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Emplacement Mechanism of the Older Ryoke Granites in the Yanai District, Southwest Japan, with Special Reference to Extensional Deformation in the Ryoke Metamorphic Belt

By

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with 12 figures

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ABSTRACT: The Ryoke metamorphic rocks in the Yanai district, southwest Japan show geological and rock structures produced by three different phases of ductile deformation. During the first phase (D_1), a distinct foliation parallel to lithologic layering was formed under the thermal peak conditions during the low-pressure facies series Ryoke metamorphism, which is ascribed to the sheet-like intrusion of the older Ryoke granites. The second phase deformation (D_2) led to the formation of mylonitic shear zones and nappes. The deformation of the third phase (D_3) was responsible for the formation of the upright folds with E-W trending axes.

In the metamorphic rocks of the Tsuzu area, which is placed in the northern part of the Yanai district, are often found melt-filled fractures of minor scales, which cut across their foliation. The deformation related to the formation of these melt-filled fractures resulted commonly from the foliation parallel extension. The overall movement picture inferred from the melt-filled fractures appears to be of the shear sense for the top to the north. The formation of the melt-filled fractures was responsible for the intrusion of the older Ryoke granites. Asymmetric textures such as extensional crenulation cleavage (ECC) and rotation of porphyroblasts, which grew under the thermal peak of the low-pressure facies series metamorphism, are also formed in the metapelites. The shear sense read from the asymmetric textures is the top to the north, though fairly dispersed. This is harmonic with the overall movement picture inferred from the melt-filled fractures. Therefore it can be said that the overall movement picture of the D_1 deformation of the metamorphic rocks in the Tsuzu area during and immediately before the intrusion of the older Ryoke granites appears to have been of the same style of extension tectonics. Consequently, the D_1 deformation occurred under extensional stress regime and the older Ryoke granites intruded in extensional fracture zones at intermediate crustal depths. The nappes of the metamorphic rocks and older granites were formed during the D_2 deformation probably under compressional stress regime.

Contents

I. INTRODUCTION

Granitic rocks are a major constituent of the continental crust. Since these are commonly intrusion bodies of large volumes, their emplacement mechanisms have so far been discussed by many authors as so-called "space problem" (cf. Paterson *et al.*, 1991). Traditionally two main emplacement mechanisms have been emphasized: 1) forceful intrusion, whereby buoyancy-driven magmas physically push the crust aside, giving rise to granitic diapirs and balloons (e.g. Brun and Pons, 1981; Sakurai *et al.*, 1983; Bateman, 1985; Ramsay, 1989); and 2) passive emplacement related to tectonic cavity opening such as great fault and cauldron subsidence with stoping (e.g. Bussell *et al.*, 1976; Pitcher, 1979; Bouchez and Diot, 1990). Guineberteau *et al.* (1987), Hutton (1982), Toyoshima and Hara (1989), Hutton *et al.* (1990), and Shimura (1992) have suggested that granitic magma intruded in the spaces created by transcurrent fault, extensional shear zone, and subhorizontal fracture zone. Hutton (1988) suggested that the emplacement mechanism (forceful or passive) depends on the ratio between the rate of buoyant uprise of magma and that of tectonic cavity opening.

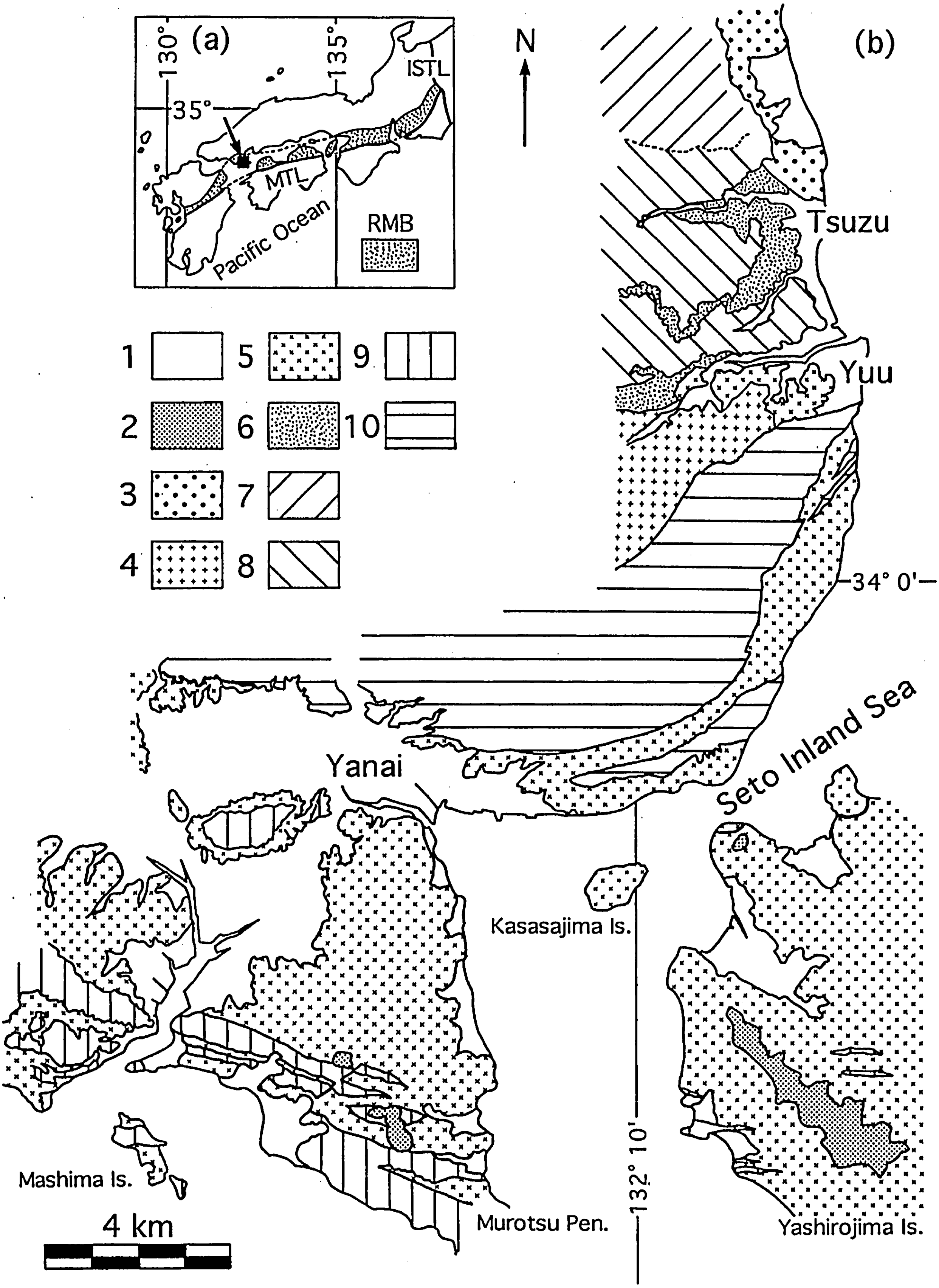

Fig. 1. a) Outline map showing the location of the Ryoke metamorphic belt of southwest Japan. RMB: Ryoke metamorphic belt. MTL: Median Tectonic Line. ISTL: Itoigawa-Shizuoka Tectonic Line. b) Geological and metamorphic zonation map of the Yanai district. 1: alluvium. 2: Tertiary volcanics. 3: Hiroshima granites. 4: younger Ryoke granites. 5: older Ryoke granites. 6: migmatites. 7 - 10: Ryoke metamorphic rocks (7 biotite zone, 8 cordierite zone, 9 sillimanite zone, 10 garnet zone).

The Ryoke metamorphic belt, southwest Japan (Fig. 1a) is mainly composed of Cretaceous low-pressure type metamorphic rocks (the Ryoke metamorphic rocks) and contemporary granitic rocks (the Ryoke granites), and then has been regarded as a typical example of low-pressure type metamorphic belts (e.g. Miyashiro, 1961).

The Ryoke granites have been divided into sheet-like bodies, those are the older Ryoke granites, and stock-like bodies, those are the younger Ryoke granites, on the basis of their intrusion forms and of timing of their intrusion (e.g. Koide, 1958; Okamura, 1960; Ryoke Research Group, 1972, 1974; Hara *et al.*, 1980, 1991; Okudaira *et al.*, 1993). Hara *et al.* (1991) and Okudaira *et al.* (1992, 1993) suggested that the older Ryoke granites appear to have intruded as sheet-like intrusions along north dipping fracture zones oriented at low angles. While Hayashi (1994) suggested that the Hiroshima granites in the Togouch-Yuu-Takehara district, which are shallow facies of the Ryoke granites and have the N-S dimension of ca. 50 km on the ground surface, appear to be related to "lateral magma movement" along shallow shear zone with low angle dip. Sakurai and Hara (1988) indicated that the younger Ryoke granite as stock-like body intruded forcefully based on the structural analysis of related rocks.

In this study, we will describe firstly the deformation structures related to the intrusion of the older Ryoke granites in the Yanai district. Secondary, we will propose a new emplacement mechanism of the older Ryoke granites which is associated to extensional tectonics in the Ryoke metamorphic belt.

II. OUTLINE OF GEOLOGY

The Yanai district (Fig. 1b) is mainly underlain by the Ryoke metamorphic rocks and their associated granitic rocks of middle Cretaceous time (e.g., Nureki, 1960; Okamura, 1960; Higashimoto *et al.*, 1983; Nishimura *et al.*, 1985; Hara *et al.*, 1991; Ikeda, 1993; Okudaira *et al.*, 1993; Miyashita and Komatsu, 1993, 1994; Fabbri, 1994). On the basis of their intrusion forms, the granitic rocks have been divided into two categories: sheet-like granites (the older Ryoke granites) and stock-like granites (the younger Ryoke granites and the Hiroshima granites) (Higashimoto *et al.*, 1983; Hara *et al.*, 1991; Okudaira *et al.*, 1993) (Fig. 1b). Because their mineralogical and chemical features indicate metaluminous I-type granitoid, they are not considered to have been *in situ* generated from middle crustal rocks but derived from lower crust and upper mantle (Honma, 1974; Kagami *et al.*, 1992).

The metamorphic rocks are mainly derived from pelites, psammites, and cherts with a subordinate amount of calcareous and basic rocks, which are considered to belong to the Jurassic accretionary complex (the Kuga Group: Higashimoto *et al.*, 1983). They were regionally metamorphosed at two phases (M_0 and M_1) during a sequence of the Ryoke metamorphism (Okudaira *et al.*, 1993, 1994a). The former was a nearly medium-pressure facies series metamorphism (ca. 30°C / km) and the latter was low-pressure facies series one (ca. 40 - 50°C / km). The Ryoke metamorphism therefore is probably concluded that firstly the rocks were heated under medium-pressure facies conditions, and then they were further heated under low-pressure facies conditions. The metamorphic rocks can be divided into four metamorphic zones for minerals crystallized under the M_1 metamorphism: biotite zone, cordierite zone (460 - 590°C, 2.5 - 3.5 kbar), sillimanite zone (620 - 720°C, 3.5 - 4.5 kbar), and garnet zone (720 - 810°C, 5.0 - 6.5 kbar). These zones are arranged in thermally harmonic fashion around the sheets of the older Ryoke granites.

The older granites and metamorphic rocks show rock structures produced by deformation of two major phases (Okudaira *et al.*, 1993); the earlier and later phases are respectively called D_1 and D_2. A distinct foliation parallel to lithologic layering of these rocks was formed at the former phase under the thermal peak during the M_1 metamorphism. The initial orientation pattern of the metamorphic zones of M_1 phase and the granite sheets is destroyed by recumbent folding and thrusting of the D_2 phase. It has been roughly assumed that the intrusion of the older Ryoke granites is probably related to the D_1 phase deformation (Okudaira *et al.*, 1993). After the D_2 phase, the deformation (D_3), which formed a series of sinistral *en echelon* upright folds anywhere in the Ryoke metamorphic belt (Hara *et al.*, 1980, 1991), also occurred in the Yanai district. After the M_1 metamorphism and D_2 deformation, stock-like intrusions (the younger Ryoke and Hiroshima granites) locally thermally affected their surrounding rocks (M_2 metamorphism) (Okudaira *et al.*, 1993).

III. DEFORMATION RELATED TO THE INTRUSION OF THE OLDER RYOKE GRANITES

In order to clarify the movement picture of the D_1 phase deformation which is probably related to the intrusion of the older Ryoke granites, we analyzed the geological structures of the Tsuzu area, because in the area is only weakly found the effects of the D_2 phase deformation.

A. GEOLOGICAL STRUCTURES OF THE TSUZU AREA

In the Tsuzu area (Fig. 2), there are the older and younger Ryoke granites, the Tengatake and Nagano migmatites (after Higashimoto *et al.*, 1983; Okudaira *et al.*, 1993), the Hiroshima granites, and the Ryoke metamorphic rocks as main constituent rocks. In the Tsuzu area the metamorphic rocks have a distinct foliation, which appears to be in general parallel to the lithologic layering. The Tengatake and Nagano migmatites developed as zones in the metamorphic rocks are intrusive bodies belonging to the member of the older Ryoke granites (Okudaira *et al.*, 1993). The migmatites are developed cutting across the lithologic layering and foliation at low angles and across the lower level of lithostratigarphy toward the north (Fig. 3). In the migmatites, there are many metamorphic xenoliths with an agmatic structure (see Fig. 4 in Okudaira *et al.*, 1993).

The geological structure shown by the lithologic layering and foliation in the area (northern block) on the north of the EW trending Tsuzu fault is characterized by an open upright antiform with a fold axis gently plunging toward ESE, though slightly disturbed by high-angle faults (Figs. 2, 3, and 4a). The

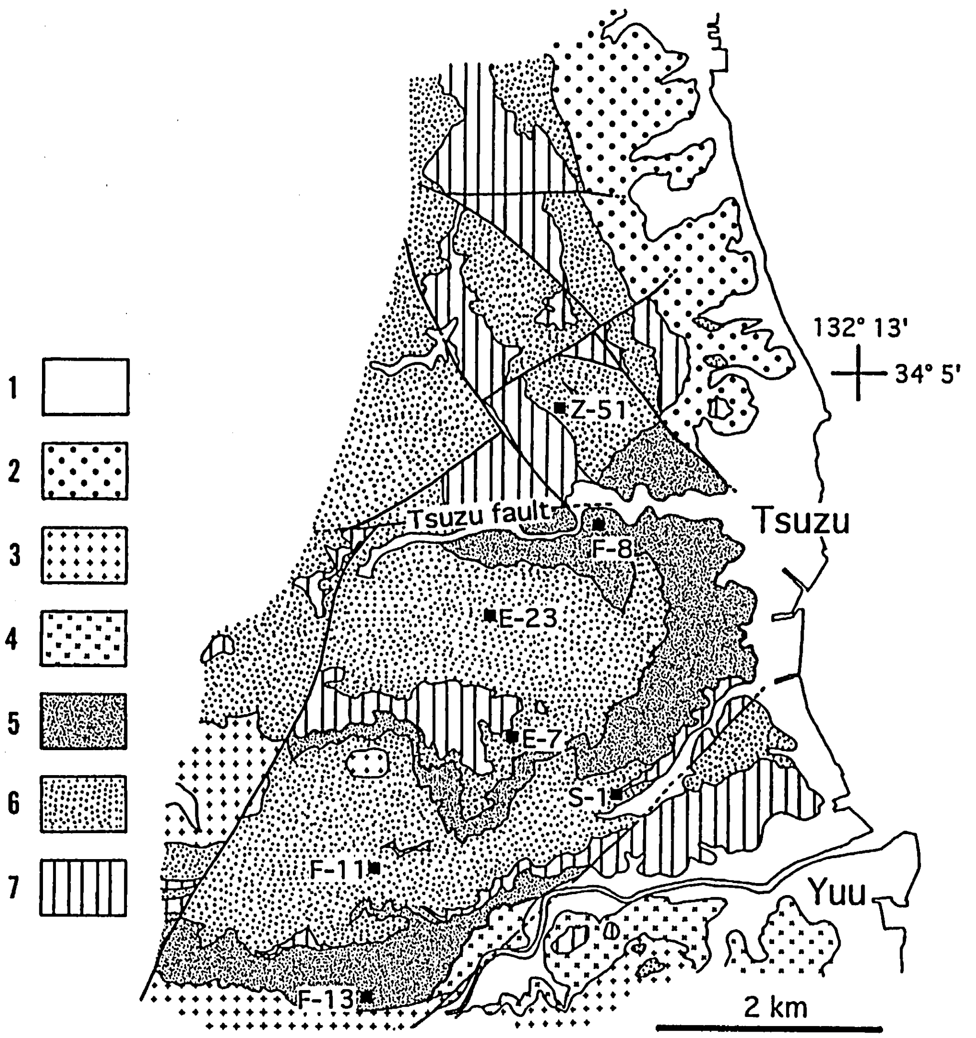

Fig. 2. Geological map of the Tsuzu area. 1: alluvium. 2: Hiroshima granites. 3: younger Ryoke granites. 4: older Ryoke granites. 5: Tengatake and Nagano migmatites. 6: metapelites and metapsammites. 7: metacherts. Closed squares indicate locations of samples using petrologically estimate of metamorphic temperatures.

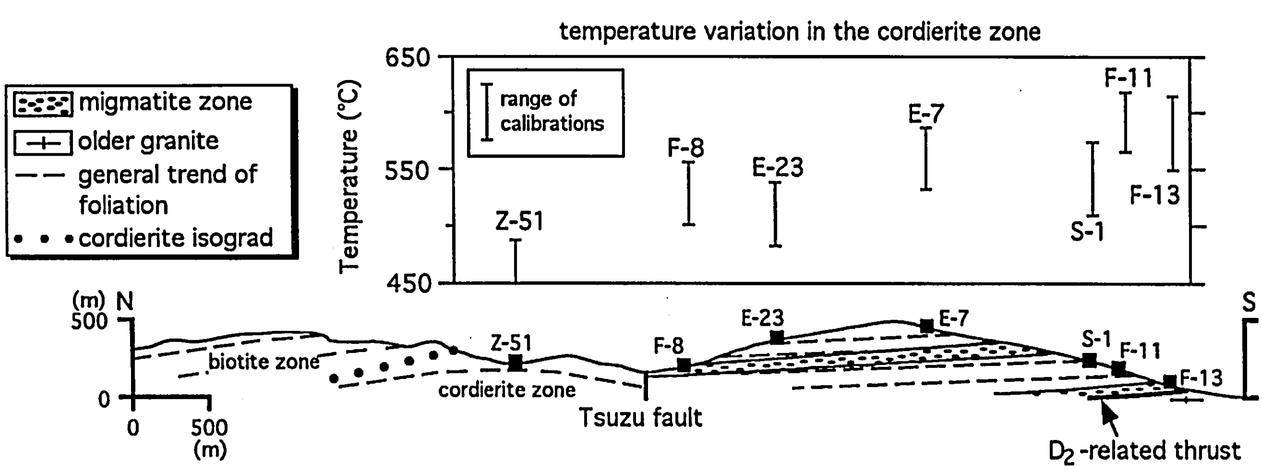

Fig. 3. Schematic structural cross section across the cordierite zone from north to south (after Okudaira *et al.*, 1994b). Closed squares indicate the locations of samples for petrological analyses of metamorphic temperature. Inset diagram shows the metamorphic temperature variation in the cordierite zone.

fold axis is placed near position Z-51 (Figs. 2 and 3). In the area (southern block) on the south of the Tsuzu fault the lithologic layering and foliation are as a whole dipping at low to moderate angles toward the north (Figs. 2, 3, and 4b), though locally folded in mesoscopic scale. The π-diagram (Fig. 4) for the foliation, which is characterized by a broad single great-circle girdle, suggests the development of mesoscopic-scale folds with the axes flat-lying in a trend of WNW-ESE (fold axis

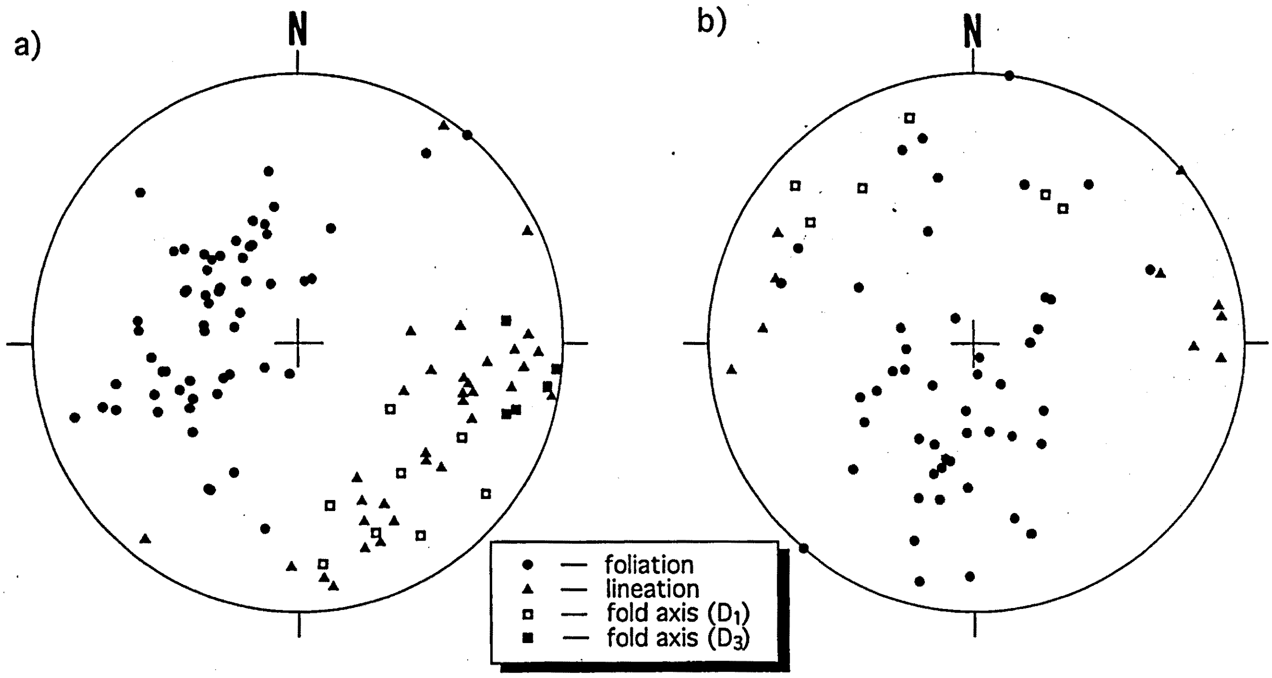

Fig. 4. Equal area plots of structural data for the metamorphic rocks in the Tsuzu area. a) northern block. b) southern block.

(D_3) in Fig. 4). Such folds are found in upright fashion in many outcrops. The upright folds of various scales in the northern and southern blocks are comparable with the upright folds developed in left-hand fashion throughout the Paleozoic-Mesozoic accretionary complexes and the Ryoke metamorphic belt of the Inner Zone of southwest Japan, which postdated the intrusion of the older Ryoke granites (e.g. Hara *et al.*, 1980).

B. METAMORPHIC ZONATION IN THE TSUZU AREA

In the Tsuzu area, the Ryoke metamorphic rocks mainly suffered from two different metamorphisms (M_0 and M_1) and those located near the younger Ryoke and Hiroshima granites were additionally affected by the M_2 metamorphism (Okudaira *et al.*, 1993). This area can be divided into two metamorphic zones (the biotite and cordierite zones) in terms of the mineral parageneses of pelitic and psammitic rocks formed during M_1 metamorphism (Okudaira *et al.*, 1993). The typical mineral assemblages are as follows:

Biotite zone:

quartz + plagioclase + biotite + muscovite,

Cordierite zone:

quartz + plagioclase + biotite + muscovite + K-feldspar + cordierite ± aluminosilicate.

Garnet crystals are not found as stable mineral in the metapelites and metapsammites, although they are often found in leucosome of the migmatites. This observation suggests that the crystallization of the garnets resulted from assimilation between the metamorphic rocks and granitic materials (Owada, 1989). The regional metamorphic zonation is shown in Fig. 5. It is not disturbed around the Tengatake and Nagano migmatites, like the cases which have been described in the Ryoke metamorphic belt of many other districts (e.g. Koide, 1958; Kutsukake, 1977; Seo *et al.*, 1981). Okudaira *et al.*

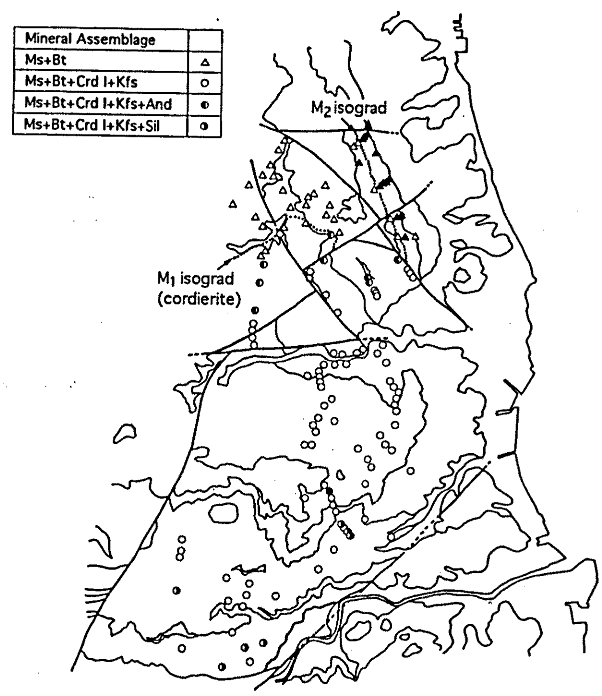

Fig. 5. Diagram illustrating the distribution of mineral assemblages crystallized under the M1 metamorphism. Closed triangle represents mineral assemblages such as quartz + plagioclase + biotite + muscovite ± andalusite ± cordierite resulted from the M2 metamorphism.

(1993, 1994a) have pointed out that the low-pressure facies series M_1 metamorphism is ascribed to the sheet-like intrusion of the older Ryoke granites. Figure 5 also represents contact aureole resulted from intrusion of the younger Ryoke and Hiroshima granites (M_2 isograd in Fig. 5). The aureole is ca. 500 m in width and is characterized by textures of overprint of new crystals, such as muscovite, andalusite, and cordierite.

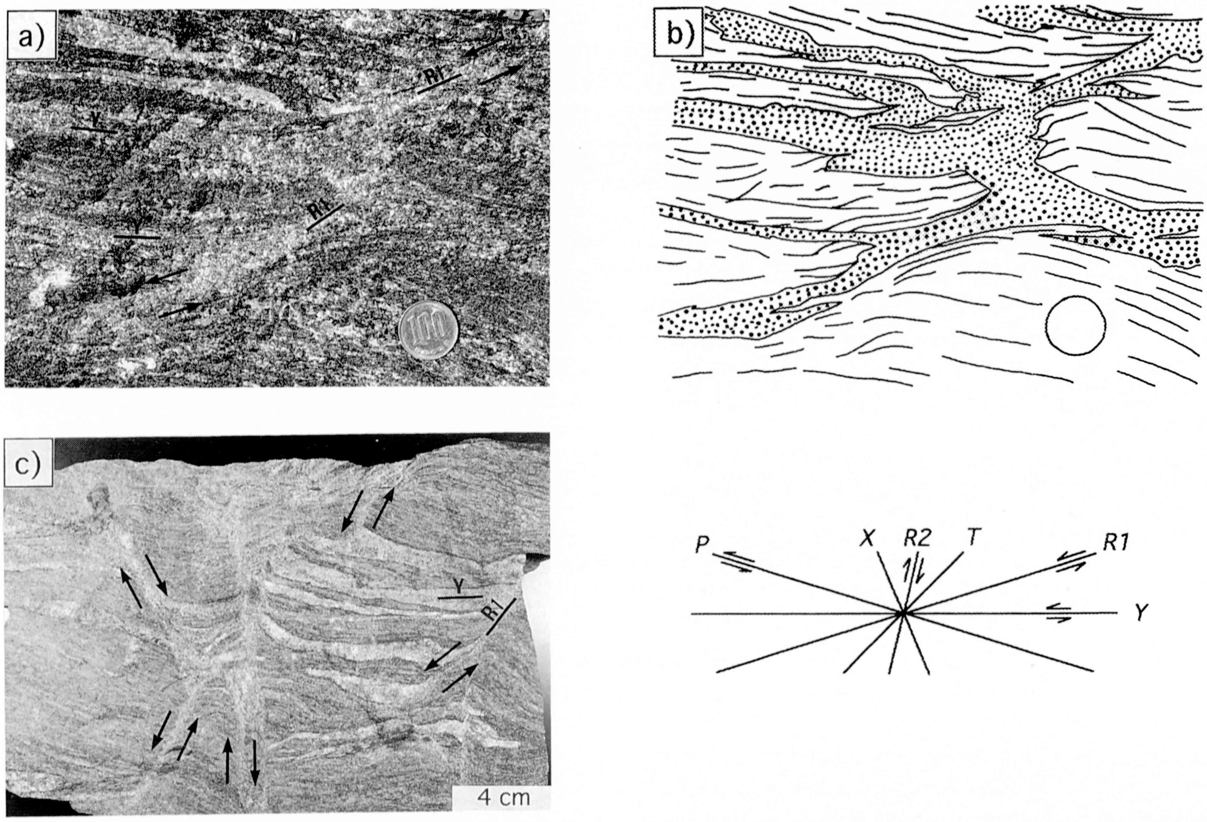

Fig. 6. a) Photograph showing the structure of melt-filled fractures around the Nagano migmatite. b) Sketched profile of photograph (a). dot: granitic part. strip: metapelite. c) Photograph showing the structure of melt-filled fractures around the older Ryoke granite.

Metamorphic minerals in the metapelites, which were crystallized under the peak metamorphic condition during the M_1 phase, are available to estimate its temperature condition using the garnet-biotite (Holdaway and Lee, 1977; Perchuk, 1977), garnet-cordierite (Holdaway and Lee, 1977; Perchuk, 1977), and two-feldspar (Stormer, 1975; Stormer and Whitney, 1977; Haselton *et al.*, 1983) geothermometers. The inset diagram in Fig. 3 represents the temperature variation in the cordierite zone which grades into the biotite zone to the north, and the garnet zone to the south (Okudaira *et al.*, 1994b). The metamorphic temperature estimated for sample Z-51 located north of the Tsuzu fault is significantly lower than those estimated for the samples located south of the fault (Fig. 3). In the southern block, the temperatures of samples F-8, E-23, and E-7 are slightly lower than those of samples S-1, F-11, and F-13 (Fig. 3). Overall, the metamorphic temperatures increase from north to south with decreasing structural level.

C. MOVEMENT PICTURE OF D_1 PHASE DEFORMATION IN THE TSUZU AREA

In the metamorphic rocks of the southern block and the southern part of the northern block are often found melt-filled fractures of minor scales, which cut across their foliation (Fig. 6). Such melt-filled fractures are parallel - subparallel to and oblique to the foliation, and the constituent minerals and minor structures in and around them suggest that they were developed by shearing along the foliation during the M_1 phase. The foliation-parallel ~ -subparallel fractures and foliation-oblique fractures are respectively comparable with the principle

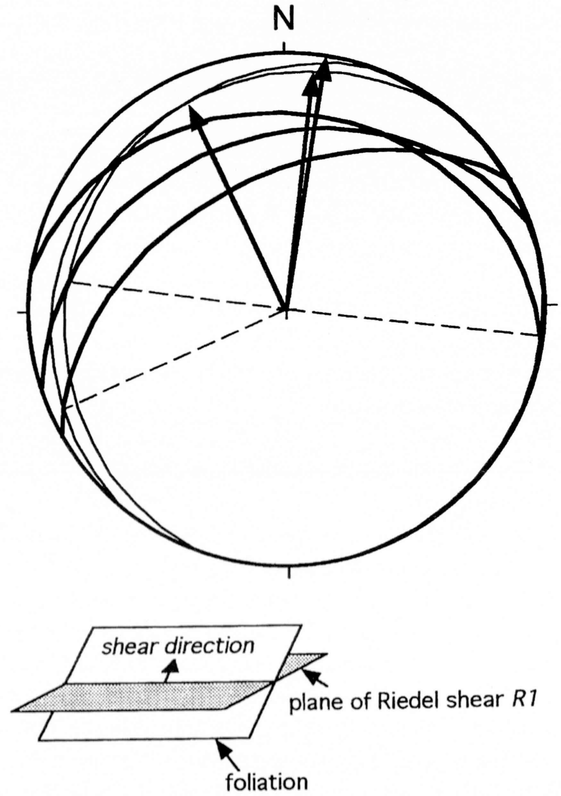

Fig. 7. Diagram showing the shear-direction (arrows) of the melt-filled fractures in the metapelites around the Iwakuni Century Golf Course. Thin solid girdles, thick solid girdles, and dashed lines represent foliation, plane of Riedel shear R1, and intersection between the former two, respectively. Lower hemisphere equal area projection.

displacement shear Y, the Riedel shear R_1, and the extension fracture T (after Skempton, 1966; Logan *et al.*, 1979; Bartlett *et al.*, 1981; Shimamoto, 1989). The deformation related to the formation of these melt-filled fractures resulted commonly from the foliation parallel extension, as inferred from the orientation pattern of the fractures (Hara *et al.*, 1991).

The melt-filled fractures appear to be especially strongly developed near the migmatites and the older granites (Hara *et al.*, 1991; Okudaira *et al.*, 1993). The metamorphic xenoliths in the migmatites, which are mainly metapelites, commonly have many melt-filled fractures which are not traced toward their surrounding granitic parts. It is clear that the xenoliths of various scales in the migmatites were derived from fractured blocks of metamorphic rocks. Okudaira *et al.* (1993) have been clarified that some metamorphic xenoliths came from the much greater depth zone than the surrounding metamorphic rocks. Therefore, the migmatites have been considered by Okudaira *et al.* (1993) to be intrusives along fracture zones, which are of the same generation as the melt-filled fractures of the surrounding metamorphic rocks. The overall movement picture inferred from the melt-filled fractures appears to be of the shear sense for the top to the north (Fig. 7). The migmatites are developed cutting across the lower structural level toward the north as is obvious in Figs. 2 and 3. The deformation related to the formation of the fracture zones, which were responsible for the intrusion of the migmatites and therefore of the older Ryoke granites, would be assumed to be of extension type.

The foliation of the metamorphic rocks in the Tsuzu area shows intrafolial folds of mesoscopic to minor scales. Their axial trends are commonly NS ~ NNW-SSE, though highly dispersed (fold axis (D_1) in Fig. 4). Figure 8 shows the time-relationship between the porphyroblastic growth of metamorphic mineral crystallized during the thermal peak of the M_1 metamorphism and the D_1 folding of intrafolial style. This figure indicates that the axial plane cleavage of crenulation

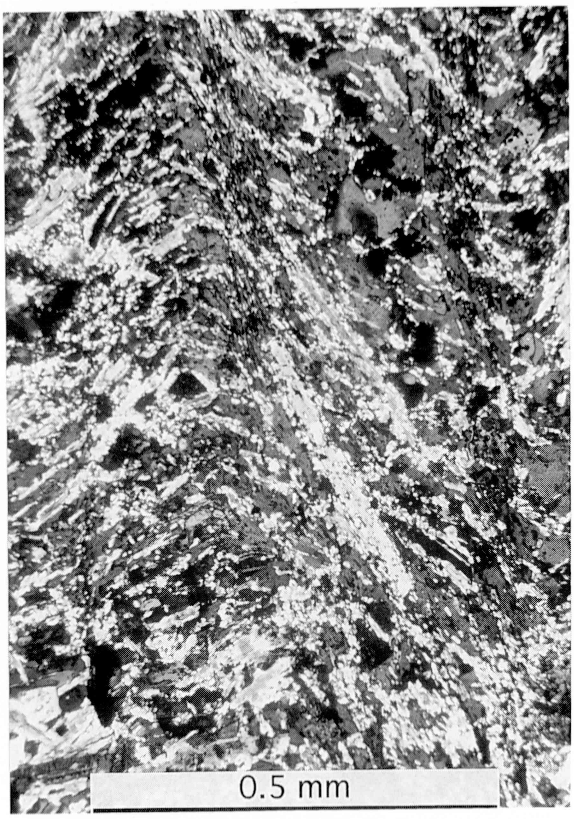

Fig. 8. Microphotograph showing the axial plane cleavage of crenulation type of D1 fold is masked by the K-feldspar porphyroblast.

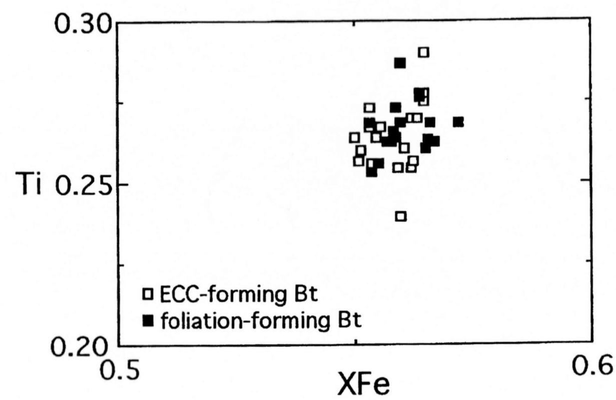

Fig. 10. Ti versus XFe [Fe/(Fe+Mg)] for biotite in metapelites from the biotite zone. Numbers of ions on the basis of 22 oxygens.

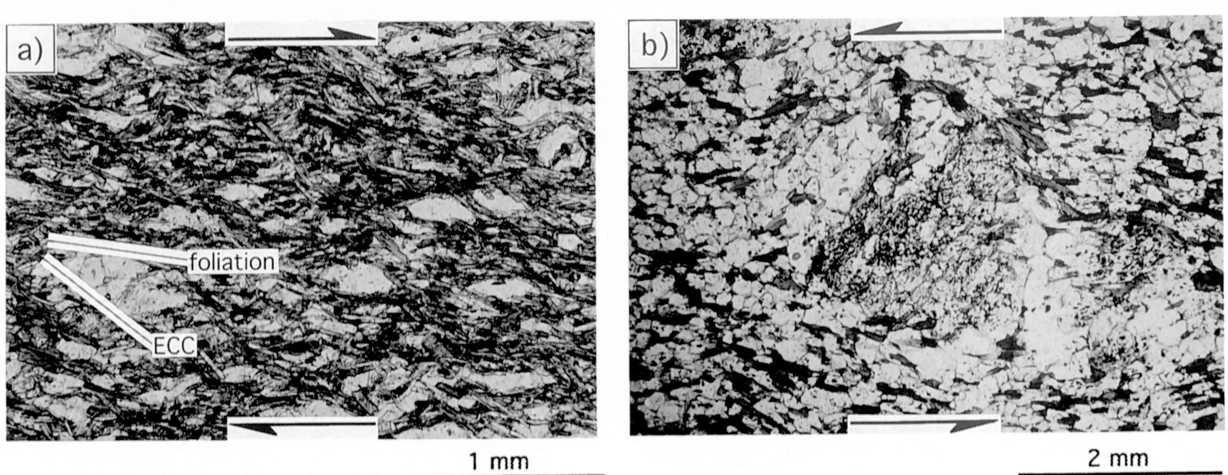

Fig. 9. Microphotographs showing asymmetric textures in metapelites of the biotite and cordierite zones. Plane-polarized light. a) extensional crenulation cleavage. b) rotation of cordierite porphyroblast. See text for details.

type of D_1 fold is masked by the K-feldspar porphyroblast. It can be said that the intrafolial folds with NS ~ NNW-SSE trending axes appear to be parallel to the shear direction inferred from the melt-filled fractures, which is the top to the north, during and immediately before the M_1 metamorphism.

Asymmetric textures such as extensional crenulation cleavage (ECC; Platt and Vissers, 1980) (Fig. 9a) and rotation of porphyroblasts (Fig. 9b) such as cordierite and K-feldspar, which were crystallized during the M_1 metamorphism, are often recognized in thin section of metapelites. These asymmetric textures are considered in relation to the M_1 metamorphism. Figure 10 illustrates the chemical compositions of the foliation-forming biotite and the ECC-forming biotite, suggesting that the former and the latter formed under the same metamorphic condition, which corresponds to the condition of M_1 metamorphism. The shear sense read from the above-mentioned asymmetric textures is top to the north, though fairly dispersed, as shown in Fig. 11. This is harmonic with the overall movement picture inferred from the melt-filled fractures (see Figs. 7 and 11). As mentioned above, the formation of the melt-filled fractures was responsible for the intrusion of the older Ryoke granites and for the M_1 metamorphism. Therefore it can be said that the overall movement picture of the D_1 deformation of the metamorphic rocks in the Tsuzu area during and immediately before the intrusion of the older Ryoke granites was of the same style of extension tectonics.

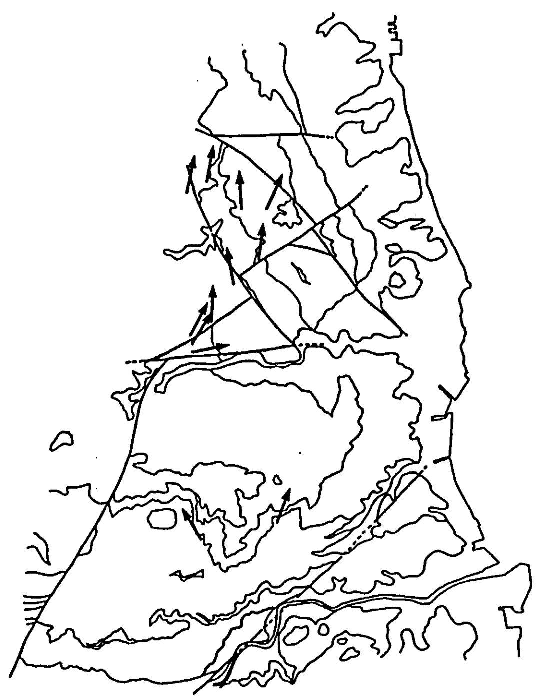

Fig. 11. Diagram showing the shear sense of the asymmetric texture in metapelites (closed arrows).

IV. CONCLUSION

Recently, Miyashita and Komatsu (1993, 1994) indicated that the deformation related to the formation of foliation in metamorphic rocks, which has a top to the north ~ northwest sense of shear, is of extension type. In this study, we also concluded that the D_1 deformation was operated under extensional stress regime and that the older Ryoke granites intruded in extensional fracture zones at intermediate crustal depths. The tectonic model for the emplacement of the older Ryoke granites is illustrated in Fig. 12. The extension tectonics occurred with the tensional stress approximately normal to the general trend of the Ryoke metamorphic belt. Following the tectonics, the Ryoke metamorphic belt suffered compressional deformation (D_2 deformation) which was related to the formation of nappes transporting toward the WSW or SW (Okudaira *et al.*, 1992, 1993).

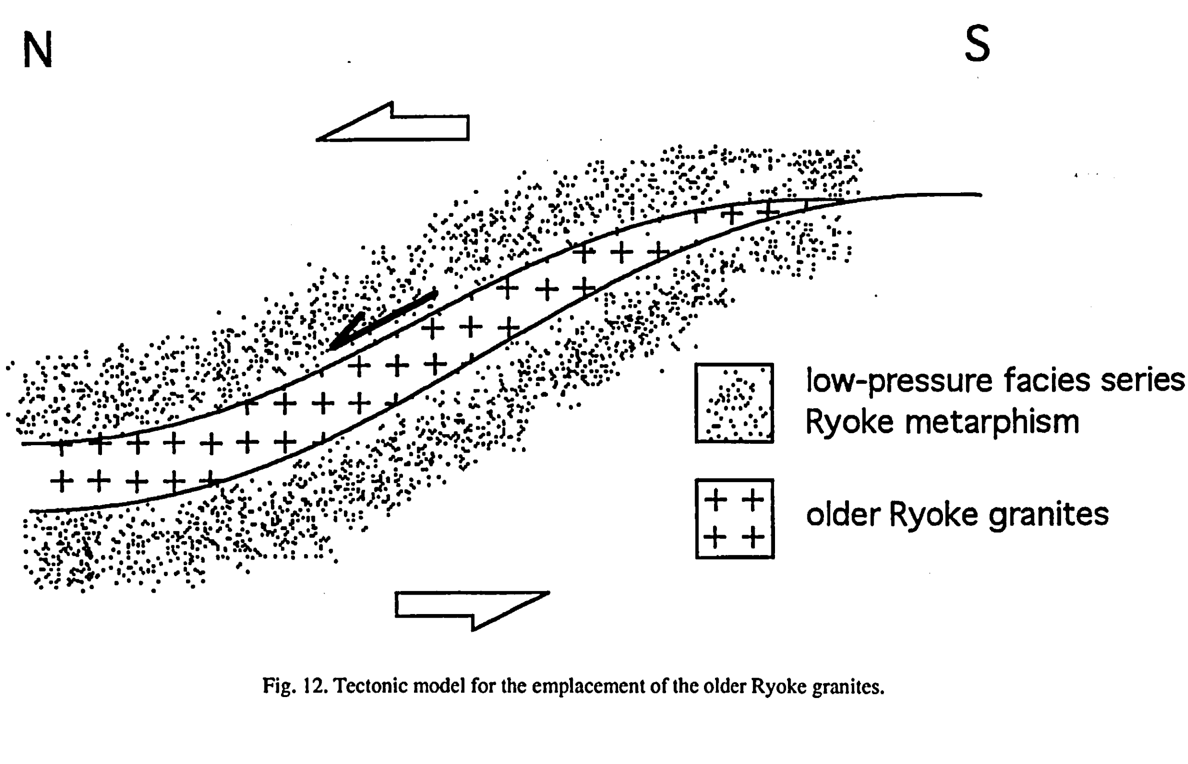

Fig. 12. Tectonic model for the emplacement of the older Ryoke granites.

Acknowledgments

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