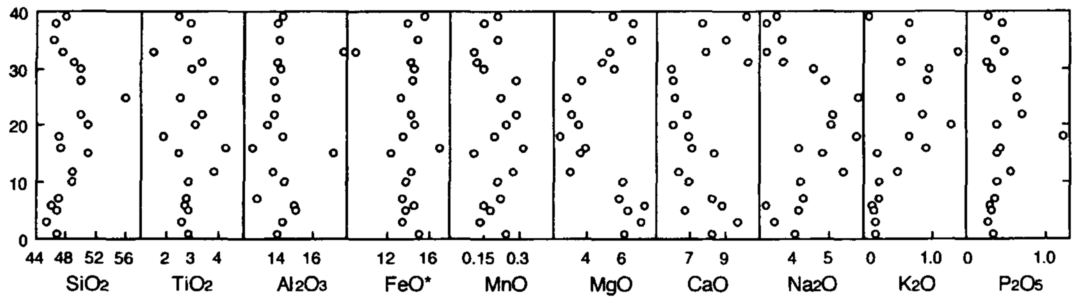

Fig. 4. Major elements variation with height of the First Sill.

height in Fig. 4. In general, Variations of composition are larger than those of the Ls Sill. The higher SiO_2, Na_2O and K_2O contents of the central zone are accompanied by a sympathetic depletion in MgO and CaO. TiO_2, Al_2O_3. FeO* shows little systematic variation. Such chemical variation suggests that some magmatic differentiation occurred in situ after the emplacement. The FeO*/MgO ratio ranges from 1.69 to 5.62.

Fig. 7 shows the SiO_2 versus oxide variation of rocks in the First Sill. With increasing SiO_2, Al_2O_3, Na_2O and P_2O_5 increase and FeO*, MgO and TiO_2 decrease, although CaO and K_2O contents are dispersed. Their compositional trends resemble those of the Second Sill.

One minor sill in the First Sill is observed at 15 meters from the lower contact in the Hyojadong valley. Specimen A282 is selected for representing composition of the minor sill, because it is the most fresh rock among collected specimens.

The Second Sill

Twenty-six specimens were selected in a vertical section. The compositions of the lower chilled marginal zones and the lower part of sill are obtained from the sample at the Sangnaeri valley. The cumulated rocks (sample A212, A213 and A242) in lower part of sill are obtained from samples at the road-cut toward Manduksa temple. The compositions of very coarse-grained rocks are obtained around the cliff at point about 2 km north of Sangnaeri town. The compositions of the upper part and the upper chilled marginal zones are obtained from the sample at the valley toward Manduksa temple. The specimen A230 is one of patches.

Table 1 shows the chemical compositions of the 28 selected samples. The chemical ranges of all compositions are the largest among the sills. Nine major oxide compositions are plotted against height in Fig. 5. The distinct features are as follows: the first is succesive chemical variation, increase or decrease, toward the very coarse-grained rock zone. The second is complicated variation in very coarse-grained zone, the zone of conspicuous heterogeneity. Rock facies changes in the scale of several tens of centimeters to several meters in this zone. The third is large compositional fluctuation in most zones. The cumulate zone is enriched especially in MgO and depleted in SiO_2, FeO* and TiO_2 relative to the chilled zone, and Al_2O_3, CaO, K_2O and P_2O_5 show little difference.

In Fig. 7, the Second Sill shows that with in-

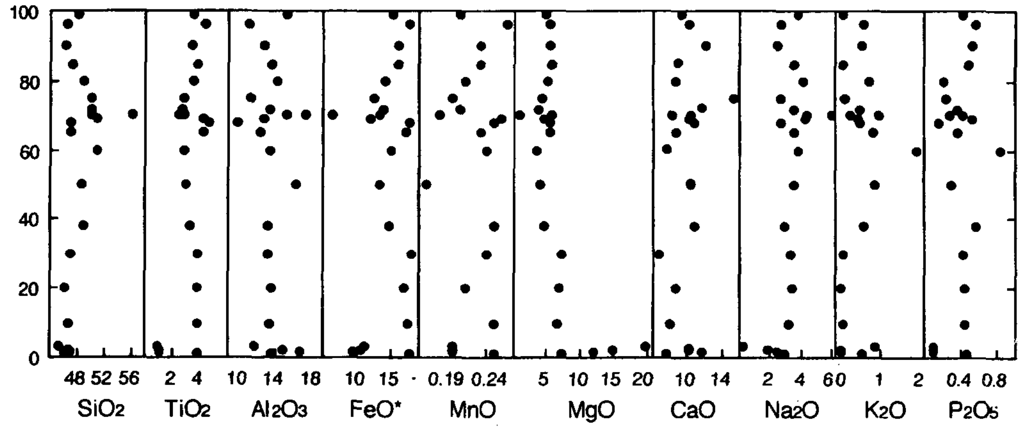

Fig. 5. Major elements variation with height of the Second Sill.

creasing the SiO_2, Na_2O and P_2O_5 increase and FeO*, MgO and TiO_2 decrease, although Al_2O_3, CaO and K_2O contents are dispersed. Three specimens of cumulate zone does not fall on smooth curves of variation diagram in $TiOa_2$, FeO* and MgO, especially. As a whole, their compositional trends overlap those of the First Sill. The compositions of specimen A230, one of the patches, shows depletion in TiO_2, FeO*, MgO and P_2Oa_5 and enrichment in SiO_2, Al_2O_3, Na_2O and K_2O. These compositional variations agree well with changes of grain size. Such chemical variation is in accord with differentiation of magma as described later.

Two minor sills are emplaced in the Second Sill. Both lower and upper minor sills are exposed in Sangnaeri valley. They are 3 meters and 30 centimeters in thickness. Three specimens are obtained from the sills and their chemical compositions are shown in Table 3.

The Third Sill

The Third Sill can be divided to two main sills and two independent minor minor sills. As shown in the schematic columnar section (Fig. 2), the main bottom sill consists of fine-grained rocks and its thickness is about 5 meters. It is difficult to regard this part as chilled marginal zone of single sill because it is too thick. Furthermore, it is impossible that one's chemical composition lead to another by fractional crystallization or mineral accumulation. Five specimens were selected in a vertical section around temple of the Manduksa and at valley about 500 m northwest of Hangog town. The two samples (A261, A262) were obtained to represent of the main bottom sill. The rest (A250, A251 and A254) are obtained for the main middle sill.

Table 1 shows chemical analysis of the 7 selected specimens and their oxide variations versus height are shown in Fig. 6. The chemical variation of main and minor sills of the third is relatively uniform. Their chemical compositions, however, markedly differ from each other. The main bottom sill shows enrichment in SiO_2, MgO and K_2O and depletion in FeO*, TiO_2, Al_2O_3, CaO and P_2O_5.

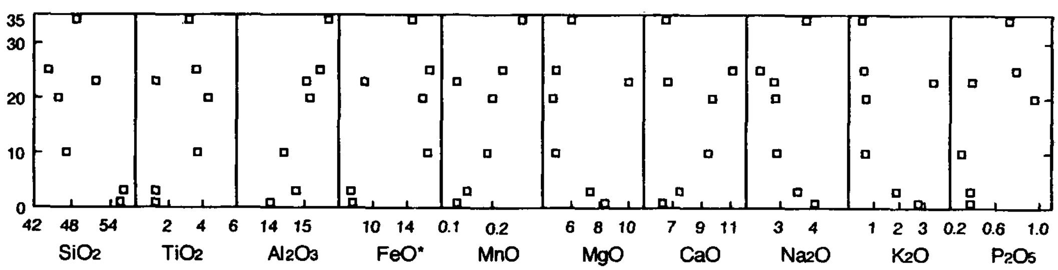

Fig. 6. Major elements variation with height of the Third Sill.

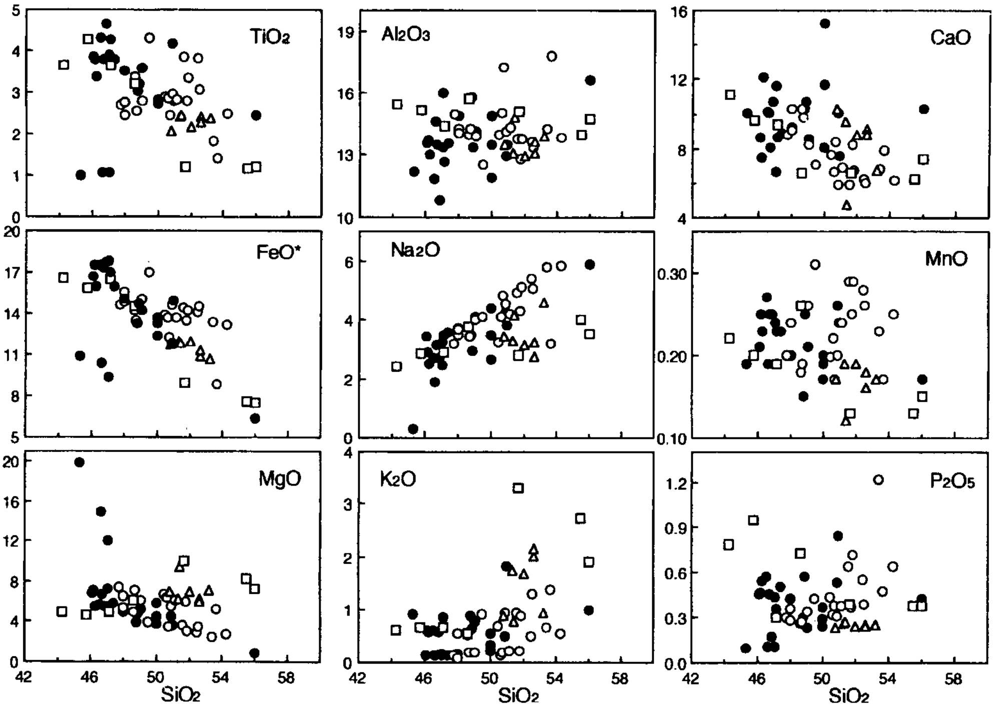

Fig. 7. SiO_2 versus oxide variation diagram for the sills in Sangnaeri area. Symbols are the same as in Fig. 3, 4, 5 and 6.

The main middle sill is characterized by depletion in SiO_2, MgO and Ka_2O and enrichment in FeO*, TiO_2, CaO and P_2O_5. In the Fig. 6, contents of SiO_2, MgO and K_2O decrease and FeO*, TiO_2, CaO and P_2O_5 increase toward middle part of the sill. Such chemical variation is difficult to explain as magmatic differentiation in a single sill after the emplacement.

Two independent minor sills are emplaced as shown in the schematic columnar section. Specimen A252 is obtained from lower minor sill and A253 is from upper minor sill. Their chemical compositions are shown in Table 4, Fig. 6 and Fig. 7. Differences of oxide contents in the two minor sills resemble those of the two main sills. These differences in the Third Sills suggest that emplacement of the silica-rich and Mg-rich magma was followed by intrusion of silica-poor and Mg-poor magma.

PETROGENETIC ENVIRONMENT

Petrogenetic environment of the Ogcheon amphibolites have been a matter of debate for a long time. The previous authors proposed that the Ogcheon amphibolites were formed in an island arc environment (Park and So, 1972) or as ophiolites

Table 2. Selected ten compositions as a intruded magma in Sangnaeri area.

selected sills	Adopted compositions	Abbr.
Ls sill	lower chilled zone (B100g)	SD1
1st sill	average chilled zones (B70, B162)	SD2
minor sill of 1st sill	single analysis (A282)	SD3
2nd sill	average chilled zones (B761, A346)	SD4
lower minor sill of 2nd sill	average of 3 analyses (A354, A355, A356)	SD5
upper minor sill of 2nd sill	average of 3 analyses (B90-a, b, c)	SD6
bottom of 3rd sill	average of 2 analyses (A261, A262)	SD7
middle of 3rd sill	average of 3 analyses (A250, A251, A254)	SD8
lower minor sill of 3rd sill	single analysis (A253)	SD9
upper minor sill of 3rd sill	single analysis (A253)	SD10

occurring along an ancient geosuture line (So and Kim, 1975). The amphibolite precursors were the products of magmatism associated with intra-continental rift-related environments (Cluzel and Cadet, 1989; Kwon and Lan, 1991; Cluzel, 1992; Kwon and Lee, 1992 and Lee and Chang, 1996).

Taking occurrence and chemical properties of amphibolites into consideration, we selected ten rock composition which may approximate those of intruding initial magma. Table 2 shows list of ten amphibolites with abbreviations. Major and trace element abundances of the amphibolites are listed in Table 3.

Fig. 8 shows the SiO_2 versus major oxide diagram of the representative 10 rocks in the Mungyong area. FeO*, TiO_2, CaO and P_2O_5 contents decrease, and MgO and K_2O increase with an increase of SiO_2. These compositional variations can not be explained by fractionation crystallization of single magma as have been shown in Second Sill. Another possibility is magma mixing with felsic magma or assimilation with felsic fragments. However, these possibilities also can not explain above variations, because felsic material with high contents in MgO is not reported.

The SiO_2 content of the representative 10 compositions in the Mungyong area ranges from 44.3 wt. % to 53.3 wt. % and in the range of basaltic composition. The SiO_2 versus Na_2O+K_2O variation of the rocks in the Mungyong area is shown in Fig. 9. The boundary dividing alkaline and subalkaline fields in after Irvine and Baragar (1971) and Miyashiro (1978). Most of the rocks straddle the boundary lines. The subdivision of volcanic rocks into alkaline and subalkaline on a total alkalis versus silica diagram is inappropriate for weathered, altered or metamorposed rocks because the alkalis are likely to be mobilized. Rocks showing obvious signs of crystal fractionation should also be avoided (Rollinson, 1993). Trace element data have important implications for the nature and previous history of the source region. Ac-

Table 3. Bulk rock compositions of selected ten compositions as a intruded magma in Sangnaeri area.

	SD1	SD2	SD3	SD4	SD5	SD6	SD7	SD8	SD9	SD10
SiO_2	53.25	48.51	48.62	47.10	49.63	50.73	55.77	47.16	51.63	44.24
TiO_2	2.37	2.63	3.68	3.65	2.71	3.05	1.19	3.72	1.21	3.65
Al_2O_3	13.94	14.12	13.14	14.32	14.14	15.22	14.36	15.09	15.07	15.46
FeO*	10.67	15.28	16.54	16.28	14.01	14.65	7.49	15.63	8.95	16.58
MnO	0.17	0.25	0.26	0.22	0.18	0.14	0.14	0.22	0.13	0.22
MgO	7.06	5.76	4.97	5.97	5.57	4.37	7.78	5.20	9.94	4.99
CaO	6.74	9.24	8.66	8.32	9.03	5.36	6.84	8.54	6.58	11.09
Na_2O	4.61	3.76	3.17	3.32	3.47	5.01	3.76	3.16	2.78	2.40
K_2O	0.94	0.14	0.49	0.38	0.92	1.09	2.31	0.63	3.32	0.60
P_2O_5	0.25	0.31	0.47	0.44	0.34	0.38	0.36	0.65	0.39	0.77
Sum	100	100	100	100	100	100	100	100	100	100
Rb	17	8		18			182	63	223	52
Sr	74	365		503			578	381	675	976
Ba	214	41		168			737	200	1140	277
Y	33	30		36			22	41	22	44
Zr	166	180		221			192	263	198	274
V	376	463		496			194	402	204	277
Cr	72	122		41			702	14	575	8
Ni	49	81		43			138	42	139	43
Cu	6	99		39			8	83	12	104
Zn	100	256		140			75	132	111	137
Nb	17	20		31			16	34	16	34
La	8	21		17			2	7	13	7
Ce	26	43		58			28	29	42	30
Sc	39	39		31			20	33	21	29
Th	4	4		4			8	4	8	1

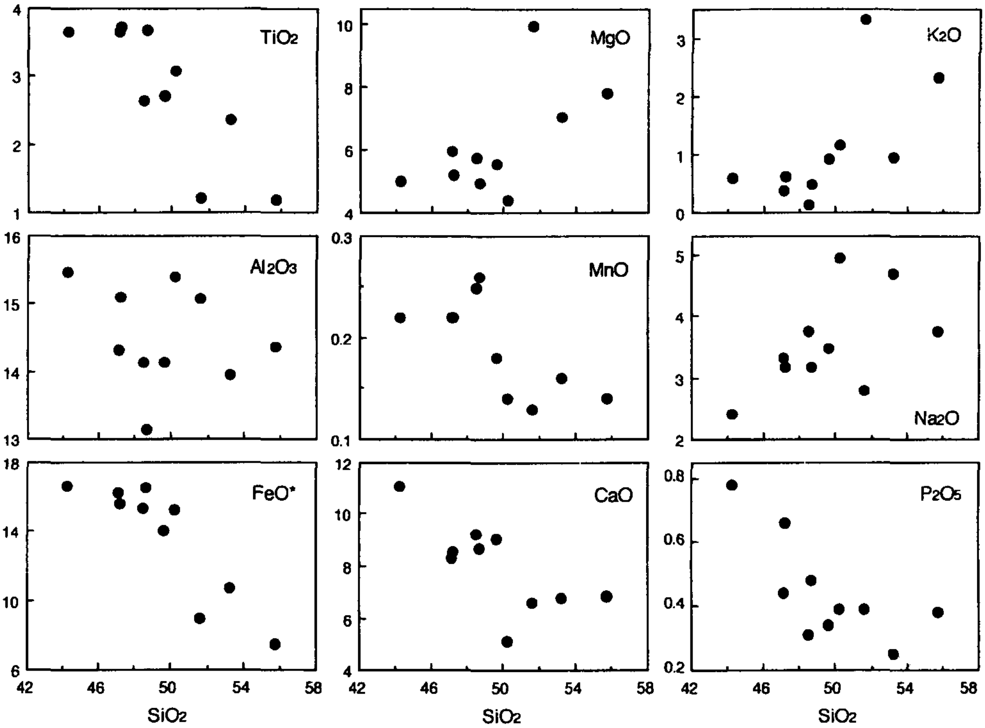

Fig. 8. SiO_2 versus oxide variation diagram for selected ten compositions of the sills in Sangnaeri area.

cording to Floyd & Winchester (1978), altered and metamorphosed volcanic suites can be characterized in terms of magma series and degree of differentiation using elements that are immobile (Ti, Zr, Y, Nb, Ce, Ga, Sc) during secondary alteration processes. The magmatic affinities are defined from discriminating diagrams using immobile elements such as Ti, V, Y, Zr, Nb and REE. On the

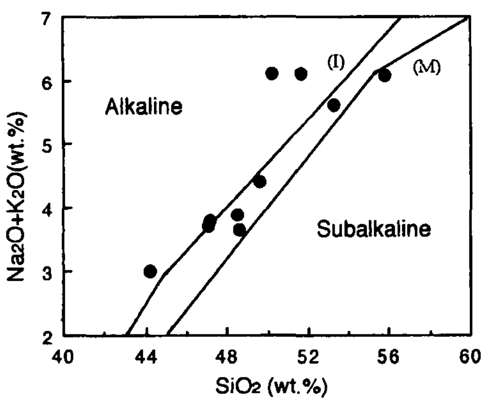

Fig. 9. Total alkali versus SiO_2 diagram for the selected ten compositions. The boundary curves (I and M) between alkaline and subalkaline are after lrvine and baragar (1971) and Miyashiro (1982), respectively.

Nb/Y versus Ti/Y diagram (pearce, 1982), the 7 representative rocks correspond with tholeiitic to transitional basalts (Fig. 10).

Fig. 11 shows incompatible element abundances in 7 representative rocks in the Mungyong area normalized to those in a typical mid-ocean ridge basalt (Pearce, 1983). In this spiderdiagram, the elements are ordered in terms of their mobility in an aqueous fluid phase and their relative compatibility. Sr, K, Rb, and Ba are

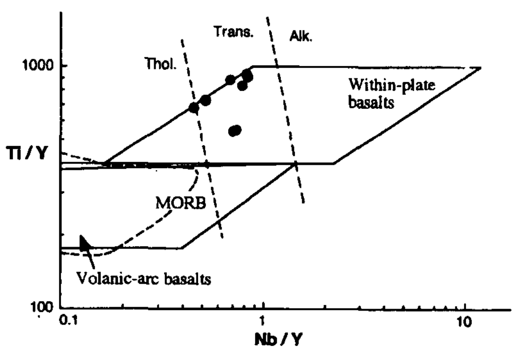

Fig. 10. Ti/Y versus Nb/Y discrimination diagram for the selected seven amphibolites in Sangnaeri area (after Pearce, 1982).

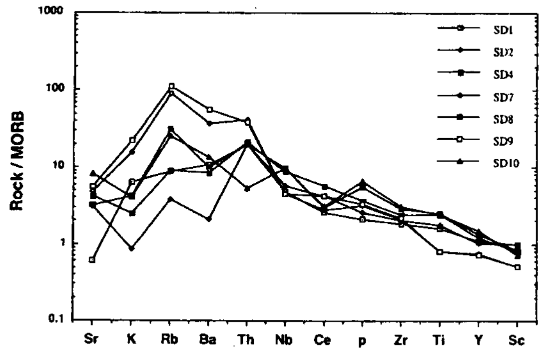

Fig. 11. MORB-normalized trace element variation diagram for the selected seven amphibolites in Sangnaeri area (after Pearce, 1983).

classed as mobile and plot at the left of the pattern, whereas elements Th to Yb is generally immobile. The elements are arranged so that the incompatibilities of both mobile and immobile elements increase from the outside to the pattern. Pearce considers that the shape of these patterns is not likely to be greatly changed by fractional crystallization or variable degrees of partial melting, and that they may consequently be used to discuss source characteristics. Normalized patterns for the 7 rocks from Mungyong area show that mobile elements (Sr to Ba) show convex upwards pattern and immobile elements (Th to Sc) show smooth decrease. This trend is similar to the pattern for within plate basalts of Pearce (1983). Willson (1989) pointed out that, in general, all basalts erupted in within-plate settings (both oceanic and continental) are enriched in most incompatible elements compared to MORB. Rocks from the Mungyong area are clearly enriched in the whole spectrum of incompatible elements relative to MORB. and the spiderdiagram patterns are similar to that of intra-continental-plate-basalt.

Nb-Zr-Y ratios of the 7 rocks in the Mungyong area plotted in Fig. 12. The boundaries which divide basaltic rocks into several areas corresponding to MORB, within-plate basalt (WPA and WPT) and Volcanic arc basalt (VAB) are also shown after Meschede (1986). All of the rocks are plotted in within-plate basalt field.

Ti/100-Zr-3Y ratios of the representative rocks in the Mungyong area plotted Fig. 13. The boundaries which divide basaltic rocks onto several areas corresponding to MORB, within-plate basalts (WPB) and Island arc tholeiites (IAT), calc-alkaline basalt (CAB) are also shown after Pearce & Cann (1973). All of the rocks are plotted in within-plate basalt (WPB) field.

In consequence, taking into account of our occurrence mode, geochemical properties, previous isotopic data (Kwon and Lan, 1991; Lee and

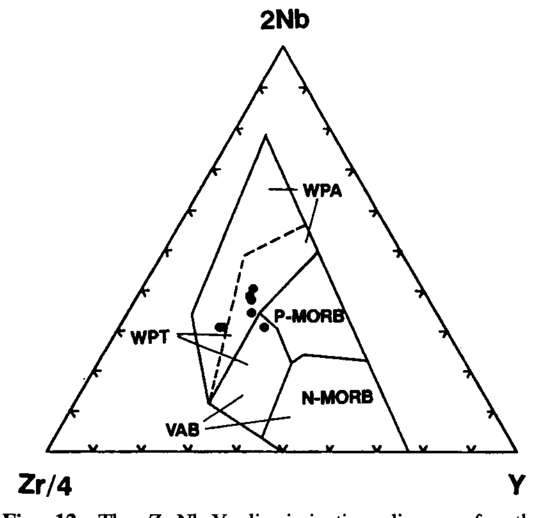

Fig. 12. The Zr-Nb-Y discrimination diagram for the selected seven amphibolites in Sangnaeri area (after Meschede, 1986).

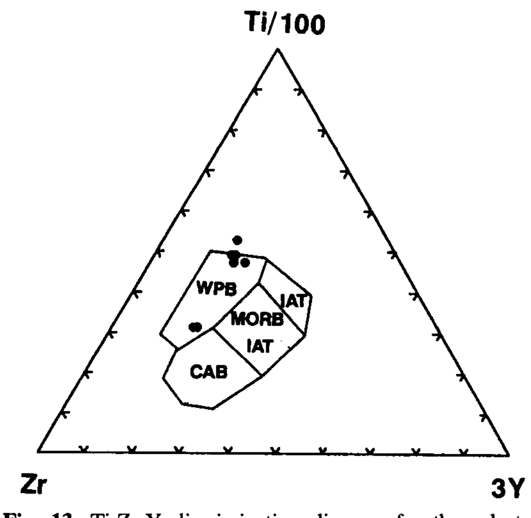

Fig. 13. Ti-Zr-Y discrimination diagram for the selected seven amphibolites in Sangnaeri area (after Pearce and Cann, 1973).

Chang, 1996), and geological view (Chough, 1981), amphibolites precursors of the study area were sill-like intrusive in an intracontinental rift environment.

CONCLUDING REMARKS

The geological and petrological studies presented in this thesis have clarified the following:

1) The amphibolites of the Sangnaeri Formation (Ogcheon Supergroup) and limestones in Chosun Supergroup on the study area are occurred as dolerite sills. The outline of each sills are roughly concordant to the general structural trend of country rocks.

2) There are four sills (the Ls Sill, the First Sill, the Second Sill and the Third Sill) so far observed in the study area. Thickness of the four sills are about 3 m, 40 m, 100 m and 40 m, respectively. The thick sills are intruded by minor sills and the Third Sill is a composite sill consisting of two main and two minor sills.

3) The thick sills are well differentiated, and include various rock facies within them. The second sill, well-differentiated sill, has cumulate zone at 2 m high from the lower contact. Grain size increases inwards from both contacts toward 2/3 part from the bottom, where patches and veins of various size occur. The rock compositions of the thick sills vary systematically with height from the base. SiO2, Na_2O, K_2O and P_2O_5 increase, whereas TiO_2, FeO, Al_2O_3 and CaO decrease toward the center.

4) We investigate in the major and trace elements variations of the ten selected rock compositions as intruding initial magma take occurrence and chemical properties into consideration. FeO*, TiO_2, CaO and P_2O_5 contents decrease, and MgO, and K_2O contents increase with an increase of SiO_2. These compositional variations can not be explaned by fractionation crystallization of single magma.

5) Geologic distribution of amphibolites, geochemical properties and previous data suggest that amphibolites precursors (basaltic magma) of the study area were intrusive as sill-like in an intracontinental rift environment.

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