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ABUKUMA AND SANBAGAWA METAMORPHIC BELTS IN THE KANTO DISTRICT

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INTRODUCTION AND GEOLOGICAL RELATIONSHIPS AMONG ABUKUMA, RYOKE AND SANBAGAWA BELTS IN THE KANTO DISTRICT

The focus of this trip is to examine the metamorphic and deformation history of the two contrasting Cretaceous metamorphic belts. Geotectonic division of pre-Tertiary geology of Japan is shown in Fig.1. Most important tectonic lines dividing pre-Tertiary Japan are the Median Tectonic Line (MTL) and the Tanakura Tectonic Line (TTL). The pre-Tertiary Geologic structure of Japan is divided into two segments, Southwest Japan and Northeast Japan by the Tanakura Tectonic Line (See Fig.1). In Southwest Japan, the Sanbagawa metamorphic rocks of the high-pressure type and the Ryoke metamorphic rocks of the low-pressure type are exposed on the south and on the north of the Median Tectonic Line, respectively. This spatial relationship led Miyashiro the paired metamorphic belts theory (Fig.2). These two types of metamorphic rocks are well traceable in Southwest Japan, but not in the most eastern part of the Median Tectonic Line, the Kanto District.

Tertiary sediments are widely exposed to the north of the Sanbagawa schists in the Kanto Mountains (Figs. 3 & 23). Hence, the exact position of the MTL is not clear in the field. However, small outcrops of Ryoke belt equivalents (late Cretaceous granitic rocks, Takagi and Fujimori, 1989; cordierite-biotite gneiss, Takei, 1982) were recently reported from the Shimonita and the Hiki Hill areas in the north of the Kanto Mountains (Fig.3), suggesting that the MTL paths through the northern margin of the Kanto Mountains.

The eastern extension of the MTL below the Cenozoic sediments of the Kanto Plain is estimated by the basement rocks recovered by deep bore-holes as shown in Fig.8. However, further eastern extension of the MTL is still under controversy as mentioned before. At present, the geometrical relationship between TTL and MTL suggests that they crosscut each other (Fig.8). The present geometry may be affected by the Cenozoic movements, such as the opening of Japan Sea during Miocene (Otofuji and

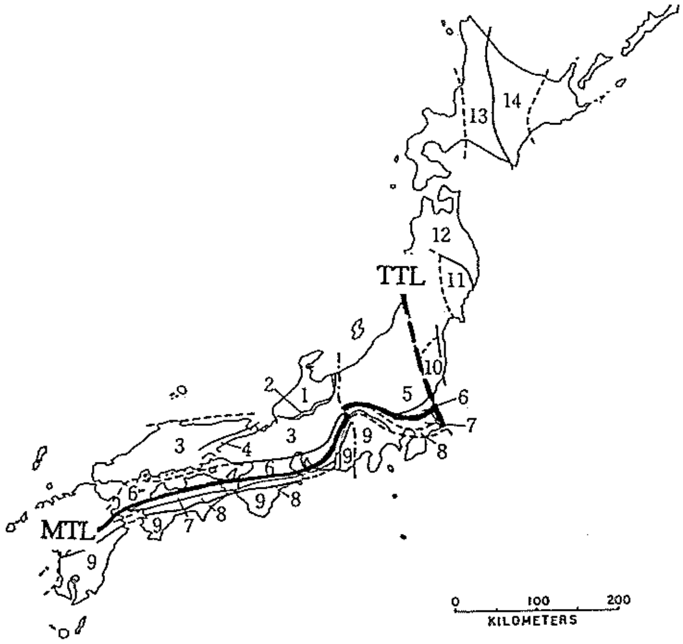


Fig. 1. Geotectonic division of the old rock terranes (slightly modified after Hashimoto, 1991 and Hirokawa et al., 1978). 1: Hida, 2: Hida Border Zone, 3: Sangun, Chugoku and Tanba-Mino, 4: Maizuru, 5: Ashio, 6: Ryoke, 7: Sanbagawa, 8: Chichibu and Sanbosan, 9: Shimanto, 10: Abukuma, 11: South Kitakami, 12: North Kitakami, 13: Ishikari-Kamui-kotan, 14: Hidaka-Tokoro, MTL: Median Tectonic Line, TTL: Tanakura Tectonic Line.

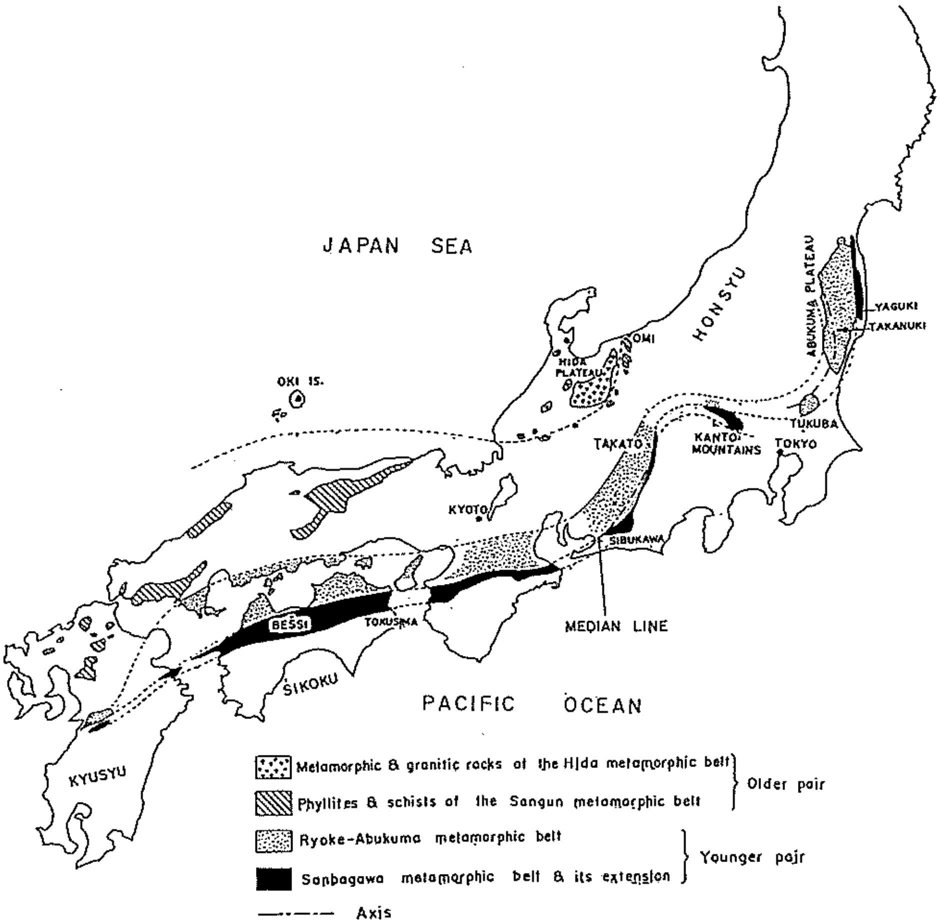


Fig. 2. Paired metamorphic belts in the main part of Japan (Miyashiro, 1961).

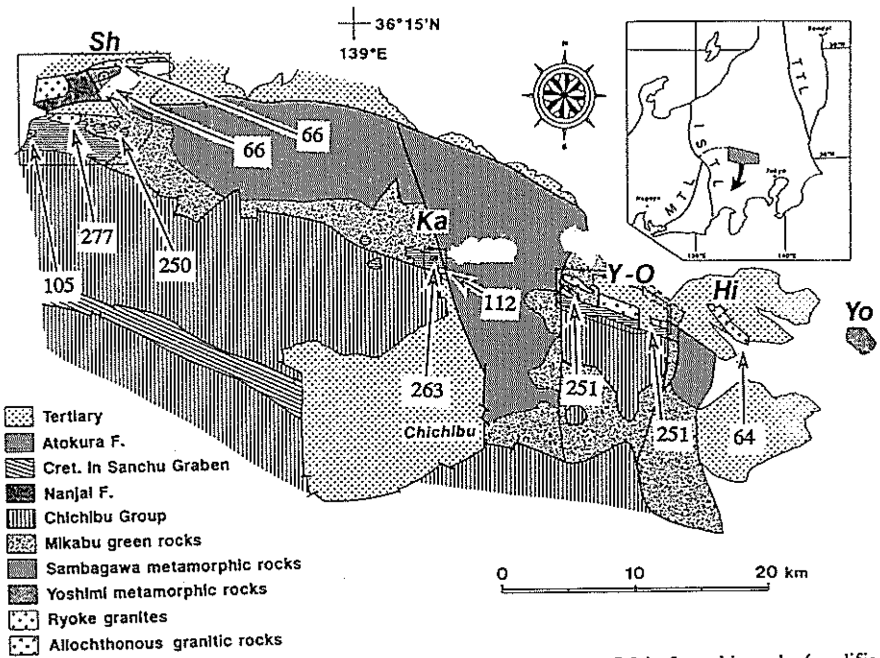


Fig. 3. Geological map of northern Kanto Mountains and isotope ages (Ma) of granitic rocks (modified after Takagi & Fujimori, 1989 and Omori et al., 1986). Sh: Shimonita area, Ka: Kanezawa area, Y-O: Yorii-Ogawa area, Hi: Hiki Hills area, Yo: Yoshimi Hill area, ISTL: Itoigawa-Shizuoka Tectonic Line.

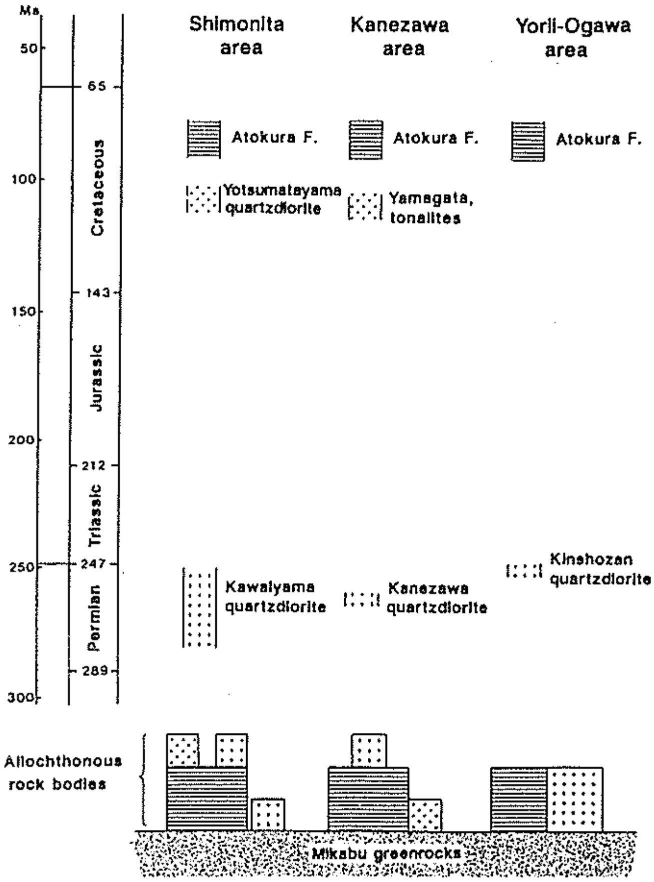


Fig. 4. Time table and schematic occurrence of the allochthonous granitic bodies and Atokura Formation in the northern marginal area of the Kanto Mountains (Takagi & Fujimori, 1989).

Matsuda, 1983) and the collision of Izu-Bonin arc with the Honshu Arc during Quaternary (Matsuda, 1978). However, petrological and geochronological data mentioned above can evaluate the proposed geotectonic models on the relationship between MTL and TTL.

Kano et al. (1973) described that the origin of the Abukuma metamorphic rocks is different in age from those of the Ryoke metamorphic rocks and that the geotectonic division of the pre-Tertiary Japan is not extendible to Northeast Japan (Fig.5).

Faure et al. (1986) proposed that the Abukuma belt is the eastern extension of the Sanbagawa belt on the basis of the similarities of the deformation style and the lithology.(Fig.6) They considered that the Cretaceous low-pressure (Abukuma) metamorphism overprinted on the H/P Sanbagawa metamorphic rocks and erased most of high-pressure mineralogical evidence (Fig.7). Such geotectonic model might be inferred from the case study of the Central Alps, where the Tertiary L/P metamorphism (Lepontine event) overprinted and almost erased the evidence of the Cretaceous H/P metamorphism (early Alpine event). This scenario in the central Alps is well documented by the radiometric dating (e.g., Hunziker, 1974); from 80-60 Ma for cooling ages of the high-pressure event and 40 Ma for the Lepontine event. In the case of the Kanto District, 120-100 Ma reported for the K-Ar ages of hornblende and biotite separated from both granitic rocks and metamorphics in the Abukuma belt (Shibata and Uchiumi, 1983; Seike, 1991) and 60-80 Ma of phengite K-Ar ages for the Sanbagawa schists (Ueda et al., 1977; Takasu & Dallmeyer, 1990; Hirajima et al., 1992). It is unlikely that the Sanbagawa metamorphism predated the Abukuma metamorphism as proposed by Faure et al. (1986). The geochronological data do not support a continuous model.

Some klippes lie on the Sanbagawa metamorphic rocks along the north margin of the Kanto Mountains (Figs. 3 and 23). The klippes are mainly composed of Cretaceous Atokura Formation and correlatives, and pre-Tertiary granitic rocks, which were overprinted by the prehnite-pumpellyite facies metamorphism (Hirajima, 1984; Shibata and Takagi, 1989). In the klippes, various kinds of metamorphic rocks, such as Jd-Qtz rock and Ep-amphibolite, occur as tectonic blocks (Hirajima, 1983, 1984). Shibata and Takagi (1989) considered the klippes derived from the Abukuma belt, mainly based on the isotopic ages and Sr isotope ratio of the granitic rocks. In this case, the high-pressure rocks in the klippes may be correlated to the Matsugadaira-Motai metamorphics in the Abukuma belt (Fig.9), although Hirajima (1984) considered that the klippes correlated to the Kurosegawa belt in the southwest Japan (Figs. 6 and 7). Shibata and Takagi (1989) proposed a geotectonic model as shown in Fig.8: the Abukuma belt is situated between the Sanbagawa and the Ryoke belts. Their scenario demands that the klippes moved from north to south. However, recent kinematic

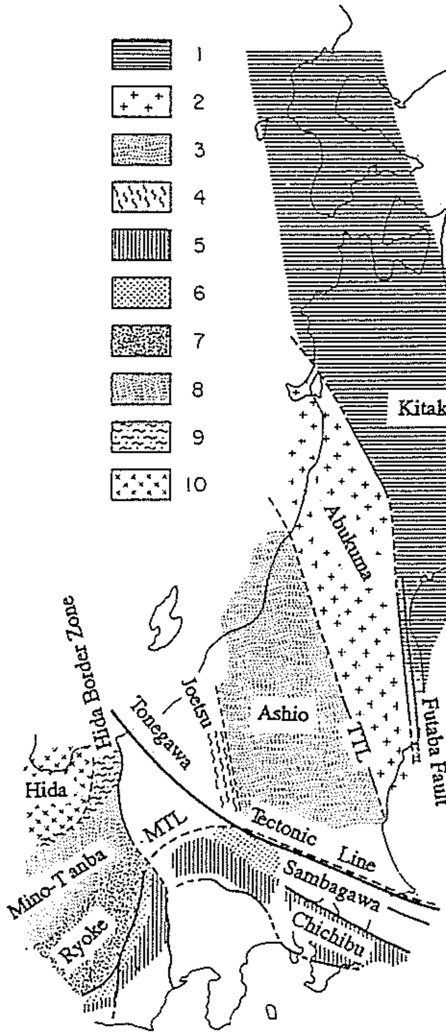


Fig. 5. Tectonic division of Northeast Japan (modified after Kano et al., 1973).

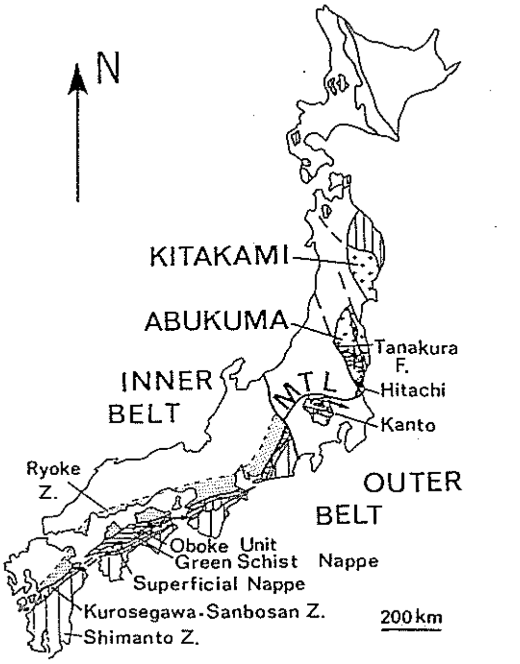


Fig. 6. General map of the Japanese Islands showing the Abukuma massif and the Ryoke zone. Arrows represent the average trend of the lineation in the Green Schist nappe of Southwest Japan and in the Hitachi and Gosaisho Groups (Faure, et al., 1986).

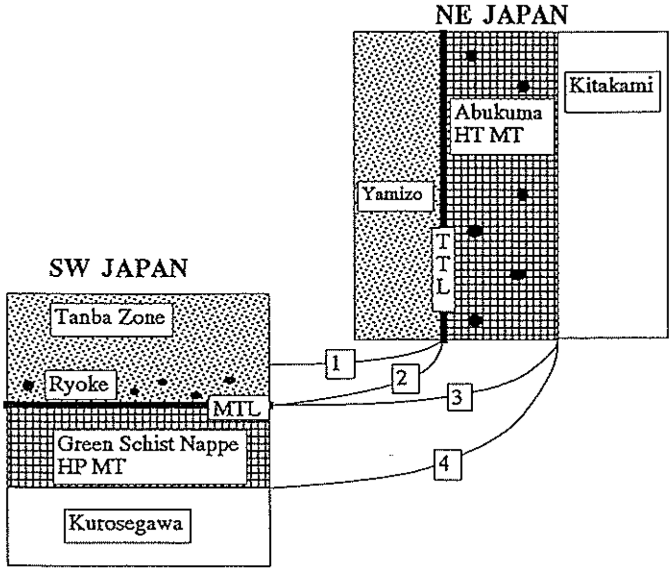


Fig. 7. Interpretation of the structural relation-ships between Northeast and Southwest Japan. The present complexity of the Jurassic chain is due to the oblique overprinting of the HT metamorphism (dotted) and late faults leading to the disappearance of some segments. Between lines 1 and 2, there is the part of the Tanba zone affected by the HT metamorphism, i.e. the Ryoke zone, which is missing in North-east Japan. Between lines 2 and 3, there is the part of the Green Schist nappe affected by the HT Abukuma metamorphism which is missing in Southwest Japan. Between lines 3 and 4, there is the part of the Green Schist nappe affected only by the HP/LT, Sanbagawa metamorphism which is missing in Northeast Japan. The Kurosegawa and Kitakami zones represent the tectonic substratum upon which the Green Schist nappe obducts (Faure et al., 1986).

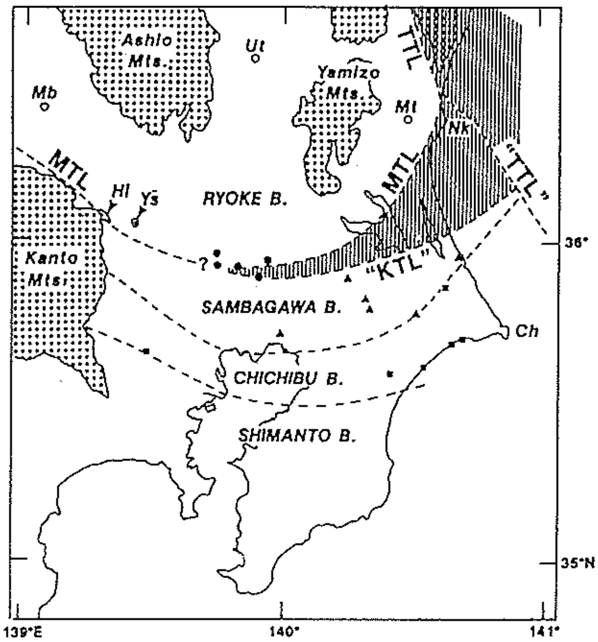


Fig. 8. Relationship between MTL and TTL in the Kanto district (Shibata & Takagi, 1989). The area hatched by vertical lines indicates the southern extension of the Abukuma zone and the South Kitakami zone. Deep bore-holes show the basement rock as follows; ●: Ryoke zone and Mino-Tanba zone, ▲: Sanbagawa zone, ■: Chichibu zone. KTL: Kanto Tectonic Line, Hi: Hiki Hills, Ys: Yoshimi Hills, Mb: Maebashi, Ut: Utsunomiya, Mt: Mito, Nk: Nakaminato, Ch: Choshi.

study along a main fault of the Atokura klippe suggests the klippe moved from south to north (Wallis et al., 1990). So, much further works are still necessary to reconstruct the paleogeography of the Kanto District.

EXCURSION TO ABUKUMA PLATEAU (by Hiroi and Tagiri)

Introduction

The metamorphic rocks in the central Abukuma Plateau of Northeast Japan are well-known in the world after the classic studies of Miysahiro (1958, 1961) and Shido (1958). They showed that the progressive mineral changes in the area differ from those in the Grampian Highland and are of low-pressure high-temperature type. Miyashiro (1961) enunciated the concepts of metamorphic facies series (baric type of metamorphism) and paired metamorphic belts based partly on these studies. The ideas offered a significant linkage between metamorphic petrology and tectonics during orogeny. Although P-T-t paths followed by metamorphic rocks are more commonly used in respect of the tectonic problems in these days, Miyashiro's metamorphic facies series is still of great importance to characterize metamorphic rocks and terranes. Except for the ultimate low-pressure character of the progressive metamorphic sequence, his concepts of the geology and petrology of the Abukuma Plateau have since been somewhat modified. For example, the metamorphic rocks in the central Abukuma Plateau are subdivided into two distinct geological units; the Gosaisyo Group in the east and the Takanuki Group in the west. The Gosaisyo Group is composed mainly of Jurassic basic and siliceous rocks and is similar to the upper portion of oceanic crust, while the underlying Takanuki Group consists dominantly of pelitic to psammitic rocks of terrigenous origin. In addition, relict kyanite was found in the Takanuki pelitic gneisses rich in cordierite, sillimanite and K-feldspar. This induced a hot argument about whether the Abukuma metamorphism was plurifacial or poly-metamorphic. Kano (1979) insisted that rocks, at least those of the Takanuki Group, had been metamorphosed twice before the contact metamorphism by the Cretaceous plutons; medium P/T metamorphism in Late Pre-cambrian time (?) and low P/T metamorphism in middle Cretaceous time (?). The latter may correspond to that Miyashiro (1958) clarified.

Now we are trying to construct a new tectonic model for the evolution of the Abukuma metamorphic rocks. Our new data include (1) re-examined progressive metamorphic zones (Kojiroi, 1986; Tagiri et al., in prep.), (2) discovery of Jurassic radiolarian fossils in the Gosaisyo metacherts (Hiroi et al., 1987), (3) MORB-like geochemical characteristics of the Gosaisyo metabasites (Nohara and Hiroi, 1989), (4) occurrence of deformed and metamorphosed calc-alkali rocks in the Gosaisyo Group (Sato and Hiroi, 1989), (5) documentation of the widespread occurrence of texturally sector-zoned and chemically growth-zoned garnet porphyroblasts in the upper amphibolite-facies Takanuki pelitic gneisses (Hiroi and Kishi, 1986, 1989b), (6) detailed examination of textural relationships between corundum, almandine, sillimanite and hercynite in the Takanuki meta-lateritic rocks (Hiroi, 1990), and between plagioclase and calcic amphiboles in the Gosaisyo meta-basites (Tagiri et al., in prep), (7) U-Pb zircon dating of meta-porphyry and K-Ar micas dating of meta-pelites (Hiroi et al., in prep), (8) Rb-Sr whole rock isochron dating of plutonic rocks intruding into the metamorphics (Shibata and Tanaka, 1987; Goto et al., 1990; Fujimaki et al., 1991) and so on.

Geological Outline of the Abukuma Plateau

The Abukuma Plateau is underlain mostly by early to middle Cretaceous plutonic rocks including olivine-hornblende gabbro. Metamorphic rocks occur rather sporadically, and are divided into three groups based on the spatial distribution as well as metamorphic ages and characteristics (Fig.9). The metamorphic rocks occurring sparsely along the northeastern margin of the Abukuma Plateau are collectively named the Matsugadaira-Motai metamorphics of Middle Paleozoic time. They belong to the Matsugadaira-Motai belt.

The metamorphic rocks in the south-central part of the plateau (the Gosaisyo-Takanuki district) have been called the Gosaisyo-Takanuki metamorphics, as a whole. However, as mentioned above, they are subdivided into the Gosaisyo and Takanuki Group, which are in fault contact. The Gosaisyo Group overthrust onto the Takanuki Group. The third metamorphic group occurs in

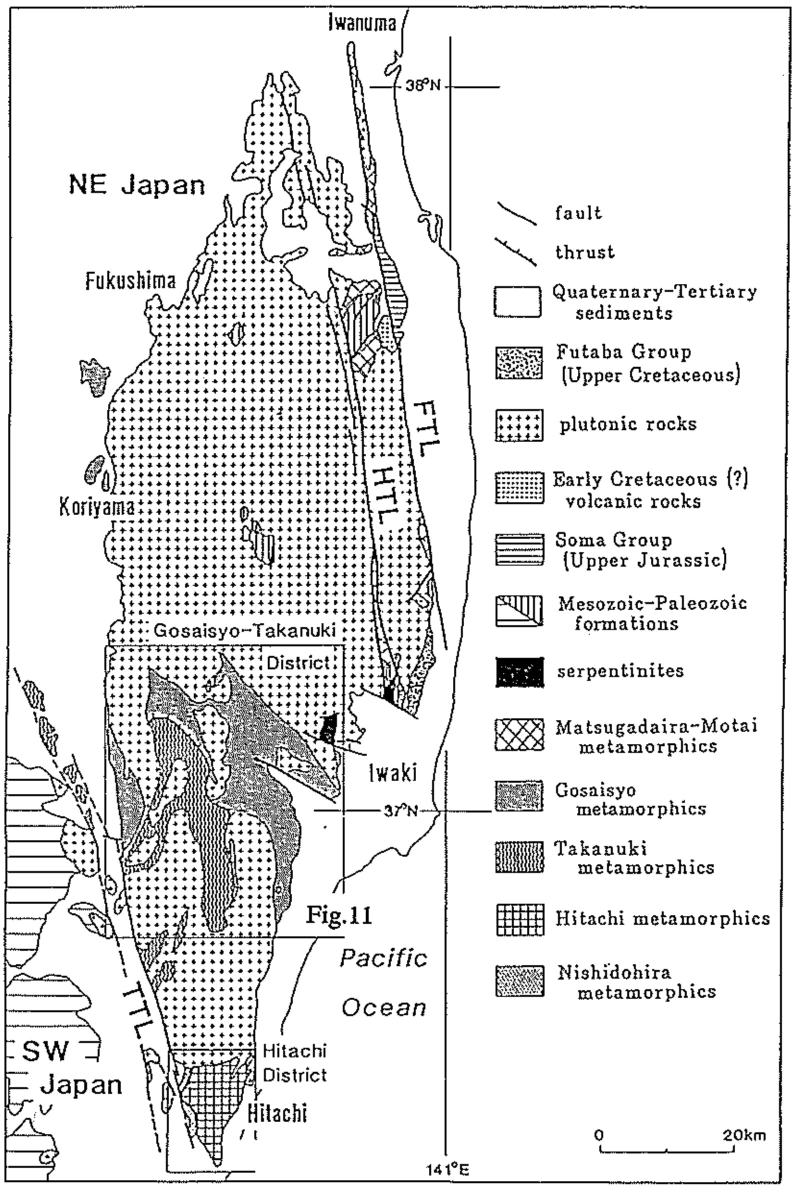


Fig. 9. Generalized geological map of Abukuma Plateau. FTL; Futaba Tectonic Line, HTL; Hatagawa Tectonic Line, TTL; Tanakura Tectonic Line.

the Hitachi district of the southernmost part of the Abukuma Plateau and is called the Hitachi metamorphics. It is commonly subdivided into the Hitachi metamorphic proper composed of four formations and the Nishidohira metamorphics. The original rocks of the Hitachi metamorphics proper are Late Paleozoic sedimentary and volcanic rocks, as evidenced by the occurrence of fossils, while the sedimentary age of the Nishidohira metamorphics is not known. The exact correlations among original sedimentary rocks of these three metamorphic groups are not established yet, but the Takanuki Group in the Gosaisyo-Takanuki district is usually correlated with a part or whole of the Hitachi metamorphics in the Hitachi district.

Gosaisyo-Takanuki Metamorphic District

Both the Gosaisyo and Takanuki metamorphic rocks are extensively intruded and thermally metamorphosed by the early to middle Cretaceous plutonic complexes. Some plutons locally called the Jumonji, Miyamoto, and Tabito masses are emplaced along or close to the boundary between the Gosaisyo and Takanuki Group (Fig.10), and this makes it difficult or impossible to examine the detailed geological relationship between these two metamorphic groups. Contact metamorphic effects by the plutonic complexes are evident in the lower-grade Gosaisyo Group rocks (Fig.15), but they are not clear in the higher-grade Takanuki Group rocks except for the case where orthopyroxene-bearing hornfelses were formed around the orthopyroxene-bearing intrusions. Determination of whole rock Rb-Sr isochron ages of plutonic rocks has yielded 120-100 Ma (Shibata and Tanaka, 1987; Goto et al., 1990; Fujimaki et al., 1991).

The Gosaisyo Group is composed mainly of basic and

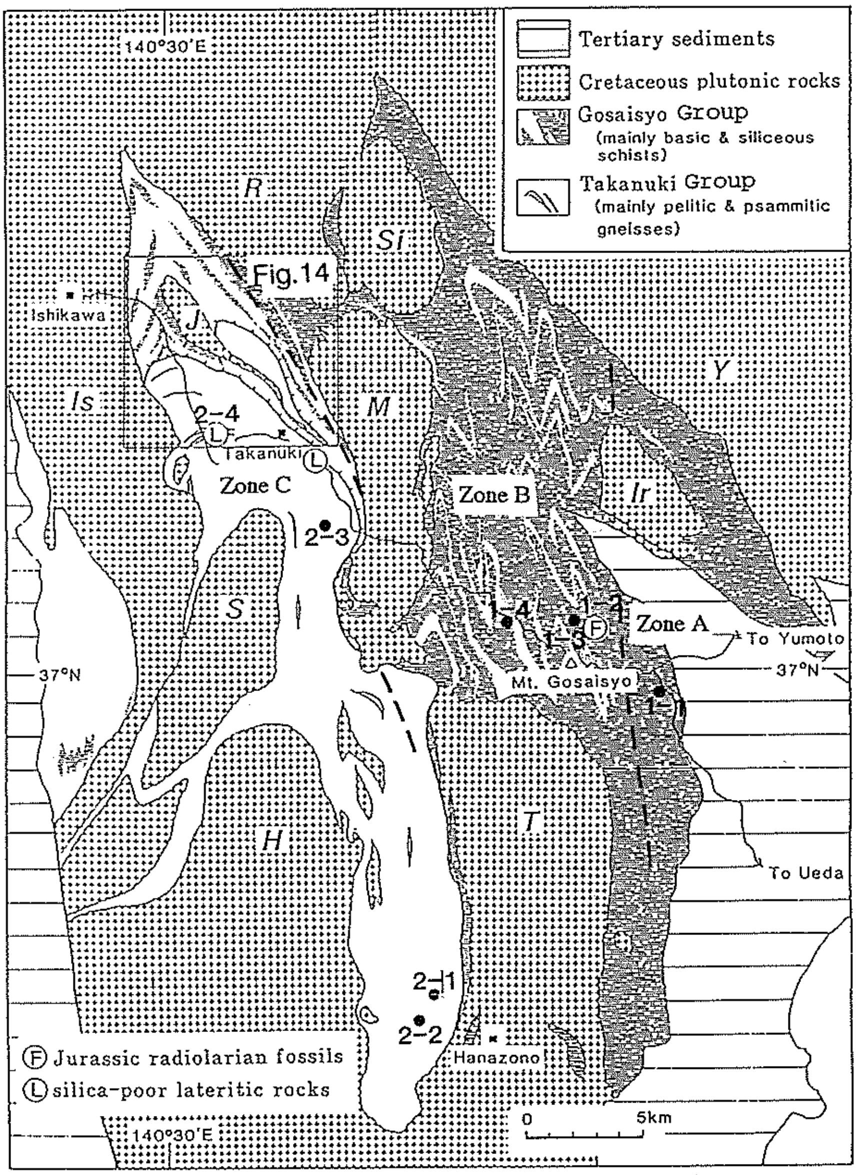


Fig.10. Simplified geological map (modified after Kano et al., 1973) and progressive metamorphic zones by Miyashiro (1958) of Gosaisyo-Takanuki District. Abbreviations of early-middle Cretaceous plutonic complexes: R; Ronden, Si; Shibayama, Y; Yoshimagawa, Is; Ishikawa, J; Jumonji, M; Miyamoto, Ir; Iritono, S; Samegawa, H; Hanawa, T; Tabito.

siliceous rocks with subordinate pelitic, calcaleous and ultrabasic rocks. Chemical compositions of homogeneous and relatively massive basic rocks (probably derived from lava) are similar to T-type MORB (Nohara and Hiroi, 1989) (Figs.11&12). Some siliceous rocks (metacherts) preserve early Jurassic radiolarian fossils and are intercalated with magnetite and hematite-rich layers (Hiroi et al., 1986). It is noteworthy that a small amount of andesitic to rhyolitic dike rocks occur in the lower-grade Gosaisyo Group (Fig.12). These dike rocks have almost the same deformation and metamorphic histories as those of the host rocks, and belong to the calc-alkalic rocks series (Sato and Hiroi, 1989) (Figs. 11&12). Three to four deformation events have been distinguished in the Gosaisyo Group on the basis of four different types of fold; F1 isoclinal flow folds, F2 predominant buckle folds with a subvertical axial plane and subhorizontal fold axis nearly parallel to mineral lineation, F3 drag folds associated with axial plane cleavage, and F4 kink folds (e.g., Ishikawa and Otsuki, 1990) (Fig.13). Ishikawa and Otsuki (1990) suggest the intimate correlation between the left-lateral ductile shearing (F-3) of the Gosaisyo Group and the activities of the Tanakura, Hatagawa and Futaba Tectonic Lines.

The Takanuki Group consists dominantly of pelitic-psammitic rocks with small amount of calcareous, lateritic, siliceous, basic and ultrabasic rocks. Pelitic-psammitic rocks are usually migmatitic, suggesting that partial melting took place during high-grade metamorphism. Takanuki siliceous rocks are far more coarse-grained than Gosaisyo metacherts, and may be originated from quartzose sandstones. Silica-poor lateritic rocks are observed only as small blocks completely included in coarse-grained calcite marbles. Ultrabasic rocks occur as

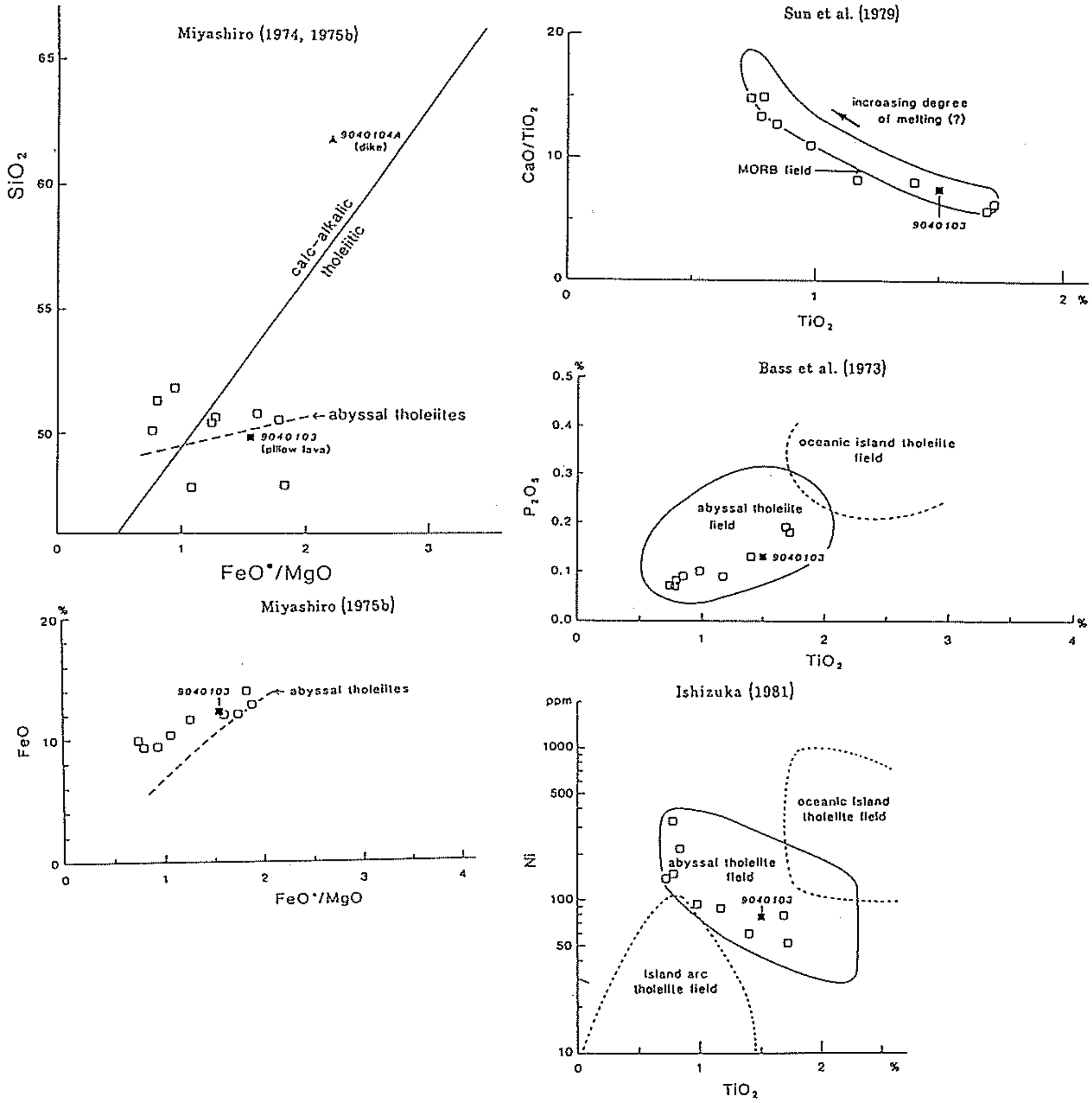
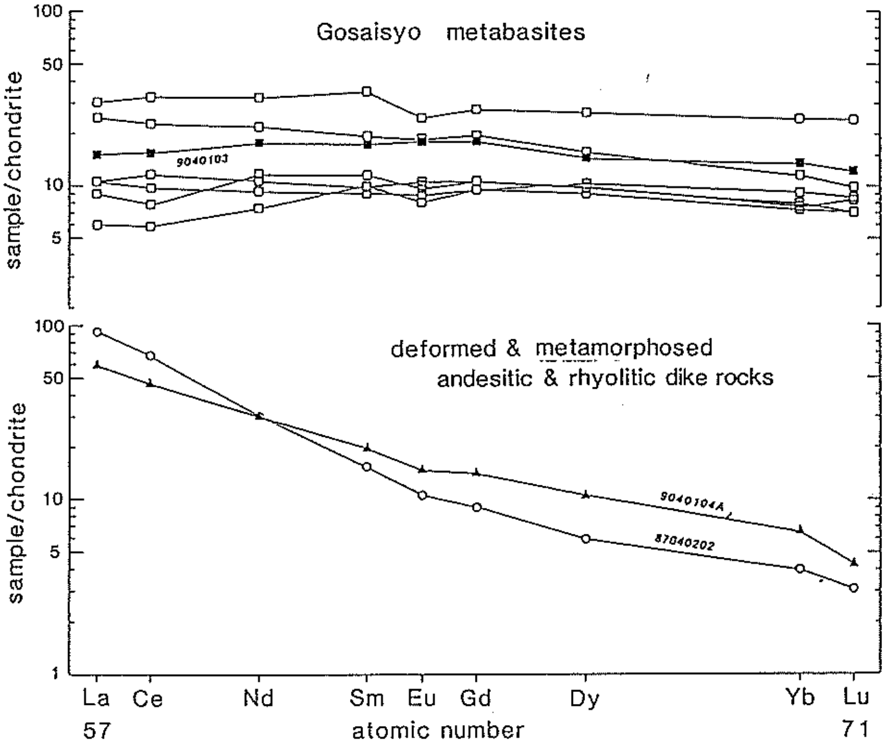


Fig. 11. Diagrams showing bulk chemical characteristics of "massive" homogeneous Gosaisyo metabasites and meta-andesitic dike rock (Hiroi et al., in prep.).

lenses and sheets of various thickness enclosed within metasedimentary rocks close to the boundary between the Gosaisyo and Takanuki Groups. The Takanuki Group, as a whole, shows gentle dome structures with cores of Cretaceous plutons locally called the Samegawa and Hanawa masses. However, it is to be noted that some Takanuki Group rocks close to the boundary between the Gosaisyo and Takanuki Groups show intense deformation suggested by sheath folds. Detailed geological survey of the northern Takanuki area, though fresh exposures are extremely poor there, has revealed that the Gosaisyo and Takanuki Groups are structurally discordant and are definitely in fault contact (Umemura, 1979; Goto, 1991) (Fig.14).

Metamorphic Zones and Facies Series in the Gosaisyo-Takanuki District

Miyashiro (1958) divided the metamorphic rocks in this district into three progressive zones, A, B and C (Fig.10), based mainly on the westward continuous mineral changes in metabasites (Fig.16a). Zones A and B comprise the Gosaisyo Group, whereas Zone C is underlain dominantly by the Takanuki Group. Zone A is a greenschist facies terrain, while zones B and C are amphibolite facies terrains, lacking the epidote amphibolite facies in this progressive metamorphic sequence. Kojiroi (1986) reexamined the progressive mineral changes in the Gosaisyo Group. He concluded that the thermal structure of the Gosaisyo Group is close to that revealed by Miyashiro (1958). Moreover, he indicated that the chemical equilibrium domain in the Gosaisyo Group is narrow, suggesting that high-temperature duration was short



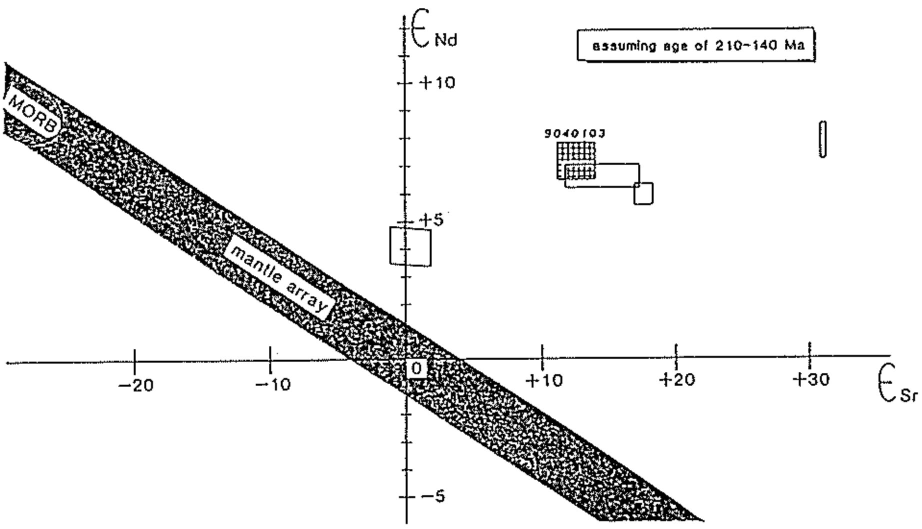


Fig. 12. Diagrams showing rare earth element and isotope (Nd, Sr) variations of Gosaisyo metabasite as well as deformed and metamorphosed andesitic and rhyolitic dike rocks (Hiroi et al., in prep.).

compared with other regional metamorphic terrains.

Recently, Tagiri and coworker (in prep.) divided the Gosaisyo Group and a part of the Takanuki Group into four metamorphic zones, I, II, III and IV (Fig.15), based on the mineral changes in various rock types (Fig.16b). Zone II is subdivided into IIa and IIb by the presence and absence of actinolite core in hornblende crystals (Figs.15&16b). They also adopted graphitization of carbonaceous material in pelitic rocks to elucidate the ultimate thermal structure (Fig.15). They concluded that the contact metamorphic effects by the Cretaceous plutons are so extensive that the presently observed thermal structure is strongly affected by them. The contact metamorphic effects are usually observed as overgrowing rims of chemically zoned minerals, especially plagioclase (Fig.16b). Minerals formed during preceding regional metamorphism, in turn, are preserved as armored cores. They revealed that the hornblende + epidote + calcic oligoclase assemblage diagnostic to the epidote-amphibolite facies was stable during regional metamorphism in rocks from their zone II (Fig.18).

The Takanuki Group, as a whole, are of upper amphibolite facies (sillimanite + K-feldspar zone) grade. Pelitic gneisses are usually composed of sillimanite, cordierite, biotite, plagioclase, K-feldspar, quartz, illmenite, apatite, zircon, graphite and pyrrhotite with or without corun-

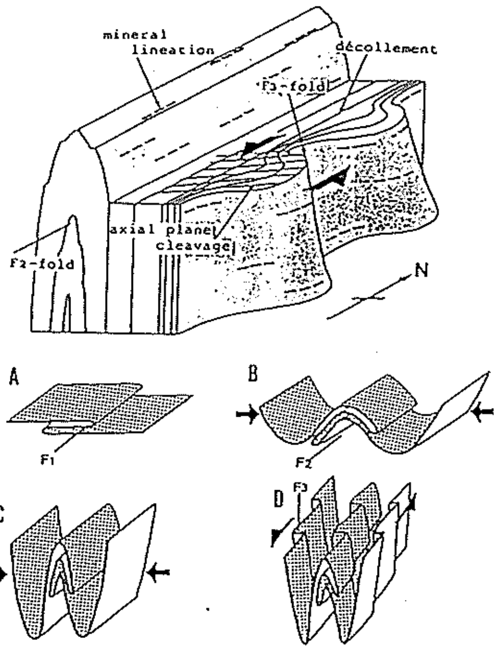


Fig. 13. Schematic diagrams showing geometrical relationship between F2 and F3 folds and deformation sequence of Gosaisyo Group (Ishikawa and Otsuki, 1990).

dum, kyanite, andalusite, staurolite, hercynite, garnet, chlorite, muscovite, rutile and tourmaline. Kyanite and staurolite are relics totally included in plagioclase (Fig.17), and are occasionally accompanied by hercynite. These minerals were first found by studies of river sands (e.g., Uruno, 1979). Andalusite occurs commonly in the Takanuki pelitic gneisses (Fig.17). Although Miyashiro (1958) considered andalusite to be a relic formed at an early stage of prograde metamorphism, its mode of occurrence clearly indicates that andalusite was formed with or without biotite, muscovite and chlorite during retrograde metamorphism, which may be coeval with the emplacement of Cretaceous plutonic complexes. Rutile occurs only as inclusions in garnet. Garnet in the Takanuki pelitic gneisses and a part of the Gosaisyo pelitic schists close to the Takanuki Group is unusual from two aspects (Hiroi and Kishi, 1989b): (1) the sector zoning displayed by the fine-grained inclusion geometry, which is similar to those described by Harker (1932) and Andersen (1984) (Figs.18-20); (2) complex compositional zoning in spite of the high metamorphic grade, which is most probably growth zoning except for the outermost rim zoning (Figs.19&20). Moreover, it is noteworthy that the garnets often contain calcic and euhedral (occasionally lath-shaped) plagioclase inclusions (Figs.18&20). Petrological significance of these features of garnet will be discussed later. The silica-undersaturated lateritic rocks carry the mineral assemblage of almandine + hercynite + sillimanite + ilmenite ± corundum

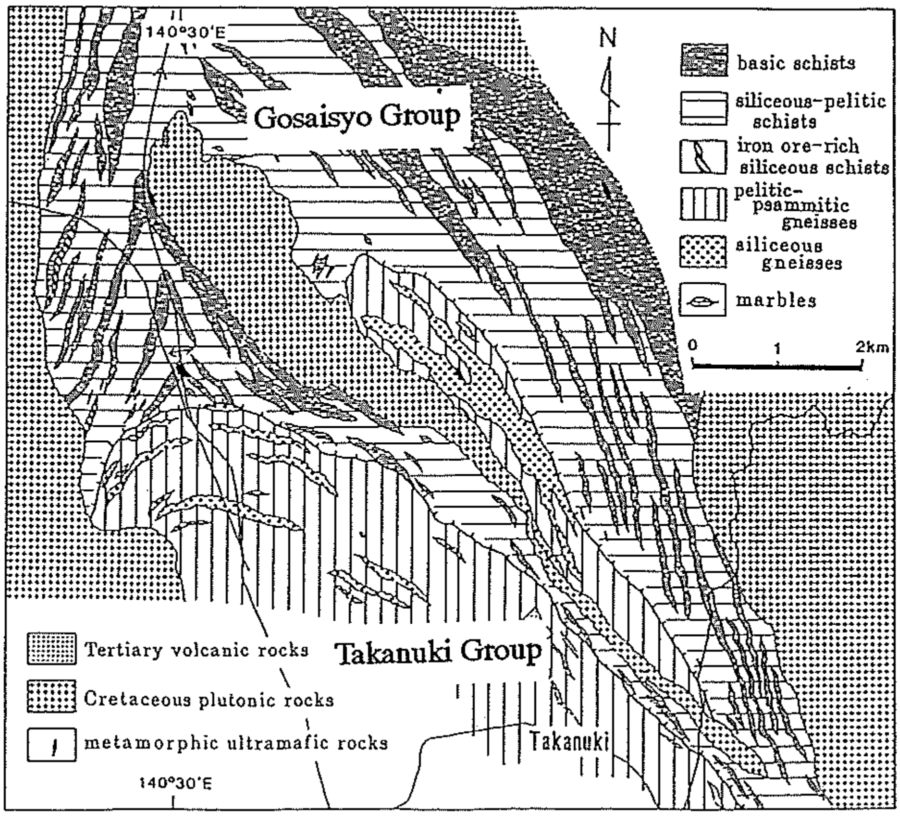
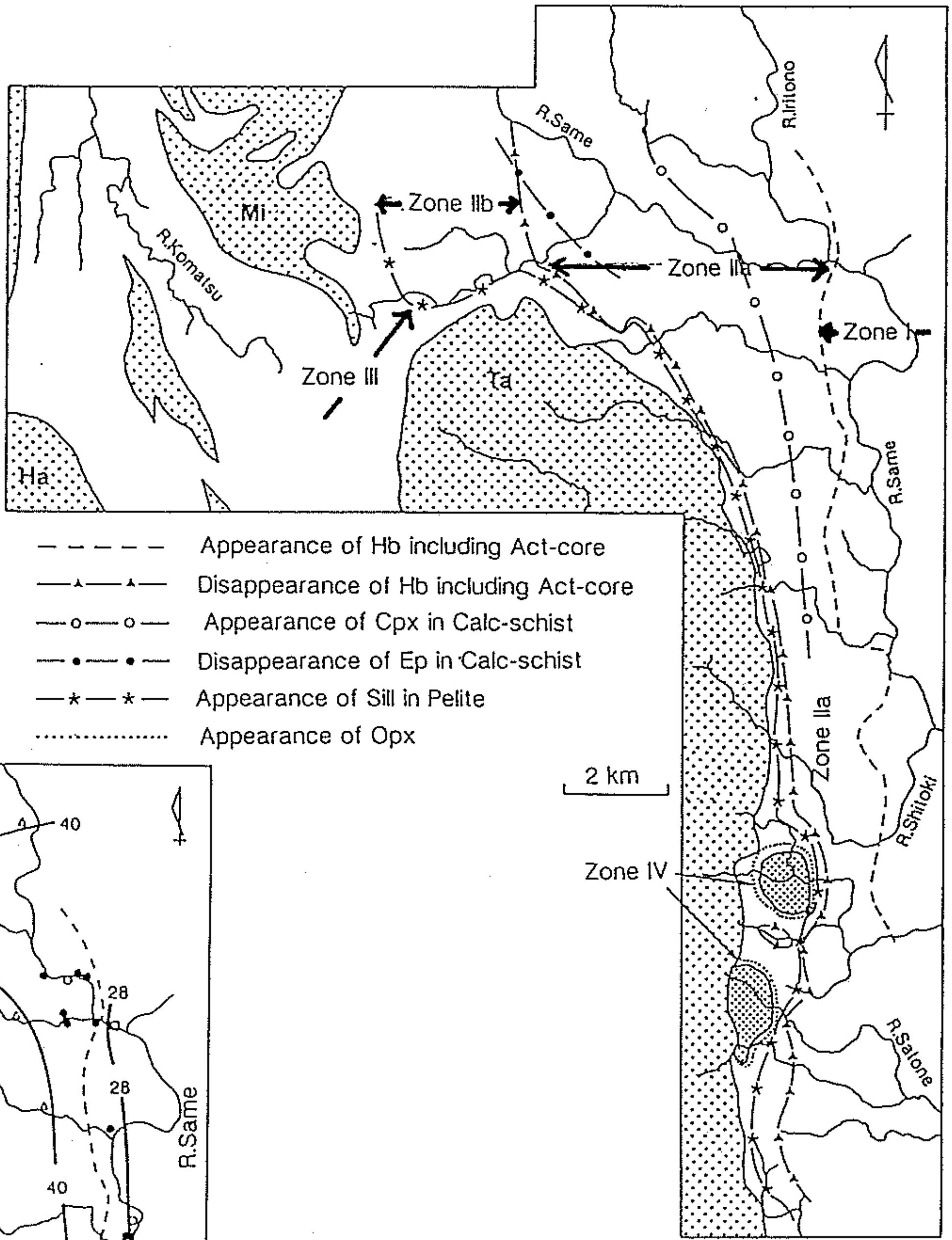


Fig. 14. Geological map of northern Takanuki area (Goto, 1991).



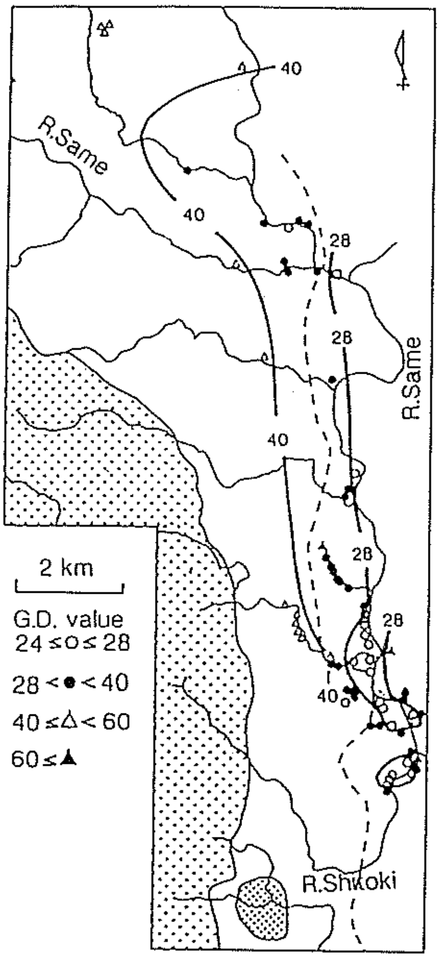


Fig. 15. Maps showing progressive metamorphic zones in Gosaisyo-Takanuki district and variation of graphitizing-degree (G.D.) of carbonaceous matter in pelitic rocks (Tagiri et al., in prep.). Note that the thermal structure is discordant to the geological structures, especially those of the Gosaisyo Group.

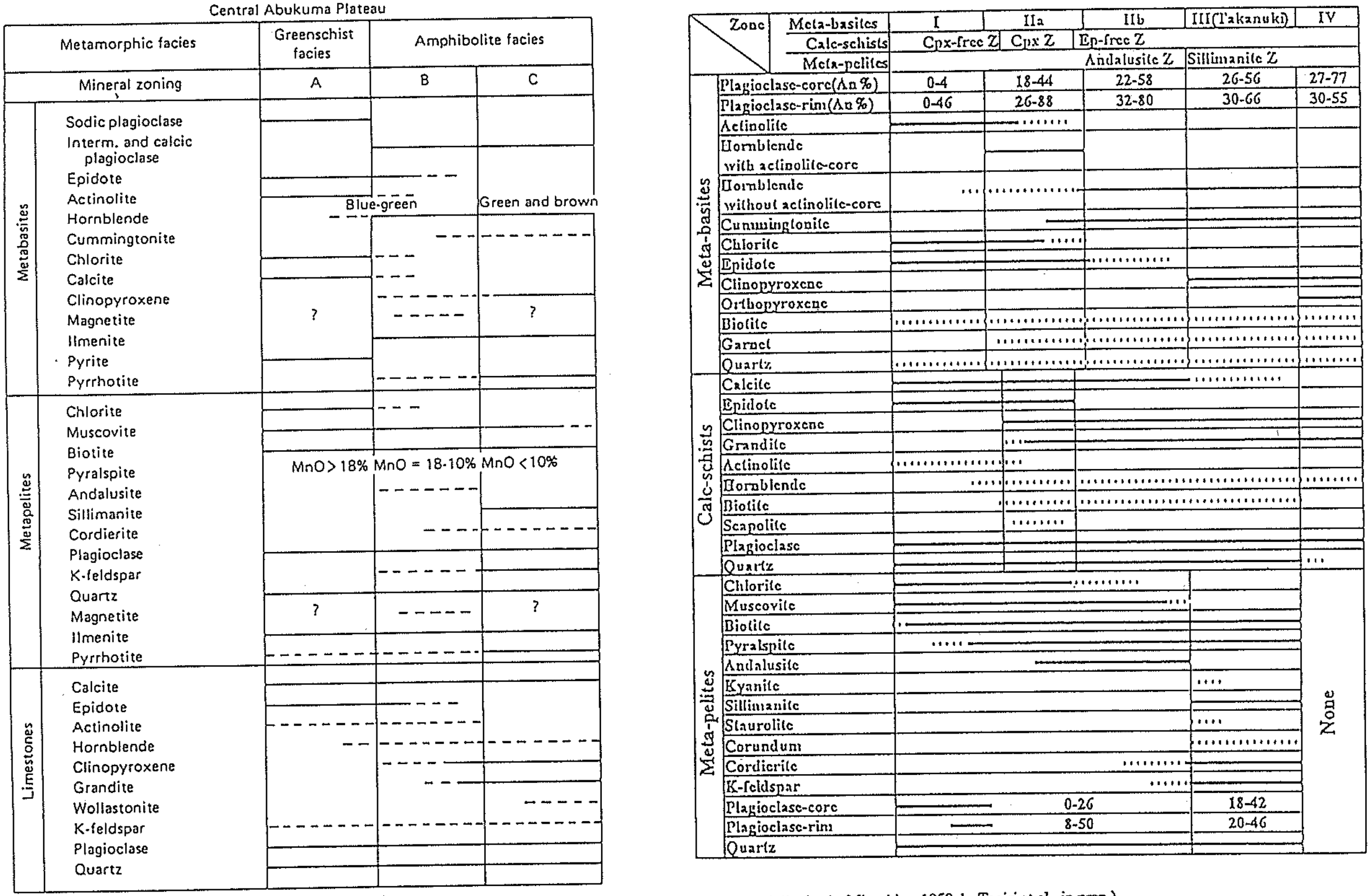


Fig. 16. Diagram showing progressive mineral changes in Gosaisyo-Takanuki district (a; Miyashiro, 1958, b; Tagiri et al., in prep.).

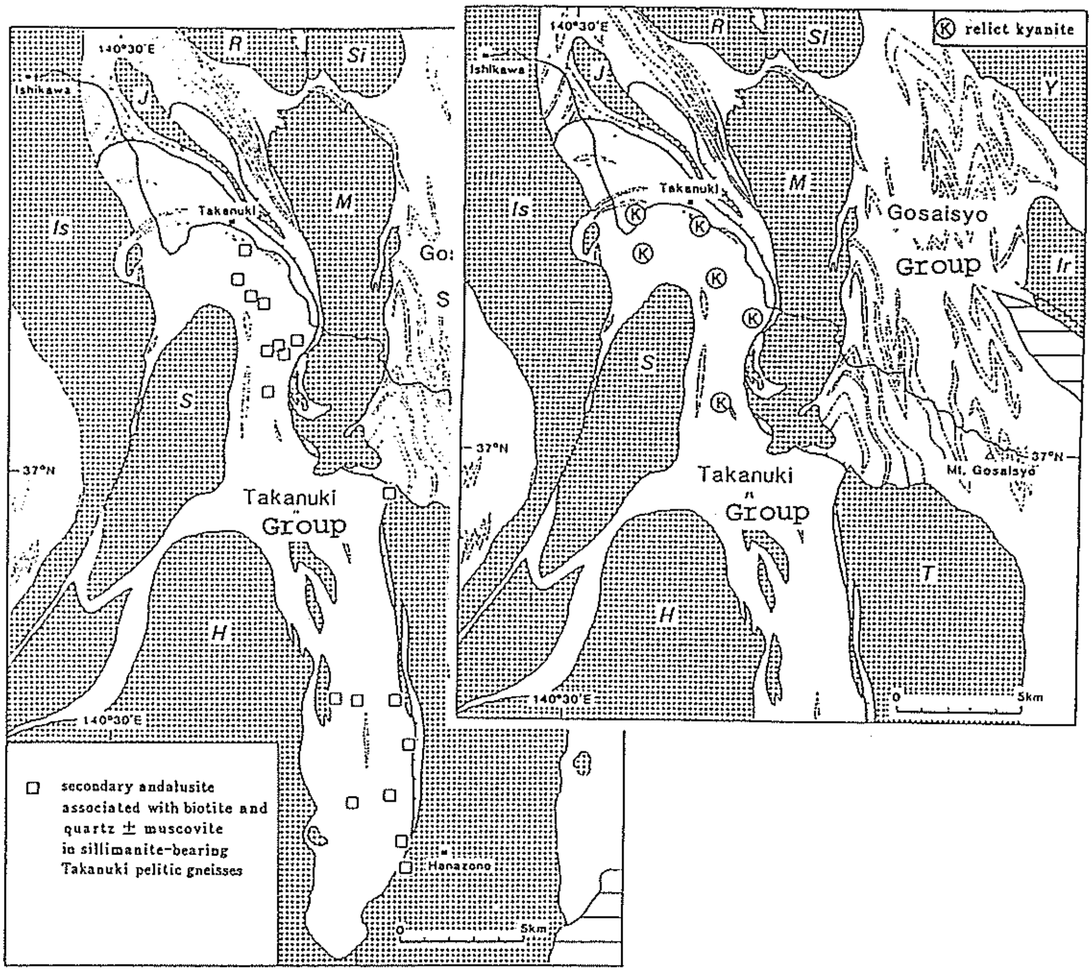


Fig. 17. Maps showing localities of relic kyanite and retrograde andalusite in Takanuki pelitic gneisses (Hiroi et al., in prep.).

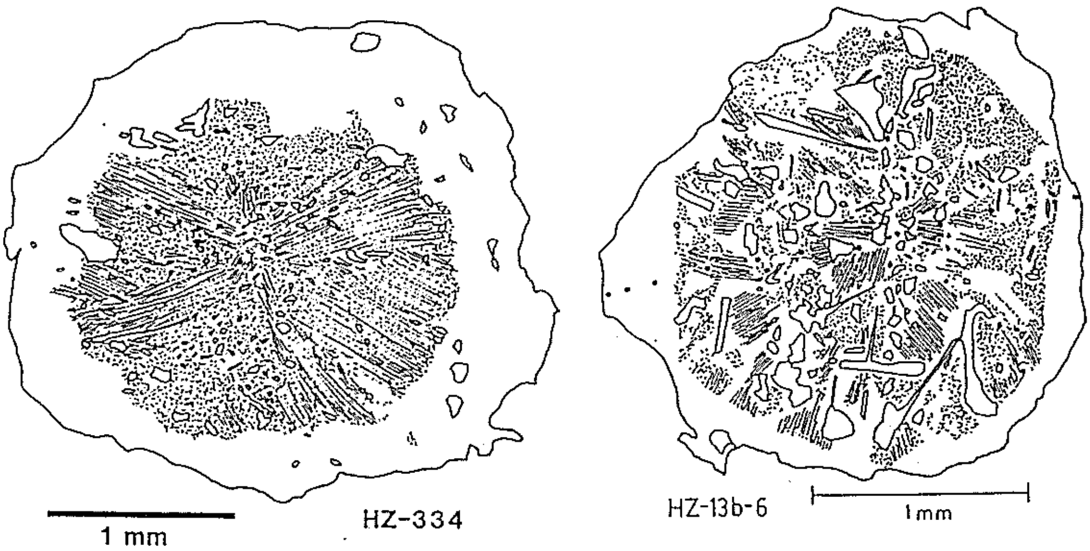


Fig. 18. Texturally sector-zoned garnet porphyroblasts in Takanuki pelitic gneisses (Hiroi et al., in prep.). HZ-334 garnet shows not only textural but also compositional sector zoning. HZ-13b garnet contains euhedral (lath-shaped) calcic plagioclase inclusions.

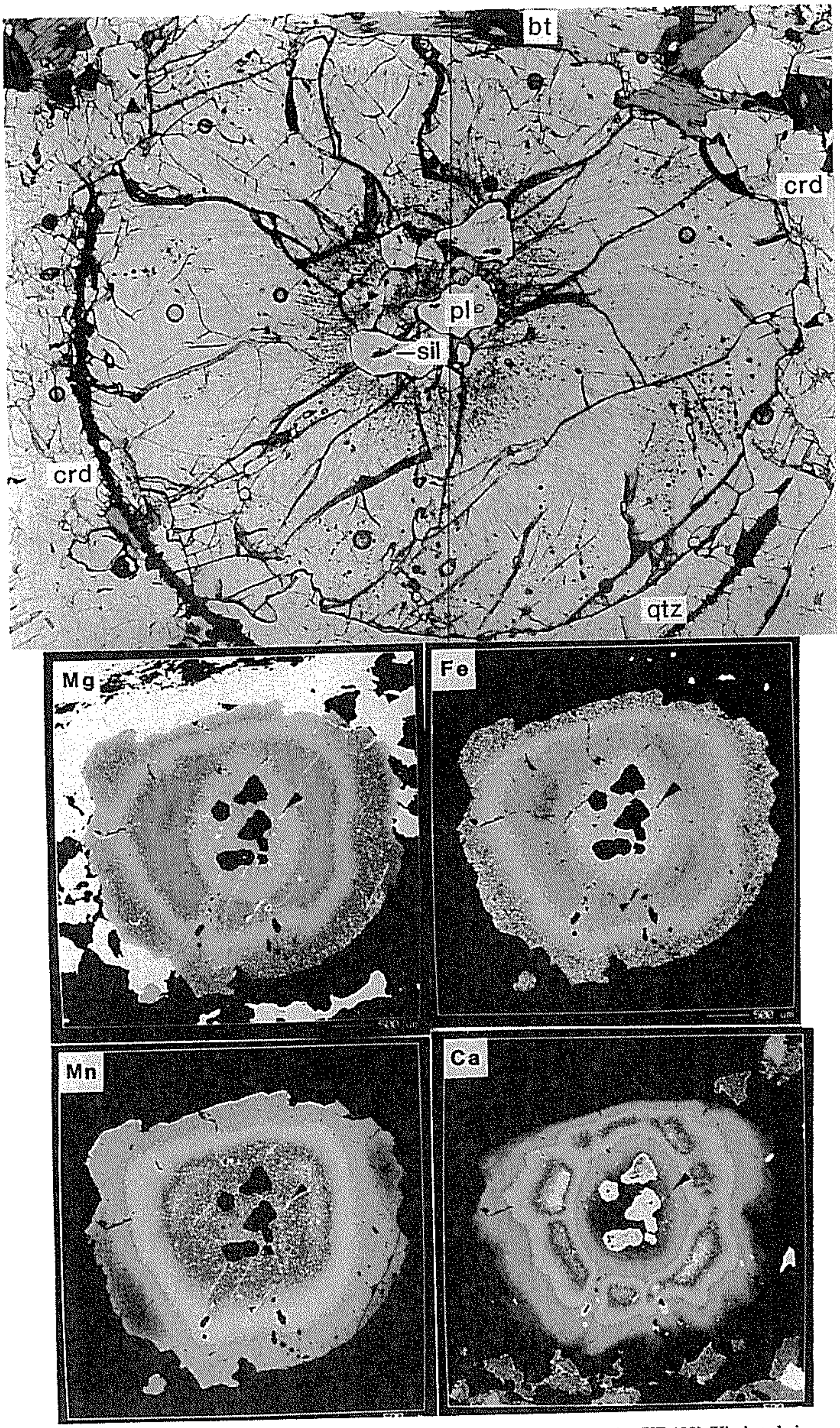


Fig. 19. Compositional zoning of texturally sector-zoned garnet in Takanuki pelitic gneiss (HZ-122) (Hiroi et al., in prep.).

± staurolite ± plagioclase ± biotite (Uruno and Kanisawa, 1965; Hiroi, 1990). The textural relations among these minerals, especially almandine, corundum, hercynite and sillimanite, will be mentioned later to unravel the P-T-t path followed by the rocks.

The most significant point to be held is that the regional metamorphic thermal structure is discordant with the geological structures, especially those of the Gosaisyo Group (Figs.10&15).

P-T-t Path

The P-T-t path followed by the Takanuki Group indicates high-temperature "rapid" loading immediately followed by unloading (Fig.21). Hiroi and Kishi (1986, 1989b) and Hiroi (1990) revealed it based mainly on (1) textural relationships between corundum, almandine, hercynite and sillimanite in the staurolite-bearing silica-undersaturated lateritic rocks and (2) textural and compositional features of garnet porphyroblasts in the pelitic gneisses.

In the lateritic rocks, stable mineral assemblages are inferred to have changed with time from almandine + sillimanite + hercynite ± staurolite through almandine + corundum + sillimanite ± staurolite to almandine + sillimanite + hercynite ± staurolite. Corundum usually occurs in a small amount as relics extensively replaced by sillimanite and hercynite, indicating that the pre-existing corundum + almandine assemblage was replaced by the almandine + sillimanite + hercynite assemblage during high-temperature decompression. However, corundum is occasionally in direct contact with almandine, and, together with adjacent almandine, contains sillimanite and hercynite inclusions. Such mineral textures suggest that the almandine + corundum assemblage was formed at the expense of pre-existing sillimanite + hercynite assemblage during high-temperature compression (see explanation of Stop 2-4 and Supplement 4).

Garnet in the Takanuki pelitic gneisses often preserves growth zoning well. Ca increases abruptly and decreases gradually while Mg/Fe ratio varies little from core to rim (Fig.19). This along with the continuous fine-grained inclusion trails displaying the textural sector zoning, indi-

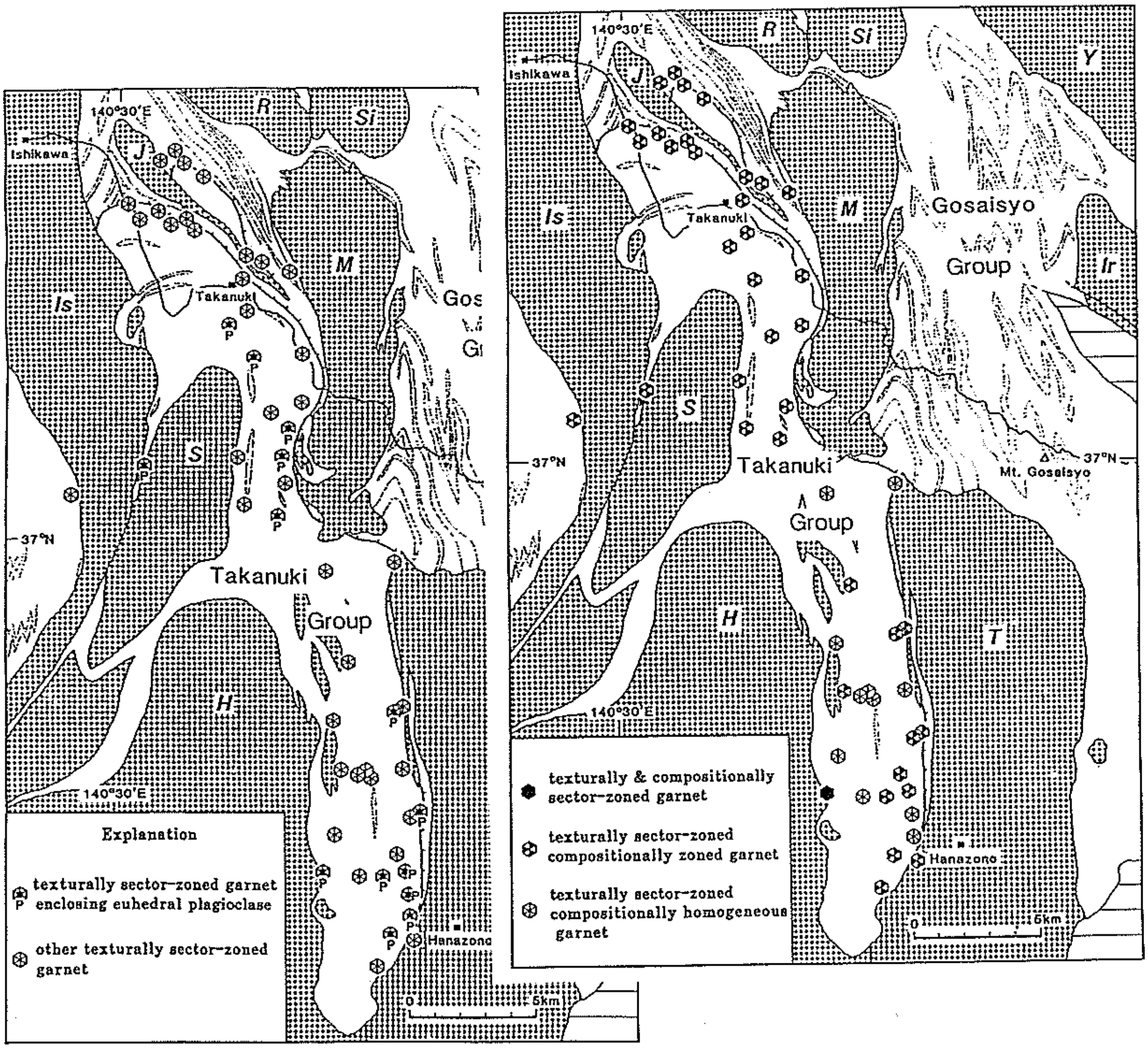


Fig. 20. Maps showing regional occurrence of texturally sector zoned garnet in Takanuki pelitic gneisses. Note that many of them preserve growth zoning and contain euhedral plagioclase (Hiroi et al., in prep.).

cates a sequence of high-temperature rapid compression and subsequent decompression. The occurrence of rutile only as inclusions in the Ca-enriched part of garnet porphyroblasts is in harmony with the interpretation. It may be possible to estimate the duration of the high-temperature events, using the fact that some garnet porphyroblasts are extensively homogenized by intra-crystalline diffusion while other are not (Fig.20). The estimated duration is ≤ 107 years. This means an average speed of burial and exhumation of the rocks ≥ 2 mm/year. The occurrence of similar garnet porphyroblasts in the Gosaisyo pelitic schists close to the Takanuki Group indicates that some Gosaisyo Group also underwent the high-temperature events in common. Hiroi and Kishi (1989b) attributed the high-temperature loading and subsequent unloading to the overthrusting of the Gosaisyo Group onto the Takanuki Group and the intrusion of Cretaceous plutons located at the cores of the domes of the Takanuki

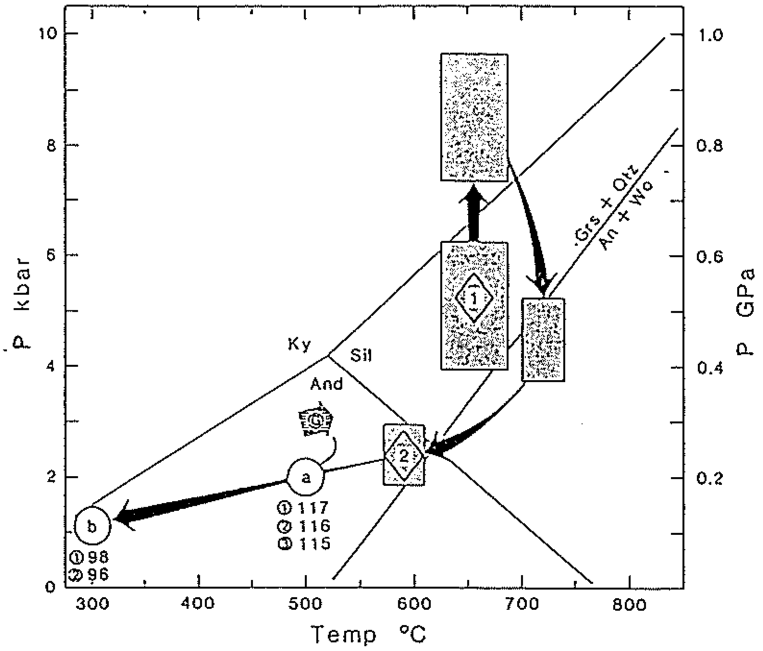


Fig.21. P-T-t path followed by Takanuki Group rocks (Hiroi and Kishi, 1989b). Estimated P-T conditions of the low-grade Gosaisyo Group rocks are also shown.

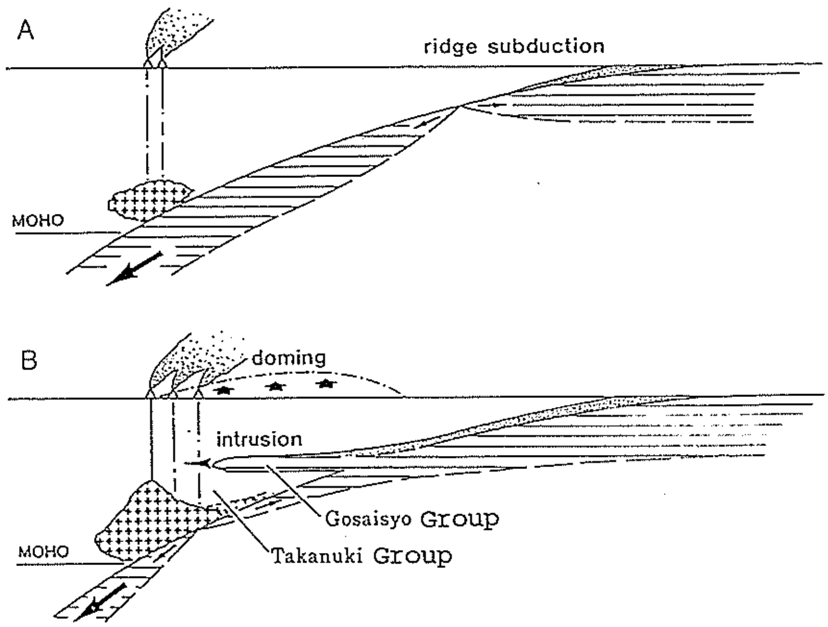


Fig. 22. Cartoon showing geodynamic evolution of Gosaisyo and Takanuki metamorphic rocks. At stage A, oceanic ridge began to subduct beneath the Asian continent. At stage B, detached Jurassic upper oceanic crust began to intrude into the continental crust along a mechanically weakened zone due to the subduction of ridge.

Group, respectively.

The common occurrence of euhedral and calcic plagioclase as inclusions within garnet porphyroblasts in the pelitic gneisses (Fig.18) and the migmatitic mode of occurrence of the rocks in the field, with some additional evidence, suggest that partial melting took place at the high-pressure stage. Effective separation of melt, however, may have not occurred, because bulk chemical compositions of the pelitic rocks are close to the average shale composition (Shaw, 1956).

Geodynamic Model of Gosaisyo-Takanuki Metamorphic Rocks

The significant geological and petrological features of the Abukuma metamorphic rocks, especially those in the Gosaisyo-Takanuki district, are summarized as follows.

1. The metamorphics are divided into two distinct geological units; the Gosaisyo Group of Jurassic upper oceanic crust origin and the Takanuki Group derived from age-unknown terrigenous sediments.
2. Calc-alkalic igneous rocks intruded into the Gosaisyo Group before, during and after intense deformation events and regional metamorphism.
3. The Gosaisyo Group overthrust onto the Takanuki Group.
4. The regional metamorphic thermal structure is discordant with the complicated geological structures, in particular, those of the Gosaisyo Group.
5. In the higher-grade Gosaisyo Group rocks, epidote-amphibolite facies mineral assemblages had been stable during regional metamorphism, and were modified at lower pressure conditions during subsequent contact metamorphism by the voluminous Cretaceous plutonic complexes.
6. The Takanuki Group, together with some Gosaisyo Group close to the Takanuki Group, suffered high-temperature rapid loading and subsequent unloading. The average speed of burial and exhumation of the rocks is estimated to have been as quick as ≥ 2 mm/year.

All these features of the metamorphic rocks as well as the occurrence of voluminous Cretaceous plutonic rocks may be most satisfactorily explained by a geodynamic model shown in Fig.22.

SANBAGAWA METAMORPHIC BELT (by Hirajima, Shimizu and Tagiri)

Foreword

The Sanbagawa (Sanbagawa) belt lies immediately to the south of Median Tectonic Line (MTL) and extends more than 800 km throughout the south-western part of Japan (Fig.2). The easternmost exposure of the Sanbagawa metamorphic rocks is in the Kanto Mountains, north-west of Tokyo. This region presents a number of geological problems. One of the major points of dispute is how to reconstruct the Cretaceous paleogeography in the Kanto district, especially concerning the relationship between the Sanbagawa and the Abukuma belts (see p.1). A second geological problem of the Kanto Mountains is the baric type of the Sanbagawa metamorphism. Miyashiro (1973) introduced this area as the typical glaucophane schists facies based on the petrologic work of Seki (1958, 1960). However, Hirajima (1983, 1985, 1989) and Kusakabe (1991) have shown that the baric type of the Kanto Mountains is similar to the Shikoku

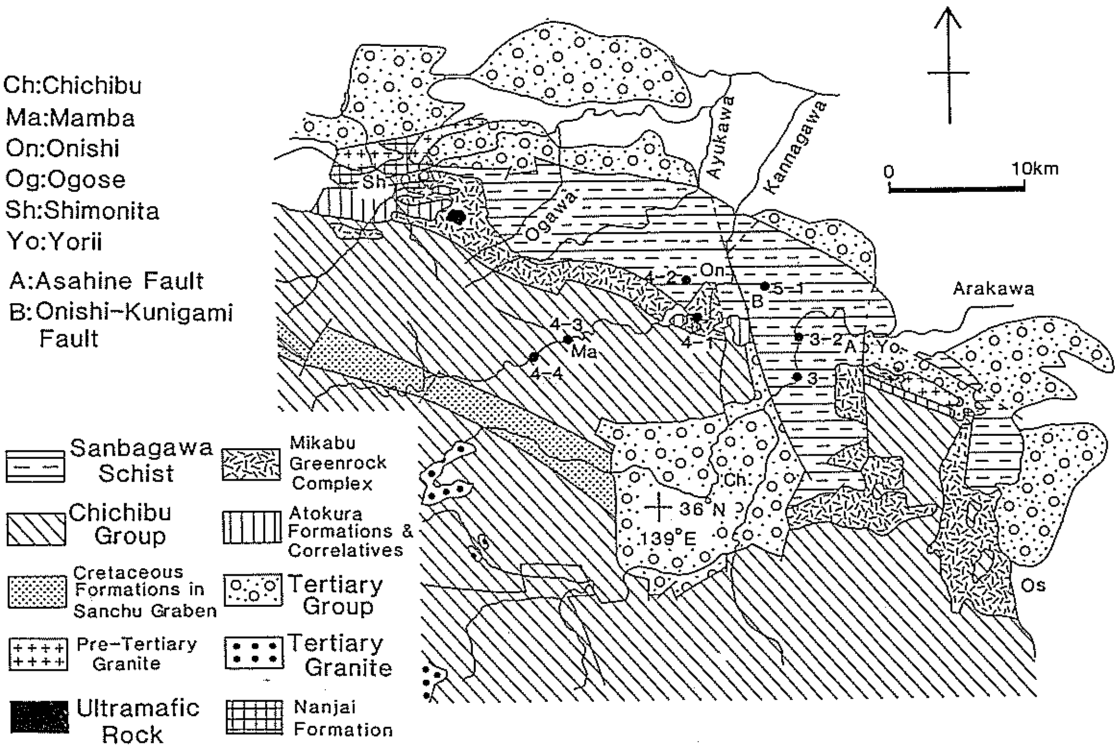


Fig. 23. Geologic outline of the Kanto Mountains.

region and belongs to the high-pressure intermediate type.

This field excursion aims to compare lithology, deformation features and metamorphic facies series between the Abukuma and the Sanbagawa metamorphic belts in the Kanto district. The latter half of the excursion will be spent studying the Sanbagawa metamorphic rocks in the Arakawa and Kannagawa areas in the Kanto Mountains. In these areas, the regional change in the metamorphic grade and deformation features are well developed.

Geologic outline of the Kanto Mountains

In the Kanto Mountains, the Sanbagawa schists, in a narrow sense, the Mikabu Greenrock Complex and the Chichibu Group show a zonal arrangement from north to south with ascending structural level (Fig.23). Evidence of the Sanbagawa metamorphism can be recognized in all three units, so the authors refer to all of them as "Sanbagawa metamorphic rocks". The post-Cretaceous Atokura nappe, comprising the Atokura Formation and correlatives and the pre-Tertiary granite, overlies the Sanbagawa metamorphic rocks in the northern part of the Kanto Mountains (Fig.23). This nappe contains various kinds of metamorphic rocks as tectonic blocks and the

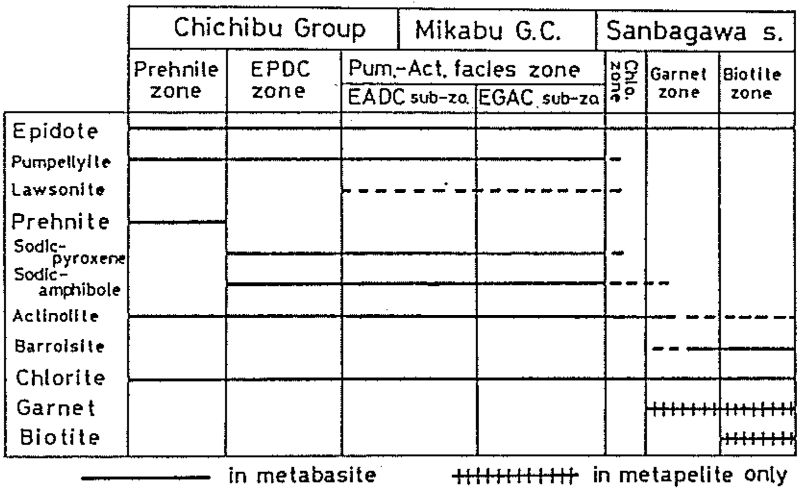


Fig. 24. Stability ranges of metamorphic minerals in the Kanto Mountains.

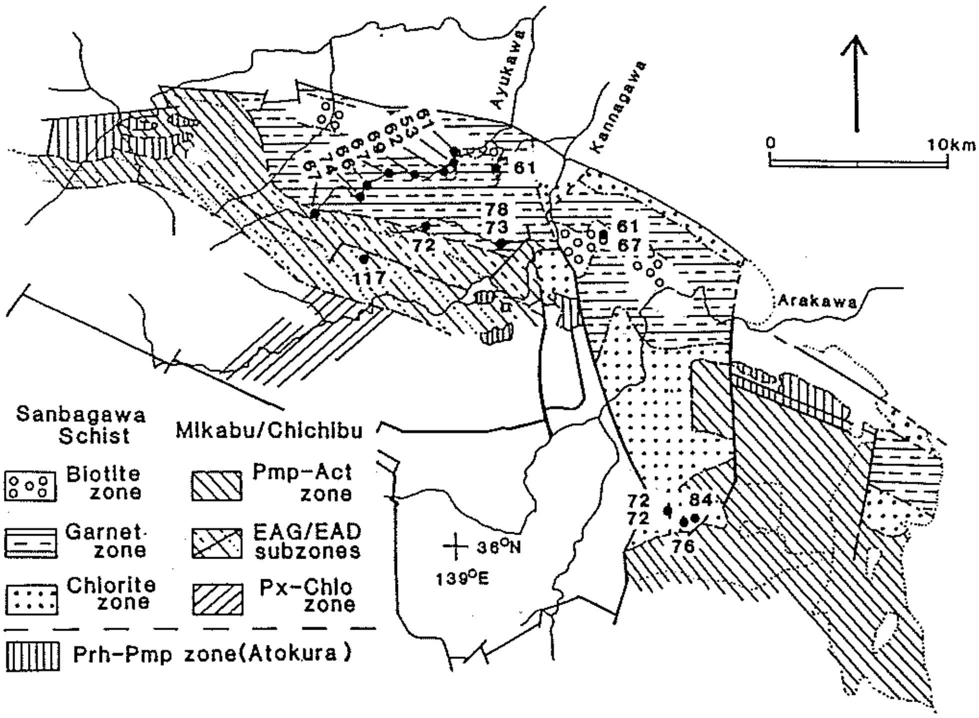


Fig. 25. Metamorphic zonal map of the Kanto Mountains with phengite K-Ar ages (Hirajima et al., 1992).

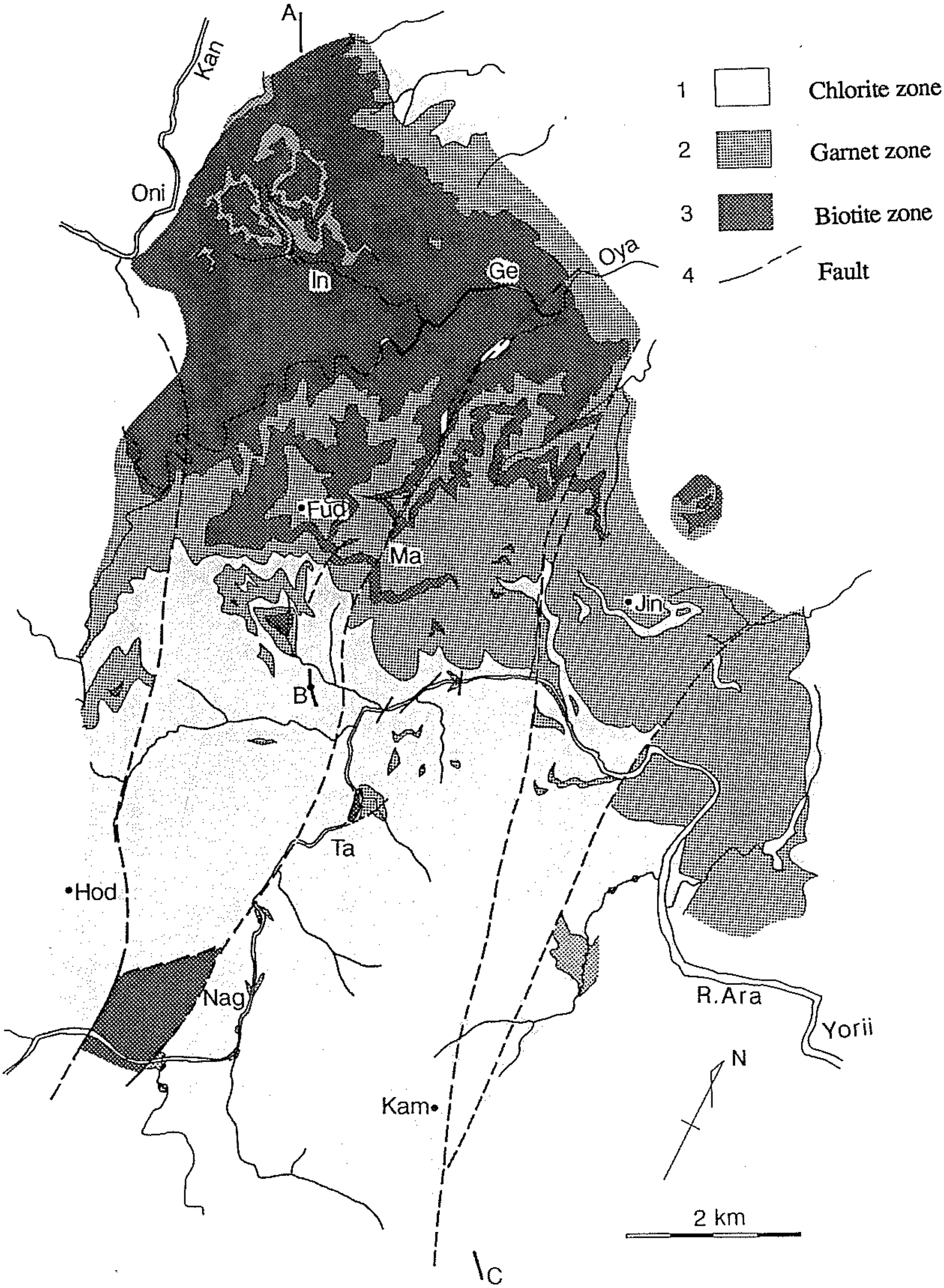


Fig. 26 b. Metamorphic zonal map of the Arakawa area.

nappe as a whole has suffered prehnite-pumpellyite facies metamorphism. However, these metamorphic events are unrelated to the Sanbagawa metamorphism.

The Chichibu Group is considered to be composed of trench-fill sediments that contain olistoliths of Carboniferous to Triassic age and were deposited from late Jurassic onwards (Sashida et al., 1981). The main rock types are phyllitic mudstone and sandstone containing olistoliths of chert, volcaniclastics, basic lava and limestone.

The Mikabu Greenrock Complex is situated between the Chichibu Group and the Sanbagawa schist (Fig.23), and is mainly composed of basic rocks intercalated with layers of mudstone and chert. The basic rocks can be divided into massive metabasites derived from gabrro, doleritic dike and pillow lava, and schistose metabasite that is derived from tuff breccia and hyaloclastite. The Mikabu Greenrock Complex is also considered to be an olistostromal deposit formed at the trench setting (Nakamura, 1986).

The Sanbagawa schist dominantly consists of metapelite intercalated with metasiliceous rock and metabasites. All lithofacies show a well-developed schistosity,.which dips very gently to south or north in general. Any sedimentary structure has not been observed, so that we cannot determined any stratigraphic sequence. Nevertheless, key beds of metasiliceous schist and metabasites can be traced for a distance of over 1 km (Fig.26). Any recumbent fold of a large scale is not recognized, though many minor folding systems such as an over-turned fold and a sheath fold are frequently observed on the outcrops.

Uyeda et al. (1977) and Hirajima et al. (1992) report K-Ar phengite ages in the Kanto Mountains. The ages show general decrease with increasing metamorphic grade, mentioned late, and with descending structural level; 117 Ma for the Chichibu Group, and the underlaying Sanbagawa schist, 87-72 Ma for the chlorite zone, 78-66 Ma for the garnet zone, and 67-53 Ma for the biotite zone. The range of the K-Ar ages is similar to that of the Sanbagawa terrain in Shikoku (Itaya & Takasugi, 1988), however, the relationship between the metamorphic grade and the K-Ar age is opposite.

Metamorphic zonation

Observation of about ten thousand thin sections under the microscope suggests the following mineral zonation: For the Sanbagawa schist in ascending order of grade, chlorite, garnet, and biotite zones. These zones are determined by the presence of critical minerals and the graphitizing-degree in metapelite (Figs. 24-26). This zonation is essentially similar to those in Shikoku (Higashino, 1975; Banno, 1986). However, unlike Shikoku, several layers of the biotite zone grade, with several tens meter thickness, are repeatedly intercalated with the layers of the garnet zone grade, and the highest grade rocks occur at the structurally shallowest levels in the Arakawa area (Hashimoto, et al., in prep.).

Metapelite of the Mikabu Greenrock Complex and the Chichibu Group don't contain garnet nor biotite. Therefore the zonation of the Mikabu Greenrock Complex and the Chichibu Group is determined by low variant mineral assemblages in metabasites as follows: pumpellyite-actinolite facies, sodic pyroxene-chlorite facies and prehnite zones (Figs. 24&25). The pumpellyite-actinolite facies is defined by the occurrence of EAPQ (epidote-actinolite-

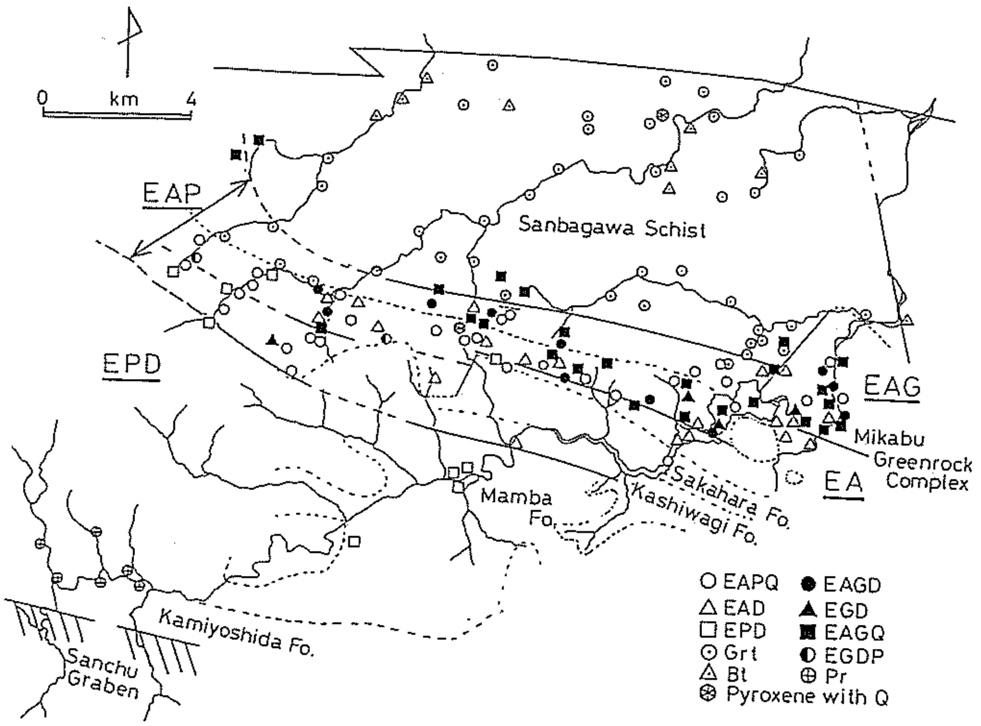


Fig. 27. Distribution of low-variant assemblages in metabasite and that of critical minerals in metapelites in Kannagawa and Ayukawa areas. Unit boundary mainly follows Uchida (1981).

pumpellyite-quartz) assemblage (Nakajima et al., 1977). This zone includes the Mikabu Greenrock Complex, the lower structural levels of the Chichibu Group, and the uppermost level of the Sanbagawa schist. The area of the pumpellyite-actinolite facies in Kannagawa and Ayukawa areas can be further divided into two subzones: EAG and EAD subzones (Fig.27). In Kannagawa and Ayukawa areas, metapelites, with or without garnet, of the Sanbagawa schist are intercalated with metabasites with the EAPQ assemblage. Hence, the pumpellyite-actinolite facies is cofacial to a part of chlorite and garnet zone of the Sanbagawa schist. The sodic pyroxene-chlorite facies zone, defined by the absence of both the epidote-actinolite assemblage and prehnite, occupies the middle structural levels of the Chichibu Group in the Kannagawa (Fig.27). The prehnite zone occupies the higher structural level of the Chichibu Group in the Kannagawa region, where sodic amphibole and sodic pyroxene are not found.

Mineralogy

<Sodic pyroxene>

Sodic pyroxene is very common in lower-grade metabasites of the study area, but is rare in the higher-grade-part, i.e., in the Sanbagawa schist. In our studies by electron microprobe, we were unable to identify sodic pyroxene in metabasites that coexists with quartz. However, sodic pyroxene + quartz assemblage was found in two other rock types; a metasiliceous rock from the Mikabu Greenrock Complex and a Fe-Mn rich nodule in the garnet zone of the Sanbagawa schist. Most of sodic pyroxene is sodic-augite, aegirine-augite and aegirine (Fig.28). However, the average Al-content gradually increases from the Chichibu Group to the Sanbagawa schist; X_{Jd}=0.05 in the Chichibu Group, 0.10 in the Mikabu Greenrock Complex and 0.25 in the Sanbagawa schist (Fig.28).

<Amphibole>

In the lower-grade metabasite, the predominant amphiboles are actinolite and sodic amphibole. In the garnet and biotite zones of the Sanbagawa schist, this changes to actinolite and barroisitic hornblende. Sodic amphibole is mostly glaucophane, crossite and magnesioriebeckite, and locally also reibeckite (Fig.29). An apparent miscibility gap between glaucophane and actinolite exists under the pumpellyite-actinolite facies. However, the gap between riebeckite and actinolite becomes narrower with increase of metamorphic grade as demonstrated by Katagas (1974), Brown (1974) and Toriumi (1975). This is because the riebeckite component of Ca-amphibole gradually increases with increase of metamorphic grade (Fig.30).

In the Sanbagawa schist, calcic amphiboles become rich in Al^{IV} with increase of the metamorphic grade (Fig.31) (Hashimoto and Funakoshi, 1991).

<Epidote>

Epidote is ubiquitous in the study area. It is relatively homogeneous and Fe^{3+} rich (Y_{Al}=0.7) in the Chichibu Group and the Mikabu Greenrock Complex, and usually shows complex zoning, ranging from Y_{Al}=0.85 to 0.75 in the garnet zone of the Sanbagawa schist (Fig.32).

<Pumpellyite>

Pumpellyite is a main constituent of the Chichibu Group and the Mikabu Greenrock Complex, and its Al content generally increases with increase of metamorphic grade (Fig.33). Pumpellyite is absent in the garnet and biotite zone of the Sanbagawa schist.

<Lawsonite>

Lawsonite was used as a critical mineral for zonal mapping in the Kanto Mountains by Seki (1958). Lawsonite rarely occurs in metabasites of the Mikabu Greenrock Complex and in metapelites of the Sanbagawa schist. However, its occurrence is restricted to certain metabasites with Al_2O_3-rich and Fe_2O_3-poor bulk composition of the Mikabu Greenrock Complex. Therefore, it is not appropriate to use lawsonite as a critical mineral for zonal mapping.

<Garnet>

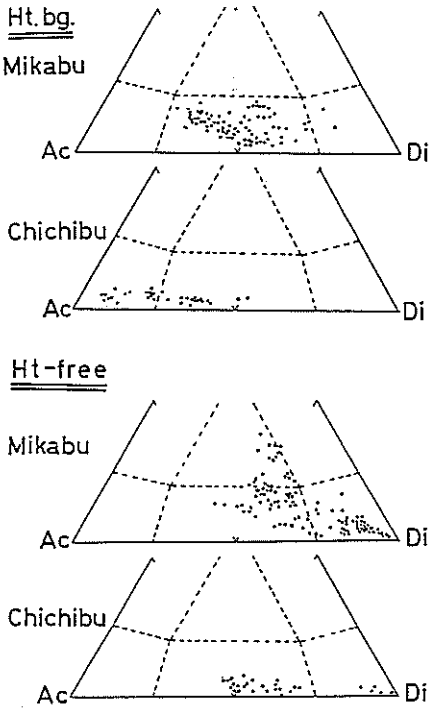
Garnet is a critical mineral for the zonal mapping of the Sanbagawa schist, and shows a typical growth zoning with Mn-rich core and Mn-poor rim (Fig.34) (Kusakabe,1991). Core composition of the biotite zone garnet is very similar to those of the garnet zone, but rim of biotite zone garnet is rich in Fe than those of the garnet zone.

<Other minerals>

The distinction of quartz from albite in the lower-grade metabasite is very difficult. Electron microprobe work found five quartz-bearing thin sections among fifty of the Mikabu Greenrock Complex and the Chichibu Group. Quartz is associated with sodic amphibole, epidote, pumpellyite, and actinolite, but not with sodic pyroxene in the studied metabasites. Although oligoclase-rim was rarely found from the biotite zone in the Kanto Mountains (Makimoto, 1987), all analyzed plagioclase is albite. Carbonate in the Sanbagawa metamorphic rocks minerals was tested with Feigl's solution, however only calcite was detected.

Schreinemakers' analysis for the observed mineral assemblages

The stability field of the observed low-variant assemblages was examined by the Schreinemakers' method. Quartz is not ubiquitous in the studied metabasites, so a chemographic tetrahedron of A(Al_2O_3)-C(CaO)-F3(Fe_2O_3)-S(SiO_2), projected from albite, muscovite and chlorite, was adopted (Fig.35). The system, composed of four components with six phases (sodic pyroxene, sodic amphibole, actinolite, epidote, pumpellyite and quartz),



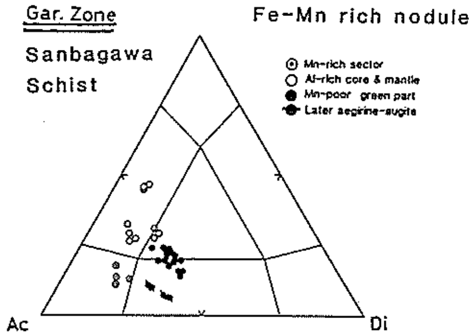


Fig. 28. Composition variation of metamorphic pyroxenes in each geologic unit.

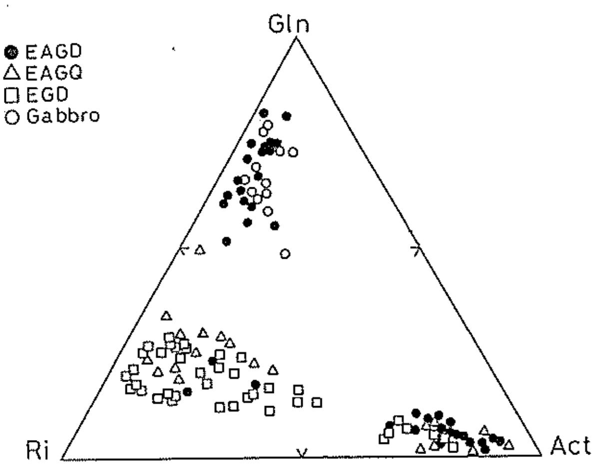


Fig. 29. Sodic, calcic and sodic-calcic amphiboles in Act <Ca>-Gl <Al(VI)>-Ri <Fe^{3+}=Na-Al(VI)> diagram.

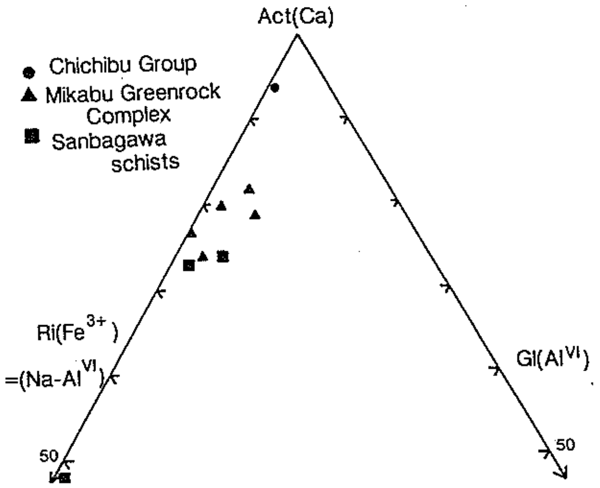


Fig. 30. Averaged compositions of actinolite in each geologic unit. Fe^{3+}/Fe^{2+} ratios of amphiboles are re-calculated on the basis of total cations = 13.0 in B, C, and T sites of amphibole formula (Leak,1978).

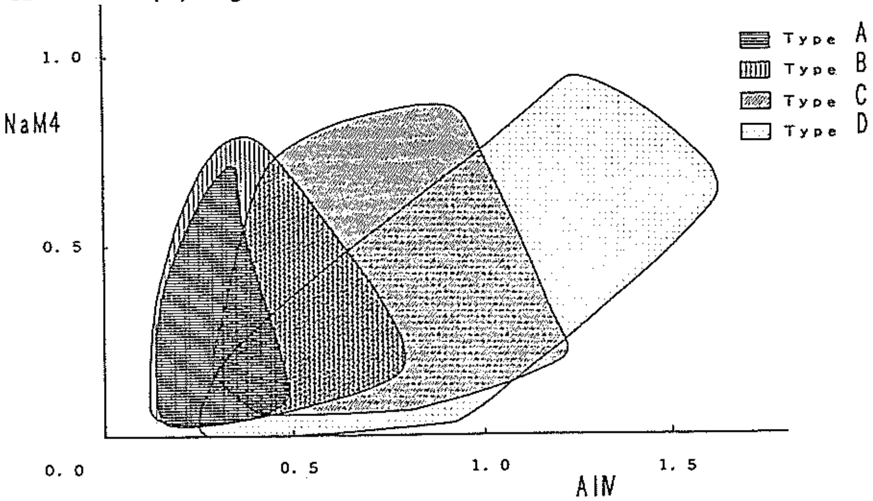


Fig. 31. Chemical variations of calcic amphibole composition from the chlorite, garnet and biotite zones. Metamorphic grade increases from the type A to the type D.

gives a single net as shown in Fig.35. This grid makes the following predictions.

1) The maximum stability field of EAPQ is defined by the two reactions, PGQ=EA and PDQ=EA.

$31Ca_4FAl_5Si6O_{23}(OH)_32H_2O + 43Na_2F_3AlFe^{3+}Si_8O_{22}(OH)_2 + 48SiO_2 = 19Ca_2F_5Si_8O_{22}(OH)_2 + 43Ca_2Al_2Fe^{3+}Si_3O_{12}(OH) + 13F_5Al_2Si_3O_{10}(OH)_8 + 86NaAlSi_3O_8 + 59H_2O$

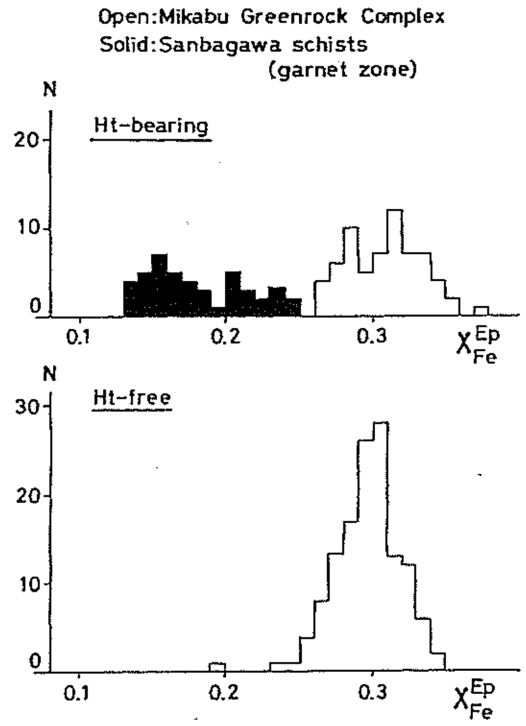


Fig. 32. Frequency distribution of X_{Fe}=<Fe/(Fe+Al)> ratios in epidote of the Sanbagawa metamorphic rocks.

pumpellyite + sodic amphibole + quartz = actinolite + epidote + chlorite + albite + H_2O -----(1)

$170Ca_4FAl_5Si_6O_{23}(OH)_32H_2O + 430CaNaFAl_{0.2}Fe^{3+}{}_{0.8}Si_4O_{12} + 91F_5Al_2Si_3O_{10}(OH)_8 + 997SiO_2 = 344Ca_2Al_2Fe^{3+}Si_3O_{12}(OH) + 211Ca_2F_5Si_8O_{22}(OH)_2 + 430NaAlSi_3O_8 + 576H_2O$

pumpellyite + sodic pyroxene + chlorite + quartz = epidote + actinolite + albite + H_2O-------(2)

The author regards the maximum stability field of the EAPQ assemblage as the pumpellyite-actinolite facies in the model four components system. The pumpellyite-glaucophane assemblage, which is one of critical assemblages in the typical glaucophane schist facies (Takayama, 1988; Maruyama and Liou, 1988), is stable on the higher-pressure side of the pumpellyite-actinolite facies.

2) Two subfacies of the pumpellyite-actinolite facies are defined by the reaction QD=EAG: EAG and EA subfacies for the higher- and the lower-temperature parts, respectively.

$310CaNaFAl_{0.2}Fe^{3+}{}_{0.8}Si_4O_{12} + 117F_5A_{12}Si_3O_{10}(OH)_8 + 30NaAlSi_3O_8 + 529SiO_2 = 77Ca_2F_5Si_8O_{22}(OH)_2 + 78Ca_2Al_2Fe^{3+}Si_3O_{12}(OH) + 170Na_2F_3AlFe^{3+}Si_8O_{22}(OH)_2 + 182H_2O$

sodic pyroxene + chlorite + albite + quartz = actinolite + epidote + sodic amphibole + H_2O---(3)

3) The EDQ assemblage is stable in the lower-pressure side of the typical glaucophane schist facies and the PDQ assemblage is stable in the lower-temperature side of the pumpellyite actinolite facies. The P-T field surrounded by the reaction (2) and the reaction (4), PG=QDE,

$77Ca_4FAl_5Si_6O_{23}(OH)_32H_2O + 211Na_2F_3AlFe^{3+}Si_8O_{22}(OH)_2 = 205SiO_2 + 190CaNaFAl_{0.2}Fe^{3+}{}_{0.8}Si_4O_{12} + 59Ca_2Al_2Fe_3+Si_3O_{12}(OH) + 104F_5Al_2Si_3O_{10}(OH)_8 + 232NaAlSi_3O_8 + 35H_2O$

pumpellyite+sodic amphibole = quartz+sodic

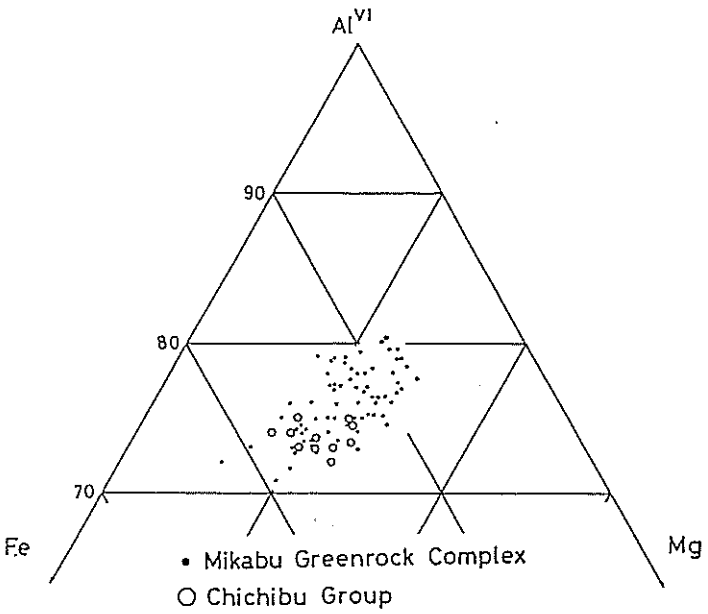


Fig. 33. Pumpellyite in Al(VI)-Fe(total)-Mg diagram.

pyroxene+epidote+chlorite+albite+H_2O-------(4), can be considered as the sodic pyroxene-chlorite facies.

As the reactions in Fig.35 have a steep positive slope, the observed assemblages indicate that the metamorphic temperature increases with descending structural level in the northern part of the Kanto Mountains. X_{Jd} in sodic pyroxene and Al content in epidote and pumpellyite also increases with descending structural level as mentioned before (Figs.28, 32 and 33), suggesting that the metamorphic pressure also increases with temperature.

Metamorphic conditions of the Sanbagawa metamorphic rocks

Lawsonite and pumpellyite roughly define the temperature range of the pumpellyite-actinolite facies and the sodic pyroxene-chlorite facies (Liou, 1971; Nitsch, 1968, 1971) and sodic pyroxene associated with quartz and albite (Holland, 1980) and calcite (Johannes and Puhan, 1971) suggest the metamorphic pressure. The inferred prograde and retrograde P-T path is shown in Fig.36. The P-T conditions of the pumpellyite-actinolite facies can be roughly estimated as 250-350°C and 4-8kbar. The sodic pyroxene-chlorite facies occupies the lower temperature area of the pumpellyite-actinolite fa-

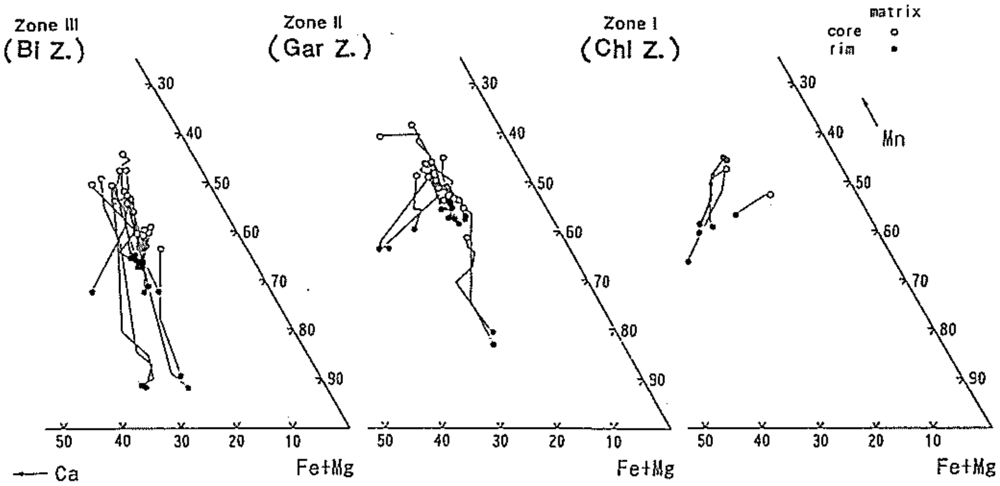
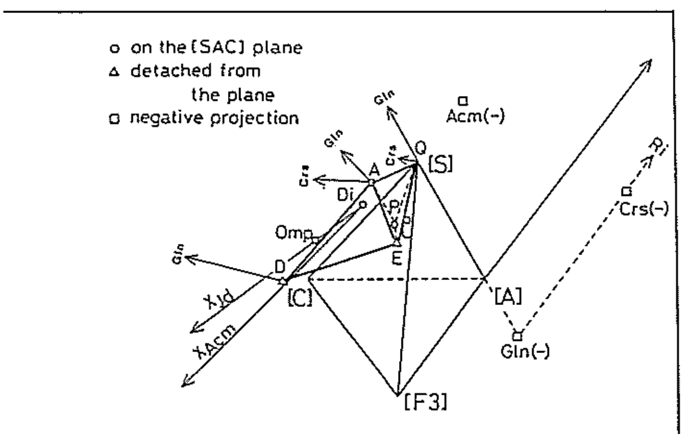


Fig. 34. Chemical variation of zoned garnet.

Abbreviations:

MINERALS	Na	Ca	F	Al	F3	Si	H
G :sodic amphibole	2	0	3	1	1	8	2
P :pumpellyite	0	4	1	5	0	6	7
A :actinolite	0	2	5	0	0	8	2
D :sodic pyroxene	1	1	1	0.2	0.8	4	0
E :epidote	0	2	0	2	1	3	1
C :chlorite	0	0	5	2	0	3	8
Ab:albite	1	0	0	1	0	3	0
Q :quartz	0	0	0	0	0	1	0
W :water	0	0	0	0	0	0	2

(FORMULA: Na, Ca, F, Al, F3, Si, H)



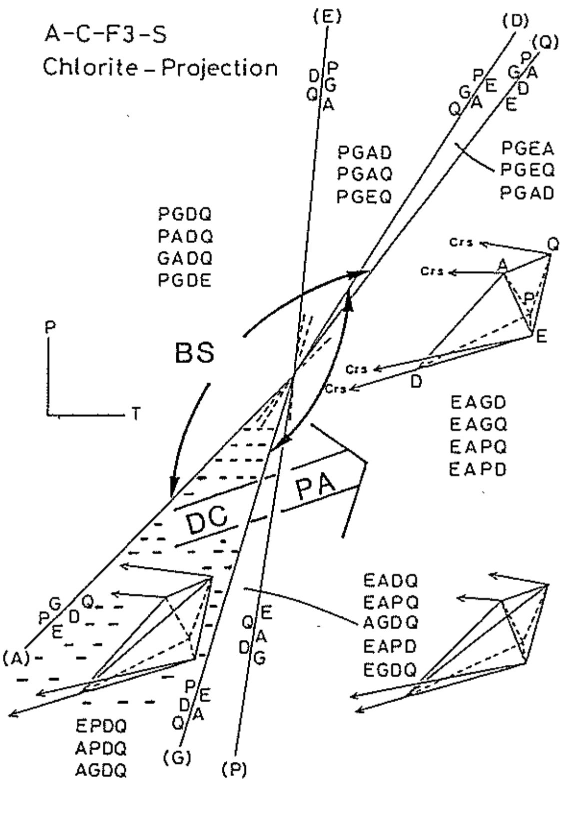


Fig. 35. Petrogenetic grid for the ACF3-S system with six phases. BS: Blue (glaucophane) schist facies, PA: Pumpellyite-actinolite facies, DC: Sodic pyroxene-chlorite facies.

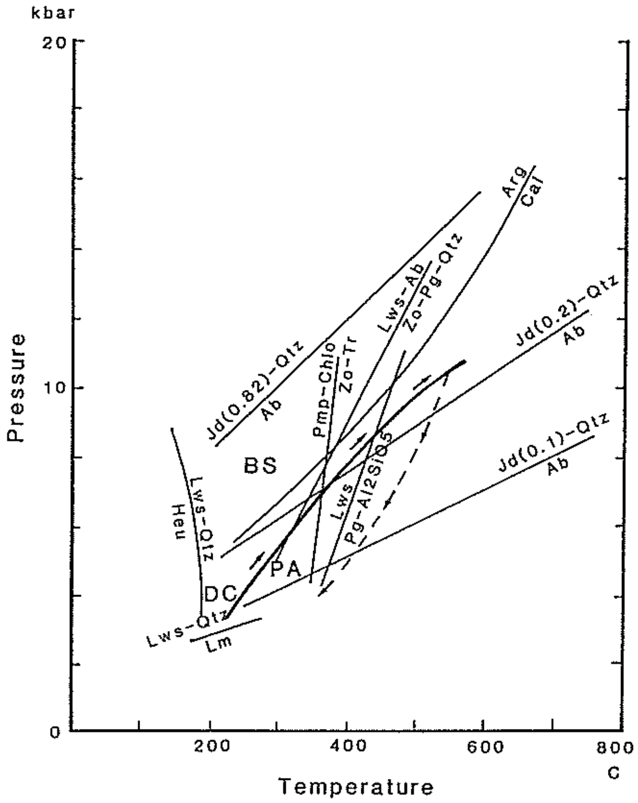


Fig. 36. P-T diagram for the Sanbagawa metamorphic rocks on the Kanto Mountains. Stability field of typical glaucophane schist facies (BS), pumpellyite-actinolite facies (PA) and sodic pyroxene-chlorite facies (DC) are shown. Thick solid line: prograde P-T path in the Kanto Mountains. Broken line: retrograde path. Sodic pyroxene isopleths were calculated from Ab=Jd+Qtz of Holland (1980). Cal=Arg: Johannes & Puhan (1971).

cies. The peak P-T conditions of the biotite zone in the Kanto Mountains is estimated to be about 7-12 kbar at 460-540°C using the composition of sodic pyroxene in a Fe-Mn rich nodule (Hirajima, 1989). This prograde path in the Kanto Mountains is essentially similar to that in the Shikoku area, i.e., the high pressure-intermediate of Miyashiro (1961).

DESCRIPTION OF FIELDSTOPS

Stop 1-1: Gosaisyo Series various schists and metamorphosed andesitic dike

Greenschist-facies basic, siliceous and pelitic schists of the Gosaisyo Series are extensively exposed here. Siliceous schists are locally accompanied by massive iron ores (mainly magnetite and hematite). A deformed and metamorphosed blastoporphyritic andesitic dike is also observed, intruding into the Gosaisyo Series rocks slightly discordantly. The dike rock belongs to the calc-alkalic rock series (Figs.11&12). All these rocks are strongly deformed, showing complex folds. Some quartz veins contain abundant tourmaline crystals in addition to a small amount of chlorite.

Mineral assemblages in each rock type are as follows. Basic-intermediate rocks; actinolite + chlorite + epidote + albite + quartz + calcite + opaque minerals. Pelitic rocks; biotite + chlorite + muscovite + albite + quartz + opaque minerals ± spessartine ± calcite. Siliceous rocks; spessartine + quartz + magnetite + hematite + calcite ± rhodonite ± rhodochrosite.

Stop 1-2: Jurassic radiolaria-bearing siliceous schists and amphibolite

Fine-grained reddish brown or gray siliceous rocks with or without thin layers of iron ores (mainly magnetite and hematite) are extensively exposed here. Some rocks contain surprisingly well-preserved Jurassic radiolarian fossils (Hiroi et al., 1987) (see Supplement 8). These rocks are associated with fine-grained basic and pelitic schists which are exposed on the west. All these rocks are of lower amphibolite-facies grade (c. 500°C) .

Mineral assemblages in each rock type are as follows. Basic-intermediate rocks; (a) hornblende + plagioclase + quartz + sphene + opaque minerals ± hlorite ± epidote ± calcite. (b) actinolite + chlorite + epidote + albite + sphene + opaque minerals ± biotite ± calcite (silica-undersaturated part). (c) hornblende + cummingtonite + plagioclase + quartz + tourmaline + opaque minerals ± biotite ± calcite.

Pelitic rocks; (a) biotite + muscovite + quartz + opaque minerals ± garnet ± chlorite ± sphene ± calcite. (b) andalusite + biotite + chlorite + plagioclase + quartz + opaque minerals.

Siliceous rocks; (a) acmite + rhodonite + quartz + hematite + magnetite ± albite ± stilpnomelane ± rhodochrosite (Al-poor part). (b) spessartine + cummingtonite + albite + quartz + hematite + magnetite ± calcite.

Stop 1-3: Metamorphosed rhyolitic dike

Deformed and metamorphosed rhyolitic dike rocks (meta-quartz porphyries) are observed, intruding into the Gosaisyo Series basic and siliceous schists. Blastoporphyritic plagioclase and quartz with pressure shadows are

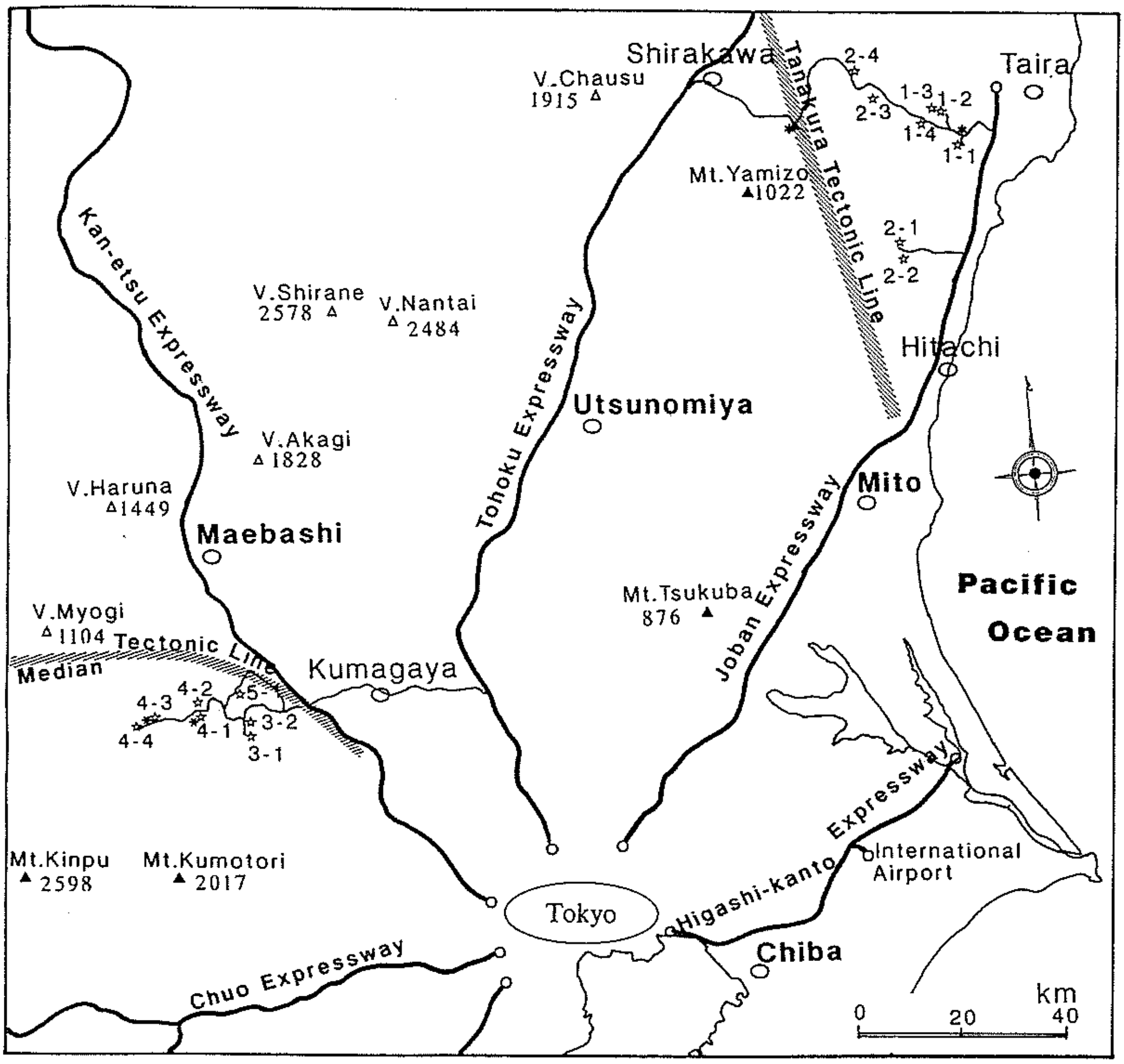


Fig. 37. Map showing route, excursion stops and lodgings. ☆:stop, ✱:lodging, △:volcano, ▲:mountain.

scattered in the fine-grained schistose matrix of the dike rocks (Supplement 9). Garnet sometimes occurs with or without muscovite and biotite in and around blastoporphyritic plagioclase.

Stop 1-4: Tourmaline-bearing meta-basites

Here you can see tourmaline-rich 'unusual' metabasites of the Gosaisyo Series. Boron constituting tourmaline may have been concentrated in the rocks during sedimentation. Rocks occurring near here are of lower amphibolite-facies grade.

Mineral assemblage of the metabasites is as follows. Hornblende + biotite + plagioclase + quartz + ilmenite + magnetite + sulfide minerals ± cummingtonite ± epidote ± hematite ± tourmaline ± apatite.

Stop 2-1: Takanuki gneisses and migmatites

Uppermost amphibolite-facies Takanuki Series pelitic-psammitic, basic and siliceous gneisses are well exposed along the Hanazono Gorge. These rocks are locally intruded by granitic dikes and veins probably originated from the nearby Tabito plutonic mass. The sillimanite-bearing pelitic-psammitic gneisses are highly migmatitic, and are occasionally cut by veins containing abundant pink andalusite crystals. This clearly indicates that andalusite was formed later than sillimanite. Pelitic-psammitic gneisses here are more or less affected by retrograde metamorphism. Cummingtonite which was probably formed after orthopyroxene and garnet locally occur in basic gneisses. The coarse-grained siliceous gneisses of probable quartzose sandstone origin are intercalated with calcareous thin layers containing anorthite and wollastonite. The anorthite + wollastonite assemblage indicates high-temperature but relatively low-pressure conditions (see Fig.22), and may have been formed after high-temperature decompression.

Mineral assemblages in each rock type are as follows. Pelitic-psammitic rocks; sillimanite + cordierite + garnet + biotite + plagioclase + K-feldspar + quartz + ilmenite + pyrrhotite + apatite + zircon + graphite ± (rutile in garnet)

± (corundum + hercynite in cordierite) ± (andalusite + chlorite + muscovite of retrograde origin). Basic rocks; hornblende + biotite + plagioclase + ilmenite + sulfide minerals ± garnet ± cummingtonite (? after orthopyroxene) ± clinopyroxene ± quartz. Calcareous rocks; anorthite + clinopyroxene + wollastonite + sphene + K-feldspar + quartz ± calcite. Siliceous rocks; garnet + biotite + plagioclase + K-feldspar + quartz + apatite + zircon ± sillimanite ± opaque minerals.

Stop 2-2: Takanuki gneisses and very old Hanazono Shrine

Uppermost amphibolite-facies Takanuki Series rocks crop out along the path and the stream. Predominant pelitic-psammitic gneisses often show tight folds, though they are highly migmatitic. Garnet porphyroblasts are conspicuous in the rocks, and usually contain euhedral (lath-shaped) and calcic plagioclase inclusions (see Fig.19), and preserve growth zoning well. On the middle way, you can see a small lens-shaped ultramafic rock enclosed in the pelitic-psammitic gneisses. Mineral assemblages of the rocks here are essentially the same as those observed at Stop 2-1.

Stop 2-3: Kyanite and staurolite-bearing Takanuki pelitic gneisses

Upper amphibolite facies pelitic-psammitic gneisses of the Takanuki Series are exposed along the roadcut. The rocks show tight folds indicative of intense deformation. On the other hand, they are accompanied by Al-rich granitic pools and veins, suggesting that partial melting took place during high-grade metamorphism. The pelitic gneisses usually consist of sillimanite, cordierite, garnet, biotite, plagioclase, K-feldspar, quartz, ilmenite, apatite, zircon, pyrrhotite and graphite. Andalusite, kyanite, staurolite, hercynite, chlorite and muscovite are additional phases in some cases. Kyanite and staurolite are relict minerals included in chemically zoned plagioclase. Andalusite is a retrograde mineral formed together with biotite or muscovite + chlorite after sillimanite, cordierite and garnet during retrograde metamorphism. At this stop, garnet occurs in a small amount, being extensively replaced by cordierite, biotite and plagioclase. At the adjacent outcrops, however, garnet porphyroblasts with sector zoning and euhedral plagioclase inclusions are observed commonly.

It is noteworthy that relict kyanite with or without sillimanite occasionally occurs in or close to the granitic vein. This suggests that partial melting occurred at a high-pressure stage, that is, after high-temperature compression.

Stop 2-4: Lateritic rocks (Supplement 4)

Upper amphibolite-facies silica-undersaturated lateritic rocks occur as blocks enclosed in coarse-grained calcite marbles of the Takanuki Series. The lateritic rocks are composed mainly of almandine, hercynite, sillimanite and ilmenite with or without lesser amounts of corundum, staurolite, biotite, plagioclase, apatite and sulfide minerals. Secondary chlorite, muscovite, margarite and calcite are not uncommon. Corundum usually occurs as relics extensively replaced by sillimanite and hercynite, suggesting the following pressure-sensitive reaction.

Almandine + corundum = sillimanite + hercynite --(1)

Staurolite also shows textures indicative of replacement by almandine, hercynite and sillimanite by the following staurolite-terminal reaction.

Staurolite = almandine + hercynite + sillimanite + H_2O --(2)

However, corundum is occasionally in direct contact with almandine, and, together with adjacent almandine, includes preferred-oriented sillimanite and hercynite. This texture suggests that the corundum + almandine assemblage was formed at the expense of preexisting hercynite and sillimanite and, therefore that reaction (1) took place in the opposite direction at high temperature conditions. Thus, high-temperature compression and subsequent decompression are suggested.

Stop 3-1: Sambagawa schists of the chlorite zone (Supplement 5)

Sambagawa crystalline schists of the higher grade part of the chlorite zone are well exposed on the riverbed of Arakawa, front of the Kaminagatoro station of the Chichibu Railway. These areas including the famous Tora-iwa (tiger stone) which is a stilpnomelane-calcite bearing siliceous schist are parked as the national monument, so that Sampling is Prohibited between the Takasago bridge to the north and the Oyahana bridges to the south along the Arakawa section. Please leave your rock-hammer in bus. Very complicated folding systems are observed here. Schistosity plane strikes NS and dips gently to E. Lineation presented by crenulation strikes E-W in general. Vertical cracks and veins which generally strike N-S are the youngest deformations. Stilpnomelane is observed by the naked eye. If we are lucky on the day, for example the ordinary level of river-water and the good weather for boating, we will enjoy shooting down the Nagatoro Rapid after this stop. It is very safe and scenic. The terminus of shooting-boat is the next stop.

Stop 3-2: Thrust sheet of the garnet zone (Supplement 6)

Alternation of metapelite, metabasite, metasiliceous rocks and serpentinites are well exposed on the riverbed of Arakawa, on the north of Takasago bridge. Here is outside of the national monument, and you can take samples. Chlorite zone is widely, but the garnet and biotite zones are sporadically distributed in this area. At this stop, the garnet and biotite zones are exposed in a limited area which lies in fault contact with the chlorite zone. You can observe albite porphyroblasts from the garnet and biotite zone rocks, but not from the chlorite zone rocks. Albite porphyroblasts of metabasites are white, but those of metapelites black megascopically. The thrust between the chlorite zone and the garnet and biotite zones strikes NNE or EW or NNW, dips E or S or W, respectively, and the garnet and biotite zone block appears as an elongated dome in the chlorite zone.

Stop 4-1: Mikabu Greenrock Complex

Mikabu Greenrock Complex of EAG subzone of the pumpellyite-actinolite facies is observed along the Samba-ishi Gorge. At this stop, main constituent is schistose metabasite derived from tuff breccia and hyaloclastite. Relatively massive and dark green metabasite commonly contains metamorphic pyroxene and/or sodic amphibole. At this grade replacement of sodic pyroxene by sodic amphibole begins and sodic pyroxene becomes rare with an increase of metamorphic grade. Riverbank of the Samba-ishi Gorge is designated as a natural monument, so Sampling is Prohibited in the Gorge. However, we got a permission to collect samples at a quarry where is about 30m above the riverbank. These rocks called "Samba-ishi" are one of the fanciest rocks for gardening.

Stop 4-2: Garnet zone rocks (Supplement 7)

Metabasites are exposed at an old quarry along the Sambagawa river, Tsukiyoshi. Metabasites consist of coarse-grained parts and fine-grained parts and are well foliated. Albite porphyroblast develops layer by layer and makes a foliation. Any apparent fold is not observed here. Main constituent minerals of this metabasites are chlorite, actinolitic amphibole, epidote and albite.

Phengite K-Ar age of metapelite is 73 Ma and that of metapsammite is 78 Ma. Many piemontite quartz schists are observed on the road-side. These rocks are mined as a gardening material.

Stop 4-3: Kashiwagi Formation, Mamba

The Kashiwagi Formation of the Chichibu Group is exposed here.

Stop 4-4: Mamba Formation, Kodaira

The Mamba Formation of the Chichibu Group exposed here belongs to the sodic pyroxene-chlorite facies.

Stop 5-1: Biotite zone rocks (Supplement 8)

Metapelites of the biotite zone are intercalated with metabasites along Koyamagawa river. Metapelites are generally very folded and contain black albite porphyroblasts. Metabasites are highly foliated but weakly folded, and consist of hornblende, chlorite, epidote, biotite, muscovite, albite and rarely quartz.

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