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Journal of Geosciences, Osaka City University
Vol. 51, Art. 1, p. 1-8, March, 2008

Strain analysis of rocks within the metamorphosed accretionary complex in the Iwakuni-Yanai district, SW Japan

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Abstract

To clarify the deformation history of rocks within the metamorphosed accretionary complex, we carried out a strain analysis of the Kuga Group, a metamorphosed Jurassic accretionary complex in the northern part of the Iwakuni-Yanai district, SW Japan. We analyzed deformed and weakly metamorphosed pebbly mudstones (low-grade metapelites) within the Kuga Group, with the aim of combining these data with those obtained previously for high-grade metapelites of the Ryoke metamorphic belt (the metamorphic equivalent of the Kuga Group) in the same district. Micro-and mesoscopic observations indicate that the low-grade metapelites deformed mainly by accretion processes under lower greenschist-facies conditions. All of the metapelites exhibit plane strain to general flattening strain. Combining our data with those for the high-grade metapelites reveals that the strain path of early bedding-normal compression resulting in flattening strain, while subsequent bedding-parallel compression generated the final prolate shapes of the pebbles. The strain path proposed here is markedly different from those described in previous studies, and is a fundamental factor in constraining the deformation history of rocks within the metamorphosed accretionary complex.

Key-words : Kuga Group, metamorphosed accretionary complex, Ryoke metamorphic belt, strain analysis, strain path

Introduction

The complete deformation history (strain history or strain path) of a metamorphosed accretionary complex is one of the most important constraints in understanding the evolutionary processes of an arc-trench system (e.g., Toriumi, 1985; Iwamori, 2003). In general, accretionary complex is formed along an active convergent plate boundaries; materials accreted on land are intensely deformed at least partly to form mélange fabrics. To clarify deformation history of rocks within a metamorphosed accretionary complex, it must be distinguished deformation due to accretion processes from deformation during high-grade metamorphism, since deformation structures related to accretion processes could be preserved even in high-grade metamorphic rocks (Okudaira and Beppu, 2008).

Toriumi and co-workers (Toriumi, 1985; Toriumi and Kuwahara, 1988) studied the strain path of the Ryoke metamorphic belt, a metamorphosed accretionary complex in Japan. The strain path can be defined as the trajectory of the integrated strain experienced at different stages during progressive deformation (e.g., Ramsey and Huber, 1983). They focused on the relationship between strain magnitude and metamorphic temperature, and proposed a strain path based on changes in strain magnitude that occurred with. Toriumi (1985) undertook a strain analysis of deformed radiolarian fossils in metacherts from the Iwakuni-Yanai district of SW Japan and the Komagane-Takato district of Central Japan, and proposed a strain path that describes regional-scale variations in strain that accompanied regional-scale changes in temperature (thick, gray arrow in Fig. 1).

In contrast, Toriumi and Kuwahara (1988) proposed four different strain paths (thin, black arrows in Fig. 1) for the Shiojiri-Ina district of Central Japan. The authors divided the district into four zones based on strain magnitude, and proposed different strain paths defined by straight lines on a Flinn diagram between zero strain and the final strain (Fig. 1), thereby suggesting a constant strain type along each strain path and assuming a constant strain type within each zone; however, this assumption has yet to be evaluated based on observations of metachert samples. The fundamental concepts employed in constructing the strain paths presented by Toriumi (1985) and Toriumi and Kuwahara (1988) are different: the strain path in the former represents a 'progressive' path, whereas those in the latter are 'prograde' paths in the context of the metamorphic pressure-temperature path. The most reliable strain paths for metamorphic tectonites are 'prograde' paths. Given the uncertainly regarding the validity of the assumptions employed in Toriumi and Kuwahara's (1988) strain analysis, it is necessary to determine reliable strain paths for the Ryoke metamorphic belt based on appropriate and accurate analyses.

In the present study, we carried out a strain analysis of the low-grade metamorphic rocks of the Kuga Group, a Jurassic accretionary complex in the northern part of the Iwakuni-Yanai district, SW Japan. Okudaira and Beppu (2008) performed a strain analysis of high-grade metapelites of the Ryoke metamorphic belt in the same district, considered to represent the metamorphic equivalent of the Kuga Group. By comparing the deformation recorded in rocks of the accretionary complex (present study) and their metamorphic equivalents (as described by Okudaira and Beppu, 2008), we discuss the deformation history of rocks within the metamorphosed accretionary complex of the Iwakuni-Yanai district.

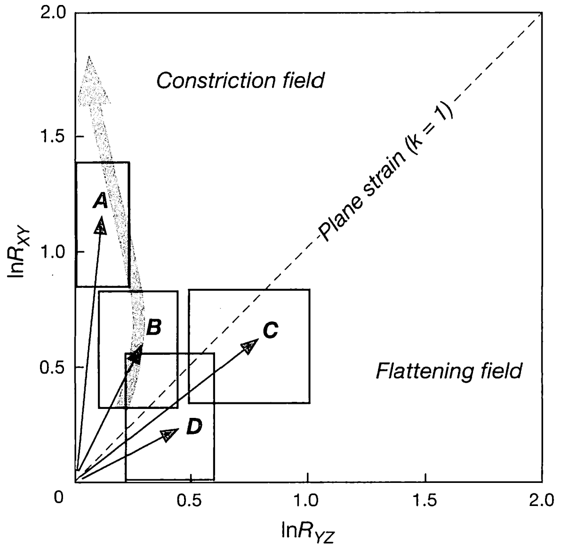

Fig. 1 Strain paths for the Ryoke metamorphic rocks proposed in previous studies. The thick, gray arrow and the thin, black arrows (labeled A-D) are the strain paths determined from strain analyses of metacherts from the Yanai-Iwakuni and Komagane-Takato districts (Toriumi, 1985) and the Shiojiri-Ina district (Toriumi and Kuwahara, 1988), respectively.

Geological background and sample descriptions

The Kuga Group in the northern part of the Iwakuni-Yanai district represents the western extent of the Mino-Tamba terrane (Fig. 2a; e.g., Higashimoto *et al.*, 1983; Ichikawa, 1990; Banno and Nakajima, 1992). The group is composed mainly of allochthonous blocks of chert, greenstone, siliceous mudstone, terrigeous sandstone, and mudstone within an argillaceous matrix (Higashimoto *et al.*, 1983; Takami and Itaya, 1996). The Kuga Group has been divided into three units (Units I, II, and III) based on radiolarian ages and the K-Ar ages of metamorphic muscovite (Fig. 2b; Takami and Itaya, 1996). The ages of the formations that make up Units I, II, and III are estimated to be late Late Jurassic, early Middle Jurassic, and middle Early Jurassic, respectively. The K-Ar ages of metamorphic muscovite grains differ among the three units, being 134-122 Ma in Unit I, 159-146 Ma in Unit II, and 182-156 Ma in Unit III (Takami and Itaya, 1996). The rocks of Units II and III contain metamorphic minerals indicative of high-pressure metamorphism associated with deep subduction; such minerals are not observed in the rocks of Unit I, suggesting that they were metamorphosed at shallow levels within a subduction zone (Takami and Itaya, 1996).

The differences in the sedimentary and metamorphic ages among the three units suggest that a pile nappe structure developed in the Kuga Group during or after the Early Cretaceous. The low-pressure/high-temperature Ryoke metamorphic belt, metamorphosed during the Mid-Cretaceous (~98 Ma; Suzuki and Adachi, 1998) and considered to be the metamorphic equivalent of the Kuga Group (e.g., Nureki, 1960; Higashimoto *et al.*, 1983), occurs in the southern part of the Iwakuni-Yanai district. The northern limit of the Ryoke metamorphic belt *sensu lato* is defined by the northern limit of the occurrence of metamorphic biotite (Higashimoto *et al.*, 1983)

Some of the metapelites in the northern part of the Iwakuni-Yanai district (Fig. 2b) contain matrix-supported clasts of 0.5-10 cm in diameter. Sandstone clasts are dominant, locally making up 20-30 vol.% of the rock mass. The metapelites exhibit millimeter-scale compositional layering oriented parallel/subparallel to lithologic boundaries (Fig. 3). A microscopic foliation is defined by an alignment of chlorite and muscovite grains of ~0.05 mm in size (Fig. 4); biotite grains are rare. The foliation develops parallel to the compositional layering. The sandstone pebbles within the metapelites are elongated and flattened within the plane of the foliation (Fig. 4). The foliation strikes E-W and dips 30-60° to the south, although it dips locally to the north. A lineation is defined by the aligned long axes of stretched pebbles, plunging to the E or W at 10-30°. An extensional crenulation cleavage, defined mainly by an alignment of chlorite and muscovite grains, is locally developed.

According to the regional metamorphic zonation proposed by Higashimoto *et al.* (1983), two of the four samples analyzed in the present study (07080204 and 07080205B) are from Zones I or II, characterized by lower greenschist-facies metamorphic minerals such as muscovite and chlorite, whereas samples 07080201A and 07080206 are from the non-metamorphic zone. The intrusion of the San-yo granitoids since the Late Cretaceous led to widespread thermal metamorphism, with Zones II, III, and IV in Fig. 2b being identified as contact aureoles. The northern limit of the Ryoke metamorphic belt, as shown in Fig. 2b, is poorly constrained (Higashimoto *et al.*, 1983); in fact, the metapelites analyzed in the present study contain biotite and occasional cordierite porphyroblasts. It is difficult to divide the samples into metamorphic and non-metamorphic rocks because it is not clear whether the biotite grains crystallized during regional Ryoke metamorphism; accordingly, in this study the four analyzed samples are described as low-grade metapelites of the metamorphosed accretionary complex.

Strain analysis

We measured the geometry and magnitude of strain in rocks from the northern part of the Iwakuni-Yanai district (Fig. 2b) via strain analyses of sandstone pebbles in metapelites. We assumed that the long and short axes of the pebbles correspond to the maximum (X-axis) and

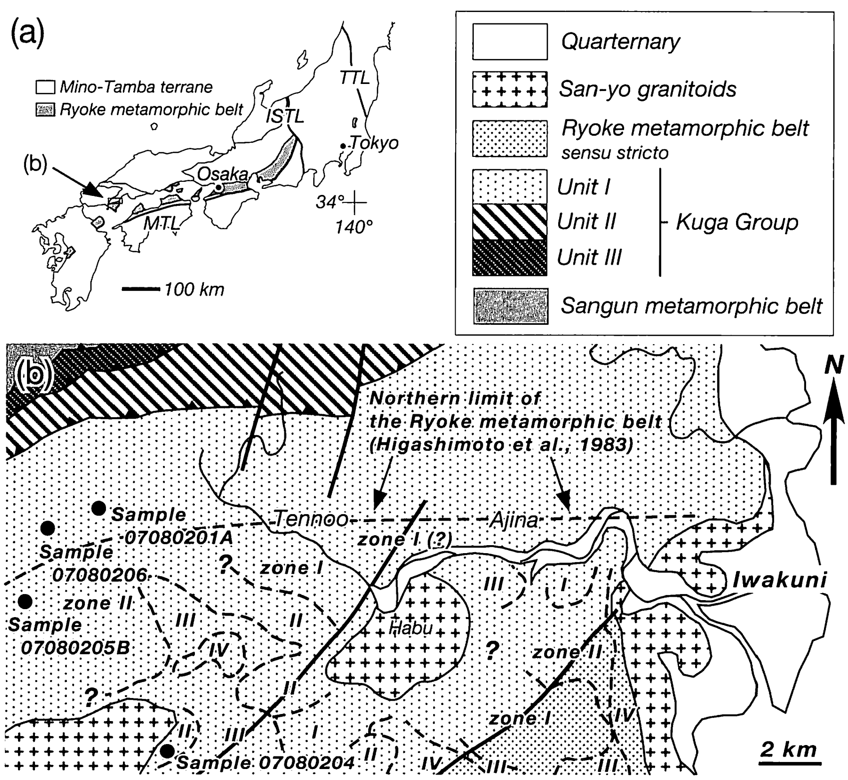

Fig. 2 (a) Map showing the distribution of the Mino-Tamba terrane and the Ryoke metamorphic belt. TTL: Tanakura Tectonic Line, ISTL: Itoigawa-Shizuoka Tectonic Line, MTL: Median Tectonic Line. (b) Map showing the geologic units in the northern part of the Iwakuni-Yanai district (Takami and Itaya, 1996). Boundaries between metamorphic zone and the northern limit of the Ryoke metamorphic belt are after Higashimoto et al. (1983). Sample localities are also shown.

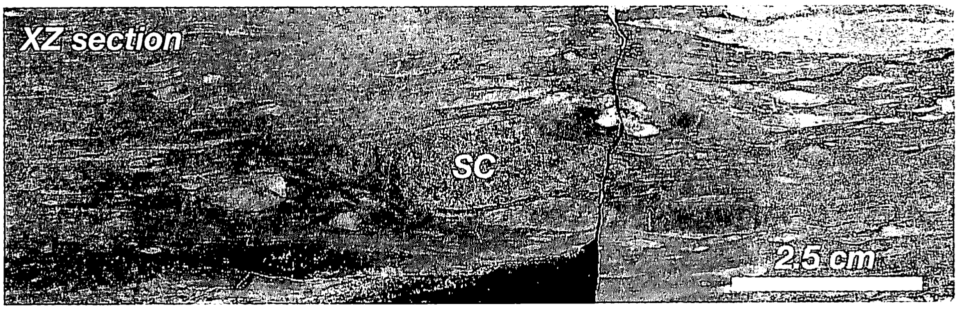

Fig. 3 Mesoscopic structures observed in metapelite (sample 07080206, *XZ*-section), showing that the rock dominantly deformed by ductile flow: brittle deformation played only a minor role. The foliation is defined by compositional layering (alternating mica-rich and mica-poor layers). Sandstone clasts (SC) are elongate parallel to the foliation.

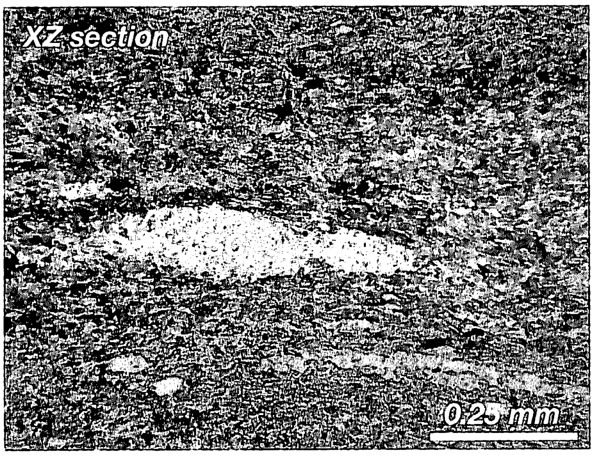

Fig. 4 Photomicrograph showing the microscopic structures observed in metapelites (sample 07080201A, XZ-section). The foliation defined by alignment of micas and chlorites that is parallel to the compositional layering. Sandstone clasts (SC) are elongated parallel to the foliation.

minimum axes (*Z*-axis) of the strain ellipsoid, respectively, with the normal to these axes being the intermediate axis (*Y*-axis). Each sample was sectioned along three mutually orthogonal planes (*XY*-, *XZ*-, and *YZ*-planes). On each of the planes, we measured the long and short axes of the pebbles and thereby calculated the aspect ratio (R_{XY}, R_{XZ}, and R_{YZ}, respectively).

We employed the R_f-ϕ method (Dunnet, 1969; Dunnet and Siddans, 1971; Ramsay and Huber, 1983; Lisle, 1985) to analyze in detail the strain recorded by deformed pebbles in the metapelite. We assumed that as the rocks deformed, passive elliptical markers were transformed to new elliptical markers with an ellipticity (i.e., aspect ratio, R_f) and long-axis orientation ϕ dependent on the original shape (R_i) and orientation (θ) of the marker ellipses, in addition to the shape (R_s) and orientation of the strain ellipse.

For an initially random distribution of long-axis orientations, the θ -curves contain half of the data between them; the value of the strain ellipse R_s was defined by finding the family of θ curves for which the $\theta = \pm 45°$ lines divided the data into two groups with the same number of data points (e.g., Dunnet, 1969). The R_f-ϕ diagrams for pebbles from the low-grade metamorphics are shown in Fig. 5. By fitting the plotted data with the $\theta = \pm 45°$ lines, we were able to determine the most suitable value of R_s. The calculated χ^2 values for most of the analyzed samples are less than 15.51 (degrees of freedom: 8; significance level: 0.05), suggesting that the initial orientations of the marker ellipses (i.e., clasts in the metapelites) were distributed randomly at the 5% level of statistical significance. The results of the R_f-ϕ analysis indicate that the initial shapes of almost all of the marker objects can be assumed to have been elliptical, with aspect ratios (R_i) of <1.5 (Fig. 5).

In the case of constant-volume deformation, the magnitude of strain ($\overline{\varepsilon_s}$) can be calculated as the quadratic mean of principal natural strains based on the following equation (Nadai, 1963; Ramsay and Huber, 1983):

$$\overline{\varepsilon_S} = \frac{1}{\sqrt{3}}\{(\ln R_{XY})^2 + (\ln R_{XZ})^2 + (\ln R_{YZ})^2\}^{1/2},$$

where R_{XY}, R_{XZ}, and R_{YZ} were estimated in the present case via the R_f-ϕ method. The corresponding *k*-values, which provide a useful means of classifying the constant-volume ellipsoids, are calculated as follows (Ramsay and Huber, 1983):

$$k = \ln R_{XY} / \ln R_{YZ}.$$

The results of strain analysis of the low-grade metamorphic rocks are summarized in Table 1 and plotted in a logarithmic Flinn diagram in Fig. 6a (Flinn, 1962).

The strain magnitudes estimated here (~0.45) are smaller than those determined for high-grade metapelites in the same district (0.5-0.9; Okudaira and Beppu, 2008). The low-grade metapelites show plane strain to general flattening strain, with minor variations; all plot close to k = 1 (range, 0.8-1.9).

Discussion

Detailed structural analyses have been performed on rocks of the Mino-Tamba terrane in Central Japan (Otsuka, 1989; Kimura and Hori, 1993; Niwa, 2006; Fukui and Kano, 2007), but not on the Kuga Group. At least two stages of regional tectonic deformation are recorded in the Mino-Tamba terrane: the first involved accretion-related back-tilting about a subhorizontal axis, resulting in the formation of thrust sheet packages that underwent imbricate stacking (forming duplexes) and out-of-sequence thrusting (Kimura and Hori, 1993; Fukui and Kano, 2007); the second involved late Early-early Late Cretaceous (Albian-Coniacian) left-lateral shearing that led to the formation of kilometer-scale upright folds with west-plunging axes (Fukui and Kano, 2007). The first stage resulted in the formation of a tectonic mélange unit consisting mainly of a volumetrically abundant muddy matrix and variously sized clasts of chert, hemipelagic siliceous mudstone, and sandstone (Fukui and Kano, 2007). According to Fukui and Kano (2007), the mélange fabrics

Table 1. Strain magnitudes and k-values calculated for low-grade metapelites from the northern part of the Iwakuni-Yanai district, SW Japan.

Sample	ε_s		k-Value	
	Shape*	R_f-ϕ	Shape*	R_f-ϕ
07080201A	0.49	0.46	0.86	0.76
07080204	0.43	0.42	1.16	1.12
07080205B	0.42	0.41	0.80	0.80
07080206	0.48	0.46	1.78	1.88

*Estimated from the harmonic means of the aspect ratios of pebbles

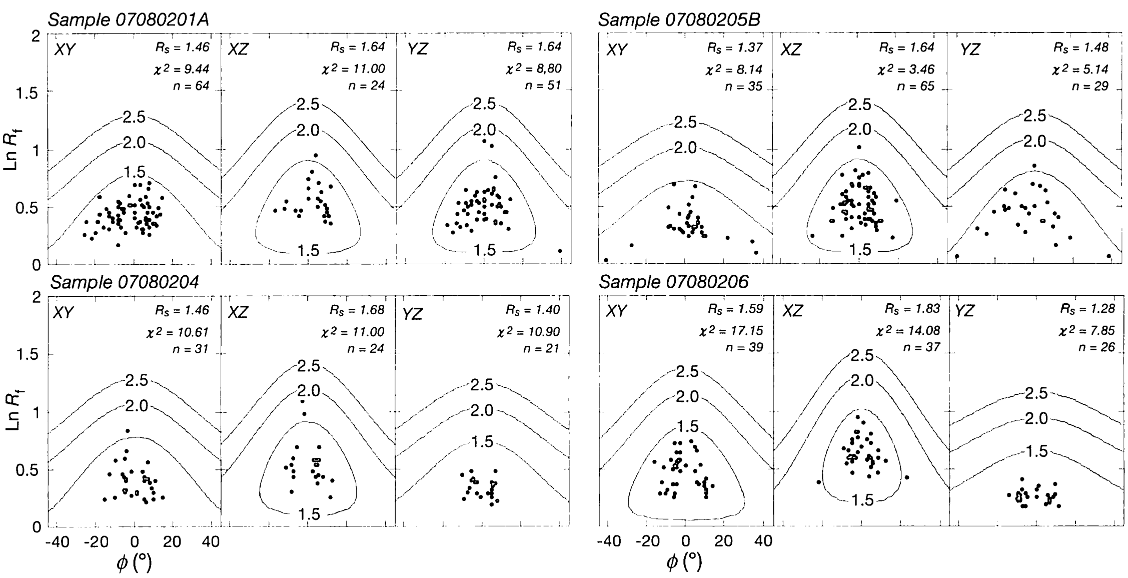

Fig. 5 R_f-ϕ plots showing data from the XY-, XZ-, and YZ- plane of deformed pebbles in metapelite samples 07080201A, 07080204, 07080205B and 07080206. Contours indicate the fields of expected R_f-ϕ plots for R_i = 1.5, 2.0 and 2.5. R_s: strain ellipse defined by determining the $\theta = \pm 45°$ lines such that they divide the data into two equal groups on each R_f-ϕ plot. χ^2: χ^2 value calculated in fitting the data to the 50% curves with R_s. n: number of data points.

developed over two periods of deformation: the first involved the fragmentation of sandstone layers in response to mud injections, while the second involved layer-parallel, non-coaxial shear that resulted in the mixing of pelagic and terrigenous clasts and the formation of S-*C*-like asymmetric fabrics and a scaly foliation.

The metapelites analyzed in the present study may have been derived from rocks with a mélange fabric and that were subjected to lower greenschist-facies metamorphism. Although the block-in-matrix structures of the metapelites are similar to those of the mélange rocks, brittle deformation structures (e.g., the development of discrete shear bands) are not observed in the metapelites, but compositional layering is developed (Fig. 3), suggesting that the deformation structures in the metapelites are more ductile than those in the mélange rocks. Furthermore, the clasts in the metapelites are ductilely flattened within the plane of the foliation (Fig. 3), indicating that deformation of the clasts was synchronous with formation of the foliation.

It is difficult to determine whether crystallization of the muscovite and chlorite grains that define the foliation occurred in association with Mid-Cretaceous Ryoke metamorphism or subduction-related metamorphism. The thermal effects of Ryoke metamorphism are likely to be relatively minor, as Ryoke metamorphism is considered as a thermal perturbation associated with intrusion of the Older Ryoke granitoids; it is therefore possible that the thermal effects of Ryoke metamorphism only occur locally in the southern part of the Mino-Tamba terrane, which is recognized as the Ryoke metamorphic belt (Okudaira *et al.*, 1993, 2001; Beppu and Okudaira, 2006; Miyazaki, 2007). In fact, the K-Ar ages of muscovite grains from Unit I are 130-120 Ma (Takami and Itaya, 1996), different to the age of Ryoke metamorphism (~95 Ma; Suzuki and Adachi, 1998).

In the Ryoke metamorphic belt of the Iwakuni-Yanai district, deformation structures have been described in association with three different stages of high-temperature ductile deformation (D_1, D_2, and D_3; Okudaira *et al.*, 1993, 2001). The structures associated with D_1 and D_3 are penetrative, affecting the entire rock mass, whereas D_2 structures are only locally developed. In all rocks, D_1 is characterized by a distinct tectonic foliation (S_1) oriented parallel/subparallel to lithologic contacts. D_2 structures include large-scale overturned folds and associated parasitic folds (F_2 folds) that face to the SE and have NNE-NE-plunging fold axes, as well as distinct shear zones (D_2 shear zones) that truncate the S_1 foliation. The shear zones are well developed near the boundaries between different regional-scale structural units. D_3 is marked by the formation of gentle upright folds (F_3 folds) with E-W-trending axes. D_1 and D_2 structures are folded by F_3 folds, although it is possible that D_3 was coeval with D_2. The D_1 and D_2/D_3 deformation phases are considered to be related to deformation at conditions of peak metamorphism at ~95 Ma and exhumation at ~85 Ma, respectively (Okudaira *et al.*, 2001).

It is possible that D_1 deformation postdates the first stage of deformation in the Mino-Tamba terrane (duplexing and out-of-sequence thrusting), as Ryoke metamorphism and subduction-related metamorphism occurred at ~95 Ma and 130-120 Ma, respectively. The similar ages of the large-scale upright folds of the second stage of deformation in the Mino-Tamba terrane and D_2/D_3 deformation in the Ryoke metamorphic belt indicate that the folds are coeval, forming during the early Late Cretaceous. Consequently, rocks of the metamorphosed accretionary complex in the Iwakuni-Yanai district have experienced at most three different deformations: pre-D_1, D_1, and D_2/D_3.

The lineations in both the low-grade and high-grade metapelites are defined by the aligned long axes of stretched pebbles parallel to the *X*-axis of finite strain, and are of similar orientations. The *XY*-planes of finite strain in both cases are parallel to the foliation defined by millimeter-scale compositional layering. These observations indicate that the geometry of finite strain is similar in both the low-grade and high-grade metapelites. According to Okudaira and Beppu (2008), D_2/D_3 strain is relatively minor in the high-grade metapelites, even in those rocks folded during D_3; the geometry of finite strain in these rocks is therefore likely to represent mainly D_1 strain.

The *k*-values estimated for the low-grade metapelites analyzed in the present study (0.8-1.9) are slightly higher than those estimated for the high-grade metapelites (0.3-0.8) that were mainly deformed during D_1 (Fig. 6a; Okudaira and Beppu, 2008). The magnitudes of strain estimated for the two rock types are also different, being ~0.45 for the low-grade metapelites and 0.5-0.8 for the high-grade rocks (Fig. 6a). Two possible explanations for these observations are presented in Fig. 6b, c. The first case (Case 1) involves large-scale strain partitioning between the low-and high-grade rocks during D_1 (Fig. 6b). The behavior of the metapelite that deformed ductilely was possibly governed by power-law creep. Given that power-law creep is a thermally activated process, the difference in the deformation temperatures of the two rock groups would have resulted in contrasting ductility (i.e., strain rate), even for the same stress regime.

The low-grade metapelites were therefore less strained (at the same k-value) than the high-grade metapelites, and the geometry of the low-grade metapelites reflects the effects of D_1; however, the k-values obtained for the low-grade metapelites are slightly higher than those for the high-grade rocks. Although meso-to microscopic D_3 folds are not observed in low-grade metapelites, they do record D_3 strain in the form of kilometer-scale upright folds (e.g., Higashimoto *et al.*, 1983). In this case, the low-grade and high-grade metapelites may have experienced contrasting D_2/D_3 strain paths, as shown in Fig. 6b.

The second explanation (Case 2) is that the low-and high-grade metapelites recorded largely different tectonic events, i.e., pre-D_1 and D_1, respectively (Fig. 6c). The slight difference in the k-values calculated for the two rock types may indicate that the tectonic strain recorded in the low-grade metapelites was not related to D_1. Given that the low-grade metapelites record no evidence of D_2 shear zones and D_3 upright folds, the deformation may predate D_1 (pre-D_1). Because the Unit I rocks within the Kuga Group are considered to be associated with relatively shallow accretion processes rather than high-pressure processes (Takami and Itaya, 1996), the pre-D_1 deformation may have involved shallow subduction-related processes such as the off-scraping or underplating of subducted material.

In Case 1, the trajectory of the strain path from the low-grade to the high-grade metapelites could represent variations in the magnitude of D_1 strain, whereas in Case 2 the trajectory could represent the strain path from subduction-related processes (pre-D_1) to the low-pressure metamorphism event (D_1). Adopting the second case, in combination with the D_1-D_2/D_3 strain path proposed by Okudaira and Beppu (2008), the complete strain path of rocks of the metamorphosed accretionary complex in the Iwakuni-Yanai district could be reconstructed as shown in Fig. 6c. In this case, however, the reason for the similarity of the attitude of strain axes of the low-grade and high-grade metapelites remains unclear.

Our strain analyses reveal that the Z-axis of the finite strain ellipsoid for the pre-D_1 and/or D_1 events is oriented normal to the foliation. Given that the axial planes of D_3 folds are oriented normal to the general trend of the foliation, the Z-axis of the D_2/D_3 event is interpreted to have been oriented parallel to the foliation (Okudaira and Beppu, 2008). Assuming that coaxial deformation was dominant in the metapelites, the strain path proposed here may indicate that early bedding-normal compression resulted in a general flattening strain, while subsequent bedding-parallel compression led to the final prolate shape of the pebbles. The strain paths determined for metapelites

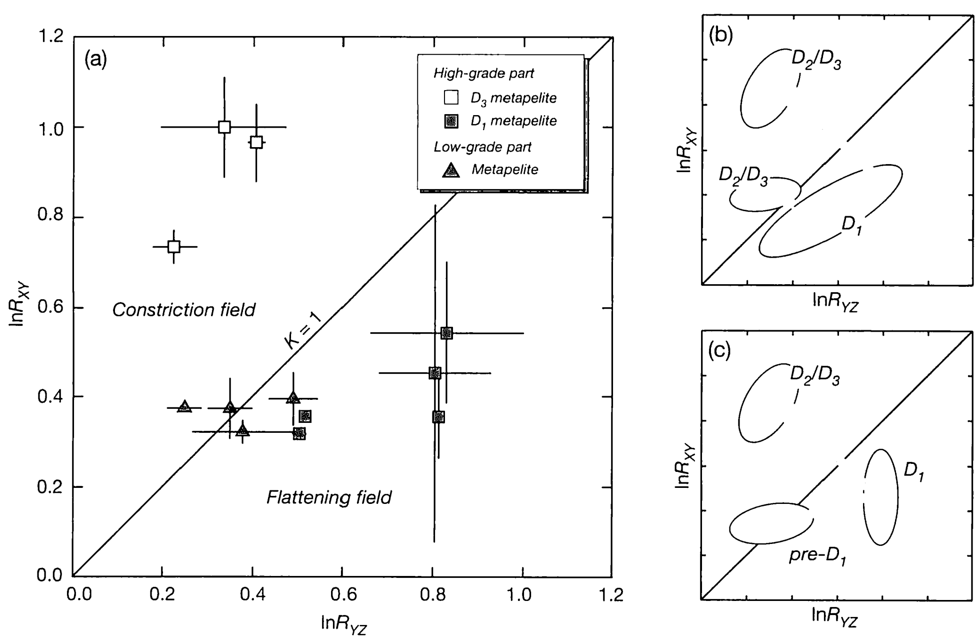

Fig. 6 (a) Logarithmic Flinn diagram showing data from the low-grade metapelites in the northern part of the Iwakuni-Yanai district (solid triangles) and folded (D_3 folding) and unfolded high-grade metapelites from the southern part of the same district (Okudaira and Beppu, 2008). Bars represent the ranges in Rs that are statistically compatible with the data within a 5% level of significance. (b) The Case 1 strain paths (arrows) show contrasting D_1-D_2/D_3 strain paths for the low-grade and high-grade metapelites. (c) The Case 2 strain paths (arrows) show sequential deformation from pre-D_1 to D_1 and finally D_2/D_3. See text for explanation.

in this study (Fig. 6b, c) are different to those reported in previous studies (Fig. 1; Toriumi, 1985; Toriumi and Kuwahara, 1988), but represent a fundamental factor in constraining the deformation history of rocks within the metamorphosed accretionary complex.

Acknowledgements

The paper benefited substantially from detailed reviews by K. Ishii (University of Osaka Prefecture) and S. Takemura (Hyogo University of Teacher Education). K. Furuyama is thanked for his editorial handling of the manuscript. We also appreciate A. Stallard for his English-language editing. This study was supported financially by a Grant-in-Aid for Scientific Research (19540485) awarded to T. Okudaira by the Japan Society for the Promotion of Science.

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Manuscript received August 31, 2007.
Revised manuscript accepted December 21, 2007.