Jour. Petrol. Soc. Korea
Vol. 4, No. 2, p. 153~167, 1995

Geochronology and Cooling history of the Mesozoic Granite Plutons in the Central Part of the Ogcheon Fold Belt, South Korea

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ABSTRACT : Emplacement ages for the granite plutons of the Jurassic and the Cretaceous times in the central Ogcheon Fold Belt were determined by Rb-Sr whole rock and mineral isochron methods. In addition mineral ages for the plutons were determined by K-Ar and fission track methods. In turn, thermal histories and uplifting rates of the granitic bodies are elucidated from the isotopic ages. The Jecheon(~203 Ma) and Mungyeong(at least~200 Ma) granites of the Jurassic and the Muamsa, Wolagsan and Daeyasan granites(~110 Ma) of the Cretaceous show high strontium initial ratios [$(^{87}Sr/^{86}Sr)_i>0.7100$], suggesting that the granitic magmas have been generated by partial melting of crustal materials (S-type), or by mixing of mantle and crustal materials. Only mineral ages of the Sogrisan and Hyeongjebong granites (~90 Ma) were determined by K-Ar method, and petrogenesis of them were not defined yet. The two Jurassic granite plutons were cooled rapidly down to 300℃, right after the plutons were slowly cooled down since then, due to their deep emplacement. During the Middle Cretaceous period, the Jurassic Mungyeong granitic pluton was intruded and thermally affected much by the surrounding Wolagsan and Daeyasan granites. Accordingly the Rb-Sr mineral age, K-Ar hornblende and biotite ages of the Mungyeong granite appear to be reduced or reset due to the thermal effects above their blocking temperatures. All the Cretaceous granites have been cooled much more simply and rapidly down than the Jurassic ones below 300℃, owing to their shallow emplacement.

Key Words : Ogcheon Fold Belt, Geothermal history, Wolagsan Granites, Sogrisan Granites, Isotopic ages, Retention temperature.

INTRODUCTION

There are two periods of granitoid intrusion in the central part of the Ogcheon fold belt in South Korea (Fig. 1 and Fig. 2). Older granitoids of Jurassic age is distributed as a large batholith (A) around the Jecheon city, and as a small pluton (B) near the Mungyeong area. Younger ones of Cretaceous age are the Muamsa (C), the Wolagsan (D), the Daeyasan (E), the Sogrisan (F) and the Hyeongjebong (G) granites.

These granitoids intruded into the Precambrian basements and the Paleozoic to Triassic sedimentary rocks in Early Jurassic, and Middle to Late Cretaceous times, respectively (Jin *et al*, 1992a; 1992b; Jin *et al.*, 1992c ; Kwon and Jin, 1992).

In fact, so called Wolagsan and Sogrisan granite plutons had been so far known to the geologists as a batholith of Cretaceous age, respectively. A small number of skarn type Fe-Pb-Zn-Mo deposits have been reported so far around the northeastern part of the Jurassic Jecheon granites, and many base metal (Cu-Pb-Zn-Mo-W-Fe-Bi etc.) and fluorite deposits associated with skarns or wall rock alteration have been reported in the area between the Wolagsan and Muamsa granites (Reedman *et al.*, 1973; Park *et al.*, 1988; Park and Jin, in print). Accordingly the ore mineralization also have been reported to be related to the Jecheon, Muamsa and Wolagsan granites with a little geological criteria, respectively.

Recently the Wolagsan and Sogrisan granite plutons have been defined to be composite plutons with different age, respectively (Jin *et al.*, 1992c; Jin *et al.*, 1993).

Now I would like to elucidate the emplacement age and cooling histories of the granitoids of each period, and discuss the tectonic implications in the central part of the Ogcheon fold belt, on the basis of isotopic age data of the rocks.

TECTONIC SETTING AND GENERAL GEOLOGY

The Korean peninsula forms a part of the China-Korea-Siberia Platform which is composed of the Precambrian metamorphic rocks. The southern half of the peninsula consists of northeast-southwest trending five tectonic units ; Precambrain Gyeonggi massif, Paleozoic Ogcheon fold belt, Precambrian Sobaegsan (Ryeongnam) massif, Cretaceous Gyeongsang Basin and Tertiary Pohang Basin (Fig. 1).

In the Ogcheon fold belt there are Cambro-Ordovician none-metamorphosed and metamor-

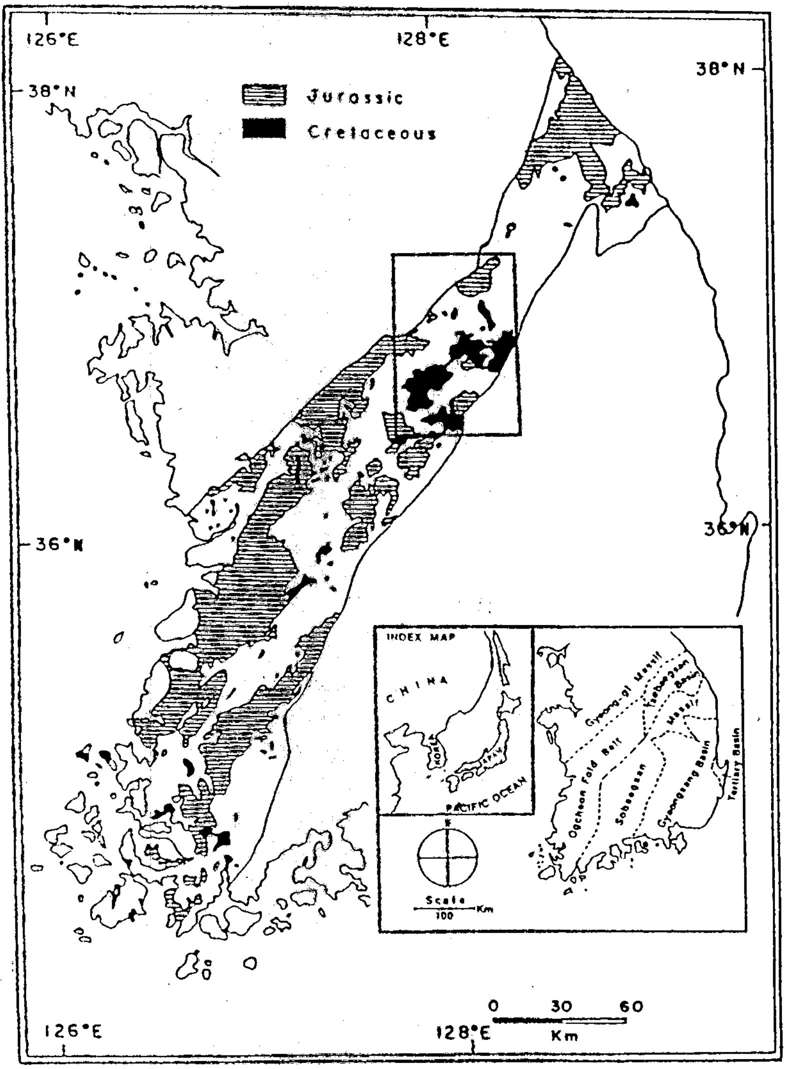

Fig. 1. Distribution of the Jurassic and the Cretaceous granitoids in the Ogcheon Fold Belt (KIGAM, 1975); the rectangular is the study area.

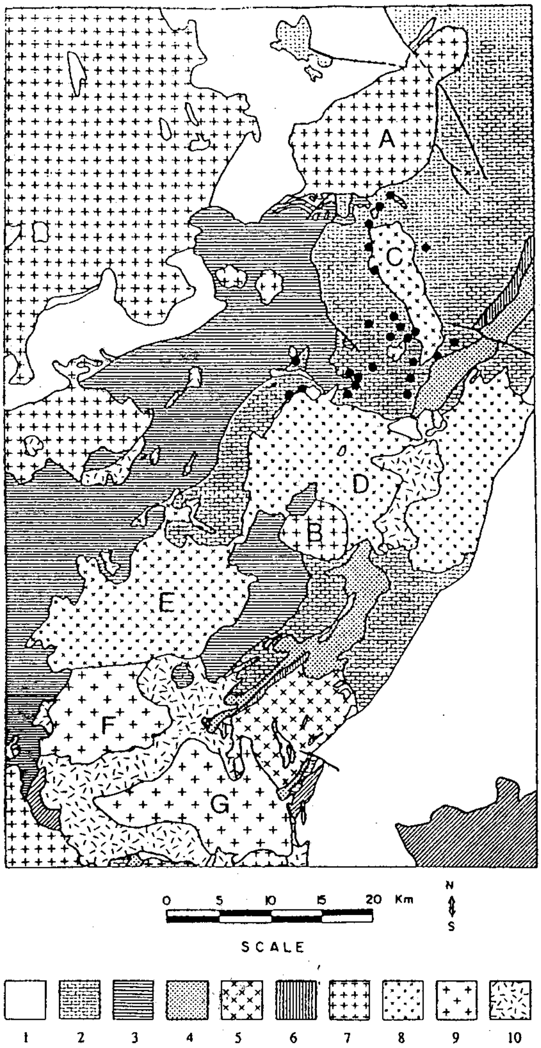

Fig. 2. Map showing the general geology of the study area and its surrounding area (after Geological and Mineral Institute of Korea, 1973). Fulled circles(●) indicate ore deposits (from Reedman *et al.*, 1973)
1; Precambrian, 2; Joseon Supergroup, 3; Ogcheon Supergroup, 4; Pyeongan Supergroup, 5; Jeomchon Granites, 6; Daedong Supergroup, 7; Early Jurassic Granites, 8; Middle Cretaceous Granites, 9; Middle to Late Cretaceous Granites, 10; Late Cretaceous Volcanics. A=Jecheon Graites, B=Mungyeong Granites, C=Muamsa Granites, D=Wolagsan Granites, E=Daeyasan Granites, F=Sogrisan Granites, G=Hyeongjebong Granites.

phosed sedimentary rocks overlying the Precambrian basement which comprises polymetamorphosed gneisses and schists; the former is mostly calcareous of the Joseon Supergroup distributed in the northeastern part of the belt, and the latter is mostly agillaceous of the Ogcheon Supergroup with intercalated calcareous beds in the central belt.

Table 1. Geologic sequences of the study area.

Middle to Late Cretaceous	Hyeongjebong Granites Sogrisan Granites Granite porphyry or Volcanic rocks
- *Extrusive and Intrusive* -	
Middle Cretaceous	Daeyasan Granites Wolagsan Granites
- *Intrusive* -	
Late Triassic to Early Jurassic	Mungyeong Granites Jecheon Granites
- *Intrusive* -	
Late Triassic to Early Jurassic	Daedong Supergroup
- *Unconformity* -	
Permian	Jeomchon Granites
- *Intrusive* -	
Carbono-Permian	Pyeongan Supergroup
- *Unconformity* -	
Cambro-Ordovician	Ogcheon Supergroup Joseon Supergroup
- *Unconformity* -	
Precambrian	Metamorphic rocks

Following the Cambro-Ordovician sedimentation, paralic marine sedimentation recommenced in Carboniferous times grading up into limnic sediments with coal measures of Permian age and thick non-marine sequences extending into the Triassic together these constitute the Pyeongan Supergroup.

The Daedong Supergroup deposited in NE striking small basins developed along the Precambrian Massifs mentioned before, is unconformably overlying the two supergroups in late Triassic to early Jurassic times. Following on the sedimentation of the Daedong Supergroup, the Jurassic granites including the Jecheon granites and Mungyeong granites, etc broadly intruded into the belt.

After a long hitus of the post-plutonism of late Triassic to early Jurassic age, big piles of fluviolacustrine sediments were deposited in the smaller basins developed along the margins of the Ogcheon fold belt and the two Precambrian Massifs in the early to middle Cretaceous. For example, some of the sediments is composed of the granite-washes deposited in situ.

In the middle Cretaceous, the central part of the Ogcheon fold belt was intruded by the Muamsa-Wolagsan-Daeyasan granitoids as large batholiths or small pluton. Following the Middle Cretaceous plutonism, intermediate to felsic magmatism was successively extended to the southwest of the belt (Fig. 2). Geologic sequences of the study area are the same as following Table 1.

PETROGRAPHY

Jurassic Granitoids (Jecheon and Mungyeong granites)

The Jecheon granite occurs as an oval shape like a small batholith with an area of about 30× 15 km^2 (Fig. 2). The granite is equigranular, medium to coarse grained hornblende-biotite granodiorite in margin, but inequgranular megacrystic, coarse grained biotite granite in the central part of the pluton. The megacrysts are all microcline ranging from 1×2×3 cm^3 up to 2×4×9 cm^3 in size, in which fine grained biotite inclusios are commonly aligned along the zonal cleavages. The granite is mostly composed of quartz, microcline, plagioclase, biotite, and little amount of hornblende. The accessory minerals are sphene, zircon, apatite and some secondary minerals. Some of major rock forming minerals are altered to secondary minerals such as sericite, chlorite and epidote (Kim, 1979; Jin *et al.*, 1992a). Around the pluton the Paleozoic calcareous sedimentary rocks are thermally metamorphosed to crystalline limestone in some areas. There are skarn-type Mo and Pb-Zn-Fe deposits near the Jecheon plutons, of which mineralization age have been still controversial (Fig. 2).

The Mungyeong granite(B in Fig. 2), which previously belonged to the Wolagsan pluton (Lee, 1971; Lee, 1978; Ishihara *et al.*, 1981; Iiyama and Fonteilles, 1981; Lee, 1981; Sato *et al.*, 1981; Shimazaki *et al.*, 1981; Tsusue *et al.*, 1981; Kim and Shin, 1990), occurs as an oval shape like a small stock with an area of about 7×8 km^2. This granite is equigranular, and medium to coarse grained in textutre, and the rock phases range from hornblende-biotite granodiorite through biotite granodiorite to biotite granite. The major rock forming minerals are quartz, alkali-feldspar (mostly pinkish microcline), plagioclase, biotite and hornblende, and other accessory minerals such as sphene, zircon and apatite. In particular some sheared fractures directing N75°E can be seen in the central part of the pluton (Jin *et al.*, 1993). The Mungyeong granite was intruded and almost completely surrounded by the Wolagsan and Daeyasan granites in Middle Cretaceous times (Fig. 2). Therefore the small pluton must have been so much affected by a large amount of heat from the large intrusive mass, and the mafic silicates of it are generally altered to chlorite, sericite and epidote (Jin *et al.*, 1992b; 1992c).

Cretaceous Granitoids

The Cretaceous granites can be divided into two groups. One is the Muamsa, Wolagsan and Daeyasan granite which appear to be cogenetic, based on their petrological and geochemical characteristics including radiogenic elements content and age data (Jin *et al.*, 1992b; 1992c). The other is the Sogrisan and Hyeongjebong granites, which also appear to be cogenetic, in terms of their petrological and geochemical characteristics such as occurrences, mineral compositions and textures (Jin *et al.*, 1992b; 1992c).

Middle Cretaceous Granitoids

The former group of middle Cretaceous age occurs as a small batholith or stock. The granites are equigranular, fine to medium grained biotite granite in margin and medium to coarse grained biotite granites in the inner part of the plutons. In particular the central part of the Wolagsan granites is unconformably overlain by the volcanic complex consisting of dacitic to rhyolitic tuff, or intruded by late Cretaceous hypabyssal rocks. In some part of the plutons, miarolitic cavities with large amethysts and micas are developed.

The granites are mostly composed of quartz, alkali-feldspar (mostly perthites), plagioclase and biotite (Yun, 1991; Jin *et al.*, 1992c). The accessory minerals are zircon, apatite and opaque minerals including sulfides, paticularly in the Muamsa granites. In the contact zones between Daeyasan granites and Sogrisan granites, most minerals are altered to secondary minerals such as kaolinite, sericite, chlorite and epidote. Around the pluton the Paleozoic calcareous sedimentary rocks are thermally metamorphosed to crystalline limestone in some areas. There are several skarn-type base metal (Cu-Pb-Zn-W-Fe) and fluorites deposits recognized in the area between the Muamsa and the Wolagsan granites (Reedman *et al.*, 1973; Park *et al.*, 1988) (Fig. 2).

Middle to late Cretaceous Granitoids

The latter group of middle to late Cretaceous age occurs as a small batholith or stock associated with volcanic equivalents of the late Cretaceous age. The granites are equigranular, and gradually change from medium grained reddish hornblende-biotite granite in margin to coarse grained reddish and leucocratic granites in inner part. The granites show a typical miarolitic texture with chlorite and quartz, and the mafic silicates are partly altered to chlorite. The relationship between the granites and volcanic equivalents are not clear yet. The granites are mostly composed of quartz, alkali-feldspar (mostly perthites), plagioclase and biotite. The accessory minerals are zircon and opaque minerals. No metal or non-metal deposit is so far reported yet around the Sogrisan and Hyeongjebong granites.

EXPERIMENTAL WORKS

Accordingly the isotopic ages of rocks or minerals are absolutely dependent on thermal or hydrothermal equilibrium system of the isotopes, not on the time of their emplacement or formation. Therefore many age data appear to be younger than those geologists expected in fields. Because the measured isotopic ages are the time elapsed since the rocks or minerals were cooled below the blocking temperature. This fact makes geologists contemplating in interpreting the geology of an area, and compells them to apply various method of dating so far developed.

In order to reveal exact thermal history on the plutons, Rb-Sr, K-Ar and fission track dating which have been done in KIGAM were applied. The Mungyeong granitic pluton of Jurassic age and the five granitic plutons of the Cretaceous were selected respectively, and sampled, crushed and pulverized for mineral separation and K-Ar and fission track dating. Some of them were ground to powder for Rb-Sr whole rock analysis.

Rb-Sr Dating

Sr isotope ratios were determined using a Varian MAT Th-5 mass spectrometer, with Rb and Sr concentrations measured by isotope di-

Table 2. Retention temperatures for whole-rock and minerals (Dodson, 1973; Wagner *et al.*, 1971; Nishimura and Mogi, 1986). (in ℃)

Materials	Rb-Sr	K-Ar	Fission-track
Whole rock	720±100	500±100	
Hornblende		500±75	
Muscovite	500±50	350±50	
Orthoclase	360±40	150±30	
Microcline	340±40	150±30	
Biotite	310±40	270±40	
Plagioclase		260(?)→400(?)	
Sphene			290±40
Zircon			200±30
Apatite			110±15

lution method. Experimental procedures have been described by Choo (1983). The ages and initial ratios were calculated by least squares regression (Wendt, 1976), using=1.419×10^{-11}/y for the decay constant of ^{87}Rb (Steiger and Jäger, 1977). Rock standard NBS 607 and GSP-1 were also measured for this study, all the analytical uncertainty (measured by 2 mean) for the Sr isotopic ratio for all samples was kept within 0.5% of the measured ratio. To correct any machine bias due to this, the Sr isotopic standard NBS 987 was measured and all measured

^{87}Sr/^{86}Sr ratios were normalized to a value of 0.71014 for NBS 987.

K-Ar Dating

Isotopic ratios of mixed argon were measured using a NUCLIDE mass spectrometer ($6''$-60° first order focussing sector type) employing an enriched 38Ar spike calibrated against both known air volumes and the standard minerals B-4B and MMHB-1 (Kim, 1986). Argon was purified using hot Zr-Al gettering and potassium concentrations were analyzed by flame photometry using IL 550 AA-AE spectrophotometer. The uncertainties associated with the determination were estimated to be 1-2% for the potassium analysis, 0.5% for ^{40}Ar/^{38}Ar, and 2% for ^{36}Ar/^{38}Ar ratios, 1% for spike calibration. The ^{40}Ar/^{40}K ratio can be determined with an accuracy of better than 2%. The minimum amount of argon which can be detected by the present apparatus is about 1×10^{-14} mole. Reproducibility of the method as studied on the sample is within 5% in most case.

RESULTS

Jurassic Granitoids

Rb-Sr dating

Three whole rock samples and seven rock forming minerals from the Jecheon Granites were selected and isotopically analyzed for Rb-Sr dating (Fig. 3). The Rb-Sr isotopic data made an isochron of 202.7±1.9 Ma with an initial ^{87}Sr/^{86}Sr ratio of 0.7140±0.0002 and mean squares of weighted deviation (MSWD) is 5.11 (Jin et al, 1992).

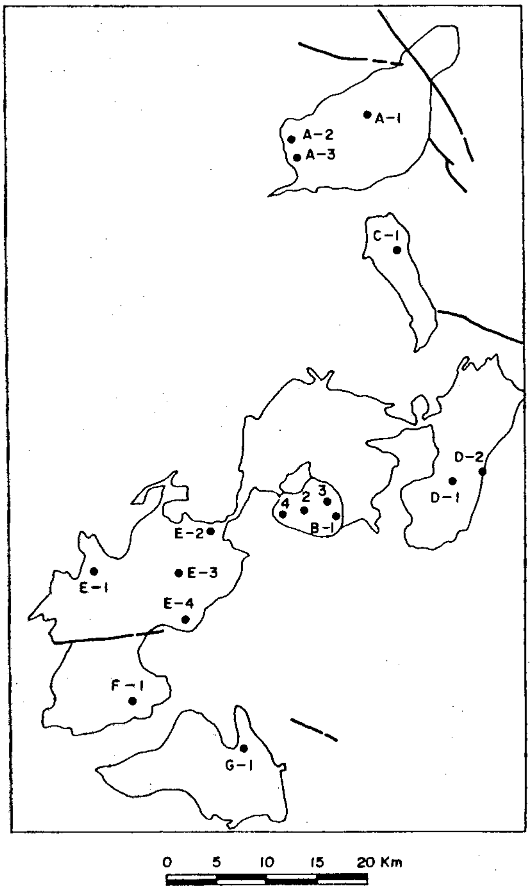

Fig. 3. Location map of the rock samples for age determination.

One whole rock and two mineral samples from the Mungyeong granites were also selected and isotopically analyzed for Rb-Sr dating (Fig. 3 and Table 3). The results make an isochron age of 119.8±3.54 Ma with an initial ^{87}Sr/^{86}Sr ratio of 0.7129±0.0006 and MSWD is 0.39 (Fig. 4). This isochron age is, of course, not emplacement age but much younger than that the geologist expected as in other Jurassic plutons such as Jecheon and Chuncheon granites (Jin *et al*, 1992a; Jin *et al.*, 1993b). It suggests that there should have been some geological ep-

Table 3. Rb-Sr isotopical analysis data of the whole rock and minerals from the Mungyeong Granites of the Early Jurassic in the central part of the Ogcheon Fold Belt

Sample No.	Nat'l Grid (x/y)	Material	Sr (ppm)	Rb (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
B-1	130.9/361.5	Whole rock	63.60	26.57	0.413	0.7137
			9	4	6	7
		Biotite	2.46	124	49.80	0.7977
			2	4	1.20	13
		Plagioclase	91.00	14.19	0.154	0.7130
			2	8	1	10

Analyst: Dr. Seung Hwan CHOO in KIGAM

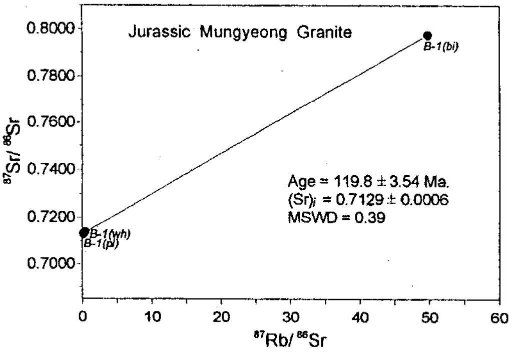

Fig. 4. A Rb-Sr isochron for the Mungyeong granites obtained from one whole rocks and minerals (one plagioclase and one biotite).

isodes or effects concerning the reset of age and reequilibrium of isotopic system.

K-Ar dating

Seven and three mineral concentrates from the Jecheon pluton(Jin *et al.*, 1992a) and Mungyeong pluton were isotopically analyzed for K-Ar dating, respectively (Table 4). The age data between the same sort of minerals from a pluton are almost consistent in error limit. Unexpectedly K-Ar plagioclase ages (about 195-207 Ma) for the Jecheon pluton are almost consitent with Rb-Sr whole rock and biotite isochron age (about 203 Ma) in comparison with its blocking temerature of about 260℃ (in Table 2). In fact concerning the retention temperature, the K-Ar age for rock forming minerals is not perfectly defined, particularly for biotite and plagioclase, and still in controversial (Dalymple and Lanphere, 1969; Dodson, 1973; Harrison *et al.*, 1979; Hunziker, 1979; Faure, 1989). But all of the K-Ar mineral age data except plagioclase are consistent with those of other laboratories' in Table 4 (Shibata *et al.*, 1983). For example, the biotite ages of the Jecheon pluton is very consistent with the previous K-Ar age data produced by other laboratory's in error limit (Table 4). Accordingly all of the K-Ar mineral age data produced by KIGAM are proved to be accurate in error limit, and the K-Ar plagioclase age can be credible in accuracy.

Concerning the retention temperature for K-Ar plagioclase age, it should be over 400℃ on the cooling curve for the pluton, in terms of our own data mentioned before. Therefore I will apply this to the interpretation of thermal history for that pluton. The K-Ar microcline ages for the Jecheon pluton are much younger than any other K-Ar mineral ages owing to its low retention temperature as shown in Table 2.

In particular for the Mungyeong pluton of Jurassic age, the K-Ar hornblende and biotite ages are much older and younger than Rb-Sr whole rock and biotite age, respectively. Nevertheless two biotite samples give almost same age of 104.3±2.0 Ma and 105.0±1.7 Ma, respectively. That suggests that there must be some big geological episodes or later hydrothermal effects causing the isotopic disturbance or reset of the Mungyeong granitoid around the period of 110±5Ma. Accordingly the K-Ar hornblende age is definitely reduced age, and the Rb-Sr age of 119.8±3.54 Ma is also disturbed or reset age.

Fission Track Dating

Two sphenes, two apatites and one zircon ages were reported from the Jecheon pluton

Table 4. K-Ar age data of minerals from the Jecheon and Mungyeong Granites of the Early Jurassic in the central part of the Ogcheon Fold Belt

Sample No.	Nat'l Grid (x/y)	Mineral dated	K (%)	^{40}Ar rad ($\times 10^{-9}$ mol/g)	^{40}Ar rad (%)	Age (Ma)
Jecheon Granites (Jin *et al.*, 1992)						
A-2	117.6/402.0	Plagoclase	1.38	0.493	84.78	195.0±1.3
A-3	118.4/399.7	Plagoclase	1.44	0.547	76.74	206.8±1.6
A-1	128.3/405.5	Biotite	5.12	1.647	96.95	176.7±2.5
A-2	117.6/402.0	Biotite	6.76	2.305	96.69	186.5±5.4
A-3	118.4/399.7	Biotite	5.45	1.862	95.28	187.0±9.2
A-2	117.6/402.0	Microcline	9.55	1.754	86.40	102.9±4.6
A-3	118.4/399.7	Microcline	9.47	2.161	92.42	127.0±5.5
Previous K-Ar age data for the Jecheon Granites (Shibata *et al.*, 1983)						
1	129.2/398.2	Biotite	6.86	41.6	92.40	179±6
2	135.0/412.0	Biotite	8.31	47.4	93.50	169±5
Mungyeong Granites						
B-2	132.0/366.5	Hornblende	0.97	0.2490	41.28	142.3±2.2
B-1	130.9/361.5	Biotite	6.69	1.246	89.32	104.3±2.0
B-2	132.0/366.5	Biotite	4.21	0.789	92.06	105.0±1.7

Analyst: Mr. Seong-Jae KIM in KIGAM

(Jin *et al.*, 1992). Two sphene F.T. ages (142.8±8.2 Ma and 138.6±7.8 Ma) are almost consistent with each other in error limit, as in K-Ar biotite ages of the samples. Two apatite ages (44.2±2.6 and 54.2±2.8) show a little difference each other, suggesting that they might have locally undergone different cooling histories in low temperature system (below the blocking temperature of apatite).

Middle Cretaceous Granitoids

Rb-Sr dating:

Three mineral concentrates of a rock samples from the Muamsa pluton were isotopically analyzed for Rb-Sr dating (Fig. 3). The analytical results are as follows in Table 5. The Rb-Sr isotopic data give an isochron of 109.9±2.5 Ma with an initial ^{87}Sr/^{86}Sr ratio of 0.7165±0.0002 (Fig. 5), and the MSWD(=1.23) is very low. And this Rb-Sr age is almost consistent with previous Rb-Sr whole rock and mineral age for the pluton (Table 7). Consequently the isochron age is very good in credibility.

Three mineral concentrates and a whole rock samples from the Wolagsan pluton pluton were also isotopically analyzed for Rb-Sr dating (Fig. 3 and Table 5). The results make an isochron age of 108.6±0.6 Ma with an initial ^{87}Sr/^{86}Sr ratio of 0.7151±0.0001 and MSWD (=9.28) is very big (Fig. 6). Accordingly the isochron age may be not so good in credibility. Nevertheless both of two Rb-Sr isochron ages are very consistent with each other, in comparison with previous Rb-Sr ages of them (Table 7).

K-Ar dating

Eleven mineral concentrates of seven rock samples taken from the Muamsa, Wolagsan and Daeyasan pluton were isotopically analyzed for K-Ar dating, respectively (Fig. 3 and Table 6). Most oldest age (114.8±1.7 Ma) of them is given from hornblende fraction of D-2 sample collected from the Wolagsan pluton. Although this oldest age is older a little than Rb-Sr mineral isochron age, it is similar a little to the Rb-Sr ages of the plutons, mentioned before.

And plagioclase fraction from the Wolagsan

Table 5. Rb-Sr isotopical analysis data of the minerals separated from the Muamsa and Wolagsan Granites of the Middle Cretaceous in the central part of the Ogcheon Fold Belt

Sample No.	Nat'l Grid (x/y)	Material dated	Sr (ppm)	Rb (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
		Muamsa Granites				
C-1	130.6/390.4	Feldspar	5.166	179.8	34.37	0.7637
			4	2	4	2
		Plagioclase	5.93	163.5	27.20	0.7536
			1	8	10	9
		K-feldspar	6.955	163.3	23.19	0.74615
			4	1.4	20	15
		Wolagsan Granites				
D-1	135.6/364.0	Plagioclase	21.64	12.273	0.5601	0.71635
			2	4	6	12
		K-feldspar	6.9667	117.5	16.55	0.73978
			8	2	3	10
		Biotite	3.475	123.2	35.0	0.77186
			6	8.1	2	9
		Whole rock	5.3933	66.3	12.24	0.73481
			7	1	2	18

Analyst: Dr. Seung Hwan CHOO in KIGAM

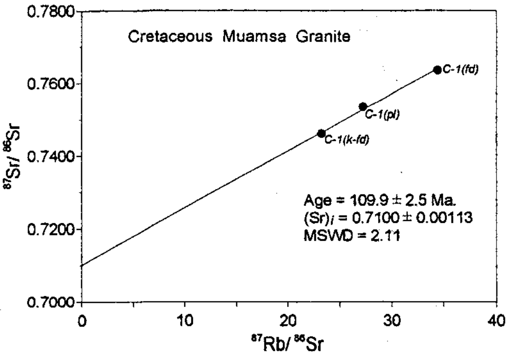

Fig. 5. A Rb-Sr isochron for the Muamsa granite obtained from minerals (plagioclase, K-feldspar and feldspar).

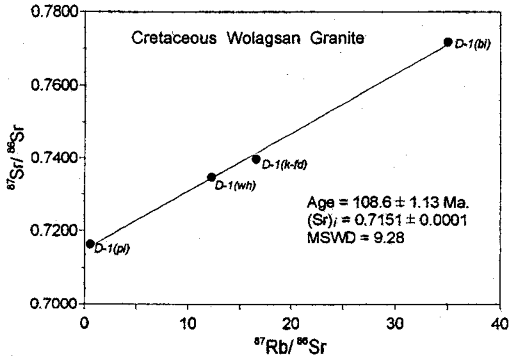

Fig. 6. A Rb-Sr isochron for the Wolagsan granite obtained from whole rock and minerals (K-feldspar and biotite).

pluton gives an age of 103.8±1.5 Ma, which is older a little than expcted in terms of its retention temperature. Five biotite ages (ranging from 86.7±4.9 Ma to 95.1±1.4 Ma) are almost consitent with each other in error limit regardless of sampling sites, except two biotites which are taken from the margin of Daeyasan pluton. These five ages are of course absolutely consistent with the previous K-Ar biotite ages (from the Muamsa and the Wolagsan plutons) (Table 7). There seems to be some geological effects controlling the reduction of K-Ar biotite ages in local scale, which is not recognized on the surface. K-feldspars ages are 76.0±1.1 Ma and 70.8±1.1 Ma for the Muamsa and Wolagsan plutons, respectively.

Middle to Late Cretaceous Granitoids

K-Ar dating:

Table 6. K-Ar mineral age data of the Muamsa, the Daeyasan and the Wolagsan Granites of the Middle Cretaceous in the central part of the Ogcheon Fold Belt

Sample No.	Nat'l Grid (x/y)	Mineral	K (%)	^{40}Ar rad ($\times 10^{-9}$ mol/g)	^{40}Ar rad (%)	Age (Ma)
			Muamsa Granites			
C-1	130.6/390.4	Biotite	7.49	1.2020	92.06	90.3±1.6
			Wolagsan Granites			
D-1	135.6/364.0	Plagioclase	0.92	0.1704	54.72	103.8±1.5
		Biotite	2.19	0.3584	91.97	92.0±4.2
		K-feldspar	8.42	1.054	82.96	70.8±1.1
D-2	139.1/365.9	Hornblende	1.22	0.2507	73.36	114.8±1.7
		Biotite	4.47	0.6888	93.46	86.7±4.9
			Daeyasan Granites			
E-1	275.8/356.2	Biotite	5.27	6.033	90.65	64.8±1.7
E-2	289.3/359.8	Biotite	4.39	5.885	88.99	75.7±1.1
E-3	285.8/353.8	Biotite	5.23	8.766	74.35	94.2±1.3
E-4	284.3/349.5	Biotite	4.78	8.089	93.37	95.1±1.4

Analyst: Mr. Seong-Jae KIM in KIGAM

Table 7. Isotopic age data so far reported for the Cretaceous Muamsa, Wolagsan and Daeyasan Granite plutons in the

Pluton name	Sample No.	Method dating	Materials dated*	Age (Ma)	Remarks	
Muamsa	C-1	Rb-Sr	WR-Pl-Kf-Bi	106.1±2.7	*Jin et al.,*	1992a
Muamsa	C-1	Rb-Sr	Fd-Pl-Kf	109.9±2.5	*Jin et al.,*	1993
Muamsa	C-1	K-Ar	Biotite	90.3±1.6	*Jin et al.,*	1992b
Muamsa		K-Ar	Biotite	87	*Kim, O. J.,*	1971
Wolagsan	D-1	Rb-Sr	Pl-Kf-Bi	105.9±0.8	*Jin et al.,*	1992a
Wolagsan	D-1	Rb-Sr	WR-Pl-Kf-Bi	108.6±0.6	*Jin et al.,*	1993
Wolagsan	D-2	K-Ar	Hornblende	114.8±1.7	*Jin et al.,*	1992b
Wolagsan	D-1	K-Ar	Kf	103.8±1.5	*Jin et al.,*	1992b
Wolagsan	D-1	K-Ar	Plagioclase	92.0±4.2	*Jin et al.,*	1992b
Wolagsan	D-1	K-Ar	Biotite	70.8±1.1	*Jin et al.,*	1992b
Wolagsan		K-Ar	Biotite	92	*Kim, O. J.,*	1971
Wolagsan		K-Ar	Biotite	91	*Seo & Choo,*	1971
Wolagsan		K-Ar	Biotite	90	*Seo & Choo,*	1971
Wolagsan		K-Ar	Biotite	90	*Seo & Choo,*	1971
Wolagsan	D-1	K-Ar	Kf	70.8±1.1	*Jin et al.,*	1992b

*WR: whole rock, Pl: plagioclase, Kf: K-feldspar, Fd: Feldspar, Bi: biotite

A hornblende and a biotite concentrates from the Sogrisan and Hyeongjebong plutons were isotopically analyzed for K-Ar dating, respectively (Fig. 3 and Table 8).

The hornblende age (89.9±1.7 Ma) from the Sogrisan pluton is older than the biotite age (83.5±1.7 Ma) from the Hyeongjebong Pluton. In comparison with previous K-Ar biotite age from the plutons, the biotite age is almost same in error limit (Table 8). Consequently the K-Ar ages of the hornblende and biotite is very credible to interpret geology in this area.

DISCUSSIONS and CONCLUSIONS

Jurassic Granitoids

Table 8. K-Ar ages of the Sogrisan and Hyeongjebong Granite plutons in the central part of the Ogcheon Fold Belt

Sample No.	Nat'l Grid (x/y)	Dated materials	K (%)	^{40}Ar rad (10~10 mol/g)	^{40}Ar rad (%)	Age (Ma)
		Sogrisan Granite				
F-1	280.3/341.5	hornblende	1.10	1.759	86.31	89.9±1.7
		Previous K-Ar age data for the Sogrisan plutons				
		Biotite			84	(Kim, O.J.,
		K-feldspar			72	1971)
		Hyeongjebong Granite				
G-1	292.1/337.3	Biotite	3.51	5.209	91.39	83.5±1.7

Analyst: Mr. Seong-Jae KIM in KIGAM

For the Jecheon granite pluton, three whole rock and seven mineral concentrates made an isochron of 202.7±1.9 Ma with an initial ^{87}Sr/^{86}Sr ratio of 0.7140. Different age data of twelve mineral concentrates are almost agreed with the retention temperature of each mineral in K-Ar and fission track methods. All the age data plotted on to the blocking temperature of each mineral against their ages in Fig. 7 (Jin *et al.*, 1992).

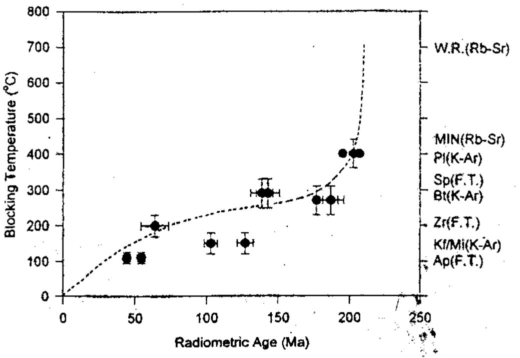

Fig. 7. Thermal history for the Jecheon granites in the study area (Jin *et al.*, 1992a).

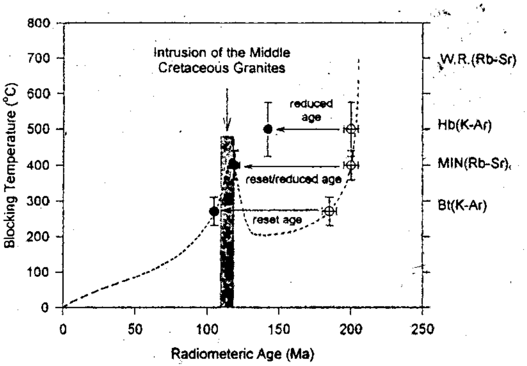

Fig. 8. Thermal histories for the Mungyeong granites in the study area. (Symbol ● implies the isotopic ages determined by each methods, and symbol ○ indicates the isotopic ages expected as in the Jurassic Jecheon and Chuncheon granites).

Accordingly the geothermal cooling histories of the Jecheon granites can be considered as follows (Jin *et al.*, 1992a): The Jecheon granitic magma had been generated by partial melting of crustal materials (S-type), or by enough mixing of mantle and crustal materials, on the basis of its high Sr initial ratio (> 0.708) (Chappell and White, 1974). It had intruded into the katazone or mesozone (7-9 km) of the central part of the Ogcheon fold belt (Cho, 1992; Jin *et al.*, 1992a) at least in the Early Jurassic (about 203 Ma), and had crystallized and cooled rapidly down from about 600℃ to 300℃ (more than 20℃/Ma), owing to thermal differences between the magma and the wall-rock. During the Middle to Late Jurassic (190-140 Ma), the cooling of the granite was likely to stop and keep thermal equilibrium with the wall-rock. The severe tectonism associated with igneous activities and active weathering on the surface in Early to Late Cretaceous time (140-70 Ma) might have accelerated the granite pluton to uplift rapidly (40-60 m/Ma in average) up to 3-4 km and cooled down from 300℃ to 200℃ (1.4℃/Ma). The granite pluton was likely to keep different uplifting and cooling rate of about 120 m/Ma and 5℃/Ma in average from the Late Cretaceous to Early Tertiary (70-50 Ma), and about 60 m/Ma and 2℃/Ma in average from about 50 Ma up to the present, respectively.

The Rb-Sr whole rock-biotite isochron age for the Mungyeong pluton is about of 119.8±3.54 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7129, and MSWD is 0.39. But the K-Ar hornblende age (142.3±2.2 Ma) is much older than the Rb-Sr age, and the K-Ar biotite ages (about 105 Ma) are also younger than those of other Jurassic granites (c.i. Jecheon Granites, Jin *et al.*, 1992a ; Chuncheon Granites; Jin *et al.*, 1993b) suggesting that there should be some particular causes affected by later regional or thermal/hydrothermal episodes as follows.

All the age data plotted on to the retention temperature of them against their ages in Fig. 8. Accordingly the thermal cooling histories of the Mungyeong granites can be considered as follows: The Mungyeong granitic magma had been generated by partial melting of crustal materials (S-type), or by mixing of mantle and crustal materials, on the basis of its high Sr initial ratio (> 0.708) (Chappell and White, 1974). The pluton was intruded and almost completely surrounded by the Wolagsan and Daeyasan granite plutons in Middle Cretaceous period (115-105 Ma), and in addition the exposure is very small in comparison with that of the Middle Cretaceous plutons. Accordingly the Mungyeong pluton must have been heated up to about 400℃, the extreme thermal effects result in reduction or reset of the Rb-Sr whole rock-biotite, K-Ar hornblende and biotite ages. Unfortunately detail thermal histories for the pluton can not be interpreted below 200℃, without any isotopic age of low retention teperature.

Middle Cretaceous Granitoids

The Rb and Sr whole rock and mineral isochron ages for the Muamsa and the Wolagsan granites are 109.9±2.5 Ma, 108.6±1.13 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7100±0.00113 and 0.7151±0.0001, respectively. The K-Ar hornblende and plagioclase ages from the Wolagsan pluton are 114.8±1.7 Ma and 103.8±1.5 Ma, respectively. And the K-Ar plagioclase age for the Wolagsan granites is older a little than expected, but the trend is just same as in the Jecheon Granites. And whereas five K-Ar biotite ages are almost consistent in error limit, except two biotite samples (Table 8). Therefore two younger K-Ar biotite ages seem to be due to local effects by later igneous activities. The K-Ar or F.T. age data covering low retention temperature are also not available, detail thermal histories for the pluton can not be explained below 200℃.

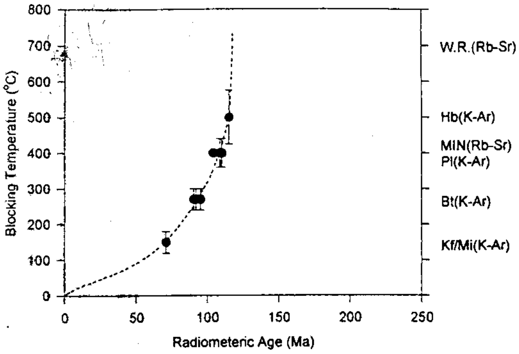

Fig. 9. Thermal histories for the Middle Cretaceous granites (the Muamsa, Wolagsan and Daeyasan plutons) in the study area.

All the age data plotted on to the retention temperature against their ages in Fig. 9. Accordingly the thermal cooling histories of the middle Cretaceous granites can be considered as follows: The plutonic magmas such as the Muamsa, Wolagsan and Daeyasan granitic magma had been generated by partial melting of crustal materials (S-type), or by enough mixing of mantle and crustal materials, in terms of its high Sr initial ratio (>0.708) just same as in the Jurassic granites (Chappell and White, 1974). They had intruded into the epizone (1.5-3 km) of the central part of the Ogcheon fold belt (Cho, 1992; Jin *et al.* 1992c), at least in the Middle Cretaceous of about 110±5 Ma, and had crystallized and cooled rapidly down from about 600℃ to 300℃ (more than 15℃/Ma), owing to big thermal differences between the magma and the wall-rock near the surface. And after reaching thermal equilibrium between them, the cooling rate of the plutons appear to have become slower gradually than initial cooling rate, (about 10℃/Ma) from about 300℃ to 150℃, in the middle to late Cretaceous (about 90 Ma) up to the late Cretaceous (70 Ma). It can be presumed that later successive igneous activities of the Late Cretaceous might have affected the initial cooling of rate much slower in this pluton.

Middle to Late Cretaceous Granitoids

Only available data so far to interprete the cooling histories of the Middle to Late Cretaceous granites such as the Sogrisan and Hyeongjebong granites are K-Ar hornblende, biotite and K-feldspar ages. K-Ar hornblende, biotite and K-feldspar ages are about 90 Ma, 84 Ma and 72 Ma, respectively (Table 9). The K-Ar hornblende age is generally commensurable to Rb-Sr whole rock age for emplacement of the igneous pluton, as mentioed before. Accordingly all the age data plotted on to the retention temperature against ages in Fig. 10.

Accordingly the thermal histories of the Middle to Late Cretaceous granites can be presumed as follows: The Sogrisan and Hyeongjebong plutonic magmas had intruded into the epizone (about 1.5-3 km) of the central part of the Ogcheon fold belt (Jin *et al.*, 1992c), at least in the Middle to Late Cretaceous of about 90 Ma, and had crystallized and cooled rapidly down from about 600℃ to 300℃ (more than 50℃/Ma), owing to thermal differences between the magma and the wall-rock near the surface. And the cooling rate of the plutons appear to have become slower than initial cooling rate, (about 10℃/Ma) from about 300℃ to 150℃, during the late Cretaceous time (84 Ma-70 Ma). The cooling rate of the Middle to Late Cretaceous pluton is likely to be same to those of the Middle Cretaceous ones such as Daeyasan, Wolagsan and Muamsa plutons below the temperature of 300℃ during the period from the Late Cretaceous up to present. Therefore it can be presumed that these two plutons might not have undergone any more later thermal effects affecting extreme disturbance in the isotopic systems except local and temporal effects.

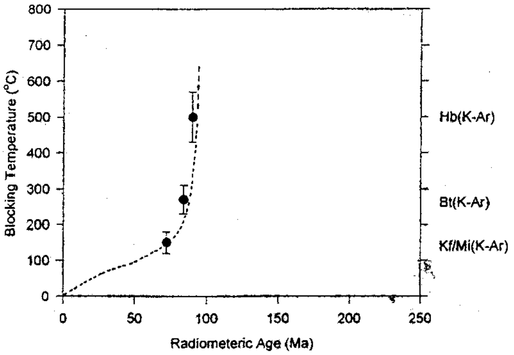

Fig. 10. Thermal histories for the Middle to Late Cretaceous granites (the Sogrisan and Hyeongjebong granites) in the study area.

In South Korea, the fact that most of the Jurassic granites are "S-type" and most of the Cretaceous granites are "I-type" has been reported (Jin, 1980 ; Jin, 1988). But according to this study, some of the Cretaceous granites, particularly distributed in Ogcheon Fold Belt are elucidated as "S-type".

Consequently most of the Jurassic and Cretaceous granitoids in the central part of the Ogcheon Fold Belt are "S-type," except the Sogrisan and Hyeongjebong granites of late Cretaceous age which are not clarified yet.

Many ore deposits recognized at the area between the Wolagsan granites and Muamsa granites are reported to have been mineralized during late Cretaceous time (80-65 Ma) (Park and Jin, in print). Therefore the Muamsa and Wolagsan granites might not be directly related to all of the deposits in the area, and there should be some concealed igneous activities of late Cretaceous age concerning these mineralizations.

In contrast, all of the Cretaceous plutons including the Muamsa, Wolagsan, Daeyasan, Sogrisan and Hyeongjebong granites are assumed to have successively intruded into the Epizone (less than 3.0 km in depth) of the Ogcheon Fold Belt in Aptian (~110 Ma) to Cenomanian (~90 Ma) of the Cretaceous respectively, and simply and rapidly crystallized and cooled down up to present.

ACKNOWLEDGMENT

This study was financialy supported by Ministry of Trade and Industry and the KOSEF from 1991 to 1993. The author is pleased to acknowledge Drs.Choo, S.H., Shin, S.C., Chi, S.J. and Mr Kim, S.J. in KIGAM and Prof. Park, Y.S. in Chosun University for their valuable helps on datings and discussions. He wishes to thank Prof. Kwon, S.T. in Yonsei University and Dr. Park, K.H., in KBSC who reviewed this paper. He also thank Dr. Kang, P.C., the President of KIGAM, who permitted this publication.

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(책임편집 : 김형식)

南韓 沃川褶曲帶 中央部의 中生代 花崗岩質岩의 生成年代와 冷却史

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요 약 : 沃川褶曲帶 中央部에 분포하는 中生代 화강암체의 全岩 및 鑛物年齡을 Rb-Sr, K-Ar, 휫션트랙법으로 측정하여, 그들 岩體의 貫入 定置時期와 地體構造 發達過程인 地熱史를 규명하였다. 이들 중생대 화강암체중 Rb-Sr법으로 등시선 연령을 구한 쥬라기의 堤川화강암체(~203 Ma)와 聞慶화강암체(~200 Ma), 그리고 白堊紀 중기의 霧岩寺화강암체(~110 Ma), 月岳山 및 大野山화강암체(~110 Ma)는 모두 스트론치움 초생값$(^{87}Sr/^{86}Sr)_i$이 0.7100 以上의 값을 나타내어, "I-型"과 "S-型"의 基準이 되는 0.708보다도 큰 값으로서, 모두 "S-型"에 속하여, 地殼物質이 部分熔融을 받아서 만들어진 마그마가 結晶分化한 "S-형"이거나, 또는 맨틀물질과 多量의 地殼物質이 混和된 "M-型"의 마그마로부터 結晶分化한 것으로 밝혀졌다. 또 위의 쥬라기 화강암체는 岩相 및 조암광물의 지화학적 연구결과 深部에 定置되어 약 300℃까지는 급히 냉각하였으나, 그 이후부터는 서서히 냉각한 것으로 생각되나, 聞慶화강암체는 ~110 Ma경에 淺部에 관입한 白堊紀 중기의 月岳山, 大野山 화강암체의 높고 큰 열로 同位元素系가 完全히 또는 部分的인 再平衡을 이루므로써, 각 年齡測定方法중 年齡保存溫度 이하의 年齡測定試料에서는 실제 提示해야 할 연령보다도 더 젊은, 후기의 지질변동시기(~110 Ma)를 제시하거나, 부분적인 연령감소를 나타내는 감소된 연령(K-Ar 각섬석 연령: 142 Ma)을 나타내고 있다. 또 白堊紀 중기(~110 Ma)의 霧岩寺, 月岳山, 大野山화강암체와 백악기 중기-말기(~90 Ma)의 俗離山 및 兄弟峰화강암체는 천처에 관입하여 매우 단순하게 그리고 급속히 냉각한 암체인 것으로 확인되었다.

핵심어 : 沃川褶曲帶, 地熱史, 月岳山 花崗岩, 俗離山 花崗岩, 同位元素年齡, 年齡保存溫度.