Structural and paragenetic evolution of garnet-bearing barroisite schist from the Suo metamorphic complex, SW Japan

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The Suo metamorphic complex in the Chugoku Mountains of southwest (SW) Japan represents Jurassic high pressure (P)/temperature (T) type metamorphic rocks. Its high-grade part is exposed in the Nichinan area, where barroisite-bearing mafic schist occurs as ~ 50–m thick layers in pelitic schist. These mafic layers contain the common matrix assemblage barroisite + epidote + albite + quartz + titanite + phengite. Relic minerals (garnet, glaucophane, aegirine-augite, Si-rich phengite and rutile) of early-stage parageneses are preserved within albite porphyroblasts. The textural relations combined with pseudosection modeling suggest a clockwise P–T trajectory from epidote-blueschist facies through the garnet + clinopyroxene stable conditions to epidote-amphibolite facies. Two distinct phases of high-strain ductile deformation (D1 and D2) can be recognized in the area, and they are related to early and late stages of exhumation. Albite porphyroblasts initially grew statically between D1 and D2 at ~ 520–530 °C and ~ 0.8 GPa, and further retrogressive growth of albite rims and chlorite at the expense of barroisite is synchronous with D2. The lithological association, deformation structures and metamorphic conditions of the Jurassic Suo metamorphic complex are very similar to those of the Cretaceous Sanbagawa metamorphic complex, suggesting they have comparable exhumation processes as coherent high–P/T metamorphic complexes.

Keywords: Barroisite, Glaucophane, Jurassic, Suo metamorphic complex

INTRODUCTION

High-pressure (P)/temperature (T) metamorphic complexes exposed along convergent plate margins mark the paleo-subduction interface at great depths. In southwest (SW) Japan, the Cretaceous Sanbagawa metamorphic complex is exposed ~ 800 km along its length with laterally traceable structural and metamorphic features, whereas pre-Cretaceous high–P/T metamorphic complexes show sporadic exposures that are intervened by granitoid intrusions and volcano-sedimentary covers (e.g., Nishimura et al., 1977; Kojima et al., 2016). Despite the limited geological records, studies on such pre-Cretaceous high–P/T metamorphic complexes are important to understand the evolution of the long-lived East Asian convergent margin.

The Suo metamorphic complex in SW Japan (Fig. 1a) represents high–P/T metamorphic rocks formed during the Late Triassic to Jurassic (Nishimura, 1998). K–Ar and Rb–Sr age data show the Jurassic Suo metamorphic rocks are widely distributed in the Chugoku Mountains (Shibata and Nishimura, 1989). Metamorphic grade of the Suo metamorphic rocks ranges from pumpellyite–actinolite facies to epidote–blueschist facies, but epidote–amphibolite facies metamorphism has been recognized in the Nichinan area of the Chugoku Mountains since the first description of barroisite-bearing mafic schist (Hashimoto, 1973). However, detailed P–T–deformation history of the barroisite-bearing mafic schist has not been clarified yet. In the present study, we report deformation structures and previously unrecognized early parageneses preserved in barroisite-bearing mafic schist in the Nichinan area, with the aim to better understand the tectono–metamorphic evolution of the Jurassic Suo metamorphic complex.

GEOLOGICAL OUTLINE

The Suo metamorphic complex in SW Japan extends from Kyushu in the east to the Chugoku Mountains in the west (Fig. 1a). High–grade parts of the Suo metamorphic complex are exposed in the Gotsu and Nichinan areas in the Chugoku Mountains (Fig. 1a), where epi-
dote–glaucophane schist (Gotsu area) and barroisite schist (Nichinan area) occur as layers in garnet–bearing pelitic schists (Hashimoto, 1973; Li et al., 2017). Shibata and Nishimura (1989) reported K–Ar ages of these areas: 195–191 Ma for phengite from the Gotsu area and 177 ± 8 Ma for barroisite from the Nichinan area.

In the Nichinan area (southwestern tip of Tottori Prefecture) (Fig. 1b), the Jurassic Suo metamorphic rocks are unconformably covered by Cretaceous rhyolitic and andesitic flows, and those are intruded by Late Cretaceous to Paleogene granitoids (Igi and Sakamoto, 1977). Shibata and Nishimura (1989) reported K–Ar ages of these areas: 195–191 Ma for phengite from the Gotsu area and 177 ± 8 Ma for barroisite from the Nichinan area.

In the Nichinan area (southwestern tip of Tottori Prefecture) (Fig. 1b), the Jurassic Suo metamorphic rocks are unconformably covered by Cretaceous rhyolitic and andesitic flows, and those are intruded by Late Cretaceous to Paleogene granitoids (Igi and Sakamoto, 1977). The Suo metamorphic rocks are also in fault contact with the surrounding rocks in some place. The contact aureole of the granitoids is defined in the Suo metamorphic rocks (Fig. 1b) by the appearance of biotite in pelitic schist (Miyakawa, 1961). This study focuses on an area with least extent of contact metamorphism (Fig. 1b). The andesite lava distributed in the south of the study area (Fig. 1c) contains abundant angular clasts of pelitic schist and rhyolite in its basal parts. The Suo metamorphic rocks in the study area are dominated by pelitic schist, with small amounts of mafic and siliceous schists (Fig. 1c). Antigorite serpentine occurs as blocks surrounded by pelitic schist. Hashimoto (1973) identified two distinct layers of barroisite–bearing mafic schist in the area, and here we refer the northern and southern mafic layers as layers 1 and 2, respectively (Fig. 1c). Previous geological maps draw mafic schist as thin E–W trending layers (Hashimoto, 1973) or small lenses (Igi and Sakamoto, 1977) in a pelitic matrix. Our detailed mapping reveals the two mafic layers reach ~ 50 m in thickness and exhibit good lateral continuity. The mafic layer 1 contains a pelitic layer and is also associated with thin mafic layers in surrounding pelitic schist (Fig. 1c).

**DEFORMATION STRUCTURE**

The orientation of mesoscopic foliation and mineral lin-
Albite porphyroblasts in pelitic schist (Figs. 2a and 2b) exhibit spindle shapes and are associated with pressure shadows. On the other hand, albite porphyroblasts in mafic schist are classified into two types. One type is spindle-shaped porphyroblasts (Figs. 2c and 2d) that are similar to those observed in pelitic schist. The other type is ameba-shaped porphyroblasts (Figs. 2e–2h) that show a highly irregular surface and are not associated with pressure shadows. Spindle-shaped albite porphyroblasts are observed both in mafic layers 1 and 2, but ameba-shaped albite porphyroblasts have been confirmed only within the mafic layer 1.

Two distinct stages of ductile deformation, D1 and D2, can be defined, based on microstructural relation with albite porphyroblasts. D1 and D2 produced two different foliations S1 and S2, respectively. Spindle-shaped albite porphyroblasts shows rhomb shapes in XZ sections and are texturally divided into a core and a rim. The core encloses an early foliation (S1) as straight inclusion trails, whereas the rim contains curved inclusion trails that are discontinuous with S1 in the albite core and are continuous with matrix schistosity S2 (Figs. 2b and 2c). S2 schistosity is defined by shape-preferred orientation of platy minerals, mainly phengite and carbonaceous matter in pelitic schist (Figs. 2a and 2b) and chlorite in mafic schist (Fig. 2c). The orientation of S2 is dominantly south–dipping, but shows a girdle distribution (Fig. 1d) due to post-D2 deformation. Shear bands associated with S2 foliation (Fig. 2a) indicate dominantly top-to-the–east sense of shear for D2 kinematics. Shape-preferred orientation of barroisite and epidote on matrix S2 schistosity in mafic schist defines an ENE–WSW to E–W trending lineation (Fig. 1d), which is parallel to D2 stretching direction inferred from pressure shadows of spindle-shaped albite porphyroblasts (Figs. 2c and 2d). Observation of XZ and YZ sections (Figs. 2c and 2d) suggests orientation of D1 internal lineation (maximum concentration of elongation direction of epidote and amphibole inclusions) in the core of spindle-shaped albite porphyroblasts is at high angle to the D2 lineation.

Ameba-shaped albite porphyroblasts enclose straight inclusion trails that are parallel to the matrix fabric as shown by XZ (Fig. 2e) and YZ (Fig. 2f) sections. On outcrops, the matrix fabric is characterized by a gently W–dipping foliation (Fig. 1d) and strong lineation defined by shape-preferred orientation of epidote, amphibole, phengite and ilmenite. The matrix fabric has no deflection around ameba-shaped albite porphyroblasts. The internal and matrix fabrics of rocks with ameba-shaped albite porphyroblasts represent the same deformation phase. Internal foliation in ameba-shaped albite porphyroblasts shows a deflection around garnet inclusions (Fig. 2g). Within the mafic layer 1, outcrop–scale tight to isoclinal folding is observed, and ameba-shaped albite porphyroblasts are preserved around fold hinges (Fig. 2h), while the rest with well-developed schistosity parallel to the fold axial plane contains spindle-shaped albite porphyroblasts. Therefore, tight to isoclinal folding in the mafic layer 1 represents S1–S2 transposition by D2 folding (F2). The main fabric in mafic schist with ameba-shaped albite porphyroblasts is assigned to D1. S1–parallel garnet-rich quartz veins (<1 cm thick) are commonly developed in the mafic layer 1 (Fig. 2h).

**PETROGRAPHY**

The thick mafic layers 1 and 2 contain barroisite and abundant albite porphyroblasts. The matrix assemblage of barroisite schist is barroisite + epidote + chlorite + albite + quartz + titanite + ilmenite/hematite + phengite, corresponding to epidote-amphibolite facies parageneses (Hashimoto, 1973). Na amphibole (length-slow blue to violet pleochroic amphibole) is newly recognized in many mafic schist samples in the study area (Fig. 1c). Na amphibole only occurs as inclusions in epidote, titanite and the inner part of albite porphyroblasts (Figs. 2e and 2f). Other than garnet-rich quartz veins (Fig. 2h), fine-grained (<0.5 mm) garnet commonly occurs as inclusions in albite porphyroblasts (Figs. 2c and 2g).

As described in the previous section, mafic schist shows variable microstructures due to D2 strain gradient, particularly in the mafic layer 1. To further describe mafic schist with spindle-shaped or ameba-shaped albite porphyroblasts, representative samples for each type were selected (Suppl. Fig. S1; available online from https://doi.org/10.2465/jmps.200127). These samples (1228_8 and 1214_2) are fresh and texturally homogeneous with no significant compositional banding.

**Mafic schist with spindle-shaped albite porphyroblasts**

Sample 1228_8 (Figs. 2c and 2d) from the mafic layer 2 contains ~35 vol% spindle-shaped albite porphyroblasts. Aspect ratios of albite porphyroblasts on YZ and XZ sections are 1.34 ± 0.19 (1σ) and 2.14 ± 0.46 (1σ), respectively. Other matrix minerals are amphibole (48 vol%), epidote (11.4 vol%), phengite (2.8 vol%), chlorite (1.2 vol%), hematite (1.1 vol%), and minor amounts of quartz, titanite, rutile, apatite, and tourmaline. Barroisite in the matrix exhibits blue-green prismatic crystals and contains inclusions of epidote, rutile and quartz. Matrix epidote occurs as yellow prismatic crystals and rarely contains
Figure 2. Photomicrographs of the Suo metamorphic rocks from the Nichinan area. (a) XZ section of pelitic schist (Sample 0319_3) showing a top-to-the-east shear fabric. Arrows indicate fine recrystallized quartz grains along shear bands (crossed polarizers, gypsum compensator inserted). (b) Albite porphyroblast in pelitic schist [crossed polarizers, same thin section as (a)] showing two distinct foliations. (c) XZ and (d) YZ sections of mafic schist (Sample 1228_8) showing microstructures of spindle-shaped albite porphyroblasts. (e) XZ and (f) YZ sections of mafic schist (Sample 1214_2) showing microstructures of ameba-shaped albite porphyroblasts. Insets show enlarged views of dotted boxes. (g) Garnet grain enclosed in ameba-shaped albite porphyroblast (Sample 1214_2). (h) Hinge of D2 fold (F2) of mafic schist with garnet-rich quartz veins (Sample 1228_1). Ab, albite; Brs, barroisite; Chl, chlorite; Ep, epidote; Grt, garnet; Hem, hematite; Ilm, ilmenite; Nam, Na amphibole; Ph, phengite; Qtz, quartz; Rt, rutile; Ttn, titanite.
Na amphibole inclusions. Phengite and chlorite flakes/fishes are arranged within the matrix schistosity (S2). The core of albite porphyroblasts encloses barroisite, epidote, garnet, rutile, phengite, quartz and hematite (Figs. 2c and 2d). Some barroisite inclusions in albite cores contain an irregular shaped core of Na amphibole. Garnet included in albite cores is subhedral and fine–grained (<0.2 mm).

The rim of albite porphyroblasts contains inclusions of barroisite, epidote, quartz and hematite and partially encloses barroisite and epidote prisms in the matrix (Fig. 2c). Hematite occurs as tabular grains in albite porphyroblasts and matrix. Hematite contains very–fine ilmenite lamellae. Titanite occurs as euhedral grains within matrix chlorite or as rims on matrix rutile. Rutile included in albite cores is not associated with titanite.

Mafic schist with ameba–shaped albite porphyroblasts

Sample 1214_2 (Figs. 2e–2g) from the mafic layer 1 contains ~ 39 vol% ameba–shaped albite porphyroblasts. Other matrix minerals are barroisite (49 vol%), epidote (6.9 vol%), titanite (2.3 vol%), phengite (1.4 vol%), and minor amounts of chlorite, ilmenite, rutile, apatite, and quartz. Grain–shape preferred orientation of barroisite and epidote defines a strong D1 lineation both inside and outside albite porphyroblasts (Figs. 2e–2g). Barroisite occurs as blue–green prismatic crystals. Epidote occurs as yellow prismatic crystals, and some epidote grains in albite porphyroblasts and matrix have a brownish core. Phengite occurs as platy crystals in albite porphyroblasts and matrix. Albite porphyroblasts show a highly irregular outline and their shapes in YZ and XZ sections are indistinguishable. Albite porphyroblasts contain Na amphibole (Figs. 2e and 2f) and garnet (Fig. 2g) in addition to the same minerals observed in the matrix. Garnet grains (<0.5 mm) in ten thin sections were examined and following mineral inclusions were identified: quartz, amphibole, clinopyroxene, epidote, rutile, titanite and zircon. These garnet grains are partially or completely replaced by chlorite. Euhedral titanite grains in albite porphyroblasts contain inclusions of Na amphibole, epidote, rutile, ilmenite and quartz. Titanite also occurs in the matrix.

MINERAL CHEMISTRY

Analytical method

Chemical analyses of minerals in samples 1214_2 and
1228_8 were conducted using a JEOL JXA–8530F electron microprobe at Shimane University. Operating conditions for quantitative analysis were WDS mode, 15 kV acceleration voltage, 20–25 nA specimen current and a beam diameter of 1–4 µm. The counting times on peak and background were 10 and 5 s, respectively. Synthetic oxides (Si, Ti, Al, Fe, Mn, and Cr) and minerals (forsterite for Mg, wollastonite for Ca, jadeite for Na, K-feldspar for K) were used as standards. The matrix correction followed the method of Bence and Albee (1968). Representative analyses are reported in Table 1.

Garnet

Ferric/ferrous iron contents in garnet were estimated on the basis of 8 cations and 12 oxygen. Garnet grains in 1214_2 display concentric compositional zoning. The major compositional change is Fe²⁺–Mn substitution with a bell-shaped Mn zoning profile and a narrow almandine-rich rim (Fig. 3a). The pyrope content is low and increases from the core (~2 mol%) to the rim (~4 mol%). XCa [= Ca/(Fe²⁺ + Mn + Mg + Ca)] ranges from 0.21–0.27. Slight Al deficiency of 1.80–1.89 atoms per formula unit (apfu) in the core is fully compensated by calculated ferric iron (Table 1). The compositional range of garnet in 1228_8 overlaps with the almandine-rich rim of 1214_2 (Fig. 3b).

Clinopyroxene

Clinopyroxene (aegirine–augite) was found as an inclusion in highly fractured garnet in 1214_2 (Fig. 4a). Ferric/ferrous iron contents were estimated based on 6 oxygen and 4 cations. By assuming negligible Ca–Tschermak component, the jadeite and aegirine contents are 18 and 37 mol%, respectively (Table 1).

Amphibole

Ferric/ferrous iron contents in amphibole were estimated based on 23 oxygen and 13 cations excluding Ca, Na and K. This procedure gives maximum ferric iron estimates,
but is compatible with wet chemical analyses of Hashimoto (1973). Nomenclature of amphibole species followed Hawthorne et al. (2012). Amphibole compositions are presented in Figure 5.

Two types of Na amphibole were analyzed: (1) inclusions in albite porphyroblasts; (2) inclusions in titanite grains included in albite porphyroblasts. The former type of Na amphibole is partially surrounded by barroisite rims, whereas the latter type lacks barroisite rims (Figs. 4b and 4c). All analyses of Na amphibole show a compositional range of $[B]Na = 1.67–1.91$ apfu (Fig. 5b), Mg/$(Mg + Fe^{2+}) = 0.54–0.67$ and $Fe^{3+}/(Fe^{3+} + [6]Al) = 0.26–0.54$ (Fig. 5d), corresponding to glaucophane (1214_2 and 1228_8) and magnesio-riebeckite (1228_8). Glaucophane included in titanite tends to show higher Al$_2$O$_3$ content (up to 9.8 wt%).

Amphibole included in garnet plots around the boundary between the barroisite and ferri–winchite fields (Fig. 5b). Barroisite inclusions in albite porphyroblasts in 1214_2 show a compositional range of $[B]Na = 0.77–1.04$ apfu and $Si = 7.42–6.62$ apfu. Barroisite rims on Na amphibole inclusions (Figs. 4b and 4c) are rich in Si (7.42–7.10 apfu) compared with unzoned barroisite inclusions in albite. In 1228_8, barroisite inclusions in the core of albite porphyroblasts show a compositional range of $[B]Na = 0.77–1.00$ apfu and $Si = 7.16–6.78$ apfu, whereas those in the rim of albite porphyroblasts show a Si–richer compositional range ($[B]Na = 0.70–1.05$ apfu and $Si = 7.47–6.86$ apfu) (Fig. 5b).

Prismatic barroisite crystals aligned in the matrix S1 foliation in 1214_2 show a compositional range $[B]Na = 0.73–1.00$ apfu and $Si = 7.14–6.59$ apfu, and they are slightly zoned with decreasing Si and increasing $Fe^{3+}$ towards the rim. Matrix amphibole arranged in S2 foliation in 1228_8 plots largely in the barroisite field, but thin ferri–winchite to actinolite rims are locally developed (Figs. 4d and 5c).

**Epidote**

Epidote composition was calculated on the basis of $Si = 3$ apfu and all Fe as trivalent state. Prismatic epidote crystals included in albite porphyroblasts and arranged within the matrix foliation show indistinguishable compositions of $X_{Ps} = Fe^{3+}/(Fe^{3+} + Al) = 0.26–0.32$ for $Ca > 1.90$ apfu. These epidote grains are concentrically zoned in light rare earth elements (REE) and show Ca depletion in cores. The brownish core in 1214_2 corresponds to allanite ($Ca = \sim 1.45$ apfu).

**Ti-rich minerals and hematite**

Titanite in all modes of occurrence shows low Al content, with $Al/(Ti + Al + Fe^{3+}) = 0.03–0.06$. Ilmenite in 1214_2 contains 1.0–6.4 wt% MnO, corresponding to 2–14 mol% MnTiO$_3$. Hematite with ilmenite lamellae in 1228_8 contains 5–15 mol% FeTiO$_3$ for host hematite and + 4.8 wt% MnO for ilmenite lamella. Rutile is almost pure in composition.

**Other minerals**

Albite only occurs as porphyroblasts and shows almost
pure composition (X_{Ab} > 0.99). The REE-rich core of epidote crystals hosts minute (<20 µm) inclusions of chlorite [Mg/(Mg + Fe_{total}) = 0.43–0.46 and Si = 2.79–2.90 apfu]. Chlorite flakes in the matrix show a compositional range of Mg/(Mg + Fe_{total}) = 0.49–0.54 and Si = 2.74–2.81 apfu. The Mg/(Mg + Fe_{total}) in matrix chlorite decreases towards the rim. Phengite inclusions in albite porphyroblasts tend to show higher Si and Mg/(Mg + Fe_{total}) compared with matrix phengite (Fig. 6). The maximum Si content of phengite inclusions in samples 1214_2 and 1228_8 reaches 3.51 and 3.56 apfu, respectively.

PHASE EQUILIBRIA

Mineral parageneses

Based on the petrographic observation and mineral chemistry presented above, here we describe the sequence of mineral formation in the Nichinan mafic schist (Fig. 7). Early metamorphic stage is defined by relic minerals preserved within ameba-shaped albite or the core of spindle-shaped albite porphyroblasts. Titanite crystals enclosed in ameba-shaped albite porphyroblasts commonly contain Al-rich glaucophane inclusions, suggesting this type of titanite inclusions preserves the earliest metamorphic records and glaucophane is the major amphibole phase present before the growth of albite porphyroblasts. Ameba-shaped albite and the core of spindle-shaped albite porphyroblasts statically grew between D1 and D2 as shown by straight inclusion trails of S1. Garnet crystals are associated with pressure shadows of S1 internal foliation (Fig. 2g), suggesting garnet growth is synchronous to or earlier than D1. Na amphibole grains enclosed in albite porphyroblasts are associated with Si-rich barrosite rims (Fig. 2e), suggesting the growth of albite porphyroblasts occurred in the barroisite stability field. The rim of spindle-shaped albite porphyroblasts grew during D2 as shown by curved inclusion trails continuous with matrix schistosity S2. The albite rim contains the assemblage barroisite + epidote + chlorite + titanite + rutile + hematite/ilmene + quartz. The matrix S2 is defined by strong shape-preferred orientation of chlorite in the presence of albite + barroisite + epidote + titanite + quartz. The local development of ferri-winchite/actinolite rims on barroisite in this assemblage (Fig. 4d) represents texturally latest paragenesis.

Pseudosection modeling

To track mineral parageneses for early and late stages of metamorphism in the study area, we utilize P-T pseudosections for 1214_2 and 1228_8, respectively. The bulk compositions were calculated by combining mean mineral compositions and mineral modes that were estimated using X-ray elemental maps (Na, Mg, Ti, and Ca) of an area (5.12 × 5.12 mm for 1214_2 and 4.10 × 4.10 mm for 1228_8). MnO in barroisite, which is not considered in solid-solution model but contributes to the bulk MnO budget, is integrated to the bulk composition only for...
Table 2. Bulk compositions (mol%) of the Nichinan mafic schist

| Sample  | Layer | SiO₂ | TiO₂ | Al₂O₃ | FeO  | MnO  | MgO  | CaO  | Na₂O | O    | Total |
|---------|-------|------|------|-------|------|------|------|------|------|------|-------|
| 1214.2  | 1     | 51.14| 1.88 | 8.04  | 13.52| 0.21 | 8.74 | 8.77 | 4.86 | 2.84 | 100.00|
| 052301-1 | 1     | 49.97| 1.91 | 8.35  | 12.45| 0.22 | 8.78 | 11.85| 3.42 | 3.05 | 100.00|
| 1228.8  | 2     | 52.85| 0.92 | 8.77  | 12.31| 0.02 | 8.77 | 7.61 | 5.51 | 3.24 | 100.00|
| 052304   | 2     | 52.11| 2.07 | 8.54  | 12.76| 0.20 | 7.44 | 9.92 | 3.09 | 3.87 | 100.00|

*Constructed from mode and mineral compositions.
**Wet chemical analyses (Hashimoto, 1973) adjusted to the MnNCFMASHTO system.

1214.2 to model early-stage parageneses. Except for higher Na₂O/CaO ratios, the estimated bulk compositions are close to the wet chemical analyses of barroisite schist from the same mafic layers (Hashimoto, 1973) (Table 2). The P-T pseudosection was calculated in the system MnNCFMASHTO (MnO–Na₂O–CaO–FeO–MgO–Al₂O₃–SiO₂–H₂O–TiO₂–O) using the software Perple_X 6.8.7 (Connolly, 2009) and the thermodynamic data of Holland and Powell (1998). The following solid-solution models were used: clinopyroxene (Green et al., 2007), amphibole (Diener et al., 2007), chlorite (Holland et al., 1998), plagioclase (Holland and Powell, 2003), garnet and epidote (Holland and Powell, 1998), ilmenite and hematite (White et al., 2000). Quartz, albite, paragonite, rutile, and titanite were used: clinopyroxene (Green et al., 2007), amphibole (Diener et al., 2007), chlorite (Holland et al., 1998), plagioclase (Holland and Powell, 2003), garnet and epidote (Holland and Powell, 1998), ilmenite and hematite (White et al., 2000). Quartzo, albite, paragonite, rutile, and titanite were considered as pure phases. The fluid was considered as pure H₂O. The calculated diagram is presented in Figure 8.

The Perple_X solution model file adopts many modifications in interaction parameters from the original models (particularly in the amphibole model). We also calculated pseudosection in the system NCFCMFASHTO using the software THERMOCALC 3.33 with the teds55 dataset (Holland and Powell, 1998) and the original version of the above-mentioned solid-solution models (Suppl. Fig. S2; available online from https://doi.org/10.2465/jmps.200127). Because the pseudosection calculated using the Perple_X in the Mn-bearing system is more compatible with the observed mineral paragenesis, we discuss metamorphic evolution using Figure 8.

Hornblende-plagioclase geothermometry

To estimate equilibrium temperatures for the barroisite-dominant assemblage developed during a period between D1 and D2, the hornblende-plagioclase geothermometer based on the reaction edenite + 4quartz = tremolite + albite (Holland and Blundy, 1994) was applied. Matrix barroisite (Si = 6.8–7.1 apfu) adjacent to albite and quartz in 1214.2 and barroisite inclusions (Si = 6.8–7.2 apfu) in the core of albite porphyroblasts in 1228.8 were selected (Table 1). Si-poor and Fe³⁺-rich rims of barroisite associated with chlorite were not used. The average temperature and associated errors (1σ) calculated from 15 analyses are presented on Figure 8.

DISCUSSION

Pressure-temperature-deformation history

Presuming that the estimated bulk composition for 1214.2 is applicable to early metamorphic stages, we discuss metamorphic evolution using Figure 8a. P-T conditions of the earliest stage preserved in titanite inclusions are inferred to be ~1 GPa and ~460 °C, based on the stability of titanite + glaucophane [Si > 7.8 apfu, [B]Na > 1.8 apfu and Fe³⁺/(Fe³⁺ + [6]Al) < 0.34]. 65 vol% glaucophane and 25 vol% epidote are modeled at the P-T conditions. Subsequent appearance of garnet (>45 mol% almandine, <28 mol% grossular and <6 mol% pyrope contents) requires pressure in excess of 1.2 GPa at ~520–550 °C. The predicted assemblage at the conditions is epidote + glaucophane + garnet + clinopyroxene (~24 mol% jadeite) + ilmenite + rutile ± quartz. Observed composition of clinopyroxene inclusion (~18 mol% jadeite content) (Fig. 4a) is reproduced outside the garnet stability field. Because garnet is highly fractured and chloritized, mineral inclusions in garnet are likely affected by compositional modifications.

The compositional change of amphibole (from low-Al glaucophane to barroisite with progressive decrease in Si content) is inferred from amphibole inclusions arranged within S1 internal foliation in ameba-shaped albite porphyroblasts (Figs. 2e and 5b). S1 internal foliation in albite porphyroblasts is deformed by compaction (Passchier and Trouw, 2005). Post-D1 growth of ameba-shaped albite porphyroblasts took place with the assemblage epidote + barroisite + ilmenite + titanite + quartz + rutile. The stability field of this mineral assemblage is further constrained to be ~0.8 GPa and ~520 °C by barroisite composition ([B]Na > 0.7 apfu) and hornblende-plagioclase geothermometry (Fig. 8a). D1 is synchronous to or after garnet growth, synchronous
to Na amphibole to barroisite transition, and prior to the growth of albite porphyroblasts. This temporal relation and $P$-$T$ constraints suggest that D1 is related to decompression from the garnet stability field to $\sim$ 0.8 GPa (Fig. 8a).

Later paragenetic evolution is discussed using pseudosection for 1228_8 (Fig. 8b). The core of spindle-shaped albite porphyroblasts formed at $\sim$ 0.8 GPa and $\sim$ 530 °C based on the stability of assemblage epidote + barroisite ([B]Na > 0.7 apfu) + hematite + albite + quartz + rutile and hornblende-plagioclase geothermometry (Fig. 8b). The inferred conditions are consistent with formation conditions of ameba-shaped albite porphyroblasts (Fig. 8a). Matrix rutile in this sample is rimmed by titanite in the presence of epidote + barroisite ([B]Na > 0.7 apfu) + chlorite + hematite + albite + quartz (Fig. 4d). This can be explained by cooling accompanied by decompression to $\sim$ 450 °C and $\sim$ 0.55 GPa. This retrograde path is associated with continuous reactions to form albite and chlorite at the expense of barroisite, maintaining constant [B]Na content in barroisite. D2 is associated with formation of syn-tectonic rims of spindle-shaped albite porphyroblasts and strong shape-preferred orientation of chlorite. Therefore, D2 is linked to retrograde metamorphism during late exhumation. The amphibole composition in modeled $P$-$T$ range (Fig. 8b) is barroisite, but local development of actinolite rims maintaining the assemblage epidote + chlorite + hematite + albite + quartz (Figs. 4d and 5c) suggests further cooling to greenschist facies (Otsuki and Banno, 1990).

Overall clockwise $P$-$T$ evolution from epidote-blueschist facies through garnet + clinopyroxene stable conditions to epidote-amphibolite facies is consistent with petrographic observations. However, accurate estimation of the prograde to peak-$P$ conditions is hampered because of large uncertainties in effective bulk compositions during early stages, limited preservation of garnet inclusion paragenesis and possible large overstepping in some periods of the metamorphic evolution. Therefore, further study is required to quantify peak-$P$ conditions using different approaches such as Raman-based geothermobarometry for associated garnet-bearing pelitic schist.

Implications for exhumation tectonics

The early glaucophane-bearing paragenesis of the Nichinan mafic schist is similar to the peak assemblage of the Gotsu glaucophane schist (Fig. 1a), except for the presence of Al-richer glaucophane in the Gotsu glaucophane schist (Fig. 5d) (Li et al., 2017). This may imply that the peak conditions of the Gotsu glaucophane schist are comparable to the prograde conditions of the Nichinan mafic schist. Other than the presence of garnet and Si-rich phengite (Si > 3.5 apfu), mineral paragenetic evolution of the Nichinan mafic schist is similar to that of hematite-bearing mafic schist in the higher garnet zone of the Sanbagawa metamorphic complex in central Shikoku.
Later E area are related to early and late stages of exhumation, (Wallis, 1998). D1 and D2 stages de–metamorphic complex. The common features include striking similarity to those described in the Sanbagawa bite porphyroblasts in the Nichinan area (Fig. 2) show metamorphic complex are very similar to those in the Suo metamorphic complexes (Otsuki and Banno, 1990). In addition to the metamorphic conditions, the petlite-dominated lithological association (Fig. 1c) and structural features in the Suo metamorphic complex are similar to those described in the Sanbagawa metamorphic complex. The common features include the main inter–tectonic growth of albite porphyroblasts followed by additional growth of syn–tectonic rims (Wallis, 1998). D1 and D2 stages defined in the Nichinan area are related to early and late stages of exhumation, and initial exhumation fabric is strongly overprinted by later E–W (or orogen–parallel) ductile flow. Thus, it is impossible to infer original orientation of the D1 finite strain. The strong exhumation–related deformation associated with late–stage orogen–parallel extension is also well–established in the Sanbagawa metamorphic complex and has been linked to an oblique subduction setting (e.g., Wallis et al., 2009).

We classify the Jurassic Suo and Cretaceous Sanbagawa metamorphic rocks as coherent–type high–P/T metamorphic complexes. This is based on the common features of laterally continuous mafic layers in a highly deformed pelitic matrix and limited mixing with serpentinized mantle rocks (e.g., Aoya et al., 2013). The relatively warm conditions in these metamorphic complex led to the reduction in effective viscosity for subducted crustal rocks. This situation in an oblique subduction setting seems to be prerequisite for exhumation of a coherent high–P/T metamorphic complex.

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SUPPLEMENTARY MATERIALS

Supplementary Figures S1 and S2 are available online from https://doi.org/10.2465/jmps.200127.

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