TEMPERATURE AND PRESSURE OF THE RYOKE GNEISSES ESTIMATED BY GARNET-CORDIERITE GEOTHERMOMETER

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Cordierite and garnet of gneissic rocks from Takato were studied to estimate temperature and pressure of the Ryoke metamorphism. It is turned out that temperature is about 600°-650°C and pressure is 4.5-5 kb.

INTRODUCTION

Metamorphic temperature and pressure may be estimated from experimental phase diagrams and thermodynamic properties of minerals and H₂O. Chemical compositions of garnet and cordierite coexisting with sillimanite and quartz have been demonstrated to be useful in estimating pressure and temperature of metamorphism (Currie, 1971; Hutcheon *et al.*, 1974; Tracy *et al.*, 1976; Thompson, 1976; Wells, 1976). In this note, this geobarometer is applied to estimate metamorphic pressure of the Ryoke gneisses in central Japan.

THERMODYNAMIC CONSIDERATION

Reaction A has been studied experimentally by Weisbrod (1973).

This reaction is represented by the equation:
 $p'_{\text{H}_2\text{O}} = p'_s = -3T + 6369 \cdots \cdots (1)$ where $p'_{\text{H}_2\text{O}}$, p'_s and T are pressure of H₂O in bars, pressure of solid phases in bars and temperature in Kelvin, respectively. Water content of natural cordierite is about 2-3

wt% on the basis of weight loss of the mineral in a reduced atmosphere. This value is consistent with water content of synthetic cordierite (Weisbrod, 1973). Therefore, $3n$ in reaction A is about 2 at $650^\circ \pm 50^\circ\text{C}$.

Reaction A in natural system depends on temperature, pressure of solid phases (p_s), activity of water and activities of Fe-cordierite and almandine components. The equilibrium of reaction A at ($T, p_s, p_{\text{H}_2\text{O}}$) can be described by

$$2\mu^\circ_{\text{H}_2\text{O}}(T, 1) + 2RT \ln f(T, p_{\text{H}_2\text{O}}) + \Delta^\circ G_s(T, 1) + (p_s - 1) \Delta V^\circ_s(T, 1) + 6RT \ln K = 0 \cdots \cdots (2)$$

where $\mu^\circ_{\text{H}_2\text{O}}(T, 1)$ is chemical potential of pure water at temperature $T^\circ\text{K}$ and 1 bar, $f(T, p_{\text{H}_2\text{O}})$: fugacity of water at T and $p_{\text{H}_2\text{O}}$, $\Delta^\circ G_s$: change in Gibbs free energy of pure solid phase components in reaction A, V°_s : volume changes of pure components of solid phases, K : equilibrium constant (mole fraction of almandine component in garnet/mole fraction of Fe-cordierite component in cordierite).

It has been assumed that volume changes of solid phases in reaction A are not functions

of pressure and temperature. An ideal solution on equivalent sites has been assumed for garnet and cordierite.

$\ln K$ would be zero for pure system, because for pure phases the activity is unity. Reaction A at (T, p'_s, p'_{H_2O}) can be described in pure system as follow:

$$2\mu_{H_2O}^{\circ}(T, 1) + 2RT \ln f(T, p'_{H_2O}) + \Delta G_s^{\circ}(T, 1) + (p'_s - 1) \Delta V_s^{\circ}(T, 1) = 0 \quad \dots (3)$$

From equations 1, 2 and 3, the following equation can be derived.

$$p_s = - \left(3 + \frac{6R \ln K}{\Delta V_s^{\circ}} \right) T - \frac{2RT}{\Delta V_s^{\circ}} \ln f/f' + 6369 \quad \dots (4)$$

where $f' = f(T, p'_{H_2O}) = f(T, -3T + 6369)$

Fugacity of water has been obtained from the results of Burnham *et al.* (1969) and ΔV_s° is -3.95 cal/bar (Weisbrod, 1973). $\ln K$ is about 0.55 ± 0.1 for the Ryoke gneisses. Substitution of these values into equation 4 yields pressure at a given temperature, provided p_{H_2O} is half of p_s . Because Ryoke gneisses contain graphite, p_{H_2O} may be equal to about half of p_s at $600 \pm 50^\circ\text{C}$ (French, 1966). In this note, $p_{H_2O} = 1/2 p_s$ is assumed in thermodynamic calculations. (If p_{H_2O} is $1/3 p_s$, pressure (p_s) becomes about 400 bars lower than that calculated below.)

Calculated pressure is relatively constant in spite of changes in temperatures. Hence, chemical compositions of garnet and cordierite can be used for a geobarometer as shown in Fig. 1. In this figure, phase relations of Al_2SiO_5 minerals after Holdaway (1971) is shown together with a p-T curve of muscovite+quartz reaction under $p_{H_2O} = 1/2 p_s$ which is calculated from the results of Chatterjee and Johannes (1974).

Fig. 1 Garnet-cordierite geobarometer $K = (\text{Fe}/\text{Fe} + \text{Mn} + \text{Mg} + \text{Ca in garnet}) / (\text{Fe}/\text{Fe} + \text{Mn} + \text{Mg in cordierite})$
M: muscovite + quartz = Al_2SiO_5 + sanidine + water, $p_{H_2O} = 1/2 p_s$.
R: possible geothermal gradient during the Ryoke metamorphism

Temperature can be calculated from enthalpy and entropy changes of iron and magnesium exchange reaction between garnet and cordierite (Hensen and Green, 1972; Thompson, 1976; Wells, 1976), although experimental results show considerable scatter of the equilibrium constant.

APPLICATION

Garnet and cordierite coexisting with sillimanite, quartz, graphite and biotite have been analyzed by means of electron probe microanalyzer. All gneisses were sampled from Takato town along the Mibu river except for one gneiss from Tenryukyo region. Analytical results are given in Table 1. Garnets in two thick segregation veins are homogeneous in chemical composi-

Table 1. Chemical data of garnet and cordierite

	garnet				cordierite			lnK	K*	°C
	X _{Fe}	X _{Mn}	X _{Mg}	X _{Ca}	X _{Fe}	X _{Mn}	X _{Mg}			
A	75.10	19.28	13.00	1.60	42.43	1.97	55.58	0.57	7.56	635
B	70.36	15.86	11.83	1.93	43.16	3.30	53.52	0.49	7.37	645
C	70.78	14.52	12.41	2.27	39.22	1.92	58.84	0.59	8.55	608
D	62.99	26.02	9.17	1.80	38.75	5.53	55.71	0.48	9.86	560
E	75.57	9.39	12.53	2.49	38.16	1.85	59.98	0.68	9.47	570
F	63.43	22.91	11.74	1.88	34.81	3.52	61.66	0.60	9.57	570
T	69.85	17.49	10.39	2.25	40.25	2.79	56.95	0.55	9.51	570

tion (A and B in Table 1). The other garnets showed reverse zonings at the crystal margins. Most of garnet listed in Table 1 are constant in composition at the crystal edges.

Calculated temperatures from the vein minerals are 635° and 645°C which are higher than the others. This result is due to the fact that segregation veins were formed during highest temperature of the Ryoke metamorphism and retrogressive metamorphism did not take place after the solidification of vein materials. Reverse zoning of garnet may be formed during cooling period of the metamorphic belt.

ln K ranges from 0.48 to 0.68. The variation is not due to analytical error because repeated analyses gave the same results. Calculated pressure is 4.5 to 5.0 kb at 650°±50°C. This estimation is based on the reasonable assumption of $p_{H_2O}=1/2 p_s$. Thermodynamic calculations of Wells (1976) indicate that p_{H_2O} is about half of p_s in upper amphibolite facies.

Sillimanite isograd which is defined by transformation of andalusite to sillimanite (fibrolite) is located below about 1.5 kb from the analyzed gneisses, provided isogradic surface is parallel to bedding planes. Sillimanite isograd is near 540°C, 3 kb according to the phase diagram of Al₂SiO₅ minerals after Holdaway (1971). This estimation is consistent with absence of kyanite and

stable association of muscovite, quartz, graphite and orthoclase at sillimanite isograd. K is 1.007 at $(T, p_s, p_{H_2O}) = (540^\circ \text{C}, 3200 \text{ bar}, 1600 \text{ bar})$. Almandine content in garnet at sillimanite isograd is approximately similar to Fe/(Fe + Mn + Mg) ratio of cordierite. As most of cordierites in the Ryoke belt are about 0.40 ± 0.04 in this ratio regardless of metamorphic grade, garnet coexisting with sillimanite, cordierite and quartz near the sillimanite isograd may be very poor in almandine component and rich in spessartine component. Garnet is, however absent in cordierite-bearing rocks near the sillimanite isograd. The lowest almandine content in garnet coexisting with sillimanite is 57 mole %, although it is the value at central part of a large garnet.

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ザクロ石-キンセイ石地質温度・圧力計による領家片麻岩の温度と圧力

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共存するザクロ石とキンセイ石の元素分配とキンセイ石の分解反応の実験データから領家片麻岩の形成条件を調べた。水の圧力は固相圧の半分として計算した結果、石英とシリマナイトと共存するこれらの鉱物の化学組成は有効な圧力計になる。温度が $650^\circ \pm 50^\circ \text{C}$ で圧力は 4.5~5.0 kb である。領家変成岩は低圧下で出来た特殊な変成岩という見方は妥当ではない。