The depth of emplacement of the Mitsuhashi Granite pluton in the Ryoke Belt, central Japan - as inferred from some geobarometric calibrations*

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Introduction

The Ryoke granitoids have been regarded to be deeper than other Cretaceous granitoids in their level of emplacement in the Inner Zone of southwest Japan. The exact depth of their emplacement, however, has not been estimated hitherto, for the lack of appropriate geobarometers. During my petrological and geochemical study of the Mitsuhashi Granite pluton in the Ryoke Belt, central Japan, I found some mineral assemblages suitable for the geobarometric calibrations. In this paper I report the result of calibrations, briefly mentioning its petrogenetic implications.

Geological outline

The Mitsuhashi Granite pluton occurs within the Ryoke metamorphic rocks in the classic Dando area, eastern Aichi Prefecture (Koide, 1958). It is one of the representative Younger Ryoke granitoids (Ryoke Research Group, 1972). It has a semi-circular form about 8 km across, including the Kamihara Tonalite of the Older Ryoke granitoids, and its associated metabasic rocks in the core (Fig. 1).

The major rock-types are hornblende-biotite tonalite and low-K₂O granodiorite, with subordinate quartz diorite. Within tens to hundreds meters from the contact, a marginal facies has developed, and some of them have assimilated the metamorphic rocks. They are composed mainly of leucocratic garnet-biotite granite and granodiorite.

Detailed petrography and geochemistry of the pluton will be treated in another paper (Kutsukake, 1997).

Petrography

Hornblende-biotite tonalite (No. 83122705) This rock is a representative of the main facies. It has a hypidiomorphic-granular texture dominated by tabular euhedral to subhedral plagioclase. Some hornblende and biotite are also euhedral and subhedral. Quartz and alkali feldspar are almost everywhere anhedral and interstitial. Allanite, apatite, ilmenite and zircon are common accessories. The modal composition is as follows : 63.6% plagioclase, 13.7% quartz, 5.5% alkali feldspar, 12.1% biotite, 3.2% hornblende and 1.5% others.

Plagioclase is zoned with An₃₆₋₅₄. Alkali feldspar rarely exhibits a tweed-texture, and has a composition of about Or₉₇ Ab₀₃. Hornblende is an olive variety, and has a high R.I. attaining $\gamma=1.706$. Biotite is dark brown in Z-axial color and has $\gamma=1.672\sim1.679$. Ilmenite occurs almost always as tiny grains included by hornblende. Allanite is deep reddish brown, and in biotite it is surrounded by a pleochroic halo.

Whole-rock analysis is shown in Table 1. This analyzed specimen (No. 91112302) was collected from the same outcrop as the specimen No. 83122705.

Garnet-biotite granodiorite (No. 93031305 A) This rock represents the marginal facies, occurring within 10 m from the contact of the Ryoke gneiss. It is a coarse-grained, leucocratic, and hypidiomorphic-granular rock. The main constituent minerals are plagioclase (48.0%), alkali feldspar (13.3), quartz (31.2), biotite (5.4), garnet (1.5) and muscovite (0.5). Apatite, zircon and ilmenite are common accessories.

Subhedral to anhedral plagioclase is zoned with distinct boundary between the calcic core and sodic rim. It has a composition of An₂₆₋₄₁. Alkali feldspar shows faint tweed texture. Red garnets are unevenly distributed and up to 5 mm across. They occur as either single crystals or as clusters. Garnet has a R.I. of $n=1.813\sim1.815$. Biotite is deep brown in Z-axial color ($\gamma=1.664\sim1.668$). Muscovite occurs both as single flake and as in intergrowth with biotite.

Whole-rock analysis is shown in Table 1.

Mineral chemistry

Hornblende Electron-probe analysis of the hornblende is shown in Table 2a. To estimate Fe⁺³ content, Stout's (1972) method has been employed : the minimum Fe⁺³/Fe⁺² ratio based on 15 cations (exclud-

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Fig. 1. Geological map of the Mitsuhashi Granite pluton. Place name : K. Kasaijima ; M. Mitsuhashi.

ing Na and K) for a 23 (O) basis. It falls in the ferro-hornblende field of Leake's (1978) diagram.

Biotite Electron-probe analyses of the biotites in both the rocks are shown in Tables 2a & 2b. The biotite coexisting with the garnet is more aluminous than that coexisting with the hornblende.

Garnet Electron-probe analysis of the garnet is shown in Table 2b. An estimate of the Fe^{+3} content of a garnet analysis may be obtained by recalculation on the basis of $\text{Si} + \text{Al} + \text{Ti} + \text{Fe}^{+3} = 10$ per formula unit. Cations total nearly 16.00, indicating this method to be reasonable. Both the core and rim have more than 75% of almandine components, so they are properly called almandine. MnO is also important, especially in the rim where 14.4% is spessartine.

Muscovite Electron-probe analysis of the muscovite is shown in Table 2b. Phengite molecule is less than 7%. This composition is very similar to those of nearby occurring Busetsu Granite. (Czamanske et al., 1981).

Plagioclase Electron-probe analyses give the

compositions of An 36.4~53.5 for the hornblende-biotite tonalite and An 30.7~36.5 for the garnet-biotite granodiorite, respectively. Or content of all analysed plagioclases falls in the range 1.0~3.7 mole %.

Alkali feldspar Electron-probe analyses revealed the compositions of alkali feldspar to be $\text{Or}_{94.2\sim99.2}$ for the hornblende-biotite tonalite, and $\text{Or}_{89.7\sim91.8}$ for the garnet-biotite granodiorite, respectively. Ca-content is almost nil. Especially in the alkali feldspar of the tonalite, Ab content is extremely low.

Ilmenite Electron-probe analysis of ilmenite in the hornblende-biotite tonalite is shown in Table 2a. Recalculated $\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3 + \text{FeTiO}_3)$ mole ratio yields 0.04. MnO content is rather low, and the individual analysis falls in the range 2.6~4.7 wt.%. Mn-rich ilmenites have not been reported from the Ryoke granitoids (Czamanske et al., 1981).

Geobarometric calibrations

Total Al in hornblende It has been claimed that the total Al in hornblende may be used as a barometer

Table 1. Chemical analyses of rocks.

Specimen No.	I	II
	91112302	93031305A
SiO ₂	65.61	68.98
TiO ₂	0.32	0.30
Al ₂ O ₃	18.02	16.70
Fe ₂ O ₃	0.13	0.02
FeO	2.62	2.34
MnO	0.05	0.06
WgO	0.56	0.47
CaO	5.58	3.72
Na ₂ O	5.08	4.50
K ₂ O	1.11	2.13
P ₂ O ₅	0.10	0.15
L.O.I.	0.85	0.99
Total	100.03	100.36

Trace elements (in ppm)

Rb	27	58
Sr	471	335
Ba	570	1186
Th	5	9
Nb	9	9
Zr	225	193
Ga	18	22
Cr	6	3
V	25	17
Ni	4	3
Zn	55	48
Pb	10	18
Y	10	38
La	45	45
Ce	79	89
Nd	35	32

Analyzed by XRF method by S. A. Brown, Department of Geology, University of Canterbury, Christchurch, New Zealand.

Table 2. a. Electron-probe analyses and structural formula for the minerals in the tonalite (No. 83122705).

	Hornblende	Biotite	Ilmenite
SiO ₂	42.57 (0.57)	33.33 (0.81)	0.07 (0.09)
TiO ₂	1.32 (0.10)	3.82 (0.29)	51.29 (0.68)
Al ₂ O ₃	10.02 (0.24)	14.49 (0.20)	0.04 (0.02)
FeO*	24.59 (0.92)	27.62 (0.75)	44.13 (0.62)
MnO	0.61 (0.92)	0.31 (0.07)	3.90 (0.81)
MgO	4.98 (0.10)	5.26 (0.19)	0.01 (0.02)
CaO	11.23 (0.26)	0.05 (0.08)	0.07 (0.09)
Na ₂ O	0.89 (0.15)	0.05 (0.02)	0.00 (0.00)
K ₂ O	1.04 (0.08)	8.26 (0.66)	0.00 (0.01)
Total	97.25	93.19	99.51
	ΣCa = 15	O = 22	Si+Ti+Al+Fe ³⁺ = 2
Si	6.562	5.449	0.004
Al ^{IV}	1.438	2.551	0.002
Al ^{VI}	0.382	0.240	—
Ti	0.153	0.469	1.954
Fe ³⁺	0.439	—	0.040
Fe ²⁺	2.950	3.775	1.850
Mn	0.080	0.043	0.167
Mg	1.143	1.282	0.001
Ca	1.854	0.009	0.004
Na	0.267	0.016	0.000
K	0.204	1.722	0.000
Mg#	0.252	0.254	—
Mg/(Mg+Fe ²⁺)	0.279	—	—

ΣCa = 15 indicates all cations except Na and K normalized to 15. FeO* denotes total Fe as FeO.

Analyst: Y. Kawachi.

Hornblende, average of 6 analyses.
Biotite, average of 8 analyses.
Ilmenite, average of 6 analyses.

Figures in parentheses indicate the standard deviations.

b. Electron-probe analyses and structural formula for the minerals in the granodiorite (No. 93031305 A).

	Garnet		Biotite	Muscovite
	core	rim		
SiO ₂	35.62 (0.21)	35.45 (0.22)	32.82 (0.21)	46.05 (0.45)
TiO ₂	0.03 (0.01)	0.00 (0.00)	3.29 (0.25)	0.33 (0.35)
Al ₂ O ₃	20.74 (0.11)	20.81 (0.07)	18.87 (0.26)	37.18 (1.19)
FeO*	33.85 (0.50)	32.78 (0.89)	24.16 (0.83)	1.49 (0.35)
MnO	4.00 (0.31)	6.20 (0.62)	0.32 (0.02)	0.01 (0.01)
MgO	1.75 (0.10)	1.37 (0.17)	4.45 (0.29)	0.55 (0.25)
CaO	2.08 (0.36)	1.70 (0.30)	0.00 (0.00)	0.00 (0.00)
Na ₂ O	0.004(0.01)	0.00 (0.00)	0.08 (0.02)	0.33 (0.05)
K ₂ O	0.00 (0.00)	0.00 (0.00)	8.95 (0.08)	10.30 (0.18)
Total	98.54	98.31	92.94	96.24
	Si+Ti+Al+Fe ³⁺ = 10		O = 22	
Si	5.885	5.893	5.279	6.057
Al ^{IV}	0.115	0.107	2.721	1.943
Al ^{VI}	3.908	3.969	0.855	3.820
Ti	0.005	0.000	0.398	0.032
Fe ³⁺	0.087	0.032	—	—
Fe ²⁺	4.677	4.539	3.244	0.164
Mn	0.582	0.873	0.044	0.001
Mg	0.389	0.340	1.066	0.107
Ca	0.407	0.303	0.000	0.000
Na	0.002	0.000	0.025	0.084
K	0.000	0.000	1.835	1.729
Alm.	77.2	75.0	FeO* denotes total Fe as FeO.	
Spes.	9.6	14.4		
Pyrrp.	6.4	5.6		
Gros.	4.5	4.2		
And.	2.3	0.8		

Analyst: Y. Kawachi.

Garnet, core: average of 5 analyses, rim: average of 7 analyses.
Biotite, average of 13 analyses.
Muscovite, average of 4 analyses.

in tonalitic rocks, and four calibrations have been proposed (Hammarstrom and Zen, 1986; Hollister et al., 1987; Johnson and Rutherford, 1989; Schmidt, 1992).

Utilizing the analysis of hornblende in Table 2a and the rim composition (An_{36.4}) of plagioclase, the hornblende-plagioclase geothermometer (Blundy and Holland, 1990) yields a temperature of 780°C. This estimated temperature falls far higher above the tonalite-solidus (Fig. 2), and Schmidt's (1992) calibration is not likely applicable for pressure estimation, because it is valid only within 30° above the solidus. In these high-temperature conditions, Johnson and Rutherford's (1989) calibration should be appropriate, and the value of Al_T = 1.820 in the hornblende yields a pressure of 0.42 GPa (4.24 kb).

Plagioclase-biotite-garnet-muscovite geothermobarometer Thermodynamic equilibrium equations of Ferry and Spear (1978) and Ghent and Stout (1981) were utilized to estimate the P-T conditions during crystallization of the garnet-biotite granodiorite. In these calculations, I assumed ideal solid solution behavior of biotite and used the garnet activity model of Hodges and Spear (1982) to correct its non-ideal behavior.

Solutions of these equations, utilizing the data of Table 2b, yield a pressure of 0.42 GPa (4.18 kb) and a temperature of 660°C based on garnet and plagioclase (An_{30.7}) rim compositions.

These two independent geobarometric calibrations give almost the same pressure of 0.42 GPa, and this seems consistent. This pressure corresponds approximately to 15 km in depth.

These calibrations are plotted on the P-T diagram (Fig. 2). Estimated P-T for the garnet-biotite granodiorite falls above the granite solidus and also below the muscovite breakdown-curve, and this is in accord with the fact that muscovite is of magmatic origin.

Discussion

The depth of emplacement of the Mitsuhashi Granite pluton appears to be ca. 15 km, as above-mentioned. The present maximum crustal thickness is 30 km or more beneath the Ryoke Belt around this pluton, as deduced from explosion-seismic observations and analyses of the Bouguer gravity anomalies (Aoki et al., 1972; Kanamori, 1963). Estimated depth of emplacement suggests the crustal thickness to be 40 km or more at the time of emplacement. The host Ryoke metamorphic rocks were formed under the P-T conditions, attaining 0.45~0.50 GPa and 650±50°C (Ono, 1977). This pluton was emplaced within these thick crustal rocks. The presence of old crustal rocks, which constitute the lower crust beneath the Inner Zone of southwest Japan, has been substantiated by isotopic evidences (Shibata and Ishihara, 1979; Kagami et al., 1993). These lower crustal rocks are most likely to be protoliths of these

Fig. 2. P-T diagram.

● Estimated P-T for the tonalite.

◆ Estimated P-T for the granodiorite.

Phase diagram for Al_2SiO_5 -polymorphs: Holdaway (1971). Muscovite + quartz reaction - curve: Evans (1965). Solidus-curves for granite (Gr) and tonalite (Tn): Stern et al. (1975). And. andalusite; Kf. K-feldspar; Ky. kyanite; Ms. muscovite; Q. quartz; Sil. sillimanite; V. vapour.

granitoids, in view of the petrological and geochemical characteristics (Kutsukake, 1997).

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