Journal of Geosciences, Osaka City University
Vol. 40, Art. 6, p.97-117, March, 1997

Geological boundary faults and late exhumation process of the Permian-Jurassic subduction complexes in eastern Yamaguchi Prefecture, Southwest Japan

Michio TAKAMI*

Department of Geosciences, Faculty of Science, Osaka City University
Sugimoto 3-3-138, Sumiyoshi-ku, Osaka 558, Japan

Abstract

Permian accretionary complex, Triassic high-P/T Suo metamorphic complex and Jurassic accretionary complex are widely distributed from north to south, forming a pile-nappe structure in eastern Yamaguchi Prefecture, Southwest Japan. The Suo metamorphic complex is separated from the overlying Permian accretionary complex by the Nishikigawa and Kitayama faults, and is also separated from the underlying Jurassic accretionary complex by the Notanigawa fault.

On the basis of mineral assemblages in basic metamorphic rocks and of graphitization of carbonaceous material from pelitic metamorphic rocks, these three complexes are divided into the following mineral zones: Jurassic and Permian accretionary complexes — pumpellyite-chlorite (P-C) zone; Suo metamorphic complex — pumpellyite-actinolite (P-A) and epidote-glaucophane (E-G) zones. P-A zone is separated into the northern side (P-A zone I) and southern side (P-A zone II) of E-G zone. The basic internal structure of the three complexes is a metamorphic zonal structure consisting of P-C, P-A II, E-G, P-A I and P-C zones, in ascending order. The Nishikigawa and Notanigawa faults are parallel or subparallel to these zones, but the Kitayama fault is clearly oblique to them.

The d_{002} values of carbonaceous material from pelitic metamorphic rocks were measured systematically across all the mineral zones. They gradually decrease from P-C zone (Permian accretionary complex) through P-A zone I to E-G zone, suggesting that a progressive geothermal structure was formed. The gaps in d_{002} values at the position of the Kitayama fault show the gap in the geothermal structure. The gaps in these values at the boundary (Notanigawa fault) between the Jurassic accretionary complex and Suo metamorphic complex also show the gap in the geothermal structure.

Thus, the Notanigawa and Nishikigawa faults are the first-stage faults that were formed in the early exhumation process of the three complexes at the nappe emplacement stage. The Kitayama fault secondarily cuts the progressive geothermal structure, suggesting that the fault is the second-stage normal fault that was formed in the late exhumation process of the three complexes at the post-nappe emplacement stage. The late exhumation process is characterized by uplift and erosion of the three complexes arising from the formation of both the second-stage Kitayama fault and the large-scale antiforms in the Early Cretaceous. An E-W-trending uplift zone, about 100 km long, has been developed in this process.

Key Words: Permian-Jurassic, subduction complexes, graphitization, metamorphic zonation, exhumation process

1. Introduction

Microfossil (conodont and radiolarian) biostratigraphy coupled with detailed field investigations has distinguished major Late Paleozoic to Mesozoic accretionary complexes in Japan in the 1980s (e.g., Yao *et al.*, 1980; Yamato Omine Research Group, 1981; Taira, 1981; Kurimoto, 1982; Ishiga, 1983; Matsuoka, 1984). This research style called "microfossil mapping" (Isozaki and Maruyama, 1991) also clarified the detailed internal structures and formation processes of anciant accretionary complexes at a subduction margin (e.g., Kimura, 1988; Taira *et al.*, 1989; Isozaki *et al.*, 1990; Nakae, 1990; Matsuda and Isozaki, 1991; Kimura and Hori, 1993).

On the other hand, the newly advanced K-Ar dating, using a small amount of fine-grained phengitic mica separates (Itaya and Takasugi, 1988), has made possible the determination of metamorphic ages of weakly metamorphosed accretionary complexes (e.g., Nishimura *et*

* present address: Hiruzen Institute for Geology and Chronology, Sai 161-1, Okayama 703, Japan.

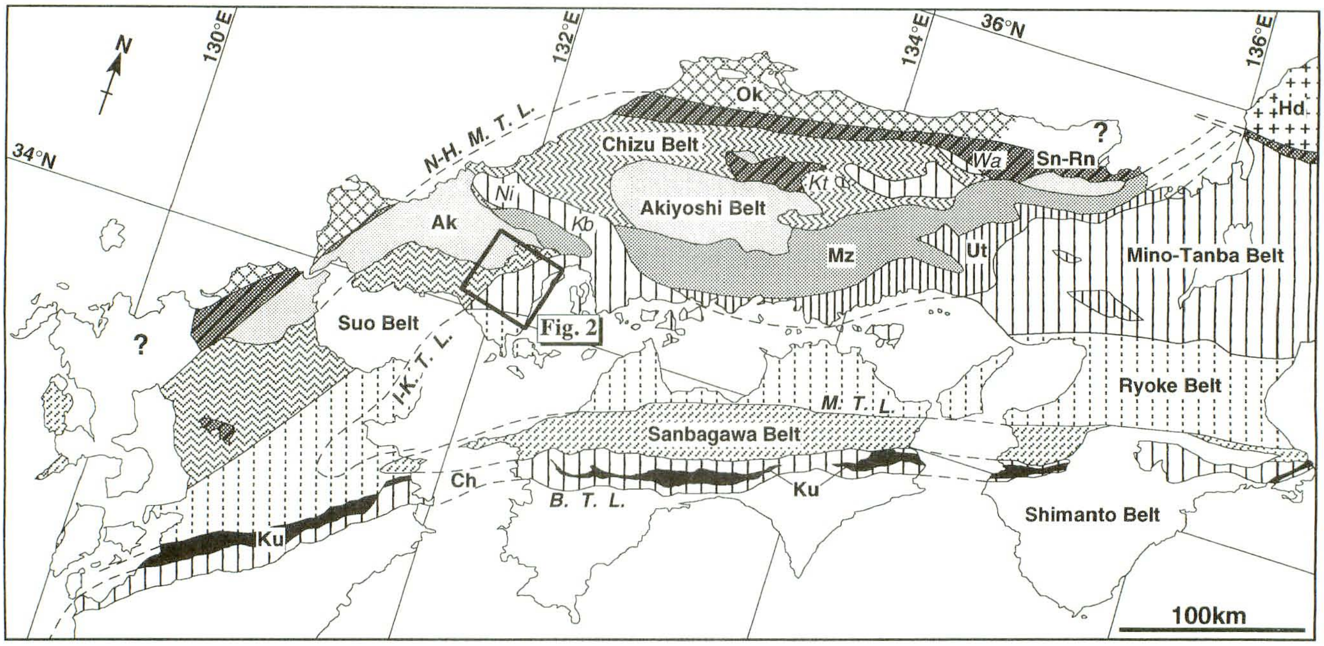

Fig. 1. Geotectonic framework of western Japan (compiled from Shibata and Nishimura, 1989; Isozaki and Itaya, 1991). Ok: Oki Belt; Hd: Hida Belt; Sn-Rn: Sangun-Renge Belt; Ak: Akiyoshi Belt; Mz: Maizuru Belt; Ut: Ultra-Tanba Belt; Ku: Kurosegawa Tectonic Outlier; Ch: Chichibu Belt; N-H. M. T. L.: Nagato-Hida Merginal Tectonic Line; I-K. T. L.: Ishigaki-Kuga Tectonic Line; M. T. L.: Median Tectonic Line; B. T. L.: Butsuzo Tectonic Line; Ni: Nichihara; Kb: Kabe; Kt: Katsuyama; Wa: Wakasa.

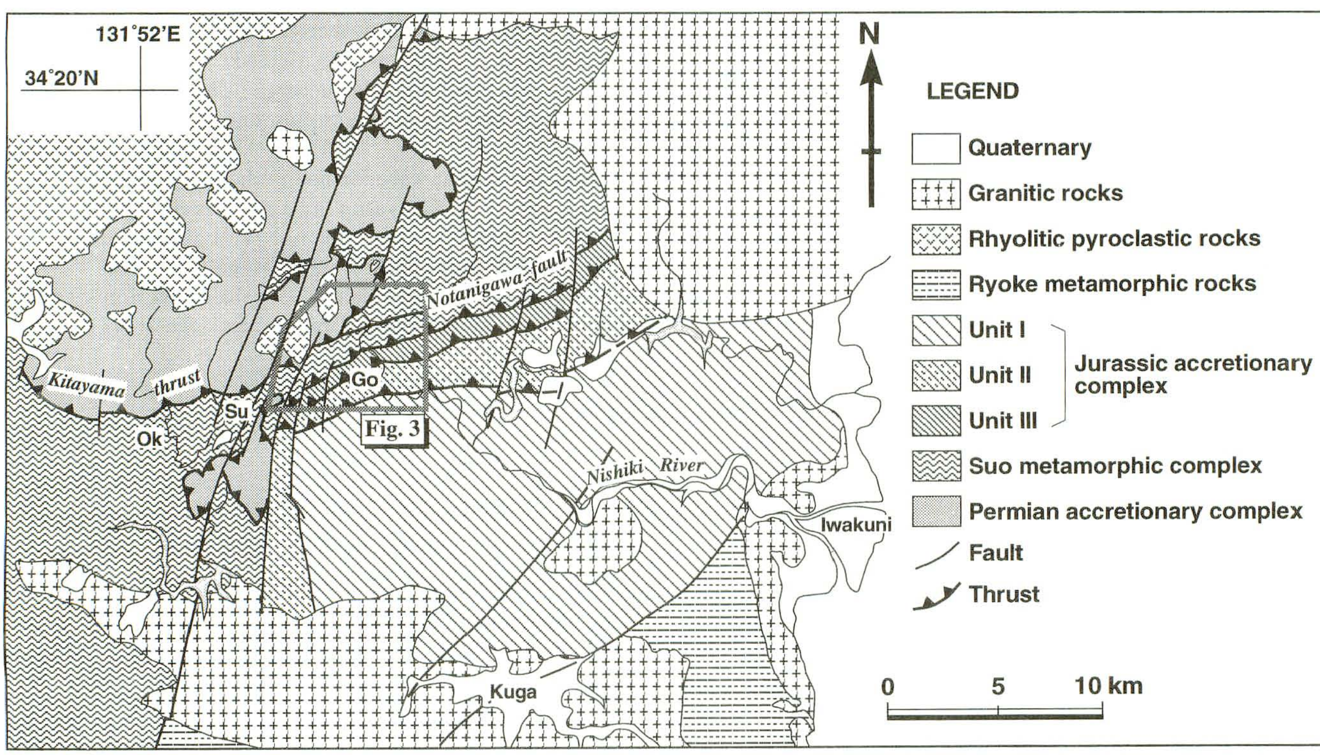

Fig. 2. Geologic sktch map of eastern Yamaguchi Prefecture (compiled from Nishimura *et al.*, 1989; Takata, 1987; Takami *et al.*, 1993; Nishimura *et al.*, 1995a; Takami and Itaya, 1996).
Go: Gonomoto area; Su: Suma area; Ok: Okuhata river area.

al., 1989; Isozaki and Itaya, 1990, 1991; Takami *et al.*, 1990, 1993; Ujiié and Nishimura, 1992), so that geotectonic boundaries between accretionary complexes, including high-P/T metamorphic complexes, have been exactly determined and redefined (e.g., Suzuki *et al.*, 1990; Kawato *et al.*, 1991; Isozaki *et al.*, 1992). This research style is called "chronological mapping" (Isozaki and Maruyama, 1991) and is characterized by coupling many K-Ar age determinations with detailed field investigations. Although the microfossil and chronological mapping techiniques use different methodologies, they reveal that the geologic structure of Southwest Japan is characterized by a pile-nappe structure composed of accretionary complexes and high-P/T metamorphic complexes with low-angle tectonic boundaries (thrusts) between them. Faure (1985) and Charvet *et al.* (1985) also pointed out a pile-nappe structure in Southwest Japan from the point of view of structural geology.

Maruyama (1990) compiled occurrences, ages and petrologies of high-P/T metamorphic complexes from about 250 areas in the world, and demonstrated that high-P/T metamorphic complexes are generally sandwiched between overlying and underlying accretionary complexes with low-angle first-stage faults of the nappe emplacement stage. He also showed that these three complexes are cut by high-angle second-stage normal faults of the post-nappe emplacement stage. These indicate that the boundary fault between an accretionary

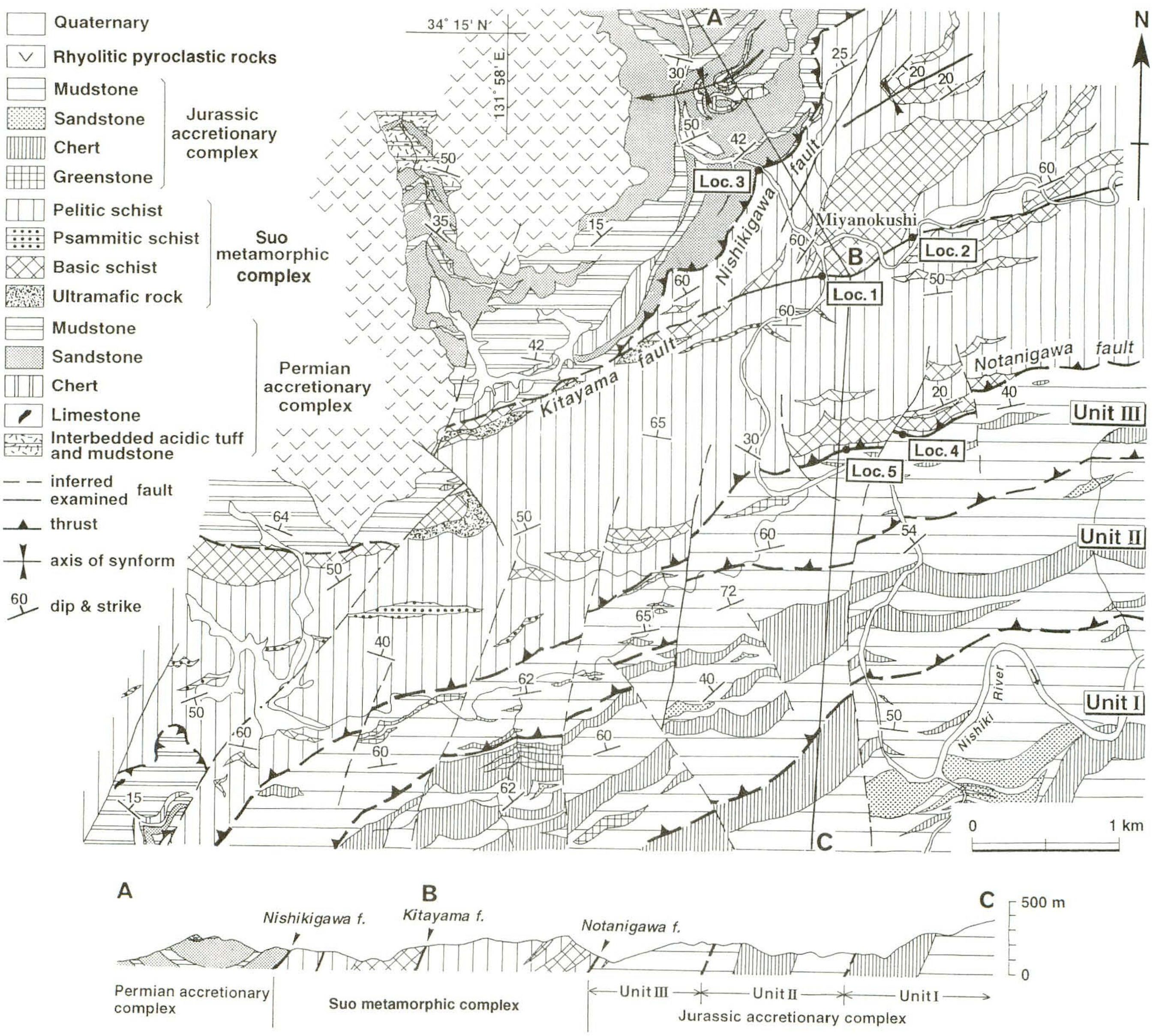

Fig. 3. Geological map and profile of the Miyanokushi area, eastern Yamaguchi Prefecture.

complex and a high-P/T metamorphic one is not only the first-stage fault but also the second-stage one. The exact distinction of these faults is significant under taking account of the exhumation process of a high-P/T metamorphic complex. This distinction, however, has not been studied in detail, and/or the boundary fault has been generally called a thrust until now.

This paper describes the nature of the geological boundary faults between the Permian accretionary complex and the Triassic high-P/T metamorphic complex, and between the Jurassic accretionary complex and the metamorphic complex in eastern Yamaguchi Prefecture, Southwest Japan (Figs. 1, 2) on the basis of: (1) the detailed field investigation; (2) metamorphic zonation based on mineral assemblages in basic metamorphic rocks; and (3) graphitization of carbonaceous material from pelitic metamorphic rocks. The systematic measurement of graphitization of carbonaceous material is available in order to clarify not only the geothermal structure of a metamorphic complex but also the geological relation between an accretionary complex and a metamorphic complex (e.g., Itaya, 1981; Nishimura *et al.*, 1989; Hashimoto *et al.*, 1992). As the result, two distinct faults, namely, first- and second-stage boundary faults, are distinguished between the accretionary complex and the metamorphic complex. The author discusses the siguificance of these faults in the exhumation process of the complexes.

2. Outline of geology

Late Paleozoic to Early Cenozoic accretionary complexes, including high-P/T metamorphic complexes, are generally distributed in an E-W direction in western Japan (Fig. 1). The Jurassic accretionary complex in the Mino-Tanba Belt is separated from the pre-Jurassic complexes (Permian complex in the Ultra-Tanba and Maizuru Belts, and Triassic to Jurassic high-P/T metamorphic complexes in the Suo and Chizu Belts) by the Ishigaki-Kuga Tectonic Line (Isozaki and Nishimura, 1989). The Jurassic accretionary complex gradually changes into the Cretaceous low-P/T Ryoke metamorphic rocks to the south (e.g., Kojima, 1953; Nakajima, 1960; Higashimoto *et al.*, 1983). The high-P/T metamorphic complexes in the Suo and Chizu Belts are also separated from the Permian accretionary complex in the Akiyoshi Belt by faults (e.g., Takeda and Nishimura, 1989; Nishimura *et al.*, 1989; Sugimoto *et al.*, 1990). The Permian accretionary complex and the Suo metamorphic complex are generally unconformably overlain by Cretaceous volcanic rocks (e.g., The Ministy of International Trade and Industry, 1980; Murakami and Imaoka, 1986).

The study area (called the Miyanokushi area in this paper) is situated northwest of Iwakuni City, Yamaguchi Prefecture (Figs. 2, 3). In this area, the Permian accretionary complex, the Triassic high-P/T Suo metamorphic complex and the Jurassic accretionary complex occur, and they show a zonal distribution from north to south. They form a pile-nappe structure bounded mutually by faults. As the Suo metamorphic complex occurs in a narrow belt (about 2 km wide) between the Permian and Jurassic accretionary complexes in the Miyanokushi area, the nature of the boundary fault and of geological structure between these complexes can be tested in this area. A brief summary of the lithology and geochronology of the three complexes is given in this paper based on the previous studies (e.g., Nishimura and Nureki, 1966; Nishimura *et al.*, 1989; Takata, 1987; Takami *et al.*, 1990, 1993; Takami and Itaya, 1996) and on this study.

The Jurassic accretionary complex is a chaotic sedimentary complex composed of argillaceous matrices and numerous allochthonous blocks of chert, greenstone, siliceous mudstone, limestone, sandstone and mudstone. These rocks range, biostratigraphically, from Late Carboniferous to latest Jurassic (e.g., Toyohara, 1976; Hayasaka *et al.*, 1983; Takata, 1987; Takami *et al.*, 1990, 1993). Takami and Itaya (1996) investigated the Gonomoto area in the southern part of the Miyanokushi area (Figs. 2, 3), and divided the Jurassic accretionary complex into three distinct geologic units. These are: Units I, II and III, from south to north or from young to old, on the basis of differences in lithologies, biostratigraphic data, metamorphic mineral assemblages in greenstone, and K-Ar age characteristics of phengitic mica separated from pelitic rocks. These units form a pile-nappe structure bounded mutually by N-dipping faults. They have slightly different ages of accretion and metamorphism. These ages are listed below (geologic time scale is after Harland *et al.*, 1990).

Unit I: accretion, latest Jurassic (ca. 147 Ma); metamorphism, Early Cretaceous (ca. 124 Ma)

Unit II: accretion, Middle Jurassic (ca. 175 Ma); metamorphism, Late Jurassic (ca. 152 Ma)

Unit III: accretion, Early Jurassic (ca. 195 Ma); metamorphism, Middle Jurassic (ca. 172 Ma)

The Suo high-P/T metamorphic complex consists mainly of pelitic schist, basic schist, psammitic schist and serpentinized ultramafic rock, with a small amount of siliceous schist and calcareous schist. Nishimura *et al.* (1989) pointed out that the Suo metamorphic complex was originally an accretionary complex on the basis of the lithologic assemblage. The accretion age is not clear because of an absence of fossils, but Nishimura *et al.* (1989) suggested it to be Middle Triassic, judging from a K-Ar age of relict hornblende (239 ±13 Ma) from metagabbro, which is enveloped in pelitic schist in the Yamaguchi area, 55 km away to the west (Nishimura and Shibata, 1989). The Suo metamorphic complex is divided into two mineral zones, namely, the pumpellyite-actinolite and the epidote-glaucophane zones, on the basis of mineral assemblages in basic metamorphic rocks. This suggests that the Suo metamorphic complex in this area has undergone a regional metamorphism of the high-pressure intermediate group (Nishimura, 1971; Nishimura *et al.*, 1989). The K-Ar and Rb-Sr ages of phengitic mica from pelitic schist suggest that the metamorphic age of the Suo metamorphic complex is around 225 Ma (Late Triassic; Nishimura *et al.*, 1989; Shibata and Nishimura, 1989).

The Permian accretionary complex consists of mudstone, sandstone, interbedded sandstone and mudstone, acidic tuff, and chert, with a small amount of greenstone and limestone. These rocks range, biostratigraphically, from Middle to Late Permian (e.g., Nishimura *et al.*, 1985, 1989; Naka *et al.*, 1986). On the basis of the youngest fossil age, the accretion age of the complex is considered to be Late Permian (Nishimura *et al.*, 1989). The Permian accretionary complex has undergone a low-grade metamorphism of the prehnite-pumpellyite facies (Nishimura, 1971; Nishimura *et al.*, 1989). On the basis of K-Ar ages of phengitic mica for pelitic rocks and of whole rock for acidic tuff, the metamorphic age of the complex is considered to be around 225 Ma (Late Triassic). This shows that the Permian accretionary complex may represent a lower grade part of the Suo metamorphic complex (Nishimura *et al.*, 1989).

3. Geological boundary fault

On the basis of detailed field investigation, distribution pattern of the pumpellyite-actinolite mineral zone and variation of d_{002} values of carbonaceous material as described later, the Suo metamorphic complex and the Permian accretionary complex are bounded by two distinct faults in the Miyanokushi area (Fig. 3). One fault is situated in the central part of this area, and runs in an ENE-WSW and/or E-W direction. The fault separates the Suo metamorphic complex from the Permian accretionary complex in the western part of this area, and its eastern lateral extension is traceable into the area of the Suo metamorphic complex. The outcrops of the fault are observed at Locs. 1 and 2, where the fault strikes E-W and dips 70° northward. This fault dips slightly steeper than the Suo metamorphic complex and the Permian accretionary complex. Although strike of the fault is almost parallel to that of the Suo metamorphic complex in the southern area of the fault, it is oblique to those of the Suo metamorphic complex and the Permian accretionary complex in the northern area of the fault. In this paper, this fault is called the Kitayama fault. The other fault is situated in the northern part of this area; it runs in a NE-SW direction and its southwestern lateral extension is cut by the Kitayama fault. The outcrop of this fault is observed at Loc. 3, where the fault strikes N60°E and dips 60° northwestward. This fault plane is almost parallel to the bedding planes of both the Suo metamorphic complex and the Permian accretionary complex; it is newly designated as the Nishikigawa fault in this paper.

The Jurassic accretionary complex and the Suo metamorphic complex are bounded by the Notanigawa fault, which runs in an ENE-WSW direction (Toyohara, 1974; Nishimura *et al.*, 1995b) (Fig. 3). The outcrops of this fault are observed at Locs. 4 and 5, where the fault strikes N80°E and dips 60-70° northward. Although this fault plane is almost parallel to the bedding planes of the Jurassic accretionary complex, it is oblique to that of the Suo metamorphic complex which generally strikes N60-80°W and dips 20-60° northward around the fault.

4. Metamorphic zonation

On the basis of mineral assemblages in basic metamorphic rocks, metamorphic zonation has been carried out in this area. Basic metamorphic rocks are not ubquitous in the area, and thus, the geologic relation between mineral zones cannot be exactly examined. The graphitization of carbonaceous material from pelitic metamorphic rocks is used for determination of their relations. Metamorphic mineral assemblages and distribution of mineral zones are described below, and the mutual relations between the mineral zones will be described later.

The Jurassic accretionary complex, the Suo metamorphic complex and the Permian accretionary complex in this area are divided into the following mineral zones (Fig. 4).

Jurassic accretionary complex : pumpellyite-chlorite (P-C) zone

Suo metamorphic complex : pumpellyite-actinolite

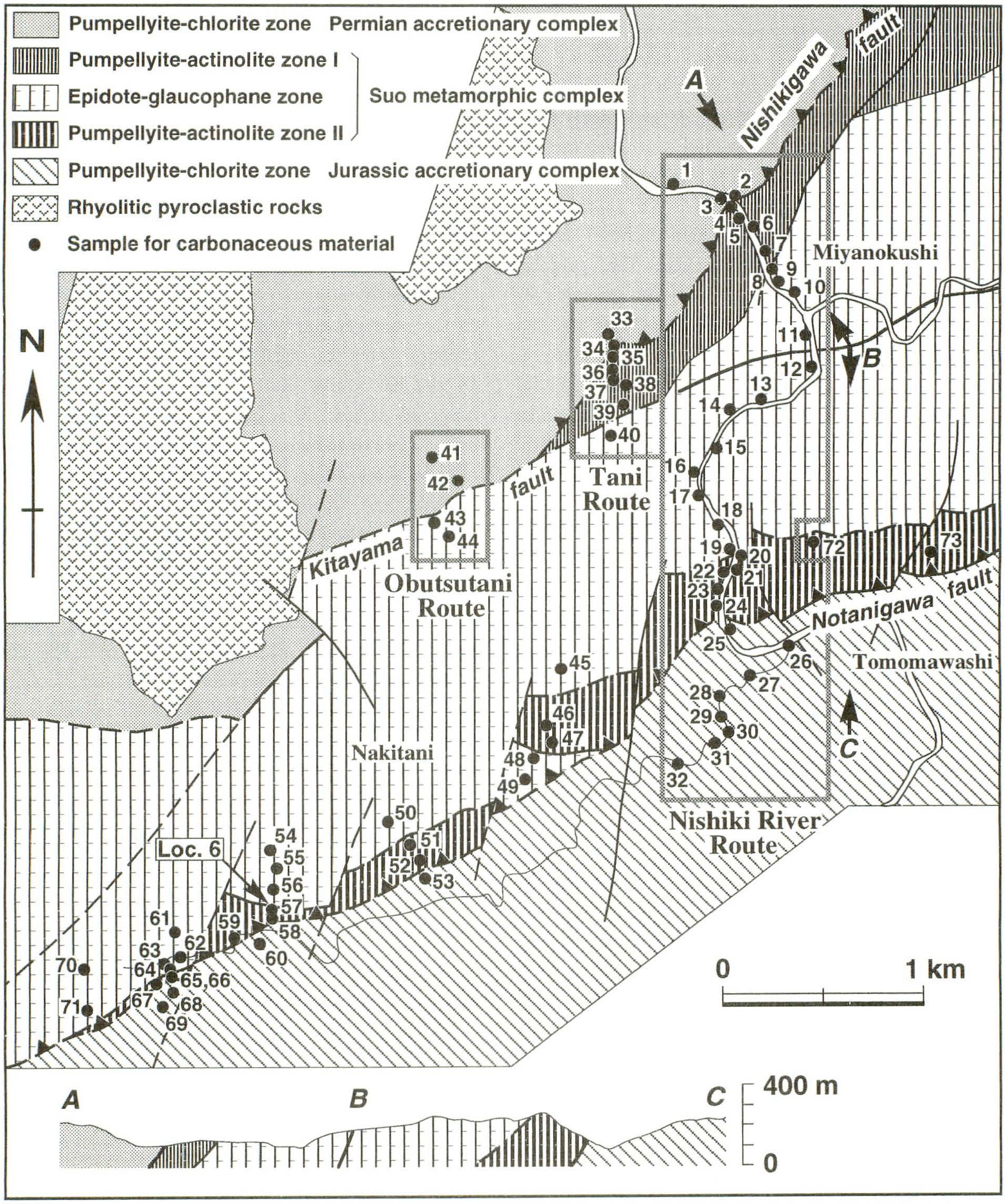

Fig. 4. Metamorphic zonal map and profile of the Miyanokushi area.

(P-A) and epidote-glaucophane (E-G) zones

Permian accretionary complex : pumpelliyte-chlorite (P-C) zone

Metamorphic mineral assemblages in greenstones of the Jurassic accretionary complex are chlorite + pumpellyite ± epidote ± stilpnomelane, chlorite + pumpellyite + actinolite, chlorite + epidote ± phengitic mica, and chlorite + phengitic mica from Unit III, and chlorite + phengitic mica ± stilpnomelane, and chlorite + pumpellyite + phengitic mica from Unit II (Takami and Itaya, 1996). Although both units are characterized by an assemblage of pumpellyite and chlorite (P-C zone), the metamorphic grade of Unit III is slightly higher than that of Unit II because of the occurrence of epidote and actinolite from the former. The metamorphic grade of Unit I is not clear due to an absence of any characteristic metamorphic minerals. The metamorphic grade of this unit is inferred to be lower than those of Units II and III, because of the relatively lower degree of recrystallization of clastic grains in the rocks and also the smaller grain size of recrystallized phengitic mica in pelitic rocks. Metamorphic mineral assemblages in greenstones of the Permian accretionary complex are chlorite + pumpellyite and chlorite + phengitic mica, and they are also characterized by the presence of pumpellyite and chlorite (P-C zone). Pumpellyite and stilpnomelane often occur in sandstone (Nishimura, 1971; Nishimura *et al.*, 1989).

The Suo metamorphic complex is divided into two mineral zones characterized by an assemblage of pumpellyite and actinolite in one (P-A zone), and by that of epidote and glaucophane in the other (E-G zone). Mineral assemblages in basic metamorphic rocks of P-A zone are chlorite + pumpellyite + actinolite + phengitic mica ± epidote and chlorite + epidote + actinolite ± phengitic mica ± stilpnomelane, and those of E-G zone are chlorite + epidote + actinolite ± phengitic mica ± stilpnomelane, chlorite + epidote + winchite + actinolite ± phengitic mica ± stilpnomelane, and chlorite + epidote + crossite ± phengitic mica ± stilpnomelane (Nishimura, 1971; Nishimura *et al.*, 1989; this study).

P-A zone is separated into the two parts (Fig. 4). One part is between E-G zone and P-C zone (Permian accretionary complex) in the northern part of this area, which is conveniently called P-A zone I. P-A zone I is distributed along the Nishikigawa fault in a NE-SW direction and its southwestern lateral extension is cut by the Kitayama fault. The other is between E-G zone and P-C zone (Jurassic accretionary complex), and is conveniently called P-A zone II. P-A zone II occurs continuously along the Notanigawa fault in an E-W and/or ENE-WSW direction. E-G zone is widely distributed in the central part of this area in a NE-SW direction. Although E-G zone occurs between P-A zone I and P-A zone II in the eastern part of this area, it occurs between P-C zone (Permian accretionary complex) and P-A zone II without P-A zone I in the western part of this area. The Suo metamorphic complex is generally sandwiched between the Jurassic and Permian accretionary complexes (Fig. 4), and shows a metamorphic zonal structure composed of P-A zone II, E-G zone and P-A zone I, in ascending order. The distribution pattern of P-A zone I is significant in the geological structure between the Suo metamorphic complex and the Permian accretionary complex, as described later.

5. Graphitization of carbonaceous material

5.1. Purpose and Method

Carbonaceous material is a common constituent of pelitic metamorphic rocks. Its chemical composition and crystal structure change systematically with increasing metamorphic temperature. In this process, carbonaceous material recrystallizes to form a graphite structure and finally reaches the structure of fully ordered graphite. This recrystallization is called graphitization (e.g., French, 1964; Izawa, 1968; Landis, 1971; Tagiri, 1981). The interplanar distance d_{002} value of carbonaceous material decreases with the graphitization. The systematic decrease of the d_{002} values with increasing metamorphic grade within a metamorphic complex shows that a metamorphic complex preserves a progressive geothermal structure. On the other hand, discontinuous change of the d_{002} values, such as the occurrence of a gap in the values within a metamorphic complex, shows a gap in the geothermal structure arising from faulting (e.g., Itaya, 1981; Nishimura *et al.*, 1989; Hashimoto *et al.*, 1992).

In order to clarify (1) the mutual relations between the mineral zones, (2) the exact positions of the boundary faults, i.e. the Nishikigawa, Kitayama and Notanigawa faults investigated in the field, and (3) the effect of the Kitayama fault on the mineral zones, the d_{002} values of carbonaceous material from pelitic metamorphic rocks of the Jurassic accretionary complex (Unit III), the Suo metamorphic complex and the Permian accretionary complex were systematically measured. Three traverse routes, the Nishiki river, Tani and Obutsutani routes from east to west, were selected to measure the d_{002} values. The Nishiki river route covers all the mineral zones in this area, i.e., the Permian accretionary complex (P-C zone), the Suo metamorphic complex (P-A zone I, E-G zone, P-A zone II) and the Jurassic accretionary complex (P-C zone) from north to south, and three faults, namely, the Nishikigawa, Kitayama and Notanigawa faults. The Tani route traverses the Permian accretionary complex (P-C zone), the Suo metamorphic complex (P-A zone I, E-G zone) and the Nishikigawa and Kitayama faults. The Obutsutani route traverses the Permian accretionary complex (P-C zone), the Suo metamorphic complex (E-G zone) and the Kitayama fault separating them. Furthermore, the d_{002} values were measured at many localities around Nakitani and in northern Tomomawashi.

5.2. Sample preparation

Samples of pelitic metamorphic rocks are phyllite or slate from the Jurassic accretionary complex (Unit III), slate from the Permian accretionary complex, and schist from the Suo metamorphic complex. Samples were collected systematically at 32 localities along the Nishiki river route, 8 localities along the Tani route, 4 localities along the Obutsutani route, and 29 localities around Nakitani and in northern Tomomawashi, making a total of 73 samples (Fig. 4).

Samples were crushed and sieved to take the fraction less than 100 mesh size. Carbonaceous material in the powdered samples was separated from silicate minerals by acid treatment in HF and HCl solution on a steambath, according to the method by Chijiwa *et al.* (1993). After the treatment, the d_{002} values of carbonaceous material were measured with a X-ray diffractometer, using the analytical procedure described by Itaya (1981).

5.3. Results

The d_{002} values are shown in Table 1, and the typical X-ray diffractograms from 15° to 35° 2θ Cu-K α of carbonaceous material from the Permian accretionary complex (No. 2), the Suo metamorphic complex (Nos. 4, 7, 8, 14, 21, 22) and the Jurassic accretionary complex (Nos. 27, 29) are shown in Fig. 5. With increasing metamorphic grade from, P-C zone through P-A zone to E-G zone, the intensity of (002) peak of carbonaceous material gradually increases, its width decreases, its position shifts towards higher 2θ, and a broad peak approaches a sharp peak, as described by Itaya (1981). Variations of the d_{002} values along the Nishiki river, Tani and Obutsutani routes are also shown in Fig. 6. The d_{002} values from the Jurassic accretionary complex (Unit III) range from 3.534 to 3.613 Å and those from the Permian accretionary complex from 3.579 to 3.604 Å, suggesting that the degree of graphitization from both complexes is almost the same. On the other hand, the d_{002} values from the Suo metamorphic complex range widely, from 3.378 to 3.542 Å, those from P-A zone are 3.424 to 3.542 Å, and those from E-G zone are 3.378 to 3.418 Å.

In the Nishiki river route, the d_{002} values from the Permian and Jurassic accretionary complexes are about 3.6 Å, and those from the Suo metamorphic complex are almost between 3.4 and 3.5 Å (Fig. 6). At the boundary between the Jurassic accretionary complex and the Suo metamorphic complex, the large gap in the d_{002} values is clearly recognized, which coincides with the position of the Notanigawa fault. Such gaps are also recognized around Nakitani (Table 1, Fig. 4). At the boundary between the Permian accretionary complex and the Suo metamorphic complex, the gap in the d_{002} values is slight, which coincides with the position of the Nishikigawa fault. The d_{002} values from P-A zone II are about 3.5 Å, and they decrease slightly from north to south. The d_{002} values from the southern part of E-G zone are about 3.4 Å. The gap in these values is

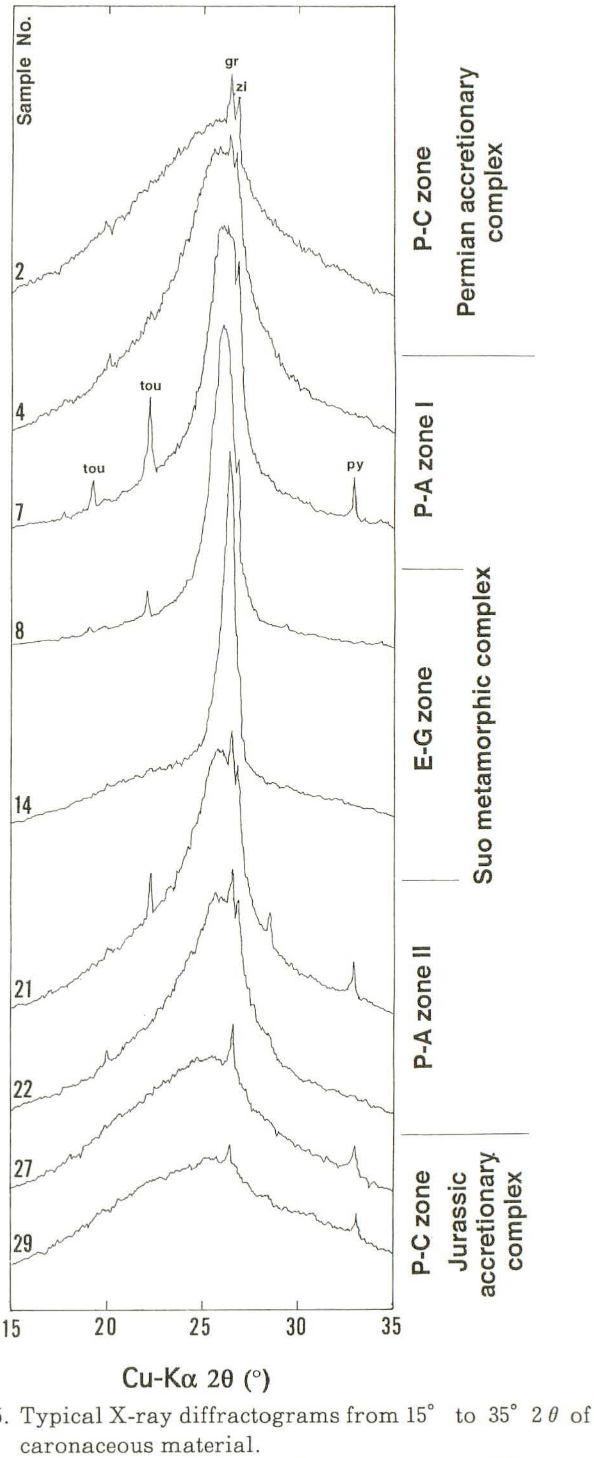

Fig. 5. Typical X-ray diffractograms from 15° to 35° 2θ of caronaceous material.
gr: detrital graphite; zi: zircon; tou: tourmaline; py: pyrite.

clearly recognized at the boundary between two zones, whch is considered to be a fault. Such gaps are also recognized around Nakitani (Table 1, Fig. 4). On the other hand, the d_{002} values from P-A zone I decrease from north to south and gradually change into those from E-G zone. The Kitayama fault in this route is situated within E-G zone, where the gap in the d_{002} values is slight.

In the Tani route, the d_{002} value from the Permian accretionary complex is 3.584 Å and those from the Suo metamorphic complex range from 3.381 to 3.542 Å (Fig. 6). The gap in the d_{002} values is slight at the boundary between two complexes, which coincides with the position of the Nishikigawa fault. The d_{002} values from P-A zone I are about 3.5 Å and they decrease from north to south, which is similar to the variation in the Nishiki river route. On the south of P-A zone I, the d_{002} values from E-G zone is about 3.4 Å and the gap in values is recognized at the boundary between two zones. This gap coincides with the position of the Kitayama fault. The gradually decreasing part of the d_{002} values from P-A zone I to E-G zone, recognized in the Nishiki river route, is absent in this route.

In the Obutsutani route, the d_{002} values from the Permian accretionary complex are about 3.6 Å, and those from the Suo metamorphic complex are about 3.4 Å (Fig. 6). The large gap in the d_{002} values is clearly recognized at the boundary between the two

Table 1. A list of d_{002} values of carbonaceous material from pelitic matamorphic rocks in the Miyanokushi area.
P-C: pumpellyite-chlorite zone; P-A I: pumpellyite-actinolite zone I; P-A II: pumpellyite-actinolite zone II; E-G: epidote-glaucophane zone.

Sample No.	2θ (°)	d_{002} (Å)	Mineral zone
Nishiki river route			
1	24.76	3.593	P-C
2	24.68	3.604	P-C
3	24.86	3.579	P-C
4	25.34	3.512	P-A I
5	25.72	3.461	P-A I
6	25.88	3.440	P-A I
7	25.98	3.427	P-A I
8	26.05	3.418	E-G
9	26.05	3.418	E-G
10	26.10	3.411	E-G
11	26.12	3.409	E-G
12	26.36	3.378	E-G
13	26.33	3.382	E-G
14	26.33	3.382	E-G
15	26.34	3.381	E-G
16	26.08	3.414	E-G
17	26.15	3.405	E-G
18	26.24	3.393	E-G
19	26.30	3.386	E-G
20	25.32	3.515	P-A II
21	25.50	3.490	P-A II
22	25.40	3.504	P-A II
23	25.54	3.485	P-A II
24	25.64	3.471	P-A II
25	24.64	3.610	P-C
26	24.62	3.613	P-C
27	24.65	3.609	P-C
28	24.66	3.607	P-C
29	24.65	3.609	P-C
30	24.65	3.609	P-C
31	24.4	3.596	P-C
32	24.66	3.607	P-C
Tani route			
33	24.82	3.584	P-C
34	25.12	3.542	P-A I
35	25.40	3.504	P-A I
36	25.42	3.501	P-A I
37	25.54	3.485	P-A I
38	25.80	3.450	P-A I
39	25.58	3.479	P-A I
40	26.34	3.381	E-G
Obutsutani route			
41	24.76	3.593	P-C
42	24.48	3.633	P-C
43	26.23	3.395	E-G
44	26.23	3.395	E-G
Nakitani			
45	26.14	3.398	E-G
46	25.46	3.496	P-A II
47	25.70	3.463	P-A II
48	26.11	3.410	E-G
49	26.19	3.400	E-G
50	26.19	3.400	E-G
51	25.66	3.469	P-A II
52	25.48	3.493	P-A II
53	25.00	3.559	P-C
54	26.26	3.391	E-G
55	26.30	3.386	E-G
56	26.28	3.388	E-G
57	25.84	3.445	P-A II
58	25.84	3.445	P-A II
59	26.00	3.424	P-A II
60	24.98	3.562	P-C
61	26.12	3.409	E-G
62	26.18	3.410	E-G
63	26.18	3.410	E-G
64	26.18	3.410	E-G
65	25.90	3.437	P-A II
66	25.60	3.474	P-A II
67	25.22	3.528	P-A II
68	25.18	3.534	P-C
69	24.80	3.587	P-C
70	26.10	3.411	E-G
71	26.14	3.406	E-G
Northern Tomomawashi			
72	25.62	3.456	P-A II
73	25.76	3.474	P-A II

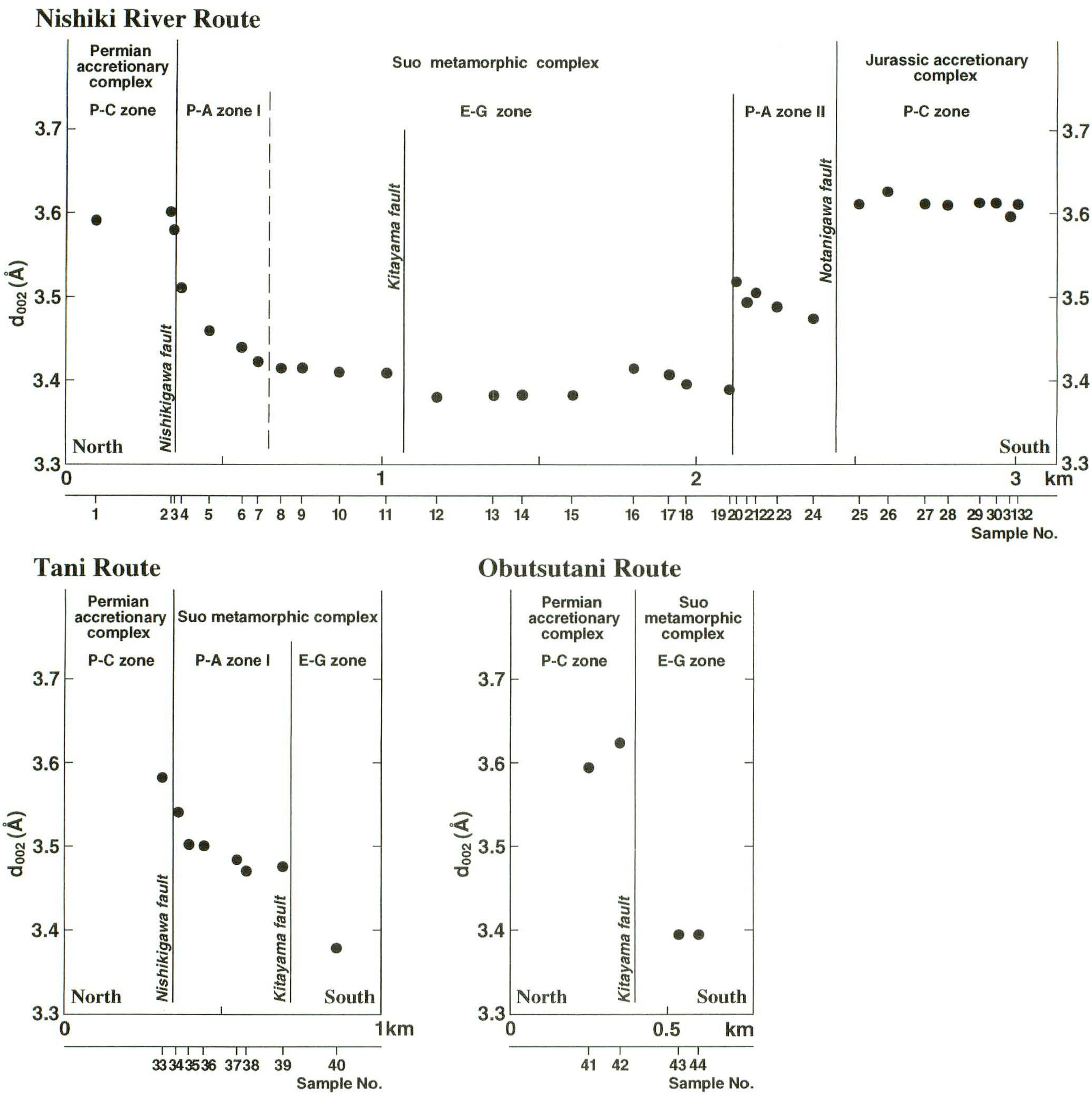

Fig. 6. Variations of d_{002} values of carbonaceous material form pelitic metamorphic rocks along the Nishiki river, Tani and Obutsutani routes.

complexes. This gap coincides with the position of the Kitayama fault. P-A zone I and the gradually decreasing part from P-A zone I to E-G zone are no longer recognized in this route.

The gaps in the d_{002} values at the boundaries between the Jurassic accretionary complex and the Suo metamorphic complex, and between the Permian accretionary complex and the Suo metamorphic complex, show the gaps in the geothermal structure. These gaps coincide with the positions of the Notanigawa, Nishikigawa and Kitayama faults investigated in the field. The d_{002} values from P-A zone I gradually change into those from E-G zone along the Nishiki river route, thus suggesting that a progressive geothermal structure from P-A zone I to E-G zone is present. On the other hand, the gap in the d_{002} values at the boundary between P-A zone II and E-G zone shows that the gap in the geothermal structure is present due to faulting. In fact, the outcrop of the fault between the two zones is observed at Loc. 6 (Fig. 4), where the fault strikes N60° W and dips 80° northeastward. In the northern part of this area, the degree of the gap in the d_{002} values recognized at the position of the Kitayama fault is different in every route; the gap becomes larger from the Nishiki river route through the Tani route to the Obutsutani route (from east to west). Furthermore, in the northern area of the Kitayama fault, the variation pattern of the d_{002} values is different in every route, according to whether P-A zone I and the gradually changing part from P-A zone I to E-G zone are present or not. In the southern area of the Kitayama fault, however, the d_{002} values from E-G zone are almost the same in all the routes. These variation patterns of the d_{002} values in the three routes clearly indicate that the Kitayama fault is oblique to the zonal distribution of P-C zone (Permian accretionary complex), P-A zone I and E-G zone from north to south, and secondarily cuts them (Fig. 4).

Nishimura *et al.* (1989) reported that the d_{002} values of carbonaceous material from pelitic metamorphic rocks gradually decrease from P-C zone (Permian accretionary complex) through P-A zone to E-G zone in the Okuhata river area, 4 km west of this area (Fig. 2), which are the same results as those in the northern part of the Nishiki river route, shown in this study. They explained that the Permian accretionary complex and the Suo metamorphic complex have undergone the same regional metamorphism, so that a progressive geothermal structure has been formed.

6. Discussion

On the basis of detailed field investigation, metamorphic zonation and d_{002} values of carbonaceous material, the nature of the geological boundary faults between the Jurassic accretionary complex, the Suo metamorphic complex and the Permian accretionary complex in eastern Yamaguchi Prefecture are discussed below. The author points out the late exhumation process of three complexes at the post-nappe emplacement stage.

6.1. First-stage fault

The Permian accretionary complex, the Suo metamorphic complex and the Jurassic accretionary complex are distributed from north to south in the Miyanokushi area and are bounded mutually by N-dipping faults, forming a pile-nappe structure. The Jurassic accretionary complex and the Suo metamorphic complex are bounded by the Notanigawa fault, and the Suo metamorphic complex and the Permian accretionary complex are bounded by the Nishikigawa and Kitayama faults. These faults are confirmed by the gaps in the d_{002} values of carbonaceous material, as mentioned above (Fig. 6). The mineral assemblages in basic metamorphic rocks and the d_{002} values of carbonaceous material from pelitic metamorphic rocks show the division of mineral zones such as P-C zone (Jurassic and Permian accretionary complexes), P-A zone I, P-A zone II and E-G zone (Suo metamorphic complex). This metamorphic zonation and the field relations suggest a basic internal structure in this area, namely, a metamorphic zonal distribution consisting of P-C zone, P-A zone II, E-G zone, P-A zone I and P-C zone, in ascending order (Fig. 4). The Nishikigawa fault separates P-A zone I (Suo metamorphic complex) from overlying P-C zone (Permian accretionary complex), and the Notanigawa fault separates P-C zone (Jurassic accretionary complex) from overlying P-A zone II (Suo metamorphic complex). P-A zone I gradually changes into E-G zone because the d_{002} values of carbonaceous material continuously decrease from the former to the latter. However, P-A zone II is in fault contact with E-G zone because the gap in the d_{002} values of carbonaceous material is recognized at the boundary between the two zones.

The distribution pattern of the mineral zones and variation in the d_{002} values are clarified in the northern part of this area in the following manner (Figs. 4, 6). (1) P-A zone I and E-G zone between the Nishikigawa and Kitayama faults become narrower towards the southwest, and disappear at the junction of the two faults, and finally, P-C zone is in direct contact with E-G zone along the Kitayama fault to the west. (2) The degree of the gap in the d_{002} values at the position of the Kitayama fault becomes larger from the Nishiki river route, through the Tani route, to the Obutsutani route (from east to west). (3) In the northern area of the Kitayama fault, the variation in the d_{002} values is different in every route, according to whether P-A zone I and the gradually changing part from P-A zone I to E-G zone are present or not. (4) In the southern area of the Kitayama fault, the d_{002} values from E-G zone are almost the same in all the routes. These lines of evidence strongly suggest that the basic internal structure is secondarily cut by the Kitayama fault, defined as the second-stage fault. The Nishikigawa fault, which is cut by the Kitayama fault is, therefore, defined as the first-stage fault, separating P-A zone I of the Suo metamorphic complex from the overlying Permian accretionary complex. P-C zone, P-A zone I, E-G zone and the Nishikigawa fault, which occur in a NE-SW direction, are apparently oblique to the trend of the

Kitayama fault at about 30° on the land surface; this is because an E-W-trending synform, with its axis plunging slightly to the west, develops in the northern part of this area, and because the Kitayama fault dips steeper northward than these zones and the Nishikigawa fault.

The areal distribution of mineral zones in and around the Miyanokushi area shown in Fig. 7 is compiled from Nishimura *et al.* (1989). Besides, in the Miyanokushi area, P-A zone is distributed in the Hirose and Suma areas, and significantly occurs between P-C zone (Permian accretionary complex) and E-G zone.

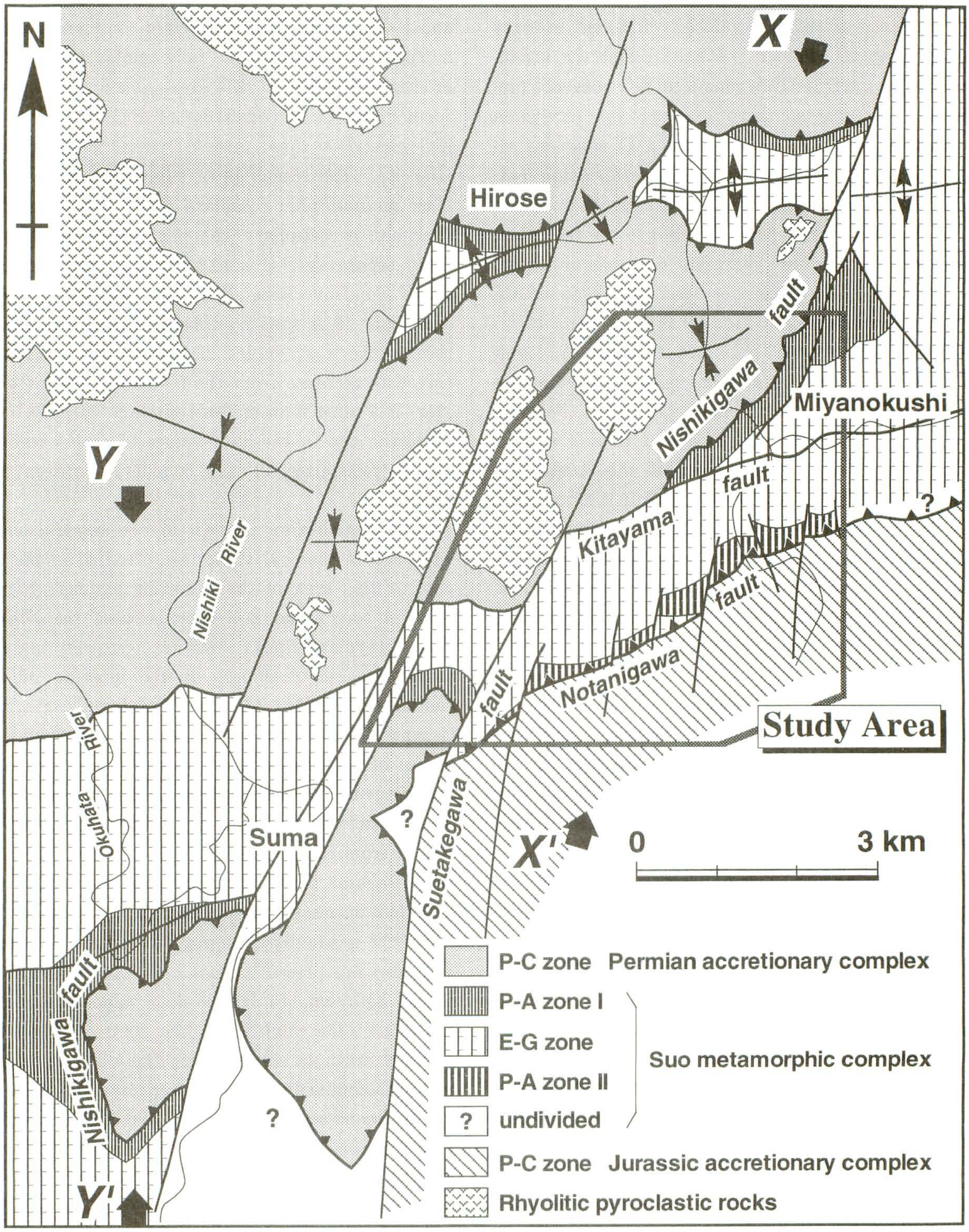

Fig. 7. Areal distribution of metamorphic zones in eastern Yamaguchi Prefecture (compiled from Nishimura *et al.*, 1989; this study).

This distribution pattern of P-A zone is the same as that of P-A zone I in the Miyanokushi area, suggesting that the boundary fault separating the Suo metamorphic complex from the overlying Permian accretionary complex in these areas is considered to be the lateral extension of the first-stage Nishikigawa fault designated in the Miyanokushi area. As the Nishikigawa fault generally dips at a low-angle northward, it shows a complicated shape on the land surface owing to E-W-trending antiforms and synforms. The fault does not have a large geothermal gap, as exhibited by the d_{002} values of carbonaceous material along the Nishiki river and Tani routes, in this study. This evidence and the coincidence of the K-Ar ages between the Suo metamorphic complex and the Permian accretionary complex strongly suggest that these complexes have together undergone the same regional metamorphism, so that a progressive geothermal structure has been formed (Nishimura *et al.*, 1989). The Nishikigawa fault was probably formed as a primary fault when these complexes were formed as accretionary complexes at a subduction margin. The fault is inferred to have partly moved during an exhumation process of the two complexes, considering the slight gap in the d_{002} values of carbonaceous material along the Nishiki river and Tani routes. The absence of P-A zone I on the land surface in the northern neighbouring area of the Miyanokushi area (Figs. 7, 8A) is considered to arise from such a movement of the fault.

The Jurassic accretionary complex and the overlying Suo metamorphic complex are bounded by the Notanigawa fault. This fault is considered to be the first-stage fault because P-A zone II on the northern side of the fault occurs continuously along the fault.

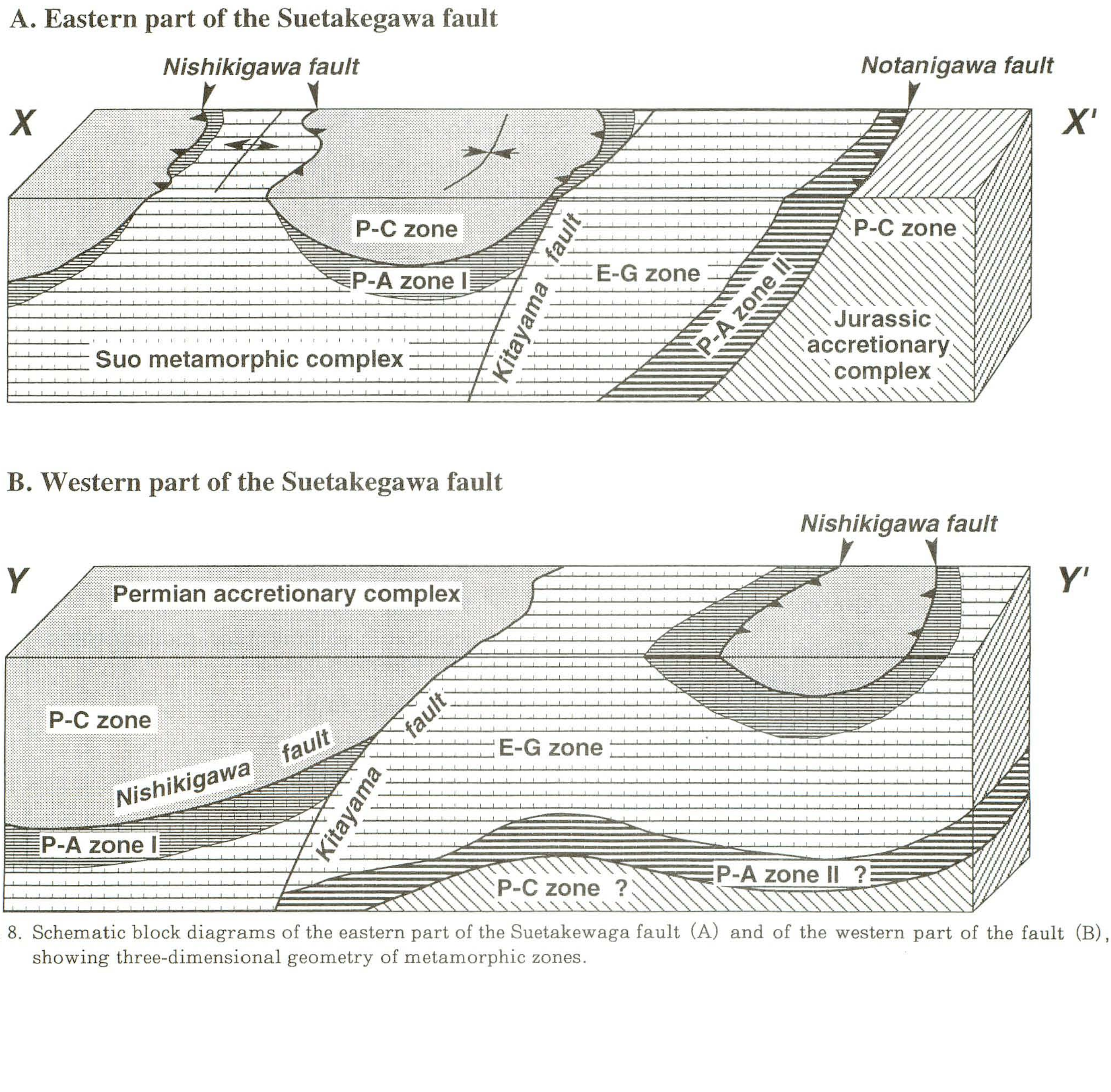

Fig. 8. Schematic block diagrams of the eastern part of the Suetakewaga fault (A) and of the western part of the fault (B), showing three-dimensional geometry of metamorphic zones.

However, the fault is slightly oblique to the internal structure of the Suo metamorphic complex because the fault plane is oblique to the bedding plane of the metamorphic complex, and because P-A zone II generally becomes narrower towards the west on the land surface (Fig. 4). The Notanigawa fault has a large geothermal gap, as indicated by the d_{002} values of carbonaceous material. On the other hand, the metamorphic age of the Jurassic accretionary complex (Unit III) is around 170 Ma (Middle Jurassic; Takami and Itaya, 1996) and that of the Suo metamorphic complex is around 225 Ma (Late Triassic; Nishimura *et al.*, 1989). Thus, the Notanigawa fault represents a large geological gap, shown not only in the metamorphism but also in the geochronology. This fault constitutes a part of the Ishigaki-Kuga Tectonic Line, which separates the Jurassic accretionary complex from the overlying pre-Jurassic subduction complexes in Southwest Japan. Its importance for the geotectonic framework of Southwest Japan was discussed by Isozaki and Nishimura (1989). The above-mentioned feature of the Notanigawa fault as the first-stage fault is significantly different from that of the Nishikigawa fault, because the latter has no metamorphic gap such as the gaps in the geothermal structure and age that exist between the Suo metamorphic complex and the Permian accretionary complex. The difference may arise from whether the fault separates the Suo metamorphic complex from the overlying accretionary complex or from the underlying one. Not only these features but also the basic internal structure, based on metamorphic zonation, may contribute to understanding the structural development of the metamor-

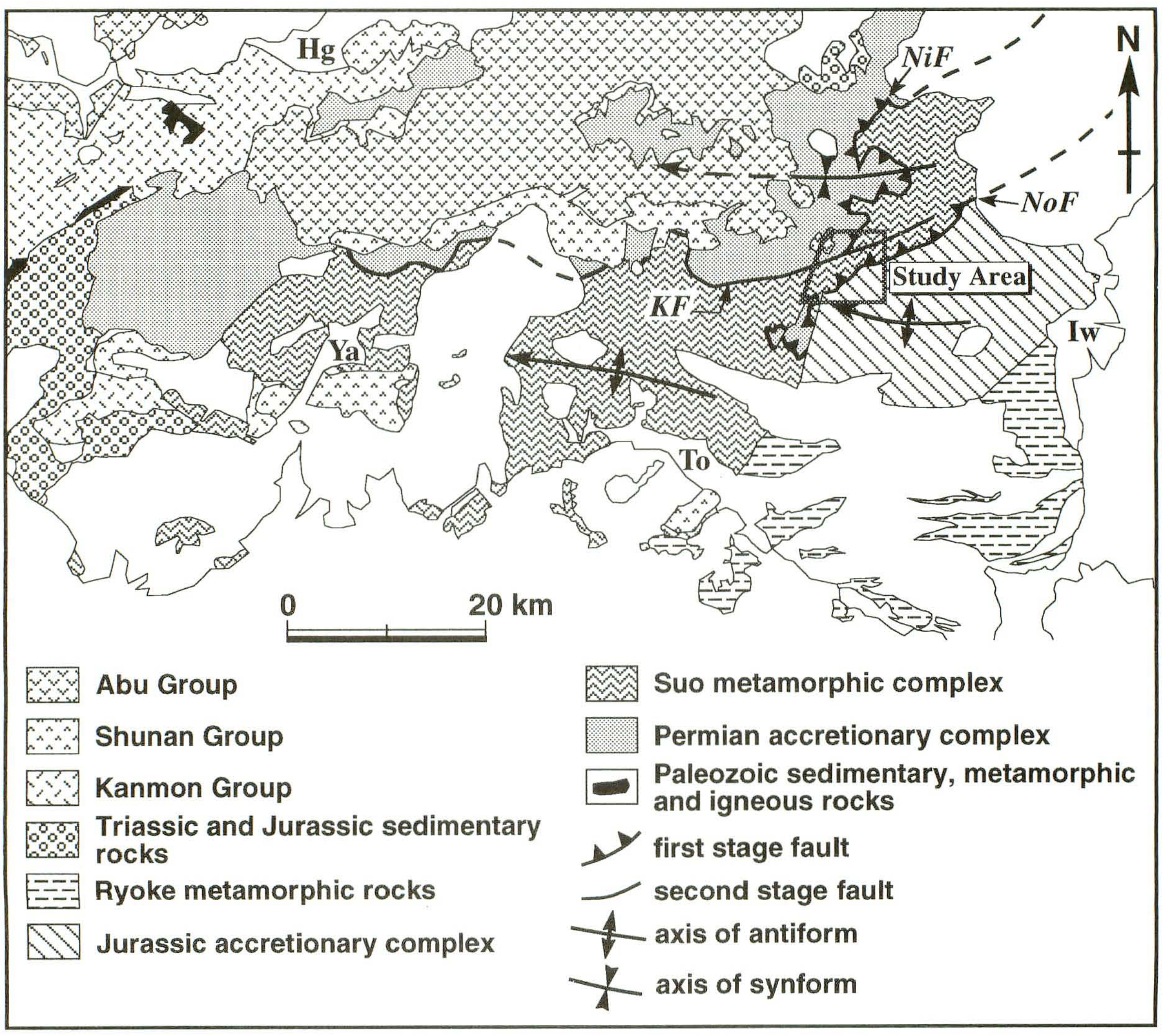

Fig. 9. Distributions of the Permian-Jurassic subduction complexes and Triassic-Creteceous sedimentary and volcanic rocks in the Yamaguchi-Iwakuni area, Yamaguchi Prefecure (complied from Nishimura *et al.*, 1995a; this study).
NiF: Nishikigawa fault; NoF: Notanigawa fault; KF: Kitayama fault; Ya: Yamaguchi; To: Tokuyama; Iw: Iwakuni; Hg: Hagi.

phic complex.

6.2. Second-stage fault

The boundary between the Suo metamorphic complex and the overlying Permian accretionary complex consists of two distinct faults, the first-stge Nishikigawa fault and the second-stage Kitayama fault, as mentioned above. The western lateral extension of the Kitayama fault in the Miyanokushi area is traceable to the Okuhata river area and further, to the Yamaguchi area (Figs. 7, 9). In the Okuhata river area, the fault is inferred to separate E-G zone (Suo metamorphic complex) from P-C zone (Permian accretionary complex) (Nishimura *et al.*, 1989), which is the same as that in the western part of the Miyanokushi area. The Kitayama fault dips 70° northward in the Miyanokushi area (Fig. 8A), but it dips about 40° northward in the Okuhata river area (Fig. 8B; Nishimura *et al.*, 1985). This difference of the dip angle between two areas is explained by the following geologic evidence. In the east of Suma, the Suetakegawa fault (Okamura and Kojima, 1951; Toyohara, 1976) is situated in a N-S and /or NE-SW direction and cuts the Kitayama fault in the Miyanokushi area (Fig. 7). Hence, the Suetakegawa fault can be called the third-stage fault. The Suo metamorphic complex and the overlying Permian accretionary complex are present in the western area of the Suetakegawa fault, and these two complexes and the Jurassic accretionary complex are present in the eastern area of the fault. At the southeast of Suma, the Permian accretionary complex occurs as a klippe upon the Suo metamorphic complex and is in direct contact with the Jurassic accretionary complex along the Suetakegawa fault. The structural relations of the Permian accretionary complex, Suo metamorphic complex, and Jurassic accretionary complex, in descending order, show that the Suetakegawa fault has a large vertical gap, and that the eastern block of the fault moved relatively upwards in opposition to the western one (Fig. 8). This movement may be in excess of the whole thickness of the Suo metamorphic complex, which is about 1600 m (Nishimura and Nureki, 1966) at the place. Therefore, the deeper level appears on the land surface in the Miyanokushi area rather than in the Okuhata river area. The deeper level of the Kitayama fault in the Miyanokushi area, which is cut by the Suetakegawa fault, also occurs on the land surface rather than in the Okuhata river area. Thus, the difference of the dip angle of the Kitayama fault between two areas is related to the difference of erosion of the complexes arising from the movement of the Suetakegawa fault. The Kitayama fault is considered to have the nature of the second-stage normal fault, the fault plane of which is not flat but has a bow shape, bending towards the north. This fault originally dips at a high angle in the lower horizontal level and at a low angle in the upper one (Fig. 8B). The fault also has a geothermal gap, indicated by the d_{002} values of carbonaceous material along the Nishiki river, Tani and Obutsutani routes in this study, and by the Okuhata river route reported by Nishimura *et al.* (1989). This suggests that an original and progressive geothermal structure from the Permian accretionary complex to the Suo metamorphic complex, with increasing metamorphic grade, was secondarily cut by the fault.

Many researchers have discussed the geological relations between the Suo metamorphic complex and the overlying Permian accretionary complex in eastern Yamaguchi Prefecture; conformity, shear zone, tectonic slide, thrust and normal fault (Kojima, 1953; Nishimura and Nureki, 1966; Nureki, 1969; Nishimura, 1971; Nishimura *et al.*, 1989; Toyohara *et al.*, 1989; Hirayama, 1992), which are summarized by Hirayama (1992). Excepting the three types of relationship, conformity, shear zone and thrust suggested by Kojima (1953), the boundary between two complexes has been regarded as the only continuous fault, e.g., the Kitayama thrust (Fig. 2; Nishimura *et al.*, 1989). The boundary between two complexes, however, consists of two distinct faults, namely, the first-stage Nishikigawa fault and the second-stage Kitayama fault, in the Miyanokushi area. Hirayama (1992) investigated the deformational structure of the Suo metamorphic complex (E-G zone) and the Permian accretionary complex (P-C zone) in the Suma area, and called the boundary fault between them the "Kitayama fault", a low-angle normal fault. He concluded that the Permian accretionary complex had not been affected by the Suo metamorphism, on the basis of the evidence of different deformational histories between the two complexes. However, this study disagrees with his view because: (1) the variation in the d_{002} values shows that the Suo metamorphic complex and the Permian accretionary complex originally form a progressive geothermal structure, consisting of P-C zone, P-A zone, and E-G zone, in descending order (Nishimura *et al.*, 1989; this study); (2) the boundary fault between the two complexes in the Suma area is regarded to be the second-stage fault cutting this original progressive geothermal structure (this study); and (3) the metamorphic age is the same between the two complexes, on the basis of radiometric datings (Nishimura *et al.*, 1989).

6.3. Late exhumation process

The geological boundary faults, the first- and second-stage faults between the Jurassic accretionary complex, the Suo metamorphic complex and the Permian accretionary complex in eastern Yamaguchi Prefecture, represent the following two processes: early and late exhumation processes of the three complexes. The early exhumation process is characterized by upthrust of both the Suo metamorphic complex and the overlying Permian accretionary complex over the Jurassic accretionary complex, forming a pile-nappe structure (Fig. 10A). This is a structural movement at the nappe emplacemant stage, which basically constitutes a part of the tectonic framework of Southwest Japan. The age of this stage is inferred to be the Middle or Late Jurassic, because the Jurassic accretionary complex (Unit III) was formed at a subduction margin in the Early Jurassic, and underwent a subsequent subduction-related metamorphism in the Middle Jurassic (Takami and Itaya, 1996).

The late exhumation process succeeded the formation of a pile-nappe structure. This process is characterized by the development of the E-W-trending, second-stage normal fault (Kitayama fault), and by the uplift and erosion of the three complexes. This is a structural movement at the post-nappe emplacement stage, which constrains a distribution pattern of the three complexes on the land surface (Fig. 10B). Owing to the normal faulting, the southern block of the fault moved relatively upwards in opposition to the northern one, thus leading to the uplift of the former consisting of three complexes. On the other hand, the Suo metamorphic complex is generally folded by an E-W-trending antiform, with its axis plunging slightly to the west in the Yamaguchi-Tokuyama area, according to the previous field investigations (Nishimura *et al.*, 1995a) (Fig. 9). This antiform is, however, not clear in the Yamaguchi area because of the Late Cretaceous igneous activity, such as formation of a cauldron (Takeda and Imaoka, 1994). The Jurassic accretionary complex is

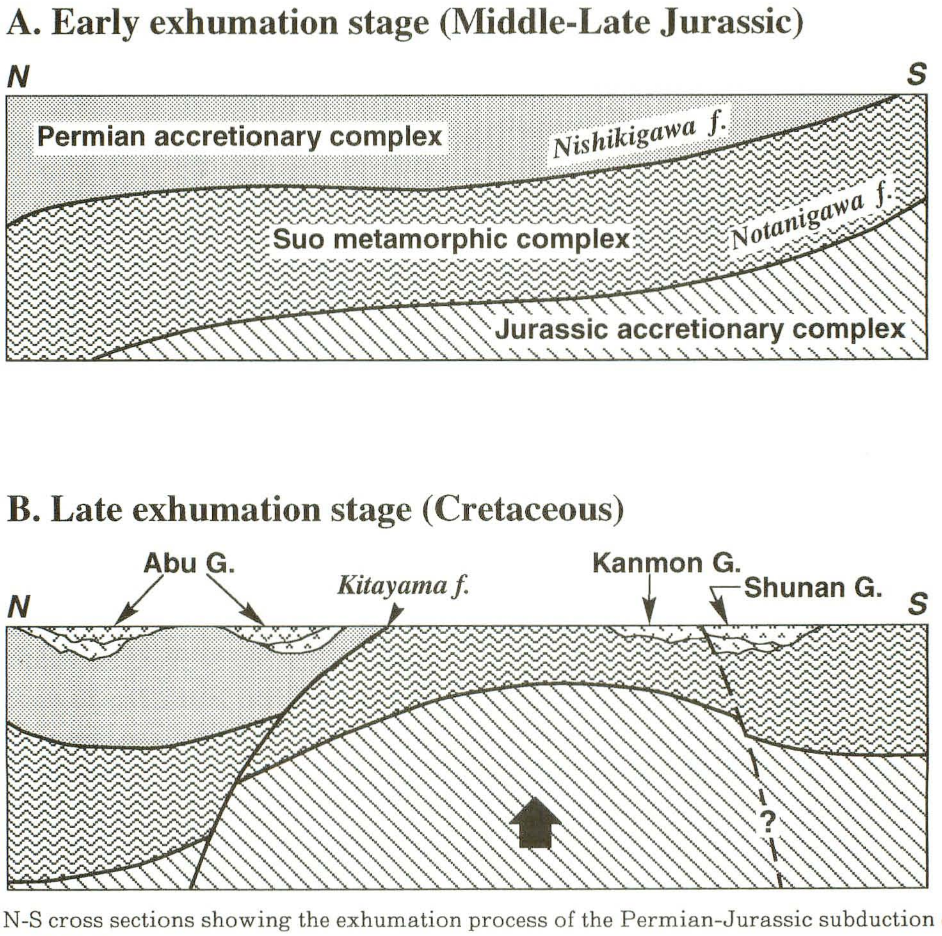

Fig. 10. Schematic N-S cross sections showing the exhumation process of the Permian-Jurassic subduction complexes in eastern Yamaguchi Prefecture.
A: Idealized pile-nappe structure before the uplift.
B: Structural relation after the uplift. The uplift has taken place with both the second-stage fault and the antiform.

also folded by a similar large-scale antiform, with its axis plunging slightly to the west in the southern neighbouring area of the Miyanokushi area. These antiforms develop regionally in the Yamaguchi-Iwakuni area, and the trends of their axes are almost parallel to that of the Kitayama fault. It is considered that not only the second-stage normal fault (Kitayama fault) but also the antiforms caused the uplift of the three complexes. The Jurassic accretionary complex (Unit I) was formed in the latest Jurassic (Takami *et al.*, 1993; Takami and Itaya, 1996) and was folded by E-W-trending antiforms before the Late Cretaceous granitic intrusion (Hara *et al.*, 1979). The Suo metamorphic was unconformably overlain by the Early Cretaceous Kanmon Group in the Yamaguchi area and by the Late Cretaceous Shunan Group in the Tokuyama area (Murakami and Imaoka, 1986). These suggest that the uplift, together with formation of both the second-stage fault and the antiforms, and the subsequent erosion of the three complexes, took place in the Early Cretaceous (Fig. 10B), although it is not clear whether or not the Jurassic accretionary complex in eastern Yamaguchi Prefecture was eroded at this time. Thus, the Yamaguchi-Iwakuni area, including the Suo metamorphic complex and the Jurassic and Permian accretionary complexes, formed an E-W-trending uplift zone about 100 km long in the late exhumation process.

Maruyama (1990) has demonstrated an exhumation process of subduction complexes, including a high-P/T metamorphic complex. He showed that a high-P/T metamorphic complex is generally sandwiched between overlying and underlying accretionary complexes with low-angle, first-stage faults, which have a large metamorphic gap between them. He also showed that these three complexes are folded by an antiform, its limbs being cut by high-angle, second-stage normal faults, forming a dome-like structure. The movement of the first-stage faults is characterized by the early exhumation process, called the wedge extrusion of a high-P/T metamorphic complex at the nappe emplacement stage; and that of the second-stage fault is characterized by the late exhumation process of a metamorphic complex at the post-nappe emplacement stage. It is considered that the Nishikigawa and Notanigawa faults in this study correspond to Maruyama's first-stage faults, and the Kitayama fault corresponds to his second-stage normal fault. Although a large metamorphic gap is recognized between the Suo metamorphic complex and the underlying Jurassic accretionary complex in eastern Yamaguchi Prefecture, it is not recognized between the Suo metamorphic complex and the overlying Permian accretionary complex. Therefore, the early exhumation process, characterized by the wedge extrusion of a high-P/T metamorphic complex by Maruyama (1990), does not fit this study.

Kurimoto (1994) described a uplift model which showed a process of disappearance of the sedimentary complex in the Chichibu Belt in the central Kii Peninsula, Southwest Japan. His model is similar to that of this study because of the involvement of secondary faults. Uplift zones, such as are present in the Yamaguchi-Iwakuni area, also probably developed in the Nichihara-Kabe and Katsuyama-Wakasa areas of the Chugoku district (Fig. 1). In these areas, the high-P/T Chizu metamorphic complex has been thrust over the Jurassic accretionary complex (e.g., Nishimura and Okamoto, 1976; Uemura *et al.*, 1979), and the Permian accretionary complex has been thrust over the Chizu metamorphic complex (e.g., Miyake, 1985; Sugimoto *et al.*, 1990). Furthermore, these complexes have been folded by E-W-trending, large-scale antiforms (e.g., Yamada, 1972; Toyohara, 1977; Fukudomi, 1990).

7. Conclusion

Two stages of geological boundary faults, namely, first- and second-stage faults, have been identified between the Permian accretionary complex, the Triassic high-P/T Suo metamorphic complex and the Jurassic accretionary complex in eastern Yamaguchi Prefecture, Southwest Japan, on the basis of detailed field investigation, metamorphic zonation and d_{002} values of carbonaceous material. Metamorphic zonation and field relations have revealed a metamorphic zonal structure consisting of P-C zone (Jurassic accretionary complex), P-A zone II, E-G zone, P-A zone I (Suo metamorphic complex) and P-C zone (Permian accretionary complex), in ascending order. The first-stage faults are parallel or subparallel to this metamorphic zonal structure, and were formed in the early exhumation process of the complexes at the nappe emplacement stage (Middle-Late Jurassic). The second-stage fault cuts a progressive geothermal structure from the Permian accretionary complex to the Suo metamorphic complex, with increasing metamorphic grade. This fault was formed in the late exhumation process of the complexes at the post-nappe emplacement stage (Early Cretaceous). Uplift and erosion of the three complexes resulted from the formation of both the second-stage fault and the large-scale antiforms in this process, so that an E-W-trending uplift zone, about 100 km long, developed in the Yamaguchi-Iwakuni area, Southwest Japan.

Acknowledgments

The author wishes to express his sincere gratitude to Prof. Yujiro Nishimura (Yamaguchi University) for his kind instruction both on the analysis of carbonaceous material in his laboratory and on the microscopic observation of thin sections. Special thanks are due to Dr. Yukio Isozaki (Tokyo Institute of Technology) for reading the manuscript and discussing it with the author.

Refereces

Charvet, J., Faure, M. and Guidi, A. (1985) Some tectonic and tectogenetic aspects of SW Japan : An alpine-type orogen in an island-arc position. In: Nasu, N., Kobayashi, K., Uyeda, S., Kushiro, I. and Kagami, H. (eds.), *Formation of active ocean margins,* Terrapub, Tokyo, 791-817.

Chijiwa, K., Kameda, N., Ishiguro, H. and Aihara, A. (1993) Preliminary study of change in physical properties of coalified and graphitized phytoclasts with grade of metamorphism －correspondence between the reflectance and the crystallinity－. *Sci. Rep. Dep. Earth and Planetary Sci. Kyushu Univ.*, **18**, 47-64 (in Japanese with English abstract).

Faure, M. (1985) The pre-Cretaceous structure of the Outer Belt of Southwest Japan. *Tectonophysics,* **113**, 1089-1114.

French, B. M. (1964) Graphitization of organic material in a progressively metamorphosed Precambrian iron formation. *Science,* **146**, 917-918.

Fukudomi, T. (1990) Jurassic melange, Kanoashi Complex, in western Shimane Prefecture, Southwest Japan. *Jour. Geol. Soc. Japan,* **96**, 653-667 (in Japanese with English abstract).

Hara, I., Higashimoto, S., Mikami, T., Nishimura, Y., Okimura, Y., Sawada, T., Takeda, K., Yokoyama, S. and Yokoyama, T. (1979) Palaeozoic-Mesozoic Group of the Yasaka Gorge district. *The Yasaka Gorge, landscape and environment,* Joint Scientific Committee for Research into the Yasaka Gorge Scenic Reserve, Hiroshima and Yamaguchi, 283-324 (in Japanese with English abstract).

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G. and Smith, D. G. (1990) *A geologic time scale 1989*. Cambridge University Press, Cambridge.

Hashimoto, M., Tagiri, M., Kusakabe, K., Masuda, K. and Yano, T. (1992) Geologic structure formed by tectonic stacking of sliced layers in the Sanbagawa metamorphic terrain, Kodama-Nagatoro area, Kanto Mountains. *Jour. Geol. Soc. Japan,* **98**, 953-965 (in Japanese with English abstract).

Hayasaka, Y., Isozaki, Y. and Hara, I. (1983) Discovery of Jurassic radiolarians from the Kuga and Kanoashi Groups in the western Chugoku district, Southwest Japan. *Jour. Geol. Soc. Japan,* **89**, 527-53 (in Japanese).

Higashimoto, S., Nureki, T., Hara, I., Tsukuda, E. and Nakajima, T. (1983) *Geology of the Iwakuni district.* Quadrangle Series, Scale 1:50,000, Geol. Surv. Japan, 79pp (in Japanese with English abstract).

Hirayama, Y. (1992) Deformational differences and geologic relation between the Sangun metamorphic rocks (Tsuno Group) and the low-grade metamorphic Permian rocks (Nishiki Group) in the Suma area, Tokuyama City, Southwest Japan. *Jour. Geol. Soc. Japan,* **98**, 1009-1030.

Ishiga, H. (1983) Two suites of stratigraphic succession within the Tamba Group in the western part of the Tamba Belt, southwest Japan. *Jour. Geol. Soc. Japan,* **89**, 443-454 (in Japanese with English abstract).

Isozaki, Y., Hashiguchi, T. and Itaya, T. (1992) The Kurosegawa klippe: an examination. *Jour. Geol. Soc. Japan,* **98**, 917-941 (in Japanese with English abstract).

Isozaki, Y. and Itaya, T. (1990) K-Ar ages of weakly metamorphosed rocks at the northern margin of Kurosegawa Terrane in central Shikoku and western Kii Peninsula: Extent of the Kurosegawa Terrane in Southwest Japan. *Jour. Geol. Soc. Japan,* **96**, 623-639 (in Japanese with English abstract).

Isozaki, Y. and Itaya, T. (1991) Pre-Jurassic klippe in northern Chichibu Belt in west-central Shikoku, Southwest Japan －Kurosegawa Terrane as a tectonic outlier of the pre-Jurassic rocks of the Inner Zone－. *Jour. Geol. Soc. Japan,* **97**, 431-450 (in Japanese with English abstract).

Isozaki, Y. and Maruyama, S. (1991) Studies on orogeny based on plate tectonics in Japan and new geotectonic subdivision of the Japanese Islands. *Jour. Geogr.*, **100**, 697-761 (in Japanese with English abstract).

Isozaki, Y., Maruyama, S. and Furuoka, F. (1990) Accreted oceanic materials in Japan. *Tectonophysics,* **181**, 179-205.

Isozaki, Y. and Nishimura, Y. (1989) Fusaki Formation, Jurassic subduction-accretion complex on Ishigaki Island, southern Ryukyus and its implication to Late Mesozoic convergent margin of East Asia. *Mem. Geol. Soc. Japan,* no. 33, 259-275 (in Japanese with English abstract).

Itaya, T. (1981) Carbonaceous material in pelitic schists of the Sanbagawa metamorphic belt in central Shikoku, Japan. *Lithos,* **14**, 215-224.

Itaya, T. and Takasugi, H. (1988) Muscovite K-Ar ages of the Sanbagawa schists, Japan and argon depletion during cooling and deformation. *Contrib. Mineral. Petrol.,* **100**, 281-290.

Izawa, E. (1968) Carbonaceous matter in some metamorphic rocks in Japan. *Jour. Geol. Soc. Japan,* **74**, 427-432.

Kawato, K., Isozaki, Y. and Itaya, T. (1991) Geotectonic boundary between the Sanbagawa and Chichibu belts in central Shikoku, Southwest Japan. *Jour. Geol. Soc. Japan,* **97**, 959-975 (in Japanese with English abstract).

Kimura, K. (1988) Geology and tectonic setting of the Ultra-Tamba Belt in the western part of Ayabe City, Kyoto Prefecture, Southwest Japan. *Jour. Geol. Soc. Japan,* **94**, 361-379 (in Japanese with English abstract).

Kimura, K. and Hori, R. (1993) Offscraping accretion of Jurassic chert-clastic complexes in the Mino-Tamba Belt, central Japan. *Jour. Struct. Geol.,* **15**, 145-161.

Kojima, G. (1953) Contributions to the knowledge of mutual relations between three metamorphic zones of Chugoku and Shikoku, Southwestern Japan, with special reference to the metamorphic and structural features of each metamorphic zone. *Jour. Sci. Hiroshima Univ.,* [C], **1**, 17-46.

Kurimoto, C. (1982) "Chichibu System" in the area southwest of Koyasan, Wakayama Prefecture — Upper Cretaceous Hanazono Formation—. *Jour. Geol. Soc. Japan,* **88**, 901-914 (in Japanese with English abstract).

Kurimoto, C. (1994) Geology of the Kudoyama area in the western Kii Peninsula, Southwest Japan, with reference to disappearance of the Chichibu terrane. *Bull. Geol. Surv. Japan,* **45**, 235-255.

Landis, C. A. (1971) Graphitization of dispersed carbonaceous material in metamorphic rocks. *Cotrib. Mineral. Petrol.,* **30**, 34-45.

Maruyama, S. (1990) Denudation process of high-pressure metamorphic belt. *97th Annu. Meet. Geol. Soc. Japan, Abstract,* 484 (in Japanese).

Matsuda, T. and Isozaki, Y. (1991) Well-documented travel history of Mesozoic pelagic chert in Japan: From remote ocean to subduction zone. *Tectonics,* **10**, 475-499.

Matsuoka, A. (1984) Togano Group of the Southern Chichibu Terrane in the western part of Kochi Prefecture, southwest Japan. *Jour. Geol. Soc. Japan,* **90**, 455-477 (in Japanese with English abstract).

Ministy of International Trade and Industry (1980) *Report of regional investigation, Nishiki river district.* The Agency of Resources and Energy, 150pp (in Japanese).

Miyake, K. (1985) Permian olistostrome complex in the Katsuyama area, Okayama Prefecture, Southwest Japan. *Jour. Geol. Soc. Japan,* **91**, 463-475 (in Japanese with English abstract).

Murakami, N. and Imaoka, T. eds. (1986) *Acid to intermediate igneous activity in West Chugoku and its adjacent areas, Southwest Japan.* Jour. Fac. Liberal Arts Yamaguchi Univ., Memorial Vol., 419pp (in Japanese with English abstract).

Naka, T., Watase, H. and Tokuoka, T. (1986) Permian Nishiki Group in the Muikaichi-cho, western part of the Sangun-Chugoku Belt, Shimane Prefecture, Southwest Japan. *Earth Sci. (Chikyu Kagaku)*, **40**, 166-176 (in Japanese with English abstract).

Nakae, S. (1990) Melanges in the Mesozoic sedimentary complex of the northern part of the Tamba Belt, Southwest Japan. *Jour. Geol. Soc. Japan,* **96**, 353-369.

Nakajima, W. (1960) Geology of the northern margin of the Ryoke Zone in the Yamato Plateau. *Earth Sci. (Chikyu Kagaku)*, **49**, 1-14 (in Japanese with English abstract).

Nishimura, Y. (1971) Regional metamorphim of the Nishiki-cho district, Southwest Japan. *Jour. Sci. Hiroshima Univ.,* [C], **6**, 203-268.

Nishimura, Y., Imaoka, T., Utamura, Y. and Kameya, A. (1995a) *1:150,000 Newly edited Geological Map of Yamguchi Prefecture, third edition.* Geological Society of Yamaguchi.

Nishimura, Y., Isozaki, Y. and Nureki, T. (1985) Sangun-Chugoku and Ryoke Belts. *98th Anuu. Meet. Geol. Soc. Japan, Excursion Guidbook,* Geol. Soc. Japan, 17-49 (in Japanese).

Nishimura, Y., Itaya, T., Isozaki, Y. and Kameya, A. (1989) Depositional age and metamorphic history of 220 Ma high P/T type metamorphic rocks: an example of the Nishiki-cho area, Yamaguchi Prefecture, Southwest Japan. *Mem. Geol. Soc. Japan,* no. 33, 143-166 (in Japanese with English abstract).

Nishimura, Y. and Nureki, T. (1966) Geological relations of the "non-metamorphic Palaeozoic formation" and the Sangun metamorphic rocks in the Nishiki-cho area, Yamaguchi Prefecture. *Jour. Geol. Soc. Japan,* **72**, 385-398 (in Japanese with English abstract).

Nishimura, Y. and Okamoto, T. (1976) Lawsonite-albite schist from tha Masuda district, southwest Japan.

Memorial Vol. Prof. G. Kojima. Hirosima Univ. Press, Hiroshima, 144-153 (in Japanese with English abstract).

Nishimura, Y. and Shibata, K. (1989) Modes of occurrence and K-Ar ages of metagabbroic rocks in the "Sangun metamorphic belt", Southwest Japan. *Mem. Geol. Soc. Japan,* no. 33, 343-357 (in Japanese with English abstract).

Nishimura, Y., Takami, M. and Nureki, T. (1995b) Suo belt - Kuga belt - Ryoke belt of eastern Yamaguchi Prefecture, Southwest Japan. *102th Annu. Meet. Geol. Soc. Japan, Excursion Guidbook,* Geol. Soc. Japan, 47-69 (in Japanese).

Nureki, T. (1969) Geological relations of the Sangun Metamorphic Rocks to the "Non-metamorphic" Paleozoic Formations in the Chugoku Province. *Mem. Geol. Soc. Japan,* no. 4, 23-39 (in Japanese with English abstract).

Okamura, Y. and Kojima, G. (1951) On the relation between the Sangun and the Ryoke metamorphic rocks, northwest of Tokuyama, Yamaguchi Prefecture. *Jour. Geol. Soc. Japan,* **57**, 342-343 (in Japanese).

Shibata, K. and Nishimura, Y. (1989) Isotopic ages of the Sangun crystalline schists, Southwest Japan. *Mem. Geol. Soc. Japan,* no. 33, 317-341 (in Japanese with English abstract).

Sugimoto, T., Hayasaka, Y. and Hara, I. (1990) Geological structure of Pre-Cretaceous accretionary complexes in the Chugoku district, Southwest Japan – Preceding history of formation of Cretaceous granitic crust–. *Monthly Chikyu,* **12**, 430-435 (in Japanese).

Suzuki, H., Isozaki, Y. and Itaya, T. (1990) Tectonic superposition of the Kurosegawa Terrane upon the Sanbagawa Metamorphic Belt in eastern Shikoku, Southwest Japan –K-Ar ages of weakly metamorphosed rocks in northeastern Kamikatsu Town, Tokushima Prefecture–. *Jour. Geol. Soc. Japan,* **96**, 143-153 (in Japanese with English abstract).

Tagiri, M. (1981) A measurement of the graphitizing-degree by the X-ray powder diffractometer. *Jour. Japan. Assoc. Min. Petr. Econ. Geol.,* **76**, 345-352.

Taira, A. (1981) Formation process of the Shimanto Belt. *Kagaku (Science)*, **51**, 516-523 (in Japanese).

Taira, A., Tokuyama, H. and Soh, W. (1989) Accretion tectonics and evolution of Japan. In: Ben-Abraham, Z. (ed.), *The Evolution of the Pacific Margins,* Oxford University Press, Oxford, 100-123.

Takami, M., Isozaki, Y., Nishimura, Y. and Itaya, T. (1990) Geochronology of weakly metamorphosed Jurassic accretionary complex (the Kuga Group) in eastern Yamaguchi Prefecture, Southwest Japan. *Jour. Geol. Soc. Japan,* **96**, 669-681 (in Japanese with English abstract).

Takami, M., Isozaki, Y., Nishimura, Y. and Itaya, T. (1993) Effect of detrital white mica and contact metamorphism to K-Ar dating of weakly metamorphosed accretionary complex – an example of Jurassic accretionary complex in eastern Yamaguchi Prefecture, Southwest Japan–. *Jour. Geol. Soc. Japan,* **99**, 545-563 (in Japanese with English abstract).

Takami, M. and Itaya, T. (1996) Episodic accretion and metamorphism of Jurassic accretionary complex based on biostratigraphy and K-Ar geochronology in the western part of the Mino-Tanba Belt, Southwest Japan. *The Island Arc,* **5**, 321-336.

Takata, M. (1987) Reexamination of the Jurassic complex (Kuga Group) in eastern Yamaguchi Prefecture, Southwest Japan –discrimination of two geologic units and its implication–. In: Nishimura, Y., (ed.), *High-P/T Metamorphic Belt in the Inner Zone of Southwest Japan,* no. 4, 27-37 (in Japanese).

Takeda, K. and Imaoka, T. (1994) Cretaceous ring dikes in Yamaguchi-Ogori area, Southwest Japan: a proposal of the Yamaguchi cauldron. In: Imaoka, T. (ed.), *Formation process of the Cretaceous-Paleogene cauldron in Chugoku district,* Semurafuropi-insatsu, Yamaguchi, 2-28 (in Japanese).

Takeda, K. and Nishimura, Y. (1989) Metamorphic rocks in the Ikura area, Okayama Prefecture, Southwest Japan: pile nappes and lithology. *Mem. Geol. Soc. Japan.* no. 33, 89-106 (in Japanese with English abstract).

Toyohara, F. (1974) On the age of the Kuga group and Ryoke metamorphic rocks in eastern Yamaguchi Prefecture. *Jour. Geol. Soc. Japan,* **80**, 51-53 (in Japanese).

Toyohara, F. (1976) Geologic structures from Sangun-Yamaguchi zone to "Ryoke zone" in eastern Yamaguchi Prefecture. *Jour. Geol. Soc. Japan,* **82**, 99-111 (in Japanese with English abstract).

Toyohara, F. (1977) Early Mesozoic development of the northwestern Chichibu geosyncline in west Chugoku, Japan. *Jour. Fac. Sci., Univ. Tokyo,* [II], **19**, 253-334.

Toyohara, F., Maesaka, I. and Tsukumo, M. (1989) Foldings in the ages of the Sangun and Ryoke metamorphisms and their superposition in West Chugoku, Japan. *Mem. Geol. Soc. Japan,* no. 33, 131-142 (in Japanese with English abstract).

Uemura, F., Sakamoto, T. and Yamada, N. (1979) *Geology of the Wakasa district.* Quadrangle series, scale

1 : 50,000, Geolo. Surv. Japan, 91pp (in Japanese with English abstract).

Ujiié H. and Nishimura, Y. (1992) Transect of the central and southern Ryukyu Island Arcs. In: Geol. Surv. Japan, (ed.), *29th IGC Field Trip Guide Book*, **5**, 337-361.

Yamada, N. (1972) Sangun metamorphic rocks of the Tottori-Ohara district, Southwest Japan. *Bull. Geol. Surv. Japan*, **23**, 525-537 (in Japanese with English abstract).

Yamato Omine Research Group (1981) Paleozoic and Mesozoic System in the central area of the Kii Mountains, southwest Japan. *Guide book for the excursion for 35th Annu. Meet. Assoc. Geol. Coll. Japan*, 88pp (in Japanese).

Yao, A., Matsuda, T. and Isozaki, Y. (1980) Triassic and Jurassic radiolarians from the Inuyama area, central Japan. *Jour. Geosci., Osaka City Univ.*, **23**, 135-154.