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Thermal and uplift histories of Mesozoic granites in Southeast Korea: new fission track evidences

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ABSTRACT : Fission track (FT) thermochronological analyses on Mesozoic granites provide new information about cooling and uplift histories in Southeast Korea. Twenty-nine new FT sphene, zircon and apatite ages and seven track length measurements are presented for eleven granite samples. Measured mineral ages against assumed closure temperatures yield cooling rates for each sample. Relatively rapid (7-15℃/Ma) and simple cooling patterns from the middle Cretaceous (ca. 90-100 Ma) granites are caused mainly by a high thermal contrast between the intruding magma and country rocks at shallow crustal levels (ca. 1-2.5 km-depths). On the contrary, a slow overall cooling (1-4℃/Ma) of the Triassic to Jurassic granites (ca. 250-200 Ma), emplaced at deep depths (≫9 km), may mainly depend upon very slow denudation of the overlying crust. The uplift history of the Triassic Yeongdeog Pluton in the Yeongyang Subbasin, west of the Yangsan Fault, is characterized by a relatively rapid uplift (~0.4 mm/a) before the total unroofing of the pluton in the earliest Cretaceous (~140 Ma) followed by a subsidence (~0.2 mm/a) during the Hayang Group sedimentation. Stability of original FT zircon ages (156 Ma) and complete erasure of apatite ages suggest a range of 3 to 5.5 km for the basin subsidence. Since 120 Ma up to present, the Yeongyang Subbasin has been slowly uplifted (~0.04 mm/a). The FT age patterns of Jurassic granites both from the northeastern wing of the Ryeongnam Massif and from the northern edge of the Pohang-Kampo Block indicate that the two geologic units have been slowly uplifted with a same mean rate (~0.04 mm/a) since early Cretaceous. Estimates of Cenozoic total uplifts since 100 Ma are different: Ryeongnam Massif (~6 km)=Pohang-Kampo Block (~6 km)>Yeongyang Subbasin (~4 km).

Key Words : Mesozoic granites, fission track thermochronology, uplift, thermal history, closure temperature

INTRODUCTION

Geologists have usually been interested in the emplacement or intrusion ages of plutons in preference to the subsequent cooling and uplift histories and post-intrusive thermal events. However, discordant cooling ages and thermally-affected ages give valuable information concerning the geological events that the rocks experienced during their lifetime. When a sample cools below a "closure temperature" at which the various systems start to retain their daughter products (Dodson, 1973), the radiogenic daughters start to accumulate and the isotopic clock starts to tick. Temperature is one of the most important parameters that control the age results. As a mineral cools from a high temperature it passes through a partial stability zone where fission tracks both accumulate and fade. The closure process for fission track (FT) is directly related to the kinetics of FT annealing.

Closure temperatures for FT retention in minerals have been empirically determined and suggested by many workers as functions of specific cooling rates. Adopted values for FT retention are: 105±10℃ for apatite at an unknown geological cooling rate (Harrison and McDougall, 1980); 200±30℃ for zircon at a cooling rate of ~10℃/Ma (Nishimura and Mogi, 1986); and 290±40℃ for sphene at a cooling rate of ~10℃/Ma (Harrison and McDougall, 1980). Closure temperatures for the argon-retention in biotite and hornblende are 280± 40℃ (Harrison and McDougall, 1980) and 500± 75℃ (Nishimura and Mogi, 1986), respectively, at a cooling rate of ~10℃/Ma. In short, an identical sample shows a sequence of age results depending on different closure temperatures: i.e., FT apatite(~100℃)<FT zircon (~200℃)<K-Ar biotite≒FT sphene(~300℃)≪ K-Ar hornblende(~500℃).

The radiation damage from the spontaneous fission of ^{238}U in uranium-bearing minerals increases with geologic time. The number of fission tracks depends not only upon the time during which they have been accumulating but also upon the uranium content of the mineral. The uranium content can be determined empirically by irradiating the sample in a nuclear reactor with monitored fluence or dose of thermal neutrons. Thermal neutrons induce fission in a fraction of the atoms of the less abundant uranium isotope, ^{235}U.

The lengths of confined spontaneous fission tracks in apatites decrease systematically as temperature increases. The distribution patterns also vary with temperature and directly give a great deal of information on the thermal history of a certain sample at temperatures typically encountered in the upper few kilometers of the Earth's crust (Gleadow and Duddy, 1981; Gleadow *et al.*, 1983, 1986a; Green, 1986).

Fission track dating (FTD) is one of the most suitable techniques for thermochronological analyses owing to the high sensitivity of fission tracks in minerals, especially apatite, to even around 100℃ during the geological times. The aims of this study are to clarify patterns and causes of differential cooling and uplift of the Mesozoic granites in different geologic units and to assess post-cooling thermal events.

REGIONAL GEOLOGY AND SAMPLES

The study area are divided into three geologic units by the Andong and Yangsan Faults (Fig. 1). The area occupies the southeastern part of the Korean Peninsula covering the northern wing of the Ryeongnam Massif, the Yeongyang Subbasin and the northern edge of the Pohang-Kampo Block (see "R", "Y" and "P", respectively, in the index map of Fig. 1).

The geology of the northeastern Ryeongnam Massif is represented by the Uljin Pluton, a small oval-shaped stock, which comprises a medium-grained equigranular biotite granite and intruded the Precambrian gneiss complex and Cambro-Ordovician limestone (Fig. 1).

The Yeongyang Subbasin was filled with Cretaceous Hayang Group sediments that are dominated by conglomerates of an active fluvial episode together with fluvio-lacustrine sandstones and mudrocks. The Cretaceous sediments overlie unconformably the pre-Gyeongsang crystalline basement (e.g., Yeongdeog Pluton) and was intruded by the Cretaceous plutons (e.g., Onjeong Pluton) (Fig. 1). The Yeongdeog Pluton is medium-grained hornblende-biotite granitic rocks (tonalite-granodiorite-granite) which occur as a batholith. The Pyeonghae Pluton occurs as isolated small bodies to the northeastern part of the basin. The Cretaceous plutons in the Yeongyang Subbasin are represented by the Onjeong and Byeonggog Plutons which are medium-grained biotite-hornblende granodiorite to granite. The Onjeong Pluton intruded into the Pyeonghae Pluton near Hup'o-myŏn and Pyŏnghae-ŭp (Fig. 1).

The Pohang-Kampo Block, a lozenge-shaped block to the east of the Ulsan and Yangsan Faults, is composed of Mesozoic granites (e.g., Namjeong and Obodong Plutons) in the northern part; Eocene Goggangdong Rhyolite in the middle part; and Miocene volcanics and sediments, and Cretaceous seiments, volcanics and granites in the southern part. The Namjeong Pluton is a fine- to medium-grained porphyritic hornblende granitic rock (diorite-quartz diorite-tonalite-granodiorite) which often includes amphibole megacryst-bearing xenoliths. The pluton was overlain unconformably by Eocene Goggangdong Rhyolite and Miocene Yeonil Group sediments

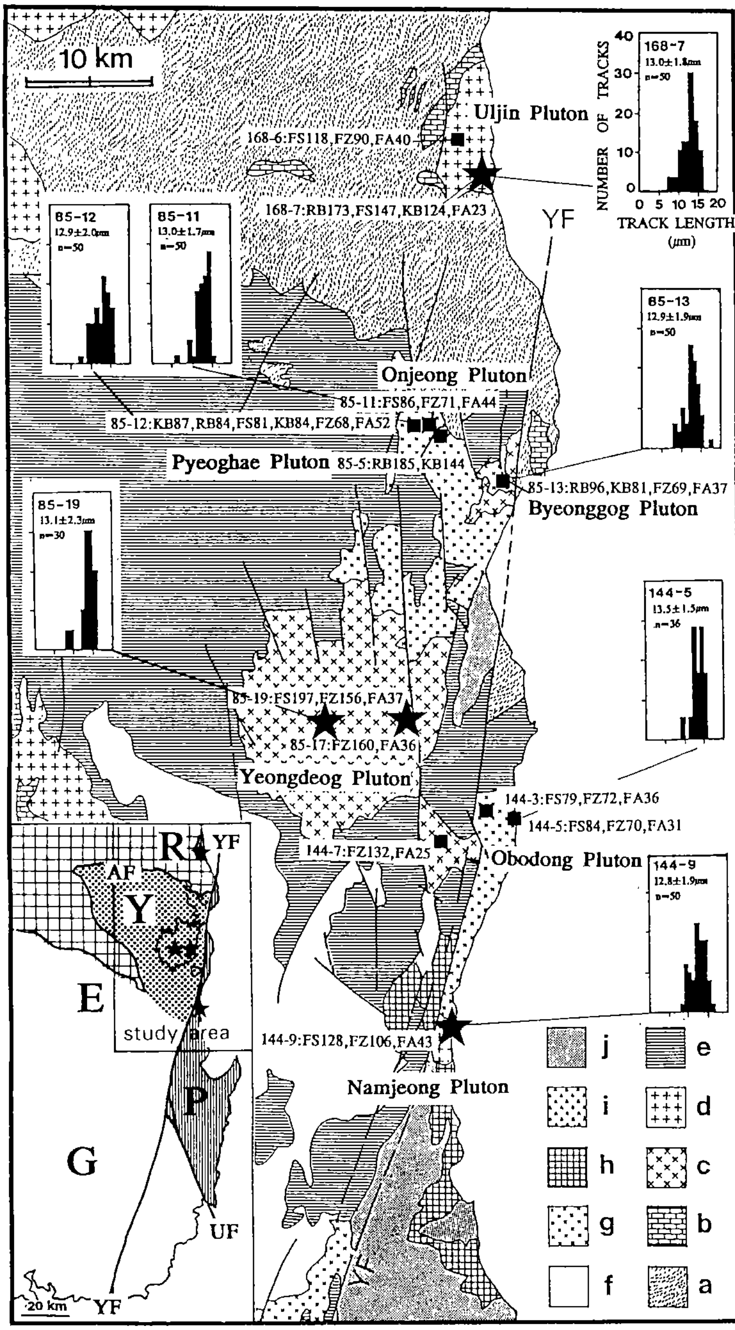

Fig. 1. Map showing radiometric ages of Mesozoic granites in Southeast Korea. Apatite track length data are also presented. Geology was modified from GMIK (1973) and Chang *et al.* (1990). Radiometric age: FS=FT sphene; FZ=FT zircon; FA=FT apatite; KH=K-Ar hornblende; RB=Rb-Sr biotite; KB=K-Ar biotite. a=Precambrian metamorphic basement (gneiss and schist complex); b=Cambro-Ordovician limestone (Joseon Supergroup); c=Triassic granites; d=Jurassic granites; e=Cretaceous sediments (Hayang Group); f=Cretaceous volcanics (Yuchon Group); g=Cretaceous granites; h=Goggangdong Rhyolite; i=Miocene volcanics (Yangbug Group); j=Miocene sediments (Yeonil Group). YF=Yangsan Fault; AF=Andong Fault; R=Ryeongnam Massif; Y=Yeongyang Subbasin; P=Pohang-Kampo Block; E=Euiseong Subbasin; G=Gyeongsang main basin. Four samples, designated by "star", are pre-Cretaceous granites for the discussion of uplift history.

(Fig. 1). The Obodong Pluton is a medium-grained equigranular biotite granitic rock (diorite-quartz diorite-tonalite-granodiorite).

Geological ages of some granitic intrusions have been classified wrong or as unknowns in different geological maps (e.g., GMIK, 1973; KIER, 1981). Cooling and thermal histories and uplift tectonics are still ambiguous despite some information from published radiometric ages (Choo *et al.*, 1982; Ferrara *et al.*, 1983). To resolve these problems, all discordant ages either from a sample or from a single body were carefully assessed in this study.

Eleven outcrop samples from six granitic plutons were dated by the FTD (8 sphenes, 10 zircons and 11 apatites) and K-Ar (1 hornblende and 1 biotite) methods. Apatites from seven samples were analyzed by track length measurement.

EXPERIMENTAL PROCEDURES

Fission Track Dating

Zircon, apatite and sphene samples were analyzed by the External Detector Method (EDM; Gleadow, 1981). Zircon and sphene were mounted in PFA-Teflon and apatite in epoxy and all crystals were polished to reveal internal surfaces. Zircon was etched in KOH-NaOH eutectic melt (Gleadow *et al.*, 1976) at 225± 1℃ for 14-25 hours and apatite in 0.6% HNO_3 at 30± 0.5℃ (Shin, 1987) for 65-100 seconds. Sphene etching used the mixed acid: $1HF+2HNO_3+3HCl+6H_2O$ (Naeser and McKee, 1970) at 30± 0.5℃ for 9-17 minutes.

Strict control of an appropriate 4π-geometry (factor=0.5) was given for only grains ensuring high etching efficiency and complete appearance of spontaneous tracks in all orientations. Complete revelation of the tracks was ensured from the optimum step-etching. Mica detectors were etched after irradiation to reveal induced tracks using 47%HF at 30± 0.5℃ for ~6 minutes.

Neutron irradiations were carried out in the Irradiation Pit No. 6 (IP-6) of the Korea Atomic Energy Research Institute (KAERI) TRIGA III raector. Thermal neutron fluences were monitored by counting induced tracks in etched muscovite detectors against three uranium dosimeter glasses NBS SRM612 and Corning Glasses CN1 and CN2. Facility KAERI IP-6 has a Cd ratio of ~12.5 for Au (Park *et al.*, 1989) and a nominal thermal neutron flux of $\sim 4\times 10^{12}$ $cm^{-2}s^{-1}$.

Spontaneous tracks were counted in the mineral crystals and induced tracks in an external detector of low uranium muscovite (Shin and Park, 1989; Shin, 1990) held in close contact with the mineral mounts during neutron irradiation. Track counting was done at a true linear magnification of 966× using a dry objective under transmitted light. Each track density for thermal neutron dosimetry was

Table 1. Sample locations and dating methods

Sheet name* (1 : 50,000)	Sample no.	National grid (X-Y)	Locality (-ri, -myŏn, -gun)	Elev. (m)	Dating method** FT	K-Ar
Ulchin	168-6	234.1-379.7	Maehwa, Wonnam, Ulchin	40	SZA	
	168-7	236.4-376.8	Osan, Wonnam	20	S A	B
Pyŏnggok	85-11	232.5-357.5	Kŭmch'ŏn, Onjŏng, Ulchin	140	SZA	
	85-12	231.5-357.6	Sot'ae, Onjŏng	130	SZA	H
	85-13	237.6-353.2	Kŭmŭm, Hup'o, Ulchin	40	ZA	
	85-17	230.2-335.7	Paegil, Yŏnghae, Yŏngdŏk	60	ZA	
	85-19	224.7-335.5	Tae-dong, Yŏnghae	180	SZA	
Yŏngdŏk	144-3	236.6-327.6	Maejŏng-dong, Yŏngdŏk-ŭp,	80	SZA	
	144-5	238.6-326.6	Obo-dong, Yŏngdŏk-ŭp	40	SZA	
	144-7	232.5-325.9	Kumi-dong, Yŏngdŏk-ŭp	30	ZA	
	144-9	234.1-313.7	Kugye-dong, Namjŏng, Yŏngdŏk	20	SZA	

*Topographic map (1 : 50,000) newly published by the National Geography Institute. The sheet number gives initial number of each sample. **S=Sphene, Z=Zircon, A=Apatite, H=Hornblende, B=Biotite.

Table 2. Fission track analytical data for Mesozoic granites

Sample no.	Mineral dated	$\rho s(Ns)$ (10^6 cm^{-2})	$\rho i(Ni)$ (10^6 cm^{-2})	$\rho d(Nd)$ (10^6 cm^{-2})	n	γ	$P(\chi^2)$ (%)	FT age ($\pm 1\sigma$, Ma)
RYEONGNAM MASSIF								
Uljin Pluton								
168-6	Sphene	3.206(409)	4.414(563)	2.956(5070)	5	0.891	60	118.4± 8.4*
	Zircon	6.949(365)	4.950(260)	1.164(4493)	5	0.917	60	90.2± 7.8*
	Apatite	0.116(100)	0.519(447)	3.255(5583)	14	0.807	60	40.3± 4.6*
168-7	Sphene	2.299(69)	2.532(76)	2.950(5060)	2	−1.000	70	147.4± 24.9
	Apatite	0.236(150)	1.852(1179)	3.244(5563)	13	0.912	(0.127)	22.9± 2.1*
YEONGYANG SUBBASIN								
Yeongdeog Pluton								
85-17	Zircon	8.528(1033)	3.079(373)	1.048(4044)	12	0.822	93	159.7± 10.7
	Apatite	0.461(333)	1.956(1413)	2.719(5828)	19	0.733	8	*35.5± 2.4**
85-19	Sphene	2.981(294)	2.505(247)	3.019(6473)	4	0.795	76	197.3± 17.9
	Zircon	14.465(1597)	5.308(586)	1.037(4003)	14	0.644	40	155.5± 8.8
	Apatite	0.240(191)	0.972(772)	2.690(5767)	12	0.906	75	*36.8± 3.2**
144-7	Zircon	4.463(421)	2.163(204)	1.163(4489)	6	0.954	98	132.2± 11.9
	Apatite	0.097(121)	0.700(870)	3.220(5523)	19	0.161	13	*24.8± 2.5**
Onjeong Pluton								
85-11	Sphene	5.404(643)	10.926(1300)	3.131(6713)	5	0.984	60	85.5± 4.7
	Zircon	5.688(939)	4.774(788)	1.081(4170)	9	0.901	75	71.2± 4.0
	Apatite	0.227(198)	0.794(694)	2.804(6011)	16	0.962	78	44.3± 3.8*
85-12	Sphene	4.133(505)	8.765(1071)	3.094(6633)	4	0.958	45	80.6± 4.9
	Zircon	5.194(1609)	4.500(1394)	1.070(4129)	12	0.454	35	68.3± 3.2
	Apatite	0.250(121)	0.739(358)	2.775(5950)	12	0.179	87	51.9± 5.6*
Byeonggog Pluton								
85-13	Zircon	5.569(1176)	4.717(996)	1.059(4087)	8	0.546	85	69.1± 3.6
	Apatite	0.336(106)	1.493(432)	2.747(5888)	10	0.594	92	37.3± 4.2*
POHANG-KAMPO BLOCK								
Namjeong Pluton								
144-9	Sphene	6.841(176)	8.746(225)	2.962(5080)	3	0.977	45	127.7± 13.3
	Zircon	9.045(892)	5.456(538)	1.163(4487)	5	0.944	60	106.3± 6.7
	Apatite	0.497(106)	2.067(441)	3.209(5503)	9	0.427	45	42.7± 4.8*
Obodong Pluton								
144-3	Sphene	6.297(540)	13.096(1123)	2.968(5090)	5	0.688	(0.481)	78.8± 4.7
	Zircon	5.479(875)	4.896(782)	1.164(4490)	9	0.824	75	71.9± 4.1
	Apatite	0.192(87)	0.968(439)	3.232(5543)	11	0.818	92	35.5± 4.3*
144-5	Sphene	9.407(121)	14.072(181)	2.269(3892)	2	1.000	91	83.8± 10.1
	Zircon	4.905(715)	5.227(762)	1.342(4314)	9	0.892	90	69.6± 4.1
	Apatite	0.514(178)	5.375(1861)	5.855(5648)	9	0.881	38	31.0± 2.6*

ρs=spontaneous FT density of mineral; ρi=induced FT density of mineral measured in mica detector; ρd=induced FT density of standard dosimeter glass (CN1) measured in external detector; Ns, Ni and Nd=total number of counted tracks in determining ρs, ρi and ρd, respectively; n=number of crystals analyzed; γ=correlation coefficient between individual track counts; $P(\chi^2)$=probability obtaining the observed value of χ^2 parameter, for ν degrees of freedom, where $\nu = n-1$ (Galbraith, 1981) (values in parentheses is $\rho s/\rho i$ for samples showing unacceptable [$P(\chi^2)<5\%$]); Age in Roman=undisturbed original cooling age; Age in italics=post-reset cooling age; Asterisked age=partially reduced age due to later thermal overprinting.

determined from more than 3000 track counts.

FT ages were calculated using the zeta calibration method (Fleischer and Hart, 1972; Hurford and Green, 1982) whereby a calibration baseline, zeta constant (ζ), is derived for each dosimeter glass by repeated datings of age standards. Only the zeta calibration can eliminate the problem in selecting a value for the ^{238}U spontaneous fission decay constant (λ_f) and the difficulties in determining the irradiation

Table 3. K-Ar analytical data for Mesozoic granites

Sample no.	Material dated	K(%)	$^{40}Ar_{rad}$ (%)	$^{40}Ar_{rad}$ (10^{-10} mol g^{-1})	K-Ar age (± 1σ) (Ma)
168-7	Biotite	7.44	92.90	1.659	124.2± 1.9
85-12	Hornblende	0.41	60.04	6.343	87.1± 2.1

Analyses done by S.J. Kim, KIGAM; Decay constants from Steiger and Jäger (1977); rad=radiogenic; Ages are thermally-unaffected primary ones.

unknowns. In this study, all FT ages were calculated by a zeta constant for standard glass CN1, viz. ζ_{CN1}=110.9± 2.7 (2σ) (Shin and Nishimura, 1991). Details on experimental procedures and zeta calibration are described in Shin (1987, 1992) and Shin and Nishimura (1991).

K-Ar Dating

Only two samples were analyzed as auxiliary data. Isotopic ratios of mixed argon were measured using a NUCLIDE^R mass spectrometer (6″-60° first order focusing sector type) employing an enriched ^{38}Ar spike calibrated against both known air volumes and the standard minerals B-4B and MMHB-1 (Kim, 1986).

Confined Track Length Measurement in Apatite

Confined fission tracks do not appear on the polished mineral surface, but intersect some other etched surface-tracks and into cracks or cleavages which facilitates the passage of etchant to the confined track. Only horizontal or sub-horizontal (inclined less than 5°) tracks, which are nearly close to the true lengths, were measured according to the recommendation of Laslett *et al.* (1982). Track lengths were measured under a high magnification with a 100× dry objective and 10× eyepieces using incident illumination. The error in the length measurement is approximately ± 0.3 µm.

RESULTS

Fission Track Ages

Different minerals show quite discordant ages depending upon their different closure temperatures. Table 2 details the analytical data on FT counts and age results. The correlation coefficient between individual track counts was also presented with the probability obtaining the Galbraith's (1981) χ^2-value. Errors (1σ) were calculated from Poissonian statistics (Green, 1981) together with an uncertainty on the zeta constant factor.

FT ages vary within a wide range: i.e., 79 Ma to 197 Ma for sphenes, 68 Ma to 160 Ma for zircons and 23 Ma to 52 Ma for apatites. The older ages were derived from the pre-Cretaceous granites (e.g., Yeongdeog, Namjeong and Uljin Plutons). The younger ages were taken from the Cretaceous Onjeong, Byeonggog and Obodong Plutons. Most of FT sphene and zircon ages would be interpreted as undisturbed cooling ages.

Apatite FT ages give very low results compared with sphene and zircon ages from the same samples. Many of apatite ages were completely reset and some were partially reduced. It is noted that even the pre-Cretaceous plutons having quite old sphene-zircon ages (e.g., Yeongdeog Pluton) yield considerably younger apatite ages regardless of their emplacement ages.

K-Ar Ages

A K-Ar hornblende age was determined for the Onjeong Pluton to understand apparent emplacement age and earlier cooling history (700-500℃) of the Cretaceous pluton. The Onjeong Pluton (sample 85-12) shows a hornblende age of 87.1 ± 2.1 Ma as compared to biotite ages (~84 Ma) by Rb-Sr (Choo *et al.*, 1982) and K-Ar (Ferrara *et al.*, 1983) methods for the same sample. A K-Ar biotite age of 124.2± 1.9 Ma was obtained from the Jurassic Uljin Pluton whose Rb-Sr biotite age

Table 4. A summary of fission track and other radiometric ages

Name of pluton	Sample no.	RADIOMETRIC AGE (± 1σ, Ma)					
		K-H	R-B	F-S	K-B	F-Z	F-A
RYEONGNAM MASSIF							
Uljin	168-6	–	–	118.4± 8.4*	–	90.2± 7.8*	40.3± 4.6*
	168-7	–	173± 0.71[a] (0.7142± 0.0009)	147.4± 24.9	124.2± 1.9	–	22.9± 2.1*
YEONGYANG SUBBASIN							
Yeongdeog	85-17	–	–	–	–	160.0± 10.7	*35.5± 2.4**
	85-19	–	–	197.3± 17.9	–	155.5± 8.8	*36.8± 3.2**
	144-7	–	–	–	–	132.2± 11.9	*24.8± 2.5**
Pyeonghae	85-5	–	185± 2.7[a] (0.7057± 0.0015)	–	143.5± 1.7[b]	–	–
Onjeong	85-11	–	–	85.5± 4.7	–	71.2± 4.0	44.3± 3.8*
	85-12	87.1± 2.1	84± 1.4[a] (0.7020± 0.0004)	80.6± 4.9	84± 4[b]	68.3± 3.2	51.9± 5.6*
Byeonggog	85-13	–	96± 1.4[a] (0.7087± 0.0007)	–	80.6± 4.0[b]	69.1± 3.6	37.3± 4.2*
POHANG-KAMPO BLOCK							
Namjeong	144-9	–	–	127.7± 13.3	–	106.3± 6.6	42.7± 4.8*
Obodong	144-3	–	–	78.8± 4.7	–	71.9± 4.1	35.5± 4.3*
	144-5	–	–	83.8± 10.1	–	69.6± 4.1	31.0± 2.6*

F=Fission Track; K=K-Ar; S=Sphene; Z=Zircon; A=Apatite; H=Hornblende; B=Biotite; Age in Roman =undisturbed original cooling age; italics=reset age; Asterisked=partially reduced age due to thermal overprints; "a" and "b"=ages reported by other workers (a=Choo *et al.*, 1982; b=Ferrara *et al.*, 1983; Jin *et al.*, 1984); parenthesized value=$^{87}Sr/^{86}Sr$ ratio from biotite-whole rock two-point isochron.

Table 5. Confined fission track length data for apatites from Mesozoic granites

Name of pluton[a]	Sample no.	FT Apatite age (± 1σ, Ma)	Mean length (± 1σ[b], μm)	Standard deviation (μm)	Number of tracks[c]	Type of length distribution[d]
Uljin	168-7	22.9± 2.1	12.99± 0.26	1.81	50	(I)
Onjeong	85-11	44.3± 3.8	12.95± 0.24	1.68	50	IV
	85-12	51.9± 5.6	12.89± 0.28	1.98	50	IV
Byeonggog	85-13	37.3± 4.2	12.89± 0.27	1.91	50	IV
Yeongdeog	85-17	35.5± 2.4	11.42± 0.98	2.76	8*	–
	85-19	36.8± 3.2	13.09± 0.41	2.26	30	(I)
Obodong	144-5	31.0± 2.6	13.51± 0.25	1.49	36	IV
Namjeong	144-9	42.7± 4.8	12.77± 0.27	1.91	50	III

(a) see Figure 1 for the locations; (b) standard error of the mean; (c) asterisked sample with poor measurement is excluded from further discussion; (d) Type I=negatively skewed broad unimode (slow cooling), not identified from this study; Type II=symmetric narrow unimode (rapid cooling), not identified from this study; Type III=bimode with separate components of shorter and longer tracks (thermal overprint); Type IV=mixed mode with an overlap of both track components (thermal overprint); Parenthesized=weak thermal overprint.

is known to be 173± 0.7 Ma (Choo *et al.*, 1982).

Confined Track Length in Apatite

Track length measurements were limited to seven samples due to lower spontaneous FT density of apatites (e.g., ~2.3 to 5.1×10^5 cm^{-2}) and subsequent poor recovery of confined tracks. Analytical results are summarized in Table 5 and the distribution patterns are shown in Figure 1. All measurements were normalized to 100 tracks for an equivalent comparison. The uncertainty quoted for each mean length was shown by the standard error of the mean. The standard deviation gives a measure of the breadth of each distribution. Mean track lengths range from 11.5 to 13.5 μm with standard deviations ranging between 1.5 and 2.8 μm.

The standard deviations increase with decreasing mean lengths illustrating the progressive broadening of the distribution towards shorter mean lengths. Shorter mean lengths with high standard deviations may suggest that these samples have suffered from heating events with elevated temperatures (Gleadow *et al.*, 1986b; Green, 1986). Mean track lengths and standard deviations show no dependence on the FT ages of apatites (Table 5).

The length distribution patterns can be classified into different types based on the peaks for both components of longer and shorter tracks (see the footnote to Table 5). The patterns were found to be charateristic depending upon the thermal histories of the samples through the apatite annealing zone. Dominance of Types III and IV from many plutons, irrespective of their emplacement ages, suggests a wide thermal overprints reaching the apatite partial annealing zone (e.g., ~70-125℃) over the study area. The Jurassic Uljin Pluton shows a simple slows cooling pattern (Type I).

DISCUSSION

Time and Depth of Emplacement and Origin of Magma

Time of emplacement of granitic plutons can be determined based upon Rb-Sr whole rock isochron data. Other radiometric ages representing high closure temperatures and/or geological evidences also give information to the estimation of the emplacement ages.

The Yeongdeog Pluton gives a FT sphene age of 197± 18 Ma which is the oldest result obtained in this study. Despite the lack of a Rb-Sr whole-rock isochron age for the pluton, the sphene age extrapolates the emplacement age of the pluton to Triassic (say ~250-200 Ma).

The Uljin Pluton was probably emplaced at least in the early Jurassic (say ~200-180 Ma) in consideration of a Rb-Sr biotite age (173 Ma; Choo *et al.*, 1982), similarly to the Andong Granite in the same geologic unit having a Rb-Sr biotite age of 172.3± 0.9 Ma (Choo and Kim, 1981). The emplacement age of the Pyeonghae Pluton can also be extrapolated to early Jurassic as indicated by a Rb-Sr biotite age of ~185 Ma (Choo *et al.*, 1982). The emplacement age of the Namjeong Pluton is still unknown due to lack of age data for minerals with high closure temperatures. But the time-cooling path suggests a similar emplacement age to those of the early Jurassic Uljin Pluton.

The approximate emplacement age of the Onjeong Pluton can be extrapolated to Cenomanian on the basis of K-Ar hornblende age (87± 2 Ma). Slightly older age (e.g., Albian) is given to the emplacement of the Byeonggog Pluton considering its Rb-Sr biotite age (~96 Ma). The emplacement age of the Obodong Pluton can be classified into middle Cretaceous (~90 Ma) based upon thermally-undisturbed FT ages for sphene (80± 4 Ma) and zircon (71± 3 Ma) and its similar time-cooling path to those of other middle Cretaceous plutons (e.g., Onjeong Pluton) (Fig. 2).

Petrological and geochemical data and $^{87}Sr/^{86}Sr$ ratios from biotite-whole rock two-point isochron (Choo *et al.*, 1982) indicate that some of the Cretaceous granites (e.g., Onjeong Pluton: 0.7020± 0.0004; Byeonggog Pluton: 0.7087± 0.0007) and a Jurassic Pyeonghae Pluton (0.7057± 0.0010) in the Yeongyang Subbasin are characteristics of both late- and post-tectonic granitoids which have been fractionally crystallized from the subduction-related calc-alkaline magmas originated from mantle or igneous sources and they can be classified into "I-type" (Chapell and White, 1974). It was known that most of the Cretaceou granites were emplaced at relatively shallow crustal depths (Jin, 1980). A geochemical study on the Triassic Yeongdeog and the Jurassic Byeonggog Pluton suggests a characteristic of the calc-alkaline I-type granite emplaced in a deep crustal environment (Kim, 1988).

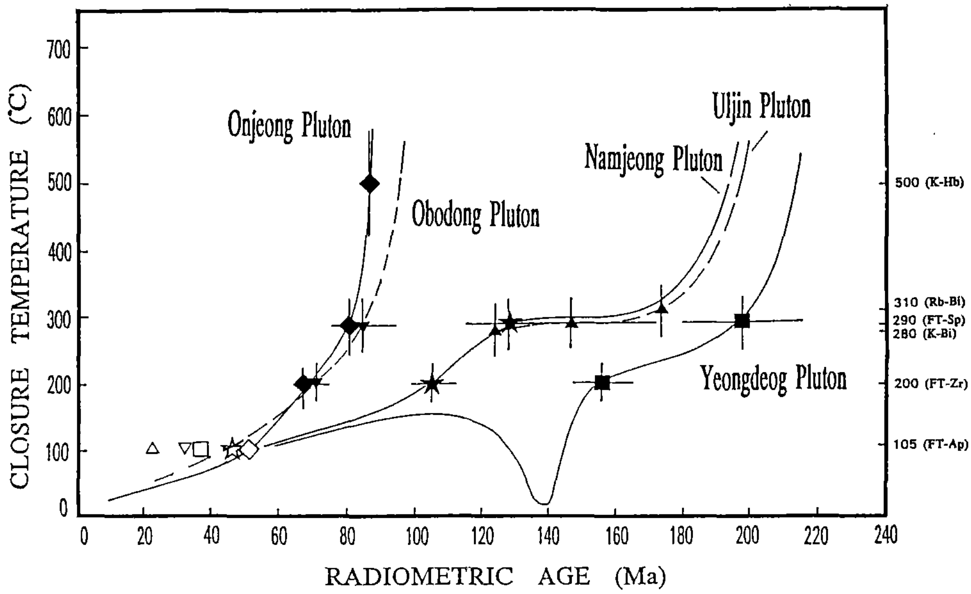

Fig. 2. Cooling curves for granitic plutons from Southeast Korea. Solid and open symbols denote thermally-unaffected and partially-reduced ages, respectively.

The Jurassic Uljin Pluton yields a $^{87}Sr/^{86}Sr$ ratio of 0.7142± 0.0009 (Choo *et al.*, 1982) which may suggest that the magma was contaminated by older crustal rocks or was derived at least partly from anatexis of continental crust. It shows the characteristics of syn- and late-tectonic granites and are classified into "S-type" (Chapell and White, 1974) that suggests a generation of granitic magma from a mixture of mantle and upper crustal materials. Mesozone or katazone was suggested in general for the depth of crystallization for the Jurassic granites based on their textures and mineral assemblages (Jin, 1980; Jin *et al.*, 1984).

In short, the magma origin of the pre-Cretaceous granitic rocks is thought to be multiple despite only scarce isotope data from the study area.

The depth of emplacement can be expected based upon cooling paths of the granitic plutons (Fig. 2). For instance, Jurassic plutons show a sudden decrease in cooling rate from ~300℃. This breaking points may indicate that they accomplished thermal equilibria with their country rocks at around 9 km-depth assuming a geothermal gradient of 30℃/km. Therefore, the depth of emplacement is expected to be much deeper than ~9 km.

On the contrary, the Cretaceous plutons show continuous cooling with intermediate rates even below much lower temperatures approaching ~100℃. The lithostatic pressures calculated from the fluid inclusion data give a range of depth between 0.7 and 1.1 km for the crystallization of the quartzs from some of Cretaceous granites in the south-central part of the Gyeongsang Basin (Jin *et al.*, 1991). A direct extrapolation based upon FT annealing data from a deep borehole (Pohang C-well) pluton suggests an epizonal emplacement of the Cretaceous granite not exceeding ~2.5 km-depth (Shin, 1992; Shin and Nishimura, 1993). At such emplacement depths as presumed above, the initial temperature contrast between the pluton and the country rock would reach at least ~300-400℃ in the Jurassic plutons and ~500-600℃ in the Cretaceous plutons.

Transfer of Cooling Rate into Uplift Rate

In general, granitic rocks close their Rb-Sr

Table 6. Cooling rates of granitic plutons from different geologic units

Name of pluton	Sample no.	Emplacement[a]	Temp. range[b] (℃)	Time period[c] (Ma)	Method[d]	Cooling rate (℃/Ma)
RYEONGNAM MASSIF						
Uljin	168-6	J	290- 13	147- 0	FS-sfc	<1
YEONGYANG SUBBASIN						
Yeongdeog	85-19	T	290-200	197-156	FS-FZ	2
Onjeong	85-12	K	500-310	87- 84	KH-RB	61
			290-200	81- 68	FS-FZ	7
			200- 13	68- 0	FZ-sfc	3
Pyeonghae	85-5	J	280- 13	144- 0	KB-sfc	2
POHANG-KAMPO BLOCK						
Namjeong	144-9	J	290-200	128-106	FS-FZ	4
			200- 13	106- 0	FZ-sfc	2
Obodong	144-3	K	290-200	79- 72	FS-FZ	13
			200- 13	72- 0	FZ-sfc	3

(a) T=Triassic; J=early Jurassic; K=middle Cretaceous. (b) Closure temperatures are shown in the text. (c) See Tables 4 for the details. (d) FS=FT sphene; FZ=FT zircon; FA=FT apatite; KB=K-Ar biotite; KH=K-Ar hornblende; RB=Rb-Sr biotite-whole rock two-point isochron; sfc=present-day surface.

whole-rock system immediately after crystallization and cool from 650-700℃, corresponding to the end of crystallization (Harrison *et al.*, 1979), down to lower temperatures. The overall cooling pattern of the granitic plutons is discussed based on new FT ages along with previous data. Table 6 summarizes the cooling rates of granitic plutons in different geologic units estimated over the various temperature ranges during different time-periods. Figure 2 shows cooling paths for different plutons which were emplaced at different geologic units in different times.

Most plutons show main differences in the cooling patterns from the temperature range between ~300℃ and ~100℃ despite their rapid initial cooling (Fig. 2; Table 6) in the earlier stage (~700℃ to ~300℃). The overall cooling paths are represented by slow and intermediate cooling rates, respectively for the pre-Cretaceous and Cretaceous plutons (Fig. 2).

Different radiometric clocks are turned on at different closure temperatures during cooling. A mean cooling rate, CR, can be calculated from a mineral pair with different closure temperatures as:

$$CR_{1-2}=[\theta_1-\theta_2]/[A_1-A_2] \quad (1)$$

where θ_1 and θ_2 are the closure temperatures of two minerals having different ages of A_1 and A_2.

When cooling was dominated by a mechanism of erosion-uplift of the rock relative to the Earth's surface, the cooling ages give the temporal and regional behavior. In this instance, the cooling rates can be transferred to uplift rates and the mean uplift rate, UR_{1-2}, is given by:

$$UR_{1-2}=CR_{1-2}/[\Delta T/\Delta Z] \quad (2)$$

where $\Delta T/\Delta Z$ is the geothermal gradient. The assumptions involved here are: the mean paleogeothermal gradient is known and remained constant; and the difference between the closure temperatures of the two minerals is constant (Zeitler *et al.* 1982).

When a pair of ages for cogenetic minerals is not available, uplift rate, UR_{1-sfc}, can be calculated using an age for a single mineral in combination with the known surface temperature of the present-time (zero age) as follows:

$$UR_{1-sfc}=[[\theta_1-\theta_{sfc}]/A_1]/[\Delta T/\Delta Z] \quad (3)$$

where θ_{sfc} is the mean annual surface temperature for the sample area.

If FT ages for a given mineral are obtained on rocks separated by a substantial amount of relief, an increase in FT age at higher altitude is usually present. In this case, mean uplift rate, UR_{elev}, is simply calculated from the elevation difference between samples divided by the age difference as follows:

$$UR_{elev} = [E_1 - E_2]/[A_1 - A_2] \quad (4)$$

where E_1 and E_2 are altitudes of each locality. Unfortunately this third method cannot be applied to the study area where none of the samples exceeds 200 meters in altitude (as presented in Table 1) and thus the difference of altitudes in a single pluton is negligible. This method was effectively applied to mountainous orogenic terrains (Zeitler *et al.*, 1982; Parrish, 1981).

Most of the Cretaceous granites in Southeast Korea have been known to be high-level plutons which were emplaced at shallow depths of less than ~3 km (Jin *et al.*, 1991; Shin, 1992). Therefore the direct transfer of the cooling rate into the uplift rate is not reasonable in this instance. These facts may indicate that the cooling of the Cretaceous granites cannot be explained by uplift at all. Their radiometric ages should be interpreted in terms of cooling depending mainly upon high thermal contrasts between the plutons and their country rocks at shallow depths. Even for the temperature range from the apatite isotherm (~105℃) to the present temperature, a simple conversion of cooling rates into the uplift rates by eq. 3 is unreasonable.

For Jurassic plutons, however, the rate of erosion-uplift can be calculated by a combination of eqs. 2 and 3 because they were emplaced at deep crustal levels and subsequently cooled slowly depending essentially upon erosional removal of thick overburden. Despite the complex inter-relationship between isotherm migration, uplift, denudation and cooling, FT-derived apparent uplift rates can be used for the interpretation without systematic correction (Parrish, 1981).

Cooling and Thermal Histories of Cretaceous Granites

The Cretaceous plutons (e.g., Onjeong and Obodong Plutons) show ubiquitiously rapid earlier cooling over the ~700-300℃ range with a mean rate of ~60℃/Ma (Table 6; Fig. 2). Such a rapid cooling in the early stage may depend largely upon the high contrast in temperatures between the intruding granitic magma and the host country rocks. After rapid cooling in the early stage, the plutons cooled through ~300℃ down to the present temperature along their characteristic time-temperature pathways.

The Cretaceous granites cooled over the 300-200℃ range with different rates depending upon the size of intrusive body and/or the kind of country rocks (Shin, 1992). For instance, small stocks (e.g., Obodong, Chunghyodong and Bangeojin Plutons) cooled over the same temperature range with relatively rapid rates (~13-15℃/Ma) (Shin, 1992). Somewhat larger batholiths (e.g., Tongdosa Pluton) show much slower coolings (~5℃/Ma). On the other hand, some small stocks around Ulsan (e.g., Nijeonri and Yulri Plutons) and in the Paegam hot spring area (e.g., Onjeong Pluton) intruding into Cretaceous sediments reveal rather slower cooling rates (~4-7℃/Ma) over the 300-200℃ range when compared to those of some large batholiths (~15-21℃/Ma: e.g., Baegunsan and West Eonyang Plutons) intruding into Cretaceous volcanics (Shin, 1992). These facts imply that subsequent cooling below 300℃ after rapid earlier cooling is not dependent directly upon the size of plutons although the initial cooling (~700-300℃) in most high-level granites depends largely upon the size of pluton (Lee, 1991). The much slower cooling of small stocks intruding into sedimentary country rocks suggests that they lost most of their heat in the initial stage to the sedimentary country rocks which had cooled to low temperatures prior to the pluton emplacements at shallow depths. It is supposed that the influx and circulation of meteoric water, ubiquitous in the shallow crust, had accelerated the sudden release of initial heat of the plutons.

The Onjeong and Byeonggog Plutons, in the Yeongyang Subbasin, whose emplacement ages can be classified into middle Cretaceous, yield consistent FT sphene and zircon ages within errors (1σ) with weighted mean ages of 83± 3 Ma for sphene and 69± 3 Ma for zircon. New FT ages and previous K-Ar and Rb-Sr data show a simple cooling history of a "J-shaped" pattern with a progressive decrease in cooling rates since their rapid initial cooling. For instance, the Onjeong Pluton cooled very rapidly (~60℃/Ma) over the 500-310℃ range during the middle Cretaceous and it cooled subsequently with a mean rate of 7℃/Ma over the 290-200℃ range during the late Cretaceous. The cooling became more slow (3℃/Ma) since Paleocene to the present (Fig. 2). Concordance in FT ages of sphene and zircon from different samples in the Onjeong Pluton imply that the cooling below 290℃ and 200℃ was taking place at the same rate over the whole body during the late Cretaceous.

The two Cretaceous plutons yielded thermally-affected FT apatite ages: i.e., ~37 Ma in the Byeonggog Pluton and 44-52 Ma from the Onjeong Pluton (Table 4). They show a track length distribution of mixed patterns (Type IV) with a combination of both components of longer and shorter tracks and have similar mean lengths (12.9-13.0 μm) and standard deviations (1.7-2.0 μm) to each other (Fig. 1; Table 5). Even the sample (85-12) with maximum apatite age (~52 Ma) shows a thermal overprinting pattern (Type IV) with a slightly broad standard deviation (2.0 μm). Quite similar mean lengths and standard deviations in the two plutons suggest that they experienced a similar degree of thermal effect.

The Obodong Pluton, in the Pohang-Kampo Block, reveals FT ages for sphene (80± 4 Ma) and zircon (71± 3 Ma) which can be interpreted in terms of undisturbed cooling ages. The Obodong Pluton cooled over the 290-200℃ range with a mean cooling rate of 13℃/Ma during the late Cretaceous (Table 6). The overall cooling history of the pluton is very similar to those of other middle Cretaceous plutons such as the Onjeong Pluton in the Yeongyang Subbasin (Fig. 2). Mixed distributions of shorter tracks (Type IV) from two samples of the Obodong Pluton indicate a later thermal overprint with temperatures extending to the apatite partial annealing zone.

Uplift Histories of Triassic-Jurassic Plutons and Estimates of Cenozoic Total Uplift

On the basis of the assumption that the cooling of deeply emplaced plutons is essentially controlled by the uplift and erosion, the cooling rates were translated into apparent uplift rates. The most important assumption is the stability, with respect to the surface topography, of isotherms during uplift. Critical isotherms should be horizontal and uninfluenced by either surface topography or variable thermal conductivity. They should also remain at a constant depth with respect to the surface regardless of uplift rate (Parrish, 1981).

A limited number of the pre-Cretaceous plutons were compared with each other to evaluate possible difference in the uplift history of different geologic units divided by major faults (Fig. 1). The relationships of the plutons with either basement or overburden as well as age data tell us that they have different uplift histories from emplacement to present day.

Table 7 shows estimates of apparent uplift rate and total uplift during late Mesozoic-Cenozoic derived from undisturbed FT ages. As apatite ages commonly show low-temperature thermal overprints, as observed by track length analyses, they were excluded in this calculation. The effect from the difference of altitude between samples on the present estimation is entirely negligible. The apparent uplift rates derived from FT ages may be equal to the actual erosion-uplift. The minor amount of tectonic movements during the Miocene as in the central Pohang-Kampo Block (Shin and Nishimura, 1993) is neglected for the present discussion.

The Triassic Yeongdeog Pluton in the Yeongyang Subbasin and two Jurassic plutons both in the Ryeongnam Massif and in the northern Pohang-Kampo Block show quite different uplift-cooling histories (Figs. 2 and 3). Figure 4 displays a scheme for different uplift and subsidence histories for the three different geologic units.

In the Yeongyang Subbasin, the pre-Cretaceous

Table 7. Estimates of uplift rates and total uplifts

Sample no.	Temp. range (℃)	Time period (Ma)	Method[a]	Cooling rate (℃/Ma)	Uplift rate[b] (mm/a)	Total uplift (km) Since 100 Ma	Since 70 Ma	Since 40 Ma
RYEONGNAM MASSIF (Uljin Pluton)								
168-6	290- 13	147- 0	FS-sfc[+]	1.9	0.06	6	4	2.5
YEONGYANG SUBBASIN (Yeongdeog Pluton)								
85-17	200- 13	160- 0	FZ-sfc[+]	1.2	0.04	4	3	1.5
85-19	290-200	197-156	FS-FZ*	2.2	0.07			
	200- 13	156- 0	FZ-sfc[+]	1.2	0.04	4	3	1.5
POHANG-KAMPO BLOCK (Namjeong Pluton)								
144-9	290-200	128-106	FS-FZ*	4.2	0.14			
	200- 13	106- 0	FZ-sfc[+]	1.8	0.06	6	4	2.5

(a) Uplift rate was estimated by eqs. 2* and 3[+] using thermally-unaffected FT ages. FS=FT sphene; FZ=FT zircon; sfc=present-day surface. (b) Assumed geothermal gradient=30℃/km; Present-day surface temperature=13℃.

plutons (e.g., Yeongdeog, Pyeonghae, Cheongsong and Jangsadong Plutons) were totally unroofed prior to early Cretaceous and they started to subside being up to several kilometers when the Gyeongsang Basin was filled by Cretaceous Hayang sediments. This fact may be supported by an absence of Precambrian basement rocks except for local outcrops at the northern margin (Fig. 1). For instance, the Triassic Yeongdeog Pluton presents thermally-undisturbed FT zircon ages (157± 7 Ma) and reset FT apatite ages (36± 2 Ma). It suggests that this I-type granite should have been placed at range of temperatures above apatite total annealing zone but below zircon partial annealing zone (e.g., between 120 and 170℃). Such a temperature zone would imply 3.5-5 km-depths for the samples, assuming a geothermal gradient of ~30℃/km, during the Cretaceous subsidence (Fig. 3). The pluton was totally unroofed prior to early Cretaceous (say ~140 Ma) and it started to subside during the Hayang sedimentation. The cooling of the pluton was slow (~2℃/Ma) over the 300-200℃ range during Jurassic but the cooling became faster with a mean rate of ~12 ℃/Ma over the range 200℃-surface temperature. The pluton was heated at a mean rate of ~6-8 ℃/Ma during the early Cretaceous basin subsidence for the Hayang sedimentation and was cooled fairly slowly, at a mean rate of ~1℃/Ma, up to present temperature (Fig. 3). The pluton gives a FT sphene age of 197± 18 Ma which is the oldest result obtained in this study. The concordant FT zircon ages from different locations (Fig 1) imply that the uplift-cooling was taken place with an equal rate over the whole body in the late Jurassic. Track length data (Fig. 1) from the Yeongdeog Pluton (sample 85-19) suggests a slow cooling pattern despite somewhat poor resolution due to lack of measured data and thermal overprint.

In the northeastern margin of the Ryeongnam Massif, Precambrian basement crops out widely and Cambro-Ordovician limestone basement is also exposed around the Jurassic Uljin Pluton (Fig. 1). The pluton shows a slight foliation of biotites and evidence of alteration near Maehwa-ri (sample 168-6). FT ages for sphene (118± 8 Ma) and zircon (90± 8 Ma) are thought to be lowered by post-late Cretaceous thermal event in the area. The Uljin Pluton shows coherently slow cooling (~2-4℃/Ma) over the 300-200℃ range and much slower cooling (~1.9℃/Ma) over the range 200℃-present temperature (Fig. 3). This simple slow cooling over a long period can be explained by a monotonous slow unroofing caused by slow erosion of the thick overlying crust. The Uljin Pluton (sample 168-7) reveals a unimodal track length distribution with a mean track length of

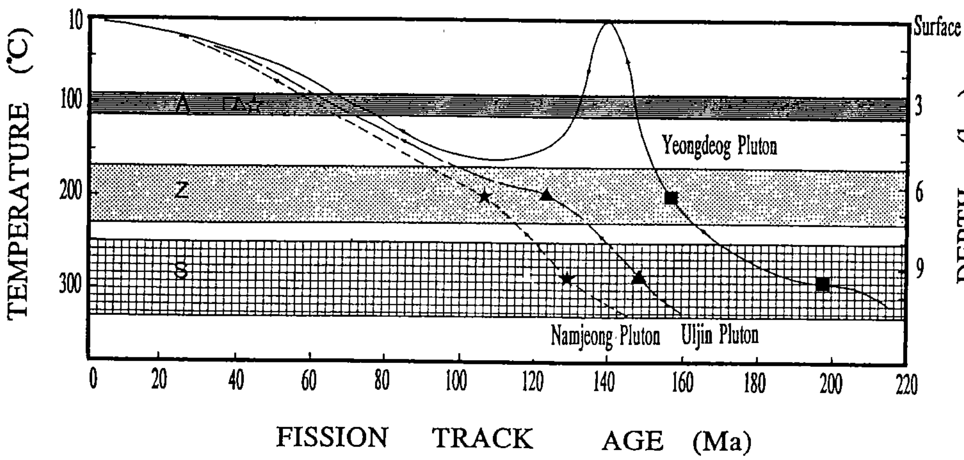

Fig. 3. Uplift and cooling paths for pre-Cretaceous granites in Southeast Korea. "S", "Z" and "A" denote annealing zones of sphene, zircon and apatite, respectively. Solid and open symbols indicate thermally-unaffected and partially-reduced ages, respectively.

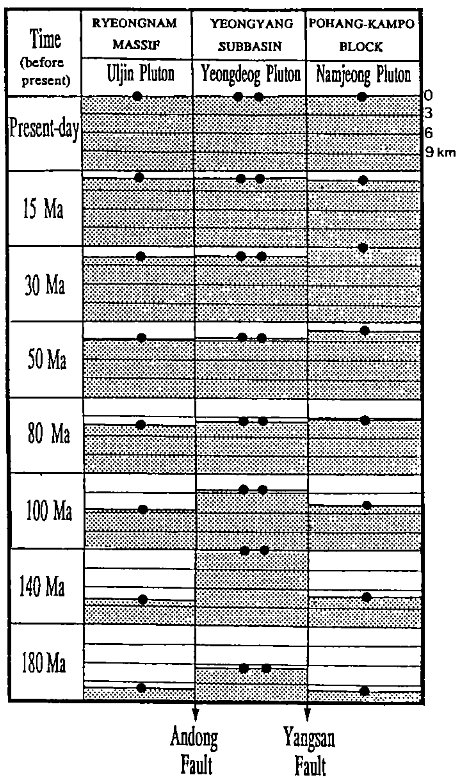

Fig. 4. A scheme for erosion-uplift histories of pre-Cretaceous granites in Southeast Korea. A horizontal heavy line represents present-day surface. Solid circle indicates the position of sample. Depths of critical isotherms for apatite, zircon and sphene annealing are shown for reference. Different uplift histories are evident in different geologic units.

13.0 μm (Fig. 1; Table 5). The pluton reveals roughly a right-skewed track length distribution with a tail of shorter (older) tracks suggesting a typical slow cooling history (Gleadow *et al.*, 1983, 1986a). Even in the same pluton, apatite ages are multiple due to different degrees of the later thermal overprints. For instance, the apatite age (~23 Ma) of a sample (168-7) would reflect a post-cooling partial annealing of fission tracks in apatites sometime during the early Paleogene. The original cooling age for apatite seems to be at least older than the maximum value (~40 Ma) of the sample 168-6.

In the northern edge of the Pohang-Kampo Block, the Jurassic Namjeong Pluton was contacted with post-Jurassic sediments and/or volcanics by the Yangsan Fault (Fig. 1). The markedly discordant FT ages for different closure temperatures indicate very slow cooling of the Namjeong Pluton (Fig. 2). The pluton cooled slowly with a mean rate of ~4℃/Ma over the 290-200℃ range taking about ~2×10^7 years (Table 6). Since middle Cretaceous (~106 Ma), the pluton cooled more slowly with a mean rate of 1.8℃/Ma over the range 200℃-present temperature (Table 7). This slow cooling can be attributed to the steady rate of removal of the overburden at about 0.06 mm/a (or 60 m/Ma) since middle Cretaceous. The Namjeong Pluton shows a typical bimodal track length distribution (Type III) which indicates an evident annealing of spontaneous tracks of apatites in the partial stability zone. Therefore, the original cooling age for apatite from the pluton should be higher than at least ~43 Ma. Although the sample is located near the Yangsan Fault and other coastal submarine faults, they do not show any evidence of tectonic heating or of hydrothermal activity related to the tectonic lines. The cause of the thermal overprinting event sometime after 43 Ma is still unknown.

The Meso-Cenozoic uplift was rather slow (~0.04 mm/a) in the Triassic Yeongdeog Pluton in the Yeongyang Subbasin compared with the two Jurassic plutons (~0.06 mm/a) in the two different geologic blocks (Fig. 3). Accordingly, estimated total uplifts since 100 Ma ago differ between different plutons in different geologic units: i.e., Uljin Pluton at the NE Ryeongnam Massif (~6 km)=Namjeong Pluton at the northern edge of the Pohang-Kampo Block (~6 km)>Yeongdeog Pluton in the Yeongyang Subbasin (~4 km) (Table 7).

The consistent values of the total uplifts for two samples from different locations in the Yeongdeog Pluton may suggest a slow and regional plateau uplift with a uniform rate over the whole body of a single pluton. It is also noted that the two Jurassic plutons in different geologic units (i.e., Ryeongnam Massif and Pohang-Kampo Block) have similar and stable uplift histories since the middle Cretaceous (Figs. 3 and 4).

CONCLUSION

The following conclusions are supported by FT thermochronological analyses of Mesozoic granites in Southeast Korea.

(1) Main difference in the overall cooling patterns are observed over a temperature range between 300℃ and 100℃ despite a rapid earlier cooling (e.g., >60℃/Ma) of most plutons. Three patterns are distinguishable: slow cooling (~1-4 ℃/Ma) for the deeply emplaced Jurassic plutons both in the Ryeongnam Massif and in the Pohang-Kampo Block; rapid to intermediate cooling (~7-15℃/Ma) for the middle Cretaceous plutons; and complicated cooling with heating episode for Triassic Yeongdeog Pluton in the Yeongyang Subbasin.

(2) The Cretaceous plutons lost most of their heat in the initial stage due to low-temperature country rocks at shallow depths. Depths of emplacement are expected based upon thermal eqilibria between intruding magma and pre-existing country rock time-cooling paths: much deeper than ~9 km and only ~1-2 km, respectively, for pre-Cretaceous and Cretaceous plutons.

(3) The Triassic Yeongdeog Pluton in the Yeongyang Subbasin, west of the Yangsan Fault, are characterized both by a rapid cooling (~12 ℃/Ma) during total unroofing and by a subsequent heating (~6-8℃/Ma) during the rapid basin subsidence in early Cretaceous. The pluton shows a complicated uplift-subsidence history: (i) slow uplift (~0.07 mm/a) over the 9-6 km-depths (~300-200℃) during the early to middle Jurassic (~200-160 Ma) → (ii) rapid uplift (~0.4 mm/a) up to surface (~200℃-surface temperature) during late Jurassic-earliest Cretaceous (~160-140 Ma) → (iii) rapid subsidence (~0.2 mm/a) down to 3-5 km-depths (~120-170℃) during early Cretaceous (~140-120 Ma) → (iv) slow uplift (~0.04 mm/a) up to present day (~120-0 Ma).

(4) The Jurassic plutons both in the northeastern wing of the Ryeongnam Massif (e.g., Uljin Pluton) and in the northern edge of the Pohang-Kampo Block, east of the Yangsan Fault (e.g., Namjeong Pluton) show coherently slow cooling (~4-2℃/Ma) over the 300℃-present temperature. The two geologic units are characterized by a slow continuous uplift: (i) slow uplift (~0.1-0.13 mm/a) over the 9-6 km-depths (~300-200℃) during middle Jurassic-early Cretaceous (~130-140 Ma to ~100-120 Ma) → (ii) continuous slow uplift (~0.06 mm/a) up to present day.

(5) The slow uplift since early Cretaceous may mainly depend upon very slow denudation of the overlying crust. Since the early Cretaceous, the Triassic pluton in the Yeongyang Subbasin uplifted rather slowly (~0.04 mm/a) compared with the Jurassic plutons (~0.06 mm/a) in the two different

geologic units. Accordingly, estimated total uplifts since 100 Ma ago are: Ryeongnam Massif (Uljin Pluton: ~6 km)=Pohang-Kampo Block (Namjeong Pluton: ~6 km)>Yeongyang Subbasin (Yeongdeog Pluton: ~4 km). The consistent values for two samples from different locations in the Yeongdeog Pluton may suggest a slow and regional plateau uplift with a uniform rate for the whole plutonic body.

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REFERENCES

Chang, K.H., Woo, B.G., Lee, J.H., Park, S.O. and Yao, A., 1990, Cretaceous and early Cenozoic stratigraphy and history of eastern Kyongsang Basin, S. Korea. J. Geol. Soc. Korea, 26, 471-487.

Chappell, B.W. and White, A.J.R., 1974, Two contrasting granite types. Pacific Geol., 8, 173-174.

Choo, S.H. and Kim, D.H., 1981, Rb-Sr age determination on Yucheon granites, Changweon granites and Andong granites and granitic gneisses. Korea Inst. Geosci. Min. Resour., Seoul, Rep. Geosci. Min. Resour., 13, 193-208 (in Korean).

Choo, S.H., Jin, M.S., Yun, H.S. and Kim, D.H., 1982, Rb-Sr age determinations on granite gneiss and granite in Seosan, Onjeongri granite, and Mesozoic granites along the east coast, Korean Peninsula. Korea Inst. Geosci. Min. Resour., Seoul, Rep. Geosci. Min. Resour., 13, 193-208 (in Korean).

Dodson, M.H., 1973, Closure temperature in cooling geochronological and petrological systems. Contr. Mineral. Petrol., 40, 259-274.

Ferrara, E., Macera, P. and Jin, M.S., 1983, Radiometric age and genesis of the Mesozoic magmatic rocks of the Korean Peninsula, with special reference to the Cretaceous magmatism (unpublished).

Fleischer, R.L. and Hart, Jr. H.R., 1972, Fission track dating: techniques and problems. In: W.W. Bishop, D.A. Miller and S. Cole (Editors), Calibration of Hominid Evolution. Scottish Academic Press, Edinburgh, pp. 135-170.

Galbraith, R.F., 1981, On statistical models for fission track counts. Math. Geol. 13, 471-478.

Geological and Mineralogical Institute of Korea: GMIK, 1973, Geological Map (1 : 250,000), Andong and Pusan Sheets.

Gleadow, A.J.W., 1981, Fission-track dating methods: what are the real alternatives? Nucl. Tracks, 5, 3-14.

Gleadow, A.J.W. and Duddy, I.R., 1981, A natural long-term annealing experiment for apatite. Nucl. Tracks, 5, 169-174.

Gleadow, A.J.W., Duddy, I.R. and Lovering, J.F., 1983, Fission track analysis: a new tool for the evaluation of thermal histories and hydrocarbon potential. J. Aust. Pet. Explor. Assoc. 23, 93-102.

Gleadow, A.J.W., Hurford, A.J. and Quaife, R.D., 1976, Fission track dating of zircon: improved etching techniques. Earth Planet. Sci. Lett., 33, 273-276.

Gleadow, A.J.W., Duddy, I.R., Green, P.F. and Hegarty, K.A., 1986a, Fission track lengths in the apatite annealing zone and the interpretation of mixed ages. Earth Planet. Sci. Lett., 78, 245-254.

Gleadow, A.J.W., Duddy, I.R., Green, P.F. and Lovering, J.F., 1986b, Confined fission track lengths in apatite: a diagnostic tool for thermal history analysis. Contrib. Mineral. Petrol., 94, 405-415.

Green, P.F., 1981, A new look at statistics in fission track dating parameters. Nucl. Track Detection, 1, 41-48.

Green, P.F., 1986, On the thermo-tectonic evolution of Northern England: evidence from fission track analysis. Geol. Mag., 123, 493-506.

Harrison, T.M. and McDougall, I., 1980, Investigations of an intrusive contact, northwest Nelson, New Zealand-I. Thermal, chronological and isotopic constraints. Geochim. Cosmochim. Acta, 44, 1985-2003.

Hurford, A.J. and Green, P.F., 1982, A users' guide to fission track dating calibration. Earth Planet. Sci. Lett., 59, 343-354.

Jin, M.S., 1980, Geological and isotopic contrasts of the Jurassic and the Cretaceous granites in South Korea. J. Geol. Soc. Korea, 16, 205-215.

Jin, M.S., Gleadow, A.J.W. and Lovering, J.F., 1984, Fission track dating of apatite from the Jurassic and Cretaceous granites in South Korea. J. Geol. Soc. Korea, 20, 257-265.

Jin, M.S., Seo, H.J., Lee, J.S., Chi, S.J., Kim, S.J., Kim, T.K. and Shin, S.C., 1991, Petrological and geochemical studies for the geothermal energy of the hot dry rock in South Korea. Korea Min. Sci. Technol., Seoul, Res. Rep. KR-91(T)-22, 168p. (in Korean).

Kim, J.W., 1988, Petrology and Fission Track Dating of the Granitic Rocks from the Vicinity of Yongdok-Onjong Area, Northeastern Gyeongsang Basin, Korea. Unpubl. Ph.D. thesis, Kyungpook Nat. Univ., Taegu, 139p. (in Korean).

Kim, S.J., 1986, K-Ar age determination of rock and

mineral. Korea Inst. Ener. Resour., Seoul, Res. Isot. Geol., KR-86-2-17, 29-97 (in Korean).
Korea Institute of Energy and Resources: KIER, 1981, Geological Map of Korea (1 : 1,000,000).
Laslett, G.M., Kendall, W.S., Gleadow, A.J.W. and Duddy, I.R., 1982, Bias in the measurement of fission track length distributions. Nucl. Tracks, 6, 79-85.
Lee, J.I., 1991, Petrology, Mineralogy and Isotopic Study of the Shallow-depth Emplaced Granitic Rocks, Southern Part of the Kyoungsang Basin, Korea—Origin of Micrographic Granite—. Unpubl. D.Sc. thesis, Univ. of Tokyo, Tokyo.
Naeser, C.W. and McKee, E.H., 1970, Fission-track and K-Ar ages of Tertiary ash-flow tuffs, north-central Nevada. Geol. Soc. Am. Bull., 81, 3375-3384.
Nishimura, S. and Mogi, T., 1986, The interpretation of discordant ages of some granitic bodies. J. Geotherm. Res. Soc. Japan, 8, 144-164.
Park, S.J., Kim, Y.J. and Jun, B.J., 1989, Thermal neutron measurement in the irradiation pipes of TRIGA Mark-III. Korea Adv. Energy Res. Inst., Seoul, Mem. Reactor Maint.-11, 17p. (in Korean).
Parrish, R.R., 1981, Cenozoic Thermal and Tectonic Histoty of the Coast Mountains of British Columbia as Revealed by Fission Track and Geological Data and Quantitative Thermal Models. Unpubl. Ph.D. thesis, Univ. of British Columbia, 166p.
Shin, S.C., 1987, Etching characteristics of fission tracks in minerals, and fission track dating and calibration of zircon. J. Geol. Soc. Korea, 23, 32-52.
Shin, S.C., 1990, Determination of low levels of uranium impurity by fission track registration. Korea Min. Sci. Technol., Seoul, Res. Rep. KR89 (B)-30, 53p. (in Korean).
Shin, S.C., 1992, Meso-Cenozoic Thermo-tectonic History of the Southeastern Korean Peninsula Evidenced from Fission Track Thermochronological Analyses. Unpubl. D.Sc. thesis, Kyoto University, Kyoto, 305p.
Shin, S.C. and Nishimura, S., 1991, Direct comparison of zeta calibration constants for fission-track dating by double-checking of two irradiation facilities with different degrees of neutron flux thermalization. Chem. Geol. (Isot. Geosci. Sect.), 87, 147-166.
Shin, S.C. and Nishimura, S., 1993, Thermo-tectonic history of the Pohang Subbasin: Fission track evidences from a deep borehole granite. J. Geol. Soc. Korea, Abstract.
Shin, S.C. and Park, K.S., 1989, Determination of low levels of uranium impurity by fission track registration using mica and polycarbonate detectors. Nucl. Tracks Radiat. Meas., 16, 271-274.
Zeitler, P.K., Tahirkhell, R.A.K., Naeser, C.W. and Johnson, N.M., 1982, Unroofing history of a suture zone in the Himalaya of Pakistan by means of fission-track annealing ages. Earth Planet. Sci. Lett., 57, 227-240.

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한국 동남부 중생대 화강암의 지열사와 지체융기사 : 새로운 피션트랙 열연대학적 증거

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요 약 : 한반도 동남부에 분포하는 중생대 화강암의 스핀, 저어콘과 인회석의 피션트랙연대 측정과 인회석내 자발 트랙의 소멸 특성을 이용한 열연대학적 연구는 심성암이 생성된 이후 지금까지 지질시대를 거쳐오면서 폐쇄온도별 냉각패턴과 복잡한 지열사의 규명은 물론, 각 암체가 속해 있는 영남육괴, 영양분지 및 포항-감포블록의 지체단위별 융기-침강사를 명확하게 해준다. 지역내의 백악기 화강암은 약 90-100 Ma 전에 정치된 이래 비교적 빠른 속도 (약 7-15℃/Ma)로 냉각하였으며, 주냉각 요인은 관입초기에 모암과의 큰 온도차에서 오는 급작스런 열의 손실에 기인한다. 폐쇄온도별 광물 연령으로 주어진 냉각곡선에 근거하면 백악기 암체의 정치 심도는 약 1-2.5 km 정도이며 선백악기 암체는 적어도 모암과의 열적 평형심도인 9 km보다는 훨씬 깊은 것으로 볼 수 있다. 양산단층의 서쪽에 자리잡은 영양분지의 영덕암체는 연구지역 가운데 가장 오래된 암석으로서 스핀의 피션트랙 연대는 197 Ma로, 관입정치시기는 트라이아스기로 분류된다. 이 암체는 약 0.07 mm/a의 속도로 천천히 융기하다가 약 0.4 mm/a의 빠른 속도로 상승한 후 백악기초에 지표에 노출되었다. 그 후 백악기 초기에는 하양층군의 퇴적에 수반된 분지침강과 더불어 약 0.2 mm/a의 속도로 다시 매몰된 것으로 밝혀졌다. 원래의 저어콘연령 (156 Ma)이 계속 안정하고 인회석연령이 완전히 리세팅된 사실은 당시 분지의 침강은 적어도 3.5 km보다는 깊고 5 km는 넘지 않았음을 지시한다. 백악기 초부터는 영양분지 지역은 침식작용에 의존한 채 매우 느린 약 0.04 mm/a의 속도로 융기하였다. 한편 안동단층의 북쪽에 해당하는 영남육괴의 북동단과 양산단층과 울산단층의 동부에 해당하는 포항-감포블록의 북단지역은 백악기초 이후 평균 약 0.06 mm/a의 속도로 매우 천천히 융기하였다. 즉 지금부터 약 100 Ma 이전인 백악기 중기부터의 총융기량은 영남육괴와 포항-감포블록의 경우는 약 6 km, 그리고 영양분지의 경우는 약 4 km로 계산된다.

핵심어 : 중생대 화강암, 피션트랙 열연대학, 융기, 지열사, 폐쇄온도