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Research Article

Blueschist-facies metamorphism during Paleozoic orogeny in southwestern Japan: Phengite K–Ar ages of blueschist-facies tectonic blocks in a serpentinite melange beneath early Paleozoic Oeyama ophiolite

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Abstract Blueschist-bearing Osayama serpentinite melange develops beneath a peridotite body of the Oeyama ophiolite which occupies the highest position structurally in the central Chugoku Mountains. The blueschist-facies tectonic blocks within the serpentinite melange are divided into the lawsonite–pumpellyite grade, lower epidote grade and higher epidote grade by the mineral assemblages of basic schists. The higher epidote-grade block is a garnet–glaucophane schist including eclogite-facies relic minerals and retrogressive lawsonite–pumpellyite-grade minerals. Gabbroic blocks derived from the Oeyama ophiolite are also enclosed as tectonic blocks in the serpentinite matrix and have experienced a blueschist metamorphism together with the other blueschist blocks. The mineralogic and paragenetic features of the Osayama blueschists are compatible with a hypothesis that they were derived from a coherent blueschist-facies metamorphic sequence, formed in a subduction zone with a low geothermal gradient (~10°C/km). Phengite K–Ar ages of 16 pelitic and one basic schists yield 289–327 Ma and concentrate around 320 Ma regardless of protolith and metamorphic grade, suggesting quick exhumation of the schists at *ca* 320 Ma. These petrologic and geochronologic features suggest that the Osayama blueschists comprise a low-grade portion of the Carboniferous Renge metamorphic belt. The Osayama blueschists indicate that the 'cold' subduction type (Franciscan type) metamorphism to reach eclogite-facies and subsequent quick exhumation took place in the northwestern Pacific margin in Carboniferous time, like some other circum-Pacific orogenic belts (western USA and eastern Australia), where such subduction metamorphism already started as early as the Ordovician.

Key words: K–Ar phengite age, Osayama blueschist, Oeyama ophiolite, Paleozoic orogeny, Renge metamorphic belt, serpentinite melange.

INTRODUCTION

The blueschist-facies metamorphic rocks provide critical evidence for paleo-subduction zones. In the circum-Pacific orogenic belts, the incipient subduction of the paleo-Pacific plate took place during the Early–Middle Paleozoic, as indicated by the blueschist-facies metamorphic rocks from the Klamath Mountains, western USA (*ca* 450 Ma, Cotkin *et al.* 1992), eastern Australia (*ca* 480 Ma, Fukui *et al.* 1995) and Kurosegawa klippe, southwestern Japan (*ca* 350–390 Ma, Ueda *et al.* 1980). Paleozoic blueschists in these regions are always associated with Paleozoic ophiolite, and occur generally as tectonic blocks in a serpentinite melange. Recent studies on Paleozoic ophiolites in the circum-Pacific region have documented the ophiolite formation in a supra-subduction zone setting (forearc, volcanic arc, or back arc; Ozawa 1988; Arai & Yurimoto 1994; Wallin & Metcalf 1998). Tsujimori (1998) also showed that some

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ophiolitic fragments enclosed in the serpentinite melange have experienced a blueschist metamorphism together with other blueschist blocks. This suggests that the hanging wall of a subduction zone was also dragged into depths by tectonic erosion and metamorphosed.

In central Chugoku Mountains, southwestern Japan, a serpentinite melange bearing blueschist blocks of various metamorphic grade (Osayama serpentinite melange, Tsujimori 1998) develops beneath the Early Paleozoic Oeyama ophiolite. This setting is a good example for studying subduction and exhumation processes through a joint geochronologic–petrologic method. This paper presents newly obtained K–Ar age data for the blueschist-facies tectonic blocks from the Osayama serpentinite melange and discusses the tectonic implications of the Paleozoic orogeny in southwestern Japan.

GEOLOGICAL SETTING

Southwestern Japan is a well-developed, circum-Pacific type orogenic belt with oceanward growth of the accretionary complex since the middle Paleozoic (Fig. 1), as determined by a large amount of field-geological and biostratigraphic

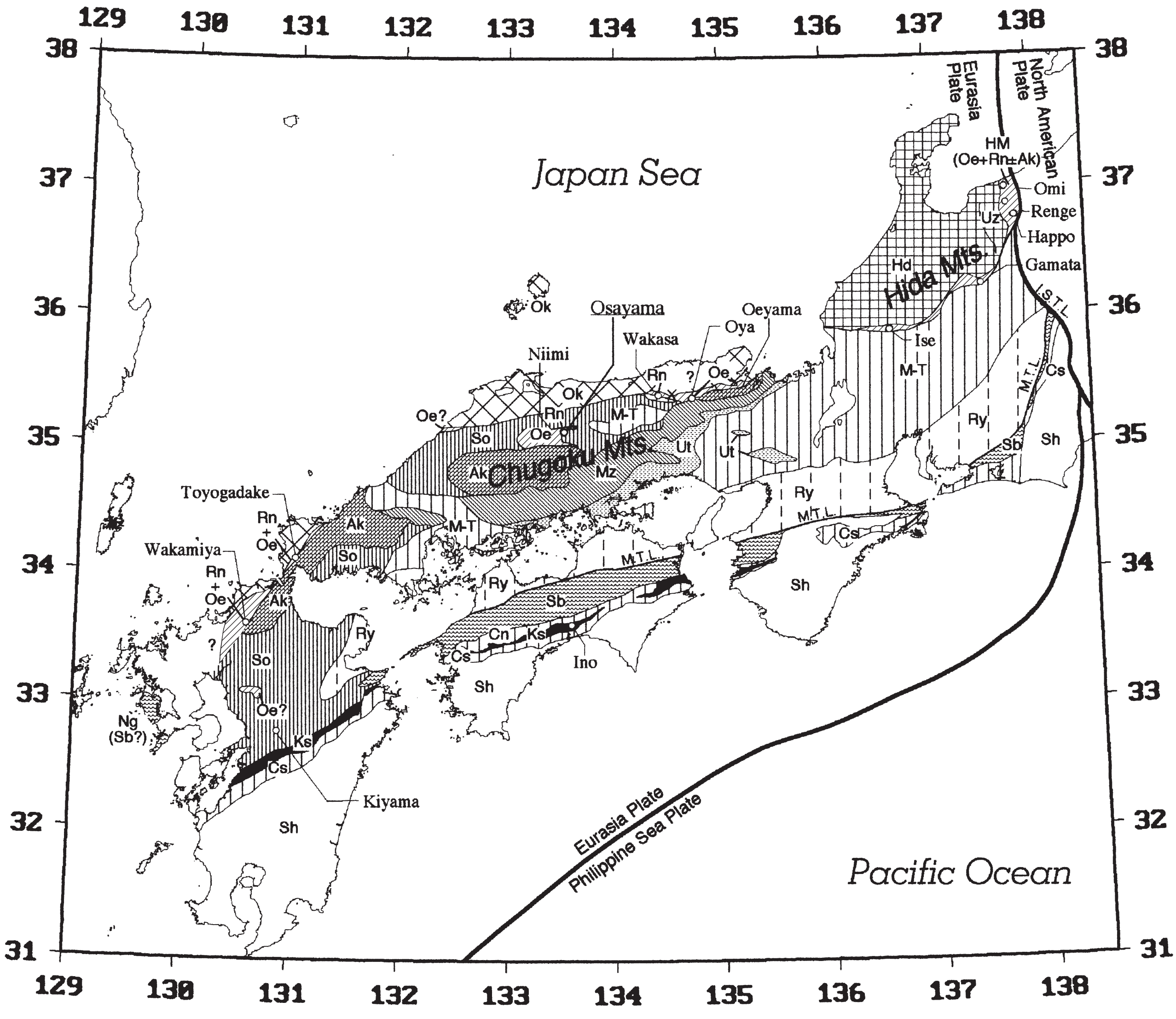

Fig. 1 Geotectonic subdivision of Southwest Japan (modified from Isozaki & Itaya 1991; Isozaki & Maruyama 1991). Localities of the Paleozoic blueschists are also shown. Hd, Hida low-P/T metamorphic belt; Ok, Oki low-P/T metamorphic belt; Oe, Oeyama ophiolite; HM, Hida marginal belt; Rn, Renge high-P/T metamorphic belt; Ak, Akiyoshi accretionary complex; Mz, Maizuru belt (Yakuno ophiolite); Ut, Ultra-Tamba accretionary complex; So, Suo high-P/T metamorphic belt; M-T, Mino-Tamba accretionary complex; Ry, Ryoke low-P/T metamorphic belt; Sb, Sambagawa high-P/T metamorphic belt; Cn, northern Chichibu accretionary complex; Ks, Kurosegawa belt; Cs, southern Chichibu accretionary complex; Sh, Shimanto accretionary complex; MTL, Median Tectonic Line; ISTL, Itoigawa–Shizuoka Tectonic Line.

data (Hayasaka 1987; Nishimura 1990; Ishiwatari 1991; Isozaki & Itaya 1991; Isozaki 1996; Nakajima 1997). Paleozoic ophiolite and blueschist have been sporadically distributed in the Chugoku Mountains, occupying the highest structural positions in the nappe pile.

RENGE BLUESCHIST

Geochronologic data accumulated since the 1980s led to the subdivision of the 'Sangun metamorphic belt' into two or three discrete units (Watanabe *et al.* 1987; Hayasaka 1987; Shibata & Nishimura 1989; Nishimura 1990; Isozaki & Maruyama 1991; Nakajima 1997). Most recently, Nishimura (1998) divided the 'Sangun metamorphic belt' into two belts: the Renge belt (330–280 Ma) and the Suo belt (230–160 Ma). We follow the terminology of Nishimura (1998) for the high-P/T schist belts in the Inner Zone of southwestern Japan. However, we distinguish the associated ophiolitic peridotite bodies from the Renge and Suo belts of Nishimura (1998) as 'Oeyama ophiolite', because they clearly pre-date the schists and have different tectono-metamorphic history.

The Renge blueschists in the Chugoku Mountains occur as thin nappes, which are overlain by the Oeyama ophiolite, and also appear as tectonic blocks within the serpentinite melange beneath the Oeyama nappe (Fig. 2). The sporadic outcrops of the Renge blueschists comprise a disrupted metamorphic belt, which has been considered as the western extension of the blueschist-bearing Omi serpentinite melange. The Renge blueschists may have constituted a late Paleozoic regional high-P/T metamorphic belt, which has been fragmented during exhumation and nappe emplacement.

OEYAMA OPHIOLITE

The peridotite bodies of the 'Oeyama ophiolite' occupy the structurally highest position in the Chugoku Mountains (Fig. 2). They are composed mainly of moderately depleted harzburgite (residual spinel peridotite) and dunite with gabbroic intrusions (diallage gabbro and dolerite). The eastern peridotite bodies such as at Oeyama have slightly more fertile features than the western bodies, such as Tari-Misaka and Osayama (Arai 1980; Kurokawa 1985; Nozaka & Shibata 1994; Matsumoto *et al.* 1995; Tsujimori 1998). The podiform chromitites enclosed in dunite are characteristically developed only in western peridotite (Tari-Misaka body, Arai 1980; Matsumoto *et al.* 1997), and amphibolites (metacumulate and gneissose metagabbro) occur as tectonic block only in eastern peridotite bodies (Oeyama body, Kurokawa 1985; Wakasa body, Nishimura & Shibata 1989). The Ochiai–Hokubo body in the

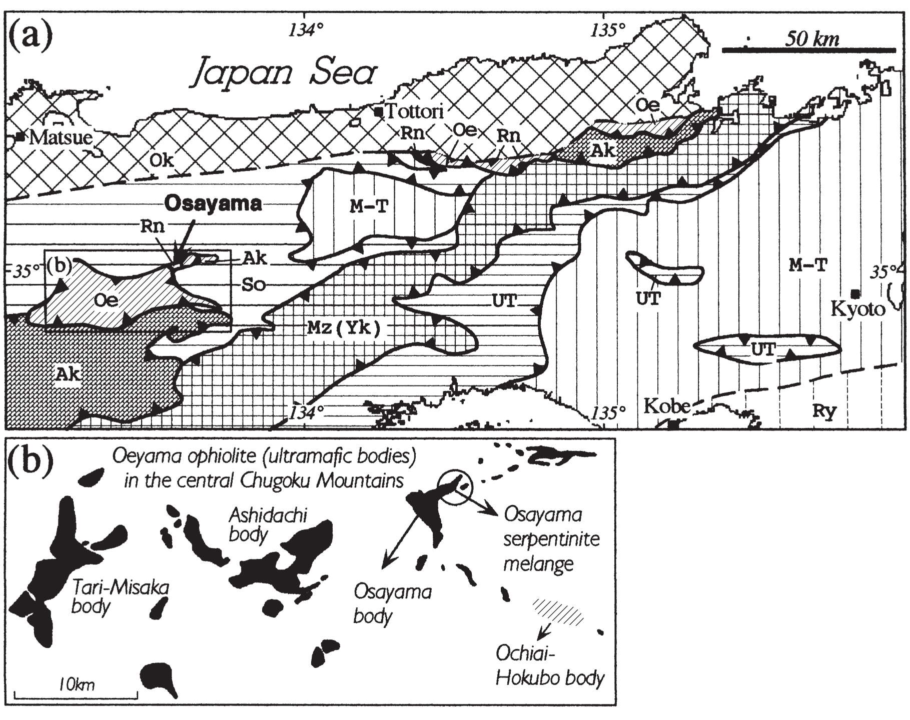

Fig. 2 (a) Distribution of geotectonic nappe pile in eastern Chugoku Mountains. (b) Distribution of the peridotite bodies of the Oeyama ophiolite in the central Chugoku Mountains. Black areas represent ultramafic bodies.

central Chugoku Mountains, which is quite different in petrologic features from the other bodies (Arai *et al.* 1988; Matsukage & Arai 1997), may be a different geological unit in view of the radiometric ages of gabbroic rocks (237–245 Ma, Nishimura & Shibata 1989).

The residual peridotites are mineralogically very similar to the estimated mantle restites of back-arc basin basalt and mid-ocean ridge basalt (MORB; Arai 1994). The presence of high-Al podiform chromitites and petrologic features of the residual peridotite strongly indicate that the Oeyama ophiolite represents a supra-subduction zone ophiolite formed in the back-arc basin or primitive arc setting (Arai & Yurimoto 1994, 1995; Matsumoto *et al.* 1997; Zhou *et al.* 1998). The gabbroic intrusions crosscutting peridotites of the Oeyama ophiolite show a MORB-like major element pattern (Hayasaka *et al.* 1995), which is also compatible with the back-arc basin setting of the Oeyama ophiolite.

GEOLOGY OF THE OSAYAMA SERPENTINITE MELANGE

The Osayama serpentinite melange develops beneath the Osayama peridotite body (Fig. 3). The serpentinite melange is tectonically underlain by the Suo schists, and is in contact with the unmetamorphosed, molasse-type shallow marine sediments of the Jurassic Yamaoku Formation (Konishi 1954) on the north by a high-angle fault. All these rocks are unconformably overlain by the Early Cretaceous Kyomiyama conglomerate. The massive peridotite unit and the Suo schists have undergone an overprint of contact metamorphism by Cretaceous granitic intrusives on the west.

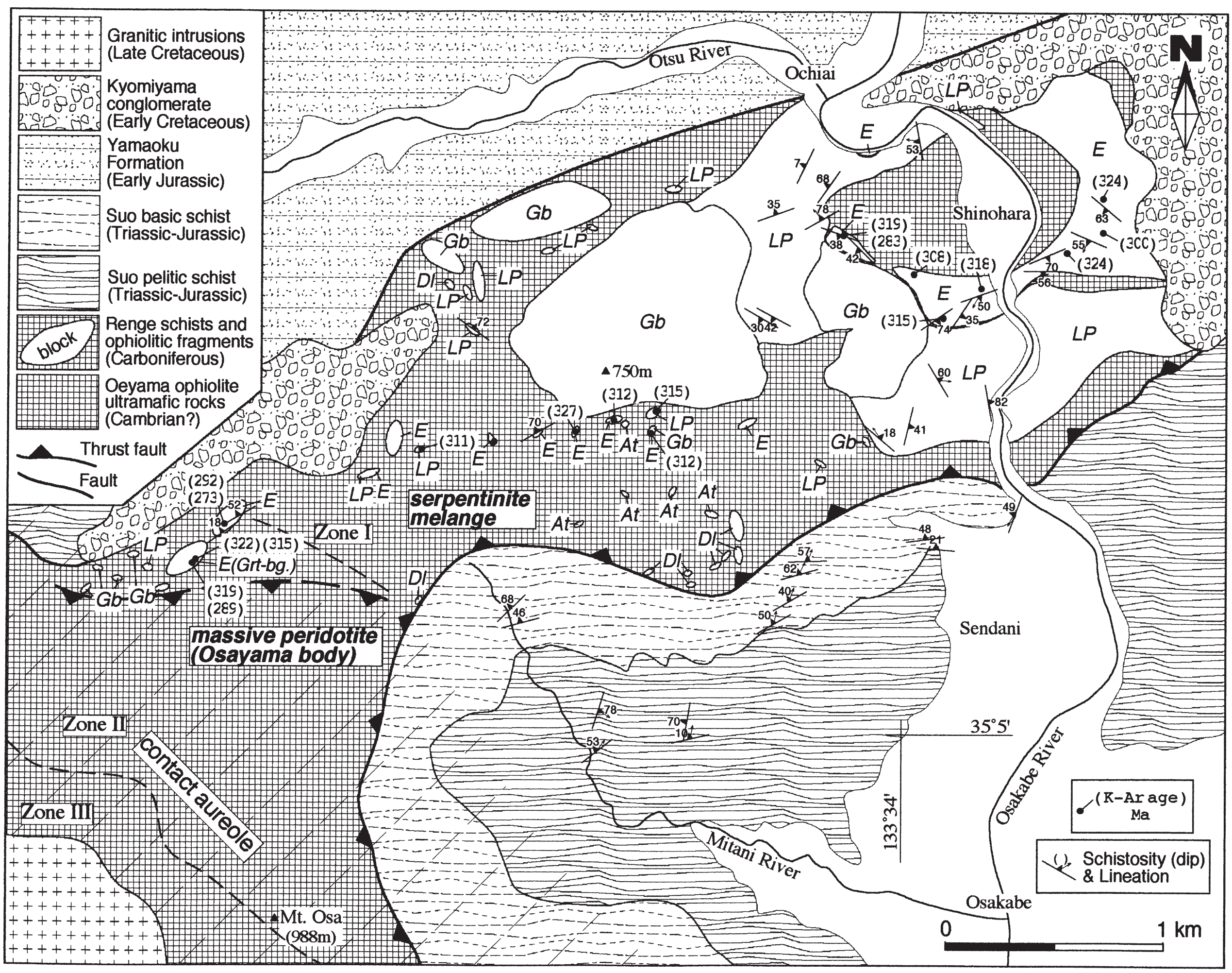

Fig. 3 Geological map of the Osayama serpentinite melange (after Tsujimori 1998). Phengite K–Ar ages obtained in this present paper are also shown in parentheses. Shaded area by broken lines represents the metamorphic zones in contact aureole by Cretaceous granites after Nozaka and Shibata (1995). LP, schist of lawsonite–pumpellyite grade; E, schist of epidote grade; Gb, diallage gabbro; Dl, dolerite; At, albitite.

The blueschist-facies schists, fragments of the Oeyama ophiolite (serpentinized peridotite, gabbro, dolerite) and metasomatic rocks (albitite, jadeitite, omphacitite, tremolite schist etc.) are enclosed as tectonic blocks of various size (10 cm to 1.5 km in length) in serpentinite matrix consisting of schistose, friable and fine-grained serpentinite with pebble-to-boulder-size fragments of serpentinized peridotite. The peridotite blocks contain $Fo_{90.5–91.5}$ olivine, orthopyroxene with 2.4–3.0 wt% Al_2O_3 and chromian spinel with a Cr/(Cr + Al) ratio of 0.40–57 as primary minerals. Petrologic features of melange matrix peridotite suggest that the melange matrix has been derived from widely varying western peridotite bodies of the Oeyama ophiolite such as the Tari-Misaka and Ashidachi bodies (Tsujimori 1998). Hashimoto and Igi (1970) first described lawsonite–glaucophane schists in the eastern part of the serpentinite melange here studied. The blueschist-facies schists are divided into the lawsonite–pumpellyite grade and epidote grades based on the mineral assemblages of basic schists intercalated in the pelitic schist. They correspond to the lawsonite–blueschist and epidote–blueschist facies varieties of Evans (1990), respectively. The epidote grades contain two varieties, a garnet-free lower-grade block and a garnet-bearing higher-grade block (garnet–glaucophane schist). The blocks of the lawsonite–pumpellyite grade are the most dominant type. The gabbro and dolerite blocks also contain blueschist-facies mineral assemblages of lawsonite–pumpellyite grade, but the gabbroic intrusives in the neighboring peridotite body do not have any blueschist-facies high-P/T minerals. The gabbroic blocks often grade into the basic schist of lawsonite–pumpellyite grade with increasing textural deformation. The chemistry of the igneous clinopyroxenes and bulk rock compositions of the Osayama gabbroic blocks indicate that the blocks have been derived from the gabbroic intrusions of the Oeyama ophiolite (Tsujimori 1998).

PETROLOGY OF BLUESCHIST-FACIES BLOCK

LAWSONITE–PUMPELLYITE GRADE (LAWSONITE–GLAUCOPHANE SCHIST AND GABBROIC FRAGMENTS)

The lawsonite–pumpellyite grade blocks are characterized by the assemblage Na-amphibole + lawsonite or Na-amphibole + pumpellyite in basic schists, although the mineral assemblage and texture are variable from block to block. The basic schists include the following mineral assemblages with albite, quartz and titanite in excess: Na-amphibole + lawsonite + chlorite + phengite, Na-amphibole + lawsonite + pumpellyite + chlorite, Na-amphibole + lawsonite + pumpellyite + stilpnomelane, Na-amphibole + pumpellyite and Na-amphibole + chlorite. In the fine-grained sample, albite and quartz are exactly identified by using an electron-probe microanalyzer. Titanite, relic augite, K-feldspar, sulfides, zircon and apatite occur as accessory minerals in some blocks. Most of the Na-amphiboles in this grade are glaucophane to ferro-glaucophane, and their compositions are variable for different mineral assemblages (Fig. 4). One block contains zoned Na-amphibole having a glaucophane core and a ferro-glaucophane rim (Fig. 4). Evidence of a greenschist-facies overprint such as an actinolitic rim on Na-amphibole is not observed in this grade.

The pelitic schists of the lawsonite–pumpellyite grade consist mainly of quartz, phengite, chlorite and albite with minor titanite and apatite. Carbonaceous matter, lawsonite, K-feldspar, tourmaline and carbonate minerals occur also in some blocks. A penetrative schistosity (S_1) defined by phengite and chlorite is commonly observed. In some cases, fine-scale crenulation cleavage (S_2) is developed and overprints a crenulated S_1 fabric. Although phengite of S_1 fabric is finer (< 0.2 mm) than that of S_2 (0.3–0.5 mm), no compositional differences are recognized.

The ophiolitic fragments (gabbro and dolerite) derived from the Oeyama ophiolite also have the blueschist-facies mineral assemblage, similar to lawsonite–pumpellyite-grade basic schists. Igneous plagioclase is replaced by aggregates of pumpellyite or lawsonite and albite and igneous ilmenite altered to aggregates of titanite. Na-amphibole occurs in three modes: overgrowing epitaxially on relict augite and hornblende, filling cracks of clinopyroxene, and replacing patched amphiboles included in clinopyroxene.

LOWER EPIDOTE GRADE (EPIDOTE–GLAUCOPHANE SCHIST)

The constituent minerals of this grade are commonly much coarser than the lawsonite–pumpellyite grade schists. The basic blocks are characterized by the assemblage Na-amphibole + epidote + chlorite. The basic schist of the lower epidote grade includes the following mineral assem-

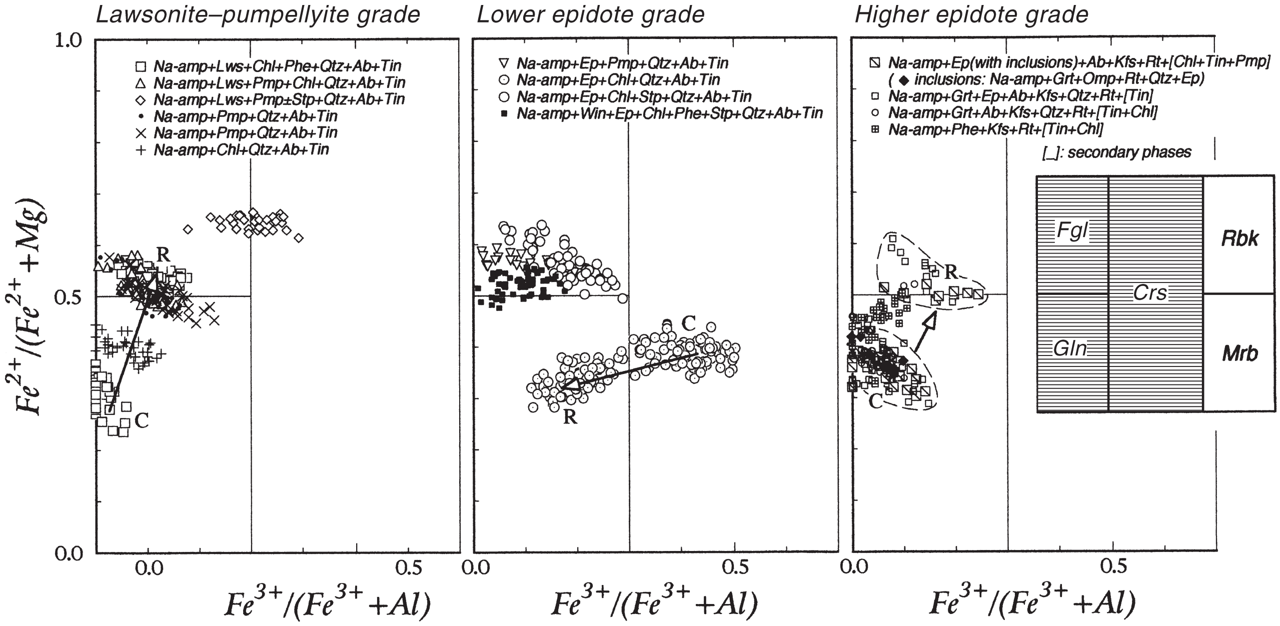

Fig. 4 Compositional variations of Na-amphiboles from the Osayama blueschists in Miyashiro's diagram of $Fe^{3+}/(Fe^{3+}+Al)$ *vs* $Fe^{2+}/(Fe^{2+}+Mg)$. The arrows show compositional zoning (R, rim; C, core).

blages with albite, quartz and titanite: Na-amphibole + epidote + chlorite, Na-amphibole + epidote + chlorite + stilpnomelane, Na-amphibole + epidote + pumpellyite and Na-amphibole + winchite + epidote + chlorite + stilpnomelane. Na-amphiboles in this grade are ferro-glaucophane to glaucophane, but some blocks of the lower epidote grade contain prograde-zoned Na-amphibole having a crossite core and glaucophane rim (Fig. 4). Albite often occurs as porphyroblasts (maximum length: 3.5 mm). Although an actinolitic rim on Na-amphibole is rarely found in some small blocks, greenschist-facies overprinting is not observed in this grade.

The pelitic schists of the grade contain mainly chlorite, quartz, albite, and phengite with small amounts of epidote and titanite. Albite commonly occurs as porphyroblasts (0.5–2.0 mm in length) which include tiny quartz, phengite, chlorite, apatite and rarely Na-amphibole. Na-amphibole, graphite, carbonate and garnet ($Prp_{1-2}Alm_{23-33}Sps_{41-57}Grs_{19-25}$) are rarely observed. A penetrative schistosity defined by coarse-grained phengite (0.5–0.8 mm in length) and chlorite is developed.

HIGHER EPIDOTE-GRADE BLOCK (GARNET–GLAUCOPHANE SCHIST WITH ECLOGITIC MINERAL ASSEMBLAGE)

The higher epidote grade is defined by the coexistence of almandine-rich garnet + glaucophane and the presence of an eclogite-facies mineral assemblage. In the garnet–glaucophane schist, two distinct blueschist-facies stages can be defined based on the texture and mineral zoning. The peak metamorphic stage is characterized by the assemblage Na-amphibole (glaucophane core) + garnet + rutile + epidote + quartz + K-feldspar. The epidote porphyroblasts (maximum length: 2 mm) sometimes include eclogite-facies mineral assemblage, garnet + omphacite ($Jd_{35-50}Di_{52-56}Ae_{<9}$) + rutile + quartz + glaucophane, as tiny inclusions (< 0.03 mm). The retrograde stage is characterized by the assemblage Na-amphibole (ferro-glaucophane rim) + chlorite + pumpellyite + titanite ± phengite, which is equivalent to the lawsonite–pumpellyite grade. In some cases, the strongly sheared phengite-rich part is developed in the outcrop. Although compositional zoning from glaucophane core to ferro-glaucophane rim is common, such zoning is not observed in the phengite-rich part (Fig. 4). Retrograde ferro-glaucophane often fills cracks of garnet. Garnet porphyroblasts (up to 3 mm in diameter) often contain tiny inclusions of rutile and quartz. Garnets in the glaucophane-rich part have higher (Mg + Fe) and lower Mn contents than garnets in the garnet-rich layer (Fig. 5). The garnets show prograde zoning where Fe and Mg increase and Mn decreases from core to rim, and compositions of garnets within epidote porphyroblast corresponds to the rim of those in the glaucophane-rich part (Fig. 5). The distribution

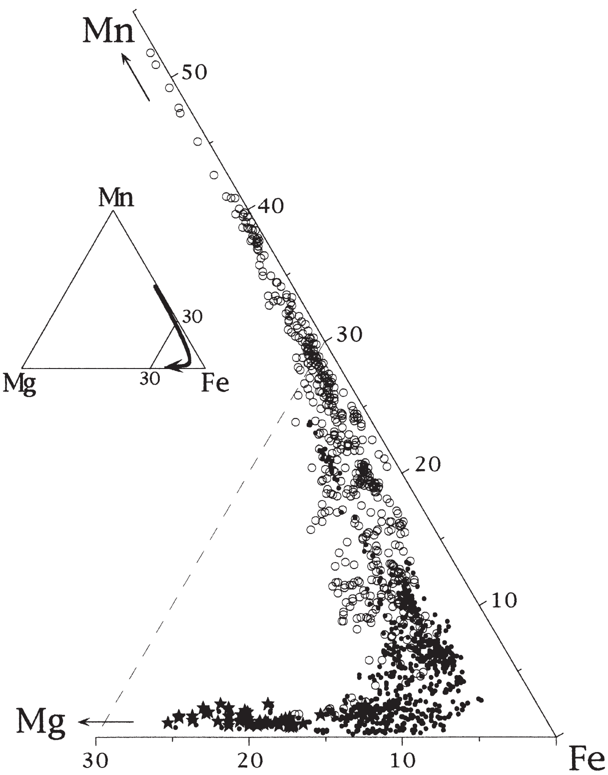

Fig. 5 Composition of garnets of garnet–glaucophane schist of the higher epidote grade in the Mn–Fe–Mg ternary diagram. Matrix garnet: (●), glaucophane rich; (○), garnet-rich. Eclogite garnet: (★), inclusions within epidote.

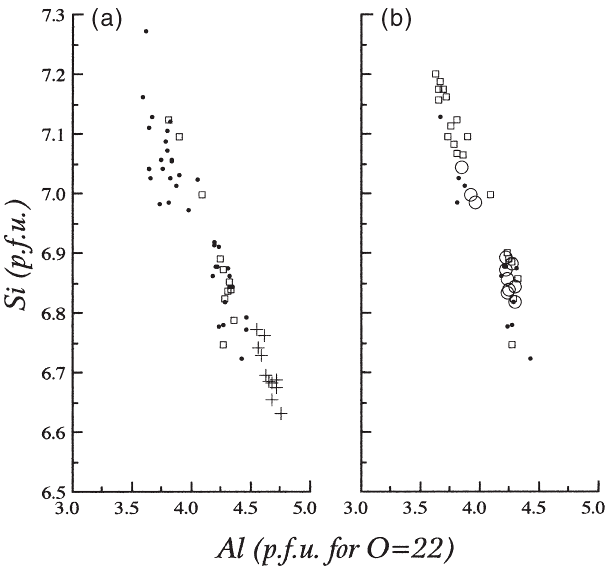

Fig. 6 Compositional variations in Al *vs* Si (p.f.u. for O = 22) for phengites from the Renge blueschists and the Suo schists. (a) Pelitic schist; (b) basic schist. Osayama blueschists: (●), lawsonite–pumpellyite grade; (□), lower epidote grade; (○), higher epidote grade. Suo schist: (+), pelitic schists (underlying the Osayama melange).

coefficients of Fe and Mg, $K_D^{Grt\text{-}Cpx}$, between garnet and omphacite in the epidote vary from 8.3 to 15.9. This garnet–glaucophane schist is a high-grade block which was overprinted with the other low-grade blueschists. More detailed petrology of the garnet–glaucophane schist will be described elsewhere.

BULK ROCK COMPOSITIONS OF THE OSAYAMA PELITIC SCHISTS

The bulk rock composition of a typical lawsonite–pumpellyite-grade pelitic schist and three lower epidote-grade schists were analyzed. No remarkable difference between the two grades was recognized. As compared with the average of the Sambagawa pelitic schists (Goto *et al.* 1996), the Osayama pelitic schists are characterized by higher MgO (2.9–3.8 wt%), FeO* (5.2–8.1 wt%), P_2O_5 (0.16–0.40 wt%), K_2O (3.3–5.6 wt%) and moderate CaO (0.8–1.4 wt%), MnO (0.08–0.17 wt%) and Al_2O_3 (14.7–19.3 wt%). The MgO/(MgO + FeO*) mole ratio is 0.39–0.45. The A′ value of AFM diagram [(Al_2O_3–3K_2O-Na_2O)/(Al_2O_3–3K_2O-Na_2O + FeO* + MgO)] varies from –0.15 to 0.00 and is significantly lower than that of the Sambagawa average (0.11). The Osayama pelitic schists are richer in mafic components than the Sambagawa pelitic schists.

METAMORPHIC CONDITIONS

The Na-amphiboles in the Osayama blueschists are characterized by a low $Fe^{3+}/(Fe^{3+} + Al)$ ratio, and are in the glaucophane and ferro-glaucophane fields except for those in some lawsonite–pumpellyite-grade blueschist, and the core composition of some zoned Na-amphiboles in the lower epidote grade (Fig. 4). Phengites in the Osayama blueschists have Si contents significantly higher than that in the underlying Suo pelitic schists (Fig. 6). The compositions of Na-amphibole and phengites of the Osayama blueschist show common high-P/T features.

Although any geothermometers based on Fe–Mg exchange reactions are not applicable for the lawsonite–pumpellyite grade of the Osayama blueschists, its approximate P–T condition can be deduced by the mineral assemblage. In the lawsonite–pumpellyite grade, glaucophane + lawsonite and glaucophane + pumpellyite assemblages are observed and albite is stable. The Schreinemakers' net for the NCMASH (Na_2O-CaO-MgO-Al_2O_3-SiO_2-H_2O) system shows that the

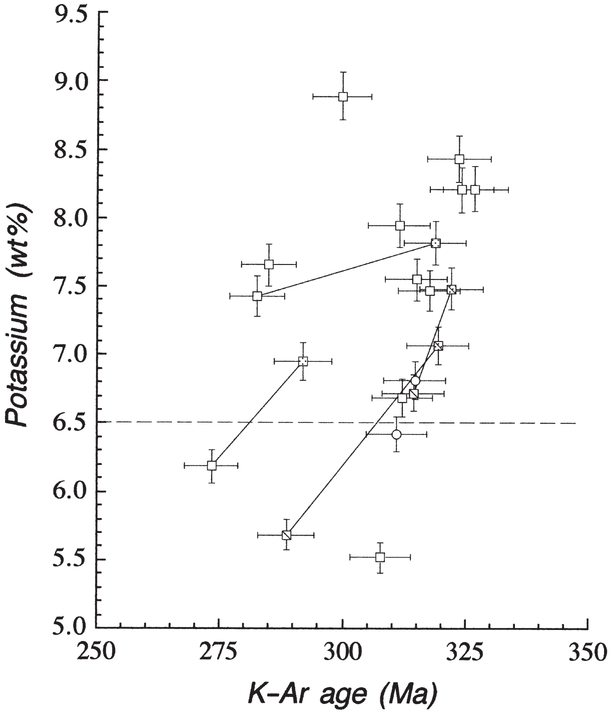

Fig. 7 K content (wt%) *vs* K–Ar age (Ma) diagram showing the effect of grain size and impurities in phengites. Tie-lined data are from the same sample and the shaded marks represent the coarser grained phengite separate. (○), (150/200) lawsonite–pumpellyite grade; (□) (150/200), (⊡) (100/150), lower epidote grade; (⧅) (150/200), (⧅) (100/150), higher epidote grade.

glaucophane + lawsonite assemblage is stable at a higher pressure than the pumpellyite–actinolite facies and pumpellyite–diopside facies (Banno 1998). The glaucophane + pumpellyite stability field also appears as a subfacies in the glaucophane + lawsonite field in NCMASH systems (Frey *et al.* 1991; El-Shazly 1994). The P–T condition of the lawsonite–pumpellyite grade is restricted in a field of the lawsonite–blueschist facies where the glaucophane + pumpellyite + albite assemblage is stable. In the same sense, the P–T condition of the lower epidote grade is limited to the albite-stable field in the epidote–blueschist facies. The petrogenetic grid proposed by Evans (1990) indicates that the lawsonite–pumpellyite grade did not reach the closure temperature (~ 350°C) of the K–Ar phengite system, whereas those of the lower epidote-grade rocks were probably above that temperature.

In the garnet–glaucophane schist of the higher epidote grade, assuming that the inclusions within epidote are in equilibrium, the garnet–clinopyroxene Fe–Mg exchange geothermometer by Krogh (1988) gives 530–620°C at 1.3 GPa. The geobarometer using the breakdown of low albite to jadeite + quartz (Ghent *et al.* 1987), assuming ideal Jd–Di solid solution, gives a minimum pressure of 1.5 GPa at ~ 550°C for omphacite (X_{Jd} = 0.35–0.50) + quartz assemblage without albite. The P–T condition of the final retrogression stage may correspond to that of the lawsonite–pumpellyite grade.

In the typical high-P/T type metamorphic belts, such as the Franciscan, Kamuikotan and New Caledonian, their low-grade portions are characterized by the common assemblage of glaucophane + lawsonite or pumpellyite, and then the glaucophane + epidote assemblage becomes gradually stable with increasing metamorphic grade (Yokoyama *et al.* 1986; Maruyama & Liou 1988; Takayama 1988; Shibakusa 1989). In the Osayama blueschist blocks, the paragenetic feature of the lawsonite–pumpellyite grade and lower epidote-grade blueschists may be interpreted as a coherent metamorphic sequence that has undergone typical high-P/T type metamorphism in the subduction zone, with a geothermal gradient close to 10°C/km (Miyashiro 1994). The presence of albite indicates that the metamorphic condition lies below the jadeite–quartz reaction line. Original coherency of the metamorphic sequence for the Osayama blueschists is also supported from the geochronologic data described in the following section.

K–AR AGE DETERMINATION

The K–Ar ages were determined for 20 phengite separates from 16 metamorphic rocks (Table 1): two basic and pelitic schists from the lawsonite–pumpellyite grade, 12 albite porphyroblast-bearing pelitic schists from the lower epidote grade, and two phengite-rich parts of a garnet–glaucophane schist (higher epidote grade). Mineral assemblages of the rocks dated are shown in Table 1.

Rock samples were crushed with a jaw crusher and then sieved to obtain a proper grain-size for concentrating phengite. The sieved fraction was washed using de-ionized water and dried in an oven at 80°C. Phengites were concentrated using an isodynamic separator and a tapping on a paper, and the collected phengite was treated with 2 mol/L HCl to dissolve out chlorite along cleavage planes. The acid-treated sample was then washed repeatedly with ion-exchanged water and dried at 80°C.

The K–Ar age determination was carried out at Okayama University of Science following Nagao *et al.* (1984) and Itaya *et al.* (1991). Potassium was

Table 1 Mineral assemblages of the samples used for the K–Ar age determination

Meta. Grade (Facies)	LP (LBS)		E (lower EBS)													E (upper EBS)	
Lithology	Basic	Pelitic	Albite porphyroblast-bearing pelitic schist													Grt–Gln schist	
Sample	OS162a	OS80	OS182	OS277	OS304	OS190	OS224	OS329	OS93	OS350	OS188	OS318	OS267	OS281		OS23	OS23B
Na-amphibole	•	—	•	•	—	—	—	—	—	—	—	—	—	—		•	•
Lawsonite	•	—	—	—	—	—	—	—	—	—	—	—	—	—		—	—
Epidote	—	—	•	•	•	•	•	•	•	•	•	•	•	•		•	•
Chlorite	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•
Garnet	—	—	—	—	•	—	—	—	—	—	—	—	—	—		•	•
Phengite	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•
Quartz	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•
Albite	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•
Titanite	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•
Rutile	—	—	—	—	—	—	—	—	—	—	—	—	—	—		•	•
Carbonaceous matter	—	•	—	—	•	—	—	—	—	•	—	•	—	•		—	—
Others																Kfs	Kfs
K–Ar age (Ma)																	
[100/150]	—	—	324	—	—	—	318	319	292	—	—	—	—	—		322	319
[150/200]	315	311		308	327	324		283	273	312	300	285	315	312		315	289

LP, lawsonite–pumpellyite grade; E, epidote grade; LBS, lawsonite–blueschist facies; EBS, epidote–blueschist facies.
Phengite K–Ar ages are also represented.

Table 2 Phengite K–Ar age data of the blueschist-facies tectonic blocks from the Osayama serpentinite melange

Sample no.	Fraction	Potassium (wt%)	Rad. argon 40 (10^{-8} cc STP/g)	Age (Ma)	Air cont. (%)
Lawsonite–pumpellyite grade					
OS162a	150/200	6.811 ± 0.136	9086 ± 88	314.7 ± 6.4	1.4
OS80	150/200	6.442 ± 0.129	8489 ± 82	311.0 ± 6.3	1.1
Lower epidote grade (albite porphyroblast-bearing pelitic schist)					
OS182	100/150	8.204 ± 0.164	11311 ± 110	324.3 ± 6.6	0.4
OS277	150/200	5.517 ± 0.110	7184 ± 72	307.7 ± 6.3	0.8
OS304	150/200	8.211 ± 0.164	11418 ± 113	326.9 ± 6.7	0.9
OS190	100/150	8.435 ± 0.169	11602 ± 110	323.6 ± 6.6	0.5
OS224	100/150	7.470 ± 0.149	10068 ± 99	317.6 ± 6.5	0.5
OS329	100/150	7.819 ± 0.156	10582 ± 103	318.8 ± 6.5	0.7
	150/200	7.422 ± 0.148	8810 ± 84	282.6 ± 5.8	0.9
OS93	100/150	6.946 ± 0.139	8542 ± 82	292.0 ± 6.0	0.4
	150/200	6.184 ± 0.124	7083 ± 69	273.4 ± 5.6	0.7
OS350	150/200	7.942 ± 0.159	10480 ± 100	311.5 ± 6.3	0.6
OS188	150/200	8.891 ± 0.178	11254 ± 108	299.8 ± 6.1	0.7
OS318	150/200	7.657 ± 0.153	9168 ± 89	284.9 ± 5.9	1.1
OS267	150/200	7.550 ± 0.151	10084 ± 101	315.0 ± 6.5	0.7
OS281	150/200	6.684 ± 0.314	8840 ± 87	312.2 ± 6.4	0.8
Higher epidote grade (garnet–glaucophane schist)					
OS23	100/150	7.483 ± 0.150	10240 ± 99	322.1 ± 6.5	0.7
	150/200	6.721 ± 0.134	8960 ± 89	314.5 ± 6.4	0.8
OS23B	100/150	7.065 ± 0.141	9578 ± 92	319.4 ± 6.5	0.7
	150/200	5.682 ± 0.114	6900 ± 66	288.6 ± 5.9	0.9

analyzed by flame photometry using a 2000 ppm Cs buffer. Argon was analyzed on a 15-cm radius sector-type mass spectrometer (HIRU) having a single collector system with an isotopic dilution method using a ^{38}Ar spike (Itaya *et al.* 1991). Decay constants for ^{40}K to ^{40}Ar and ^{40}Ca, and the ^{40}K abundance used in age calculation are 0.581×10^{-10}/year, 4.962×10^{-10}/year, and 0.0001167, respectively (Steiger & Jager 1977). The results are presented in Table 2 and are also shown visually in Figs 7 and 8.

Phengite K–Ar ages of the Osayama blueschist-facies tectonic blocks of the lawsonite–pumpellyite, lower epidote and higher epidote grade yield 311–315, 273–327 and 289–322 Ma, respectively, which are concentrated around 320 Ma as a whole. The phengite separates dated have potassium contents ranging from 5.52 to 8.89, and most of them (16 samples) are greater than 6.5 wt% in potash. As mentioned earlier, the samples of the lawsonite–pumpellyite grade never reached the closure temperature (~350°C) of the K–Ar phengite system, whereas those of the epidote-grade rocks were probably above that temperature. Itaya and Takasugi (1988) argued that the K–Ar phengite age of the low-grade Sambagawa schists, which have not experienced a culmination temperature higher than the closure temperature of the phengite K–Ar system, represented the timing of exhumation/cooling ages because of the argon depletion from phengite by ductile deformation during the exhumation of the host schists. Thus, we interpret the K–Ar phengite ages as the exhumation/cooling age soon after the blueschist-facies metamorphism. However, the range of K–Ar ages of the phengite separates from the blueschist-facies schist tectonic blocks, wider than analytical error of individual analysis. They may be due to either or both of (i) the different cooling age among the schists at the time because of different argon depletion processes during ductile deformation in exhumation of schists; and (ii) the effect of impurities in the phengite separates because some finer grained fractions have significantly lower potassium content and younger age (Fig. 7). Although the phengite K–Ar ages of the Osayama blueschists-facies schists have some variation, the concentration at 320 Ma indicates that the exhumation of schists took place approximately at that time.

DISCUSSION

GEOLOGICAL SIGNIFICANCE OF THE OSAYAMA BLUESCHISTS

In southwestern Japan, late Paleozoic high-P/T schists are sporadically distributed (Fig. 1).

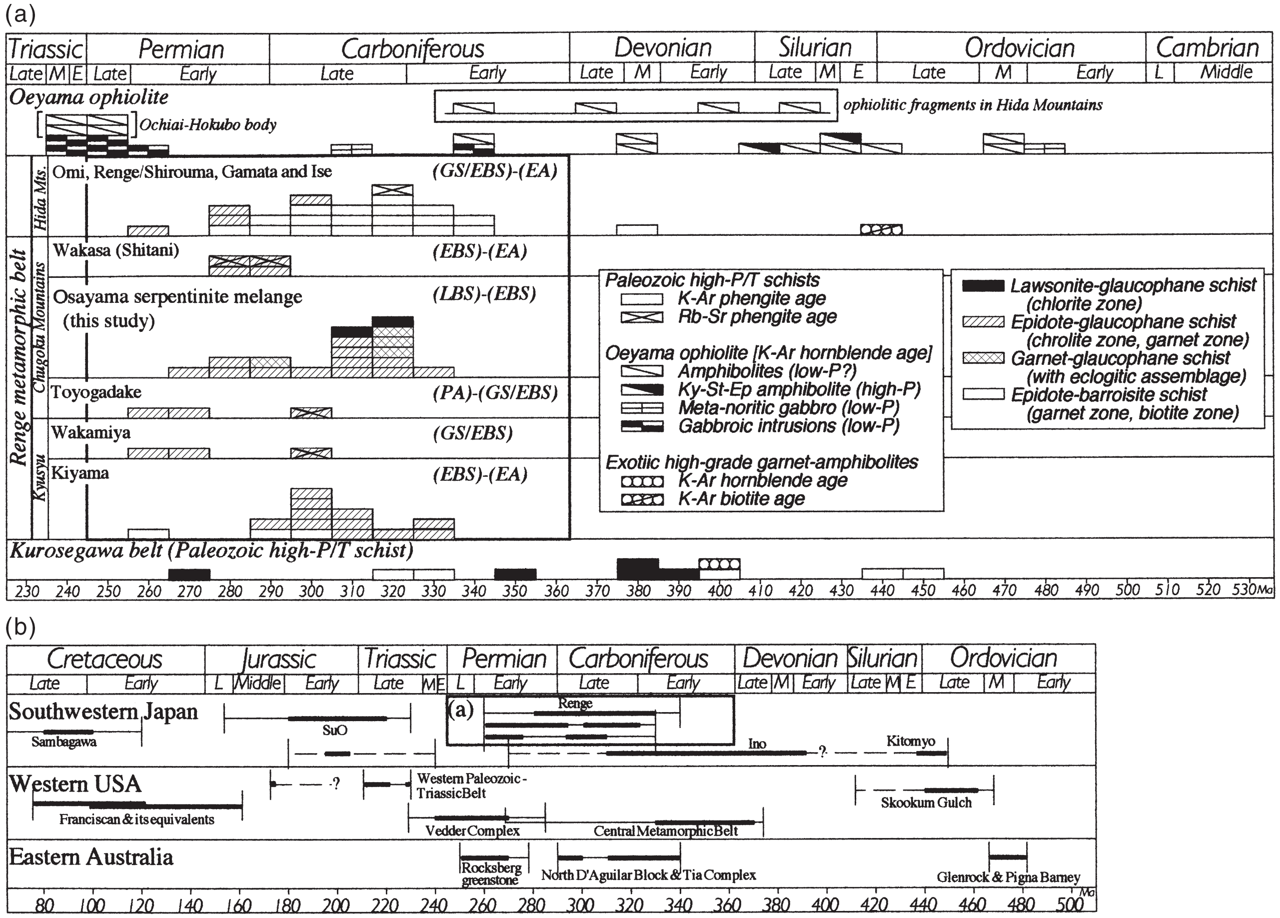

Fig. 8 (a) Frequency distribution of K–Ar and Rb–Sr phengite (white mica) ages of Paleozoic high-pressure schists in southwestern Japan (compiled from Maruyama & Ueda 1974; Maruyama *et al.* 1978; Shibata & Ito 1978; Ueda *et al.* 1980; Shibata & Nishimura 1989; Isozaki *et al.* 1992; Kabashima *et al.* 1995; Kunugiza *et al.* 1997), and of K–Ar hornblende ages for the amphibolites and gabbroic intrusions of the Oeyama ophiolite (Shibata *et al.* 1979; Shibata 1981; Nishimura & Shibata 1989; Nishina *et al.* 1990). The metamorphic facies of the schists are distinguished. PA, pumpellyite–actinolite facies; LBS, lawsonite–blueschist facies; EBS, epidote–blueschist facies; GS/EBS, transitional facies between greenschist and epidote–blueschist facies; EA, epidote–amphibolite facies. (b) Isotopic age relations of the Cordilleran high-pressure metamorphic belts in southwestern Japan, western USA, and eastern Australia (compiled from Patrick & Day 1995; Isozaki & Maruyama 1991; Little *et al.* 1993; Fukui *et al.* 1995; Nishimura 1998). The time scale is after Harland *et al.* (1990).

Although they generally occur as tectonic blocks in a serpentinite melange, a series of high-P/T schists have been considered to be the constituents of a late Paleozoic regional high-P/T metamorphic belt, called the Renge belt (Nishimura 1998), based on the geochronologic data shown in Fig. 8. The phengite K–Ar ages from the Osayama blueschists are within the age variation of the high-P/T schists in the Omi, Wakasa, Toyogadake, Wakamiya and Kiyama areas of the Renge belt, indicating that the Osayama blueschists is a constituent of the Renge belt.

Most of the Renge schists have recorded greenschist, epidote–blueschist or epidote–amphibolite facies assemblages, and the lawsonite–blueschist facies rocks are extremely rare in the Renge belt (Banno 1958; Nishimura *et al.* 1983; Nakamizu *et al.* 1989; Nishimura 1990). The Osayama blueschists having the assemblages glaucophane + lawsonite or glaucophane + pumpellyite belong to a typical high-P/T type metamorphic facies series formed in the subduction zone. The differences of the recorded P/T conditions between the Osayama blueschists (typical high-P/T type) and the other Renge schists (intermediate high-pressure type) may be due to the following reasons: (1) local diversity of geothermal gradient in the subduction zone; and/or (2) the different exhumation rate overprinted various lower P/T conditions. The Renge basic schists of the Wakasa area have barroisite rimmed by actinolite, suggesting greenschist-facies overprint after epidote–amphibolite facies (T. Tsujimori, unpubl. data), although there is no evidence of greenschist-facies overprint in the

Osayama blueschists. This suggests that the Osayama blueschists were formed in the subduction zone with the lowest geothermal gradient of the Renge belt. Absence of the greenschist facies overprinting in the Osayama blueschists suggests a quick exhumation, which is supported by the homogeneous K–Ar age, soon after the blueschist-facies metamorphism in the subduction zone.

Recent advanced studies of the Oeyama ophiolite have revealed that they represent a supra-subduction zone ophiolite formed beneath the back-arc basin or primitive arc setting (Arai & Yurimoto 1994, 1995). Some fragments of the Oeyama ophiolite pre-dating the Osayama blueschists have also suffered the blueschist facies metamorphism together with the Osayama blueschists as mentioned before. It follows that the Oeyama ophiolitic lithosphere was close to the trench of the Carboniferous subduction zone system, and was eroded and dragged down to a deeper part of the subduction zone to undergo blueschist-facies metamorphism together with the Renge schists. Such tectonic erosion of the supra-subduction zone lithosphere has been documented in the modern subduction system of the Mariana arc–trench system (Bloomer 1983; Maekawa *et al.* 1995).

COMPARISON WITH OTHER PALEOZOIC HIGH-P/T SCHISTS IN SOUTHWESTERN JAPAN

The subduction-related metamorphic rocks predating the Renge schists in southwestern Japan have already been reported (Fig. 8). In the Kurosegawa belt of the Outer Zone of southwestern Japan, which is interpreted as a tectonic klippe consisting of pre-Jurassic equivalents of the Inner Zone (Isozaki & Itaya 1991), the pumpellyite–glaucophane schists, epidote–barroisite schists and epidote–hornblende schist have been reported (Maruyama & Ueda 1974; Nakajima & Maruyama 1978; Nakajima *et al.* 1978). The former has petrographic features similar to the Osayama blueschists but gives K–Ar phengite ages of 352–394 Ma (Ueda *et al.* 1980), significantly older than those of the Osayama schists. The latter has two groups of K–Ar ages; one is 317–327 Ma (Ueda *et al.* 1980), similar to the Renge belt; and the other is 402–445 Ma (Maruyama & Ueda 1974) demonstrating the oldest high-pressure schists in southwestern Japan.

Amphibolites as tectonic blocks in the Oeyama ophiolite have undergone epidote–amphibolite facies metamorphism and have demonstrated hornblende K–Ar ages from 469 to 336 Ma (Kurokawa 1985; Nishimura & Shibata 1989; Nishina *et al.* 1990). A garnet amphibolite giving a K–Ar biotite age of 442 Ma (Matsumoto *et al.* 1981) occurs as tectonic blocks within the 320-Ma Renge schists in Hida Mountains (Nakamizu *et al.* 1989). A clinopyroxene-bearing garnet–amphibolite with a K–Ar hornblende age of 409 Ma (Yoshikura *et al.* 1981) occurs as tectonic blocks in the Kurosegawa belt. To reveal the timing of igneous activity of the Oeyama ophiolite, the gabbroic intrusions have been dated. They gave the hornblende K–Ar ages from 343 to 239 Ma (Shibata *et al.* 1979; Nishina *et al.* 1990). Some of those ages are clearly younger than those of the Renge schists, namely, they contradict the fact that some fragments of the Oeyama ophiolite are enclosed as tectonic blocks in the serpentinite matrix and have suffered the Renge blueschist metamorphism together with the other blueschist blocks. These young ages of the gabbroic intrusions are likely to be due to the rejuvenation by the post-dating metamorphism because the igneous brown hornblende in the gabbroic intrusions is commonly rimmed by actinolite (Yamaguchi 1989). Recently, Hayasaka *et al.* (1995) preliminarily reported the Sm–Nd ages of *ca* 560 Ma for gabbroic intrusions in central Chugoku Mountains, suggesting a time of formation of the Oeyama ophiolite as the Cambrian.

BLUESCHIST-FACIES METAMORPHISM DURING PALEOZOIC OROGENY IN SOUTHWESTERN JAPAN

In the circum-Pacific orogenic belt, Paleozoic blueschist facies metamorphic rocks also occur in western USA and eastern Australia (Fig. 8). The Skookum Gulch blueschist (*ca* 450 Ma) distributed in the Yreka Terrane, eastern Klamath Mountains, is characterized by the mineral assemblage glaucophane + lawsonite, resembling the Osayama blueschists (Cotkin 1987). The Skookum Gulch blueschist is tectonically overlain by serpentinized peridotite of the Cambro-Ordovician Trinity ophiolite, and blueschist contains 570-Ma tonalite blocks derived from Trinity ophiolite (Wallin *et al.* 1988). The New England Fold Belt in eastern Australia includes three Paleozoic subduction-related metamorphic rocks, *ca* 260, *ca* 340–310, and *ca* 470 Ma (Fukui *et al.* 1995). The oldest rocks contain 467–481-Ma epidote–glaucophane schist occurring along the ophiolitic serpentinite melange zone in the Glenrock–Pigna Barney area, northeastern New South Wales (Fukui *et al.* 1995). They are also closely associated with 530-Ma ophiolitic rocks

(Aitchison *et al.* 1992). It is considered that an active continental margin formed an accretionary complex, high-P/T schists and volcano-plutonism at the circum-Pacific orogenic belt (Isozaki 1996; Maruyama 1997). In southwestern Japan, the Ordovician schists of the Kurosegawa belt (Maruyama & Ueda 1974) is evidence for an incipient subduction of the paleo-Pacific Plate, and typical blueschists appear from the Devonian (Ueda *et al.* 1980) (Fig. 8). The petrologic and geochronologic comparison of the Paleozoic high-P/T metamorphic rocks in southwestern Japan revealed that the geothermal gradient in the subduction system was relatively high to form the epidote–amphibolite facies metamorphic rocks in Late Ordovician–Silurian time (e.g. Maruyama & Ueda 1974). The low geothermal gradient to form the blueschists in the Devonian–Carboniferous could be attained by an active subduction of the paleo-Pacific oceanic plate. In early history of the circum-Pacific orogenic belt, the subduction system in western USA and eastern Australia had reached the low geothermal gradient to form the blueschists as early as the Ordovician, when the system in southwestern Japan still had a high gradient.

The tectonic association of Paleozoic ophiolite and Paleozoic high-P/T schist is pervasive throughout the circum-Pacific region. This suggests that each orogenic belt in the circum-Pacific region had experienced an early history similar to that in southwestern Japan.

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