Differential stress of the low P/T type Ryoke regional metamorphism, in central Kinki, Japan

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Studied is metachert, which has been subjected to the low P/T type Ryoke regional metamorphism, in central Kinki, Japan. Deformed radiolarian remains included in metachert indicate that the deformation during the metamorphism seems to be uniaxial and the maximum extensional direction is parallel to the principal lineation, as already demonstrated in the Sanbagawa metamorphic terrane, forming "a pair" with the Ryoke metamorphic terrane. The grain size paleopiezometer (Mercier *et al.*, 1977) and the dislocation density paleopiezometer (McCormick, 1977) of quartz give about 75 MPa and 40 MPa of the flow stress in the low metamorphic grade zone and about 10 MPa and 8 MPa in the high grade zone, respectively. The natures of the paired metamorphic belts seem to be very similar in such rheological aspects as the apparent uniaxial strain of fossils and the magnitude of differential stress.

Introduction

Miyashiro (1961) demonstrated that two regional metamorphic belts showing similar geologic ages but having different metamorphic facies series run side by side, forming a pair, in the Circum-Pacific regions. The concept of "paired metamorphic belts" significantly shows that the belts of high and low geothermal gradients intimately run side by side in an "orogenic belt".

Some authors have supposed that the arc-trench gap existed between the sites of "paired" metamorphism. Assuming that the surface heat flow across the typical arc-trench system reflects the geothermal gradient in the upper crust, some authors correlated the tectonic site of the high P/T type regional metamorphism to the trench region and that of the low P/T type one to the volcanic arc region (*e.g.* Oxburgh and

Turcotte, 1971; Miyashiro, 1972). On the other hand, the others consider the absence of the "arc-trench gap" the original situation because a high P/T type regional metamorphic belt is often in immediate contact with a low P/T type one at a tectonic boundary (Scholz, 1980). It may be said without exaggeration that the analysis of the strain and paleo-differential stress during metamorphisms gives some important criteria to solve the question of how and where "paired metamorphic belts" were formed.

Recently some quantitative researches on the rheology of some regional metamorphisms have been made. As for the high P/T type regional metamorphism, Toriumi (1982) and Noda and Toriumi (1982) estimated the strain and flow stress of metacherts in the Sanbagawa metamorphic terrane. Their results imply that

the Sanbagawa regional metamorphism occurred in a large-scale ductile shear zone under the condition of the very high differential stress.

On the other hand, as for the Ryoke metamorphic terrane, which forms a pair with the Sanbagawa metamorphic terrane, no systematic study has been made, although the few data by Toriumi (1978) and Masuda (1980) mean that the flow stress during the low P/T type regional metamorphism was much lower than that during the high P/T type regional metamorphism. This paper estimates the flow stress and strain during the Ryoke regional metamorphism mainly in the lower metamorphic grade zones in order to compare the data with those of the Sanbagawa metamorphic terrane and to consider the tectonics forming the paired metamorphic belts.

Outline of geology

The studied area is located in the southern margin of the Tamba belt and in the northern margin of the Ryoke metamorphic belt (Fig. 1). The outline of geology has been revealed by several authors (*e.g.* Nakajima, 1960; Hara, 1962; Yoshizawa *et al.*, 1966; Yao, 1968; Yokota *et al.*, 1976). A simplified geologic map is shown in Fig. 2.

The pre-Cenozoic sedimentary piles in the Tamba belt are composed of mudstone, sandstone and chert (usually bedded) with small bodies of limestone, "greenstones" and andesitic tuff (Nakajima, 1960; Yao, 1968). Middle Permian fusulinids occur in some limestone (Nakajima, 1960; Yao, 1968) and Triassic conodonts in some bedded chert (Yoshida, 1978). These lithofacies of the pre-Cenozoic sedimentary piles can be correlated to the geosynclinal piles in the

Fig. 1. Index map of the studied area.

Inner Zone of Southwest Japan. So these piles are likely to compose the tectono-stratigraphic units formed by the large-scale horizontal reconstruction of strata in latest Jurassic or earliest Cretaceous age (Mizutani, 1982).

The crystalline piles in the Ryoke metamorphic belt are composed of siliceous and pelitic gneiss, the original rocks of which are probably correlated with the pre-Cenozoic sedimentary piles in the Tamba belt, and of sheet-like granitic bodies emplaced concordantly with those metamorphic rocks (Nakajima, 1960; Hara, 1962).

Discordant granitic intrusive bodies caused contact metamorphisms in the pre-Cenozoic sedimentary and/or crystalline piles within narrower zones (Nakajima, 1960).

The bedding plane of the sedimentary and crystalline piles, which generally strikes

Fig. 2. Simplified geologic map of the studied area compiled from Yoshizawa *et al.* (1966), Yao (1967) and Yokota *et al.* (1976).

1, Cenozoic sediments; 2, Granitic intrusives; 3-5, Pre-Cenozoic sedimentary piles (3, Mudstone; 4, Chert; 5, Sandstone); 6-7, The Ryoke metamorphic piles (6, Gneiss; 7, "Older granitic rocks")

G, Gonokuchi; K, Kasagi; W, Wazuka.

WNW-ESE and dips steeply northward, is regionally stable though mesoscopic minor-scale folds often occur in some places. The principal planar structure, easily recognized

as cleavage and/or dimensional preferred orientation of very fine phyllosilicates, is nearly parallel to the bedding plane. The principal planar structure runs across the

Fig. 3. Metamorphic zoning map and sample localities.

1, Zone I; 2, Zone II; 3, Zone III; 4, Granitic intrusives; 5, Cenozoic sediments; 6, Sample localities.

G, K, W, see Fig. 2.

bedding plane where the latter shows minor-scale folds in some bedded chert (Hara, 1962). The principal lineation, represented by faint parallel striations or grooves and sometimes lattice preferred orientation on the principal planar structure, generally strikes WNW-ESE and plunges slightly westward. Hara (1962) revealed that the sedimentary piles generally have the con-

cordant regional structures with the crystalline piles from micro- to macro-scopic orders.

The studied area is roughly divided into three regional metamorphic grade zones, the Zone I, Zone II and Zone III with increasing metamorphic grade, and subordinate contact aureoles (Nakajima, 1960; Hara, 1962) (Fig. 3). The rocks in the Zone I are poorly recrystallized (neomineralized)

and bear metamorphic chlorite, muscovite and few amounts of biotite in pelitic rocks. Lattice preferred orientation of quartz in meta-chert is hardly recognized, which makes it ambiguous whether the rocks in the Zone I suffered the Ryoke regional metamorphism. In the Zone II chlorite is not common and both muscovite and biotite are abundant in pelitic rocks. Lattice preferred orientation of quartz in metachert is distinct in this and the next zones. The Zone III is located in the northern margin of the Ryoke metamorphic belt. Metachert, meta-sandstone and metapelite appear typical gneiss structures. Metamorphic cordierite and/or andalusite are abundant in metapelite. Though the Zone I and Zone II have been conventionally assigned within the Tamba belt, the petrological data of Nakajima (1960) and Hara (1962) and the

rheological data of this study (see the following chapter) show that both the Zone I and Zone II have been subjected to the Ryoke regional metamorphism.

Studied are 30 samples of metachert (22 samples in the Zone I, 7 in the Zone II and 1 in the Zone III), shown in Fig. 3. Metachert is one of the most appropriate materials for rheological studies because (1) it is mono-mineralic rock lacking of detrital quartz and (2) it includes good strain markers, radiolarian remains, whose original shape is statistically spherical (Toriumi, 1982).

Solid state plastic flow of quartzose rocks

The following two sections of some samples are preliminarily made; one is

Fig. 4. Photomicrographs of deformed radiolarian remains.
 A, Sample no. 12, cut along the bc plane (Zone I).
 B, Sample no. 12, cut along the ac plane.
 C, Sample no. 56, cut along the bc plane (Zone I).
 D, Sample no. 56, cut along the ac plane.
 Bar represents 100 μm in length.

parallel to the principal lineation and perpendicular to the bedding plane (bc section) and the other is perpendicular to both (ac section). They reveal that the radiolarian remains are deformed and that the strain seems to be uniaxial and the maximum extensional direction is parallel to the principal lineation (Fig. 4). This is the same as that of the Sanbagawa metamorphic terrane (Toriumi, 1982; Noda and Toriumi, 1982). The magnitude of the strain will be expressed in terms of the principal extensional strain estimated from the deformed radiolarian remains as

$$e = 2/3 \times \ln(a_1/a_3) \quad (1)$$

in which a_1 and a_3 are the lengths of the

maximum and minimum axes of the elliptical radiolarian remains, respectively (Toriumi, 1982).

Table 1. Data of strain estimated from deformed radiolarian remains

Zones	Sample Nos.	Strain (%)	σ	N. R.
I	10	73	18	29
	11	58	14	40
	12	56	20	35
	41	71	16	14
	43	56	20	31
	44	53	15	31
	48	97	16	25
	49	46	13	39
	57	39	10	40
	58	53	14	40
	61	53	11	40
	65	56	08	32
II	15	75	15	38
	19	46	07	16

σ , standard deviation; N.R., Number of measured radiolarian remains.

Fig. 5. Photomicrographs of microstructures of metachert cut along the bc plane. Crossed polarizers.

A-C, Equant quartz grains and phyllosilicates showing dimensional preferred orientation.

A, Sample no. 10 (Zone I)

B, Sample no. 19 (Zone II)

C, Sample no. 25 (Zone III)

D, Equant quartz grains composing deformed radiolarian remains. Sample no. 56 (Zone I)

Bar represents 100 μm in length.

The axes of 14–40 deformed radiolarian remains are measured on the bc section of each sample and the magnitude of the strain is calculated by the equation (1). The radiolarian remains included in the muddy layers of bedded chert are not measured because they sometimes give the larger strain than those in the siliceous layers. The results are listed in Table 1. It obviously shows that the radiolarian remains are strongly deformed than those commonly recognized in the Inner Zone of Southwest Japan reported by Iwao (1962, Fig. 2). In addition to the deformed radiolarian remains, Yao (1968) reported abnormally elongated fusulinids in limestone at Loc. X (Fig. 3). The strain of the fusulinids seems to be uniaxial and the maximum extensional direction is parallel to the principal lineation. Thus the plastic deformation of those rocks is considered to have taken place during the Ryoke regional metamorphism.

Flow stress inferred from the dislocation density and grain size paleopiezometers

Flow stress during deformation of rocks can be inferred from paleopiezometers. When metals or minerals are in steady state plastic deformation (flow) under constant differential stress, unbound dislocation density and syntectonically recrystallized grain size give steady state (constant) values. For the first approximation the steady state dislocation density and grain size do not depend on the temperature, the confining pressure or the strain rate but only on the applied differential stress (*e.g.* Weathers *et al.*, 1979). Assuming that these microstructures were in steady state and that these have been frozen, we can infer the

differential stress during the steady state flow by examining these microstructures, which is a principle of the paleopiezometer as the paleo-stress scale.

It must be impressed that the rate of each microstructural change is quite different. The generation of nuclei and the growth of new grains needs "more periods (time and/or strain)" than the migration of dislocations, in other words, the grain size is more refractory than the dislocation density (Weathers *et al.*, 1979).

Dislocation density is calculated from X-ray line broadening. Assuming that the stored energy calculated from the broadening of the X-ray line profile is wholly ascribed to the elastic energy around dislocations and that dislocations homogeneously distribute and don't interact together, then for quartz

$$(0.74 \beta / 4 \tan \theta)^2 = 4.175 \times 10^{-17} \rho \ln 0.1148 \times 10^8 \rho^{-0.5} \quad (2)$$

where ρ , β and θ are dislocation density (/cm²), broadening of full half maximum value of X-ray line profile (rad) and Bragg's angle, respectively (Aikawa, in prep.). The dislocation density calculated in this way is preferable for geological uses to what is directly counted with a transmission electron microscope (TEM) because the former represents a mean value of many grains in a hand specimen.

Samples are mechanically powdered, purified of impurities except quartz in hot phosphoric acid. No plastic flow occurs during grinding processes under room temperature and an atmospheric pressure (Bursill and McLaren, 1965). In order to relax the residual stresses between grains or subgrains and to remove the size effects of very fine particles, the sizes of the powder are limited from 5 μ m to 20 μ m obtained

by means of precipitation in ethanol using the Stokes' formula (lower limit) and meshing by a sieve (20 μm , upper limit). The sizes of almost all grains of quartz in meta-chert are larger than 5 μm in all samples under an optical microscope and the X-ray line broadening ascribed to the fine particle size is not detected except for one sample which is rejected in this study. Because the most grains of quartz in metachert range from 10 μm to 25 μm in diameter, the purified quartz powder ranging from 5 μm to 20 μm in diameter should remain no or little residual elastic strain. So it may be supposed that the X-ray line broadening is ascribed only to the local elastic strain around dislocations in quartz.

The operating conditions of the X-ray powder diffractometer are as follows: Cu-K α radiation 35 KV 15 mA, Ni-filter, slit 1°–0.15 mm–1°, range 200 cps, time constant 1 sec, scanning rate 1/4 degree/min (2 θ), chart speed 10 cm/min. Dislocation density is calculated in six line profiles, namely 206, 413, 420, 315, 324 and 216, the line broadenings of which are normalized by the standard line profiles of Brazil quartz prepared in the same way. Flow stress is determined as a mean of the six values calculated in each line profile by the relation of McCormick (1977):

$$\sigma = 1.64 \times 10^{-4} \rho^{0.66} \quad (3)$$

where σ and ρ are differential stress (MPa) and dislocation density (/cm²), respectively.

The sample appropriate for the paleo-stress estimation by the grain size paleo-piezometer is limited because a lot of veins and/or fine-grain minerals except quartz prevent the measurement of the grain sizes of quartz. Grain size as a geometric mean of the maximum and minimum diameters is measured on polished bc section under an optical microscope. The aspect ratio of the

Table 2. Data of flow stress estimated from dislocation densities using the relationship of McCormick (1977) and grain sizes using that of Mercier *et al.* (1977)

Zones	Sample Nos.	D. D. ($10^6/\text{cm}^2$)	Stress (MPa)	σ	G. S. (μm)	Stress (MPa)	σ
I	10	153	40	13	11	69	+18-11
	11	68	23	8	10	74	+21-12
	12	46	18	4	11	71	+16-11
	41	166	43	11	10	74	+32-16
	42	147	40	7	13	62	+25-13
	43	118	35	6	9	80	+26-15
	45	104	32	7	9	80	+15-11
	46	168	43	12			
	47	165	42	14	12	65	+15-09
	48	121	35	9	11	69	+18-11
	53	37	16	5			
	56	65	23	6			
	57	19	10	3	16	53	+12-08
	58	10	7	3	17	53	+10-09
	60	88	28	7	14	57	+17-10
	61	26	12	6	13	62	+18-11
	63	4.3	4	2	17	51	+12-09
	65	26	12	5	22	43	+10-06
	66	4.5	4	1	11	69	+17-11
	67	8.8	6	3	20	45	+09-06
II	15	30	14	4	17	51	+14-08
	17	65	23	6	21	44	+11-07
	18	54	20	5	22	42	+14-07
	19	28	13	3	42	27	+10-05
	50	77	25	10	16	53	+12-08
	51	99	30	9	21	44	+14-08
	52	49	19	8	23	41	+15-08
III	25	24	12	4	180	9	+03-02

D.D., Dislocation density; G.S., Grain size; σ , Standard deviation.

quartz grain is usually less than 2, which is smaller than that of the deformed radiolarian remain. A mean value of 40 grains except the grains of porphyroblasts, radiolarian remains and veins is adopted and flow stress is calculated by the relation of Mercier *et al.* (1977):

$$\sigma = 381 \times D^{-0.71} \quad (4)$$

where σ and D are differential stress (MPa) and grain size (μm), respectively. The results of the paleo-stress estimation are listed in Table 2.

The graphical comparison between the flow stresses inferred from the grain sizes and dislocation densities shows that the data of the Zone II and Zone III appear nearly the linear relation and that those of the Zone I are widely scattered (Fig. 6).

The distribution of the low stress inferred from the dislocation densities has

Fig. 6. Comparison between flow stresses inferred from grain sizes and dislocation densities of quartz in metachert using the relations of Mercier *et al.* (1977) and McCormick (1977), respectively.

systematically influenced by the huge granitic intrusive bodies: the lower values of the stress distribute near the granitic bodies (Fig. 7). Moreover, Fig. 6 shows that the range of the scattering values inferred from the grain sizes is narrower than that inferred from the dislocation densities so far as the samples in the Zone I are concerned. These implies that the granitic bodies annealed the quartz with the high lattice strain under the condition of the low differential stress. Because the grain size is more refractory than the dislocation density, the grain size must have hardly changed to the larger one while the disloca-

tion density should have decreased more rapidly.

In order to remove the annealing effect by the granitic intrusive bodies, only the data which give greater than 30 MPa of the flow stress by the dislocation density paleopiezometer are to be adopted as the data in the Zone I. The selected flow stresses inferred from two paleopiezometers clearly have the linear relationship, say, the flow stresses decrease with the increasing metamorphic temperature (Fig. 8). Reasonable is that the high flow stresses of the Zone I are caused by the Ryoke regional metamorphism, because (1) the high dislocation densities cannot be obtained during the static processes of diagenesis, (2) meta-chert in the studied area suffered the solid state plastic deformation of more than 50% in strain during the Ryoke regional metamorphism, (3) the tectonic stress accompanied with the post-metamorphic uplift cannot be significant judging from the low values of the stress estimated in the high metamorphic grade zones, which were buried to the deeper site than the lower grade zone and (4) the data indicate the flow stress prior to the post-metamorphic granitic intrusions.

Discussion

In order to examine the rheology of the regional metamorphic belt, the data in higher metamorphic grade zones as well as in lower grade zones are also important. Our preliminary study (Nagao and Aikawa, in prep.) in the Mikawa Plateau has revealed that the flow stresses recorded in the siliceous gneiss are very low, as outlined in Fig. 8., in the andalusite zone (approximately correlated with the Zone III in this study), the sillimanite zone and the

Fig. 7. Areal distribution of flow stress estimated from dislocation densities using the relation of McCormick (1977).

Other legends are to be referred to Fig. 3.

sillimanite-K-feldspar zone defined by Asami *et al.* (1982). Led is the fact that the stress distribution across the Ryoke metamorphic terrane consists of two levels: the high stress in the Zone I and the low stress in the Zone III and the higher grade zones in the Mikawa Plateau. The similar stress distribution is also recognized in the Sanbagawa metamorphic terrane (Toriumi, 1982).

The distinct decrease of the flow stress seems to occur at nearly the same metamorphic temperature in both the Ryoke and Sanbagawa metamorphic terranes. In the Sanbagawa metamorphic terrane, the stress decreases near the boundary between the greenschist facies zone and the epidote-amphibolite facies zone (Toriumi, 1982), while the same phenomenon is recognized near the boundary of the Zone I and Zone

Fig. 8. Comparison of selected flow stresses so as to remove the annealing effect by the granitic intrusives.

The values of stress decreased with the rise of metamorphic grade. Additionally shown is the range of the values of the higher grade zones in the Mikawa Plateau.

II in the Ryoke metamorphic terrane. As previously mentioned, chlorite disappears at the boundary between the Zone I and Zone II, which is roughly correlated to the epidote-amphibolite facies zone (Ono, 1969).

The possible two extreme interpretations on the abrupt decrease of the stress are the mechanical weakening of quartz during the metamorphism and the post-metamorphic annealing above the "critical" metamorphic temperature. If the metamorphic temperature became above the *critical temperature* at which quartz mechanically weakens, then the flow stress should

have abruptly decreased as a result of the hydrolytic weakening of quartz (Griggs, 1967). On the other hand, if the tectonic stress had been relaxed before the temperature decreased to the critical temperature under which the grain size and dislocation density are practically frozen, then dislocation annihilation and grain growth should have occurred because both grain growth and dislocation migration are thermally activated processes. Either of these two interpretations can explain the stress distribution in Fig. 8. It is very difficult to emphasize one from the two alternative interpretations. Thus the authors tentatively regarded the value of stress in the low metamorphic grade zones under the critical temperature as the magnitude of the differential stress which characterizes the regional metamorphism.

The flow stress during the Ryoke regional metamorphism is estimated at about 40 MPa from the dislocation density paleopiezometer and about 75 MPa from the grain size paleopiezometer in the lowest metamorphic grade zone, or the Zone I (Fig. 8). On the other hand, the grain size of quartz in metachert in the Sanbagawa metamorphic terrane is about 10 μm except the highest grade zone (Toriumi, 1982), which gives some 75 MPa as flow stress during the Sanbagawa regional metamorphism using the relation of Mercier *et al.* (1977). This value is not significantly different from that of the Ryoke regional metamorphism, and so the flow stress during the low P/T type Ryoke regional metamorphism may be as high as that during the high P/T type Sanbagawa one.

Needless to say, as the paleopiezometers themselves have some kinds of ambiguity, the authors do not adhere to the reliability of the absolute values of the differential

stress. They should be used as the excellent relative scale of paleo-differential stress. The authors wish to emphasize that the natures of the paired metamorphic belts seem to be similar in terms of such rheological aspects as the uniaxial strain of fossils and the magnitude of differential stress. The higher grade zones of the Ryoke metamorphic terrane may have been more extraordinarily deformed because of nearly the same differential stress and higher metamorphic temperature than the Sanbagawa metamorphic terrane, which suggests the possibility that the paired metamorphic belts were originally formed in immediate contact with each other in large-scale shear zone.

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- * in Japanese
- ** in Japanese with English abstract

低圧高温型領家広域変成作用の変形差応力

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近畿中央部の丹波帯南縁部に分布する、低圧高温型の領家広域変成作用を被った metachert の検討を行った。Metachert 中に含まれている放散虫化石が示す歪は見かけ上一軸対称性であり、最大伸長歪の方向が広域的な線構造に平行である。この変形特性は、領家変成帯と対をなす三波川変成帯での変形特性と同じである。石英の grain size paleopiezometer 及び dislocation density paleopiezometer を用いて求めた変形差応力は、低温部でそれぞれ約 75 ないし 40 MPa、高温部でそれぞれ約 10 ないし 8 MPa である。ただし、それぞれ Mercier *et al.* (1977), McCormick (1977) の式を用いた。対の変成帯の性質の類似性が、化石の示す変形特性や変形差応力の大きさなどの見地から示された。

Kasagi: 笠置
Wazuka: 和束

Gonokuchi: 郷ノ口
Mikawa Plateau: 三河高原