International Geology Review, 2015
Vol. 57, Nos. 5–8, 1014–1022, http://dx.doi.org/10.1080/00206814.2014.973915

Taylor & Francis
Taylor & Francis Group

White mica K–Ar geochronology of Sanbagawa eclogites from Southwest Japan: implications for deformation-controlled K–Ar closure temperature

Tetsumaru Itaya[a]* and Tatsuki Tsujimori[b]

[a]*Research Institute of Natural Sciences, Okayama University of Science, Okayama 700-0005, Japan;* [b]*Institute for Study of the Earth's Interior, Okayama University—Misasa, Tottori-ken 682-0193, Japan*

(*Received 23 September 2014; accepted 2 October 2014*)

White mica (phengite and paragonite) K–Ar ages of eclogite-facies Sanbagawa metamorphic rocks (15 eclogitic rocks and eight associated pelitic schists) from four different localities yielded ages of 84–89 Ma (Seba, central Shikoku), 78–80 Ma (Nishi-Iratsu, central Shikoku), 123 and 136 Ma (Gongen, central Shikoku), and 82–88 Ma (Kotsu/Bizan, eastern Shikoku). With the exception of a quartz-rich kyanite-bearing eclogite from Gongen, white mica ages overlap with the previously known range of phengite K–Ar ages of pelitic schists of the Sanbagawa metamorphic belt and can be distinguished from those of the Shimanto metamorphic belt. The similarity of K–Ar ages between the eclogites and surrounding pelitic schists supports a geological setting wherein the eclogites experienced intense ductile deformation with pelitic schists during exhumation. In contrast, phengite extracted from the Gongen eclogite, which is less overprinted by a ductile shear deformation during exhumation, yielded significantly older ages. Given that the Gongen eclogite is enclosed by the Higashi-Akaishi meta-peridotite body, these K–Ar ages are attributed to excess ^{40}Ar gained during an interaction between the eclogite and host meta-peridotite with mantle-derived noble gas (very high ^{40}Ar/^{36}Ar ratio) at eclogite-facies depth. Fluid exchange between deep-subducted sediments and mantle material might have enhanced the gain of mantle-derived extreme ^{40}Ar in the meta-sediment. Although dynamic recrystallization of white mica can reset the Ar isotope system, limited-argon-depletion due to lesser degrees of ductile shear deformation of the Gongen eclogite might have prevented complete release of the trapped excess argon from phengites. This observation supports a model of deformation-controlled K–Ar closure temperature.

Keywords: Sanbagawa metamorphic belt; eclogites; phengite K–Ar geochronology; excess argon; Pacific-type orogen

1. Introduction

The K–Ar system dating of white mica is routinely used to determine the cooling ages of high-pressure and ultrahigh-pressure (H*P*–UH*P*) metamorphic rocks. However, discordant ages can occur from rocks within the same metamorphic unit (Chopin and Maluski 1980; Tonarini *et al.* 1993; Li *et al.* 1994; Arnaud and Kelly 1995; Ruffet 1995; Scaillet 1996; Ruffet *et al.* 1997; Sherlock and Arnaud 1999; Giorgis *et al.* 2000; Sherlock and Kelley 2002; Gouzu *et al.* 2006a; Itaya *et al.* 2009; Beltrando *et al.* 2013; Halama *et al.* 2014). For example, UH*P*-metamorphosed continental crust of the Dola Maira massif (western Alps, Italy) shows a chronological discrepancy because of the presence of excess argon in white micas inherited from the precursor rocks (e.g. Itaya *et al.* 2011). However, age discordance due to excess ^{40}Ar is limited mainly to metamorphic terranes in continental suture zones or intercontinental collision zones that have experienced polyphase metamorphism. Excess ^{40}Ar is negligible in most metamorphosed oceanic materials in Pacific-type H*P* metamorphic belts that usually record only a single metamorphic event. In other words, the K–Ar system in syn-metamorphic white mica is sufficiently reset during fluid-induced metamorphic recrystallization at a Pacific-type convergent margin so that no excess Ar exists. This hypothesis is supported by systematic K–Ar geochronology from the Sanbagawa, Suo, and Renge metamorphic belts in Southwest Japan, and from the Otago metamorphic belt in New Zealand (Itaya and Takasugi 1988; Tsujimori and Itaya 1999; Nishimura *et al.* 2000; Miyashita and Itaya 2002; Nuong *et al.* 2008, 2011). Even in the Italian Alps, which represent a continental collision belt, laser-probe Ar/Ar geochronology of H*P*–UH*P* metamorphosed oceanic lithologies has revealed negligible excess ^{40}Ar in eclogite-facies phengite (Gouzu *et al.* 2006b).

In preparation for the 2001 International Eclogite Conference held in Japan, we determined K–Ar ages of phengite and paragonite from the eclogite-facies Sanbagawa metamorphic rocks in Shikoku (Figure 1A). A total of 21 ages were obtained from four different localities, including Seba (84–89 Ma), Gongen (123–136 Ma), and Nishi-Iratsu (78–80 Ma) in central Shikoku and Kotsu/Bizan (73–88 Ma) in eastern Shikoku. As we describe in this article, the significantly older K–Ar age from the Gongen eclogite is due to excess argon. Important questions are where and how has the excess ^{40}Ar been trapped in phengite crystals and why has the

---

*Corresponding author: Email: itaya@rins.ous.ac.jp

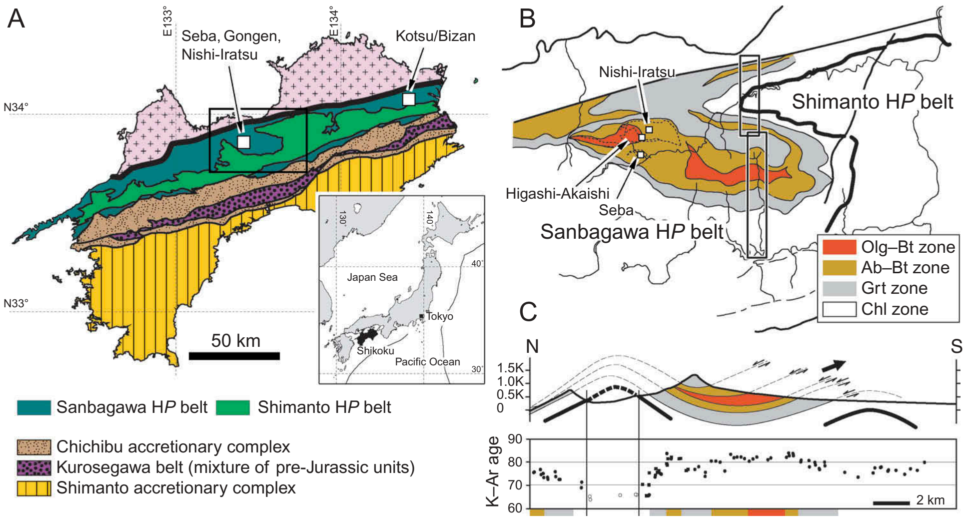

Figure 1. (A) Geological Map of Shikoku Island, Southwest Japan. The unit boundaries are modified after Aoki *et al.* (2011) and Itaya *et al.* (2011). (B) Metamorphic zonation of Sanbagawa metamorphic belt in central Shikoku after Higashino (1975, 1990). (C) A N–S traverse of white mica K–Ar ages from pelitic schists in central Shikoku (Itaya *et al.* 2011). The Sanbagawa metamorphic sequence has a thermal structure in that the highest-grade zone rocks occur in the middle part of the apparent stratigraphy.

excess ^{40}Ar in phengite been retained? In this article, we discuss possible mechanisms whereby excess ^{40}Ar may or may not be retained in white mica.

2. K–Ar geochronology of Sanbagawa belt

The Sanbagawa metamorphic belt of S–W Japan is one of the best-studied H*P* metamorphic belts in the world. It trends roughly E–W over 800 km in central to S–W Japan. The Sanbagawa belt consists of an Early Cretaceous accretionary complex that was subjected to prograde subduction-zone metamorphism reaching peak P–T conditions (P = 1.5–2.2 GPa, T = 500–750°C) at about 120 Ma, followed by retrograde metamorphism (P = 0.7–1.1 GPa, T = 460–510°C) at around 86 Ma (e.g. Isozaki and Itaya 1990; Aoki *et al.* 2011; Itaya *et al.* 2011). Regional metamorphic mapping shows a systematic sequence of appearance of characteristic Fe–Mg silicate minerals in metapelites (Kurata and Banno 1974; Higashino, 1975, 1990; Enami 1983; Banno and Sakai 1989). In order of increasing metamorphic grade, these zones are the chlorite, garnet, and biotite zones. The biotite zone is further subdivided into the albite-biotite and oligoclase-biotite zones (Figure 1B). H*P* schists of the Sanbagawa belt have been strongly deformed as documented by microstructural features that include a strong stretching mineral lineation and sheath folding (e.g. Faure 1983, 1985; Wallis 1990; Hara *et al* 1992).

Protoliths of the Sanbagawa belt include a variety of oceanic rock types with a long age span ranging from the Triassic to Early Cretaceous. These rocks were subjected to H*P* subduction-zone metamorphism and contain mineral assemblages from the pumpellyite-actinolite facies all the way up to the eclogite facies. The age of peak metamorphism of high-grade (biotite zone) schists is 122 ± 12 (Itaya *et al.* 2011) using the Rb-Sr whole-rock isochron method of Minamishin *et al.* (1979) and a new decay constant for Rb. An ion-microprobe U–Pb age of metamorphic zircon yielded around 120 Ma (Okamoto *et al.* 2004; Arakawa *et al.* 2013).

Since 1965, white mica K–Ar and Ar/Ar geochronology has been applied intensively to pelitic schists in central Shikoku. So far, up to 270 age dates have suggested that exhumation of the Sanbagawa belt occurred in the Cretaceous (e.g. Itaya *et al.* 2011). Recent subdivisions of the metamorphic belt, based on detrital zircon U–Pb geochronology, suggest that the belt in central Shikoku consists of two subunits; namely the ‘Sanbagawa H*P* belt’ and the ‘Shimanto H*P* belt’ (e.g. Aoki *et al.* 2011) (Figure 1A). White mica K–Ar ages along a N–S traverse in central Shikoku show systematic changes between these two subunits (Itaya and Takasugi 1988; Aoki *et al.* 2008) (Figure 1C). The K–Ar geochronology also defines a positive correlation between age and apparent metamorphic gradient in central Shikoku (Itaya and Takasugi 1988).

3. Eclogite and eclogite-facies rocks

Eclogites and eclogite-facies relict mineral assemblages have been described both in central Shikoku and eastern Shikoku (e.g. Wallis and Aoya 2000). The most eclogitic rocks are surrounded by pelitic schists and have suffered severe ductile deformation together with pelitic schists (e.g. Aoya 2001; Yamamoto *et al.* 2004).

In this study, we determined white mica K–Ar ages of eclogites from the Nishi-Iratsu, Gongen, and Seba areas in central Shikoku and Kotsu/Bizan area of eastern Shikoku. In the Seba and Kotsu/Bizan areas, we also examined pelitic schists associated with the eclogite. Each eclogite locality is described briefly below.

3.1. Central Shikoku

Large mafic–ultramafic complexes, all with abundant eclogite-facies relict mineral assemblages, are distributed throughout an intermediate structural level (thermal core) of the Sanbagawa belt in central Shikoku (e.g. Terabayashi *et al.* 2005; Figure 1A). The largest body (Iratsu) extends E–W for about 8 km and N–S for about 3 km and is surrounded by non-eclogitic schists (mainly pelitic schist) of the biotite zone. The western portion of the Iratsu body (Nishi Iratsu) consists of eclogitic metabasalts and metagabbros with intercalations of marble, quartzofeldspathic gneiss, and metacarbonate. The mineral assemblages of Nishi Iratsu eclogites suggest peak metamorphic conditions of T = ~500–650°C and P = 1.4–2.5 GPa (Ota 2004). The eclogites underwent epidote-amphibolite facies hydration and ductile shear deformation during exhumation. Eclogite yielded a Lu–Hf garnet age of 115.9 ± 0.5 Ma (Endo *et al.* 2009).

A small body (20 × 100 × 750 m) of quartz-rich kyanite-bearing eclogite, called 'quartz-eclogite' (Banno 1964), occurs at Gongen Pass of the Higashi Akaishi meta-peridotite (mainly dunite with minor amount of garnet-clinopyroxenite layers). The Gongen eclogite is enclosed by meta-peridotite (Kugimiya and Takasu 2002) and has a bulk-rock composition similar to greywacke (Okamoto *et al.* 2004; Miyamoto *et al.* 2007). Ion-microprobe U–Pb study of metamorphic zircons yielded an age of around 120 Ma for a peak eclogite-facies metamorphism (Okamoto *et al.* 2004; Arakawa *et al.* 2013) and subsequent partial melting at about 110 Ma (Arakawa *et al.* 2013). The peak metamorphic condition was estimated as P = 2.3–2.4 GPa and T = 675–740°C (Miyamoto *et al.* 2007); it is noteworthy that the eclogite body records the highest T conditions in comparison to other Sanbagawa eclogites. Although Gongen eclogite is partially overprinted by later epidote-amphibolite facies mineral assemblages, this eclogite body is less overprinted by a ductile shear deformation during exhumation. The eclogite body preserves various melting textures (e.g. Figure 2 of Arakawa *et al.* 2013).

South of the Higashi-Akaishi meta-peridotite body, mafic schists with relict eclogite and eclogite-facies mineral assemblages occur in the Seba area (Takasu 1984; Aoya 2001). The Seba eclogite also underwent post-peak epidote-amphibolite facies recrystallization together with various degrees of ductile deformation similar to that of the surrounding pelitic and psammitic schists during exhumation (Aoya 2001). The P–T estimate for the Seba eclogites suggests peak metamorphic conditions of

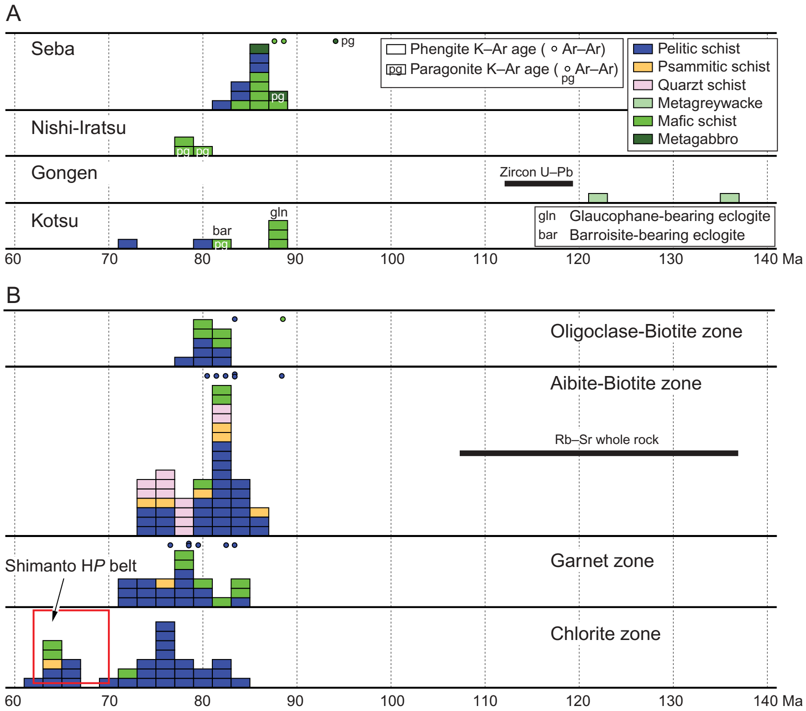

Figure 2. Histograms of white mica K–Ar ages of eclogites and eclogite-facies rocks (this study) and surrounding schists (see references in Itaya *et al.* (2011)'s Supplementary Material).

1.4–2.4 GPa at 610–640°C (Aoya 2001). The Seba eclogites yielded amphibole Ar–Ar ages of 89–95 Ma, phengite Ar/Ar ages of 88–94 Ma (Dallmeyer and Takasu 1991), and a Lu–Hf garnet age of 88.8 ± 0.6 Ma (Wallis *et al.* 2009).

3.2. *Eastern Shikoku*

In eastern Shikoku (about 80 km east of the Iratsu body), a blueschist unit in the Kotsu/Bizen area contains relict glaucophane-bearing epidote eclogite (Matsumoto *et al.* 2003). Recently, lawsonite was found as inclusions in the core of a zoned garnet in a glaucophane-bearing eclogite (Tsuchiya and Hirajima 2013). The eclogite-facies mineral assemblage constrains a peak P–T condition of 1.4–2.5 GPa at around 600°C (Matsumoto *et al.* 2003). The eclogite yielded a Lu–Hf garnet age of 88.2 ± 0.5 Ma (Wallis *et al.* 2009).

4. K–Ar ages

We carried out K–Ar analyses of phengite and paragonite on 16 eclogite samples from Seba (8), Gongen (2), Nishi-Iratsu (2), and Kotsu/Bizan (4). Seven pelitic schists associated with eclogite were also investigated geochronologically.

The samples were crushed with a jaw crusher and then sieved. White micas were separated from the several size fractions of the samples. We chose most abundant purest fractions for K and Ar analyses. Analysis and calculations of ages and errors were carried out following methods described by Nagao *et al.* (1984) and Itaya *et al.* (1991). Potassium was analysed by flame photometry using a 2000 μg g^{-1} Cs buffer with an analytical error of 2% at a 2σ confidence level. Argon isotopes were analysed on a 15 cm-radius sector type mass spectrometer with a single collector system, using the isotopic dilution method with a ^{38}Ar spike. Multiple runs of the standard (JG-1 biotite, 91 Ma) gave an error of about 1% at a 2-sigma confidence level (Itaya *et al.* 1991). The decay constants of ^{40}K to ^{40}Ar, ^{40}Ca, and ^{40}K content in potassium used in the age calculations are 0.581×10^{-10} year^{-1}, 4.962×10^{-10} year^{-1}, and 0.0001167, respectively (Steiger and Jäger 1977).

Our results are listed in Table 1 and shown in a histogram in Figure 2. The eclogites give ages of 85–89 Ma from Seba, 123–136 Ma from Gongen, 78–80 Ma from Nishi-Iratsu, and 82–88 Ma from Kotsu/Bizan. In sample WK1320b of Nishi-Iratsu, phengite and paragonite separated from the same sample do not show a significant age difference. In the Seba area, the results of pelitic schists associated with eclogite (84–86 Ma) overlap with eclogites (85–89 Ma). In the Kotsu/Bizan area, phengite ages of glaucophane-eclogites (88 Ma) are slightly older than paragonite ages of the barroisite-eclogite (82 Ma) and pelitic schists (73–79 Ma).

5. Discussion

5.1. *Age interpretations*

Overall, white mica ages in Seba and Nishi-Iratsu are consistent with the previously known range of phengite K–Ar ages of pelitic schists of the Sanbagawa metamorphic rocks in central Shikoku (Figure 2). The Seba data also overlap with phengite Ar/Ar ages reported by Dallmeyer and Takasu (1991). Our data confirm that none of the investigated eclogites belong to the Shimanto H*P* belt. White mica K–Ar ages of Kotsu/Bizan eclogites are comparable with those from eclogites in central Shikoku. The similarity of white mica K–Ar ages between eclogite and surrounding pelitic schists suggests that eclogite and surrounding high-grade Sanbagawa schists were subjected to coeval post-eclogite-facies retrograde metamorphism and deformation during exhumation (Figure 3). Although white mica K–Ar ages of the Seba and Kotsu/Bizan eclogites overlap with garnet Lu–Hf ages from those bodies, the interpretation of Lu–Hf ages of zoned garnets with abundant inclusions in Sanbagawa eclogites are still debated (e.g. Itaya *et al.* 2011).

Phengite K–Ar ages of the Gongen eclogite (123 and 136 Ma) are significantly older than the previously known range of phengite K–Ar ages for both the Sanbagawa H*P* belt and Shimanto H*P* belts. These ages are also older than U–Pb ages of syn-metamorphic zircon. There is little doubt that these old apparent ages have resulted from excess ^{40}Ar trapped in phengite. The protolith of the Gongen eclogite is considered a trench-fill deposit, based on the whole-rock composition and the presence of detrital zircons (e.g. Okamoto *et al.* 2004). This rules out the possibility that the excess ^{40}Ar was inherited from pre-existing older rocks. The Gongen eclogite is enclosed by meta-peridotite (Kugimiya and Takasu 2002). Thus, it is natural that the excess ^{40}Ar was attributed to an interaction between the meta-sediment (Gongen eclogite) and the meta-peridotite (Higashi-Akaishi peridotite) during metamorphism. Mantle materials have extreme ^{40}Ar/^{36}Ar ratios of about 3500 to 8000 (e.g. Kaneoka and Takaoka 1980; Farley and Poreda 1993; Burnard *et al.* 1994). During fluid exchange between deep-subducted sediments and lithospheric peridotite, mantle-derived extreme Ar gas might have diffused from the peridotite into the sediments. High solubility of argon in hydrous fluids (cf. Kelley 2002) also would have enhanced the argon diffusion.

In theory, K–Ar closure temperature of white mica is a function of both cooling rate and grain size. However, the white mica K–Ar geochronology suggests that ductile deformation may play a critical role in resetting the K–Ar system in white micas (e.g. Itaya and Takasugi 1988). This is supported by systematic K–Ar age mapping not only in the Sanbagawa but also in the Suo metamorphic belts (e.g. Nishimura *et al.* 1989; Nuong *et al.* 2008). A systematic K–Ar age mapping along transects

Table 1. White mica (phengite and paragonite) K–Ar ages of Sanbagawa eclogites and eclogite-facies rocks from Seba, Gongen, Nishi-Iratsu, and Kotsu/Bizan areas.

Area	Sample	Rock-type	Zone	Mineral	K (wt.%)	Error	Rad. ^{40}Ar	Error	Age (Ma)	Error	Non-rad. ^{40}Ar (%)	Position (WGS84 Datum)
Seba	DSB6	Bar-Ep eclogite (Gb)	Ab-Bt	Ph	7.676	0.15	2619.4	26.2	85.9	1.9	1.2	N33.86080 E133.37601
Seba	ISB8	Bar-Ep eclogite (Gb)	Ab-Bt	Pg	0.725	0.014	255.7	3.1	88.7	2.0	1.4	N33.86056 E133.37823
Seba	BSB3	Bar-Ep eclogite (R)	Ab-Bt	Ph	8.319	0.16	2874.0	29.1	86.9	1.9	1.2	N33.86157 E133.37732
Seba	OSB9	Bar-Ep eclogite (I)	Ab-Bt	Ph	8.426	0.17	2884.5	29.2	86.1	1.9	1.2	N33.85891 E133.38265
Seba	ESB46	Bar-Ep eclogite (I)	Ab-Bt	Ph	8.130	0.17	2827.6	28.9	87.5	1.9	1.2	N33.85891 E133.38265
Seba	CSB53	Bar-Ep eclogite (L)	Ab-Bt	Ph	8.104	0.16	2761.5	28.2	85.8	1.9	1.2	N33.85650 E133.38832
Seba	ESB44	Bar-Ep eclogite (L)	Ab-Bt	Ph	8.445	1.71	2903.9	29.2	86.5	1.9	1.2	N33.85718 E133.38566
Seba	JSB3	Bar-Ep eclogite (L)	Ab-Bt	Ph	8.546	0.17	2886.1	29.3	85.0	1.9	1.2	N33.85961 E133.38371
Seba	FSB2	Pelitic schist	Ab-Bt	Ph	6.681	0.13	2300.6	23.2	86.6	1.9	1.2	N33.85723 E133.38438
Seba	DSB23	Pelitic schist	Ab-Bt	Ph	7.675	0.15	2608.2	26.1	85.5	1.9	1.2	N33.86080 E133.37601
Seba	RSB34	Pelitic schist	Ab-Bt	Ph	7.492	0.15	2511.1	26.0	84.3	1.9	1.2	N33.85491 E133.38949
Seba	RSB41	Pelitic schist	Ab-Bt	Ph	8.657	0.17	2884.5	28.8	83.9	1.8	1.2	N33.85253 E133.39083
Seba	OSB17	Pelitic schist	Ab-Bt	Ph	8.217	0.16	2766.2	28.4	84.7	1.9	1.2	N33.85962 E133.39432
Gongen	QE9605	Qz-Ky-Gln-Ep eclogite	Ab-Bt	Ph	8.372	0.17	4145.1	48.8	123.3	2.8	1.8	N33.87896 E133.38612
Gongen	GO17O01b	Qz-Ky-Gln-Ep eclogite	Ab-Bt	Ph	8.211	0.16	4500.9	58.1	136.0	3.1	2.1	N33.87896 E133.38612
Nishi-Iratsu	WK1302b	Bar-Ep eclogite	Ab-Bt	Ph	5.778	0.12	1781.9	18.5	77.8	1.9	1.1	N33.89499 E133.38698
				Pg	0.715	0.01	226.1	3.7	79.8	1.9	1.5	N33.88877 E133.38899
Nishi-Iratsu	WK1308	Bar-Ep eclogite	Ab-Bt	Pg	0.556	0.01	171.2	2.5	77.7	1.9	1.4	N33.88877 E133.38899
Kotsu	KKT6	Gln-Ep eclogite	Grt	Ph	7.939	0.16	2784.9	28.0	88.2	1.9	1.2	N34.02180 E134.23276
Kotsu	EDC10	Gln-Ep eclogite	Grt	Ph	8.153	0.16	2839.5	29.4	87.8	1.9	1.2	N34.02180 E134.23276
Kotsu	EDD108	Gln-Ep eclogite	Grt	Ph	7.983	0.16	2787.1	28.3	87.6	1.9	1.2	N34.02349 E134.23132
Kotsu	SKT3	Bar-Ep eclogite	Grt	Pg	0.717	0.014	234.5	2.7	82.3	1.9	1.2	N34.01175 E134.23476
Kotsu	20140309-1	Pelitic schist	Grt	Ph	8.156	0.16	2355.8	22.6	72.9	1.6	1.5	N34.03278 E134.23556
Kotsu	20140309-3	Pelitic schist	Grt	Ph	7.787	0.16	2447.9	24.2	79.2	1.7	2.0	N34.02167 E134.23250

Notes: Gb, gabbro protolith; R, I, L, deformation type of eclogite (see Wallis and Aoya 2000 and Aoya 2001); Bar, barroisite; Gln, glaucophane; Ep, epidote; Ky, kyanite; Qz, quartz; Ph, phengite; Pg, paragonite; Ab, albite; Bt, biotite; Grt, garnet.

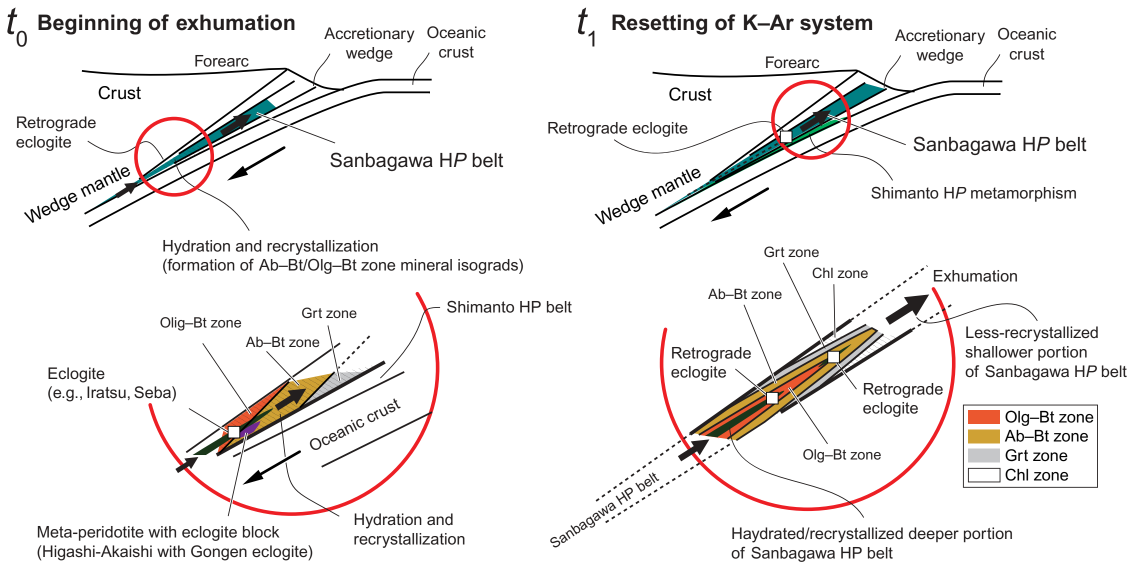

Figure 3. Schematic model of evolution of the Sanbagawa eclogites from t_0 (beginning of exhumation) to t_1 (resetting of K–Ar system); the model is modified after Itaya *et al.* (2011). Exhumation started at t_1, and the exhumed deeper portion (eclogite-facies depth) of the metamorphosed accretionary complex suffered intense deformation at the middle crustal depth at t_1.

perpendicular to metamorphic thermal gradients by Itaya and Takasugi (1988) revealed a relationship between temperature and deformation/recrystallization in a coherent metamorphic sequence; they found a positive correlation between white mica K–Ar age and the metamorphic gradient that formed during the post-metamorphic peak dynamic recrystallization (Figure 4). According to this model, we conclude that the Gongen eclogite suffered little ductile shear deformation during exhumation. This is the reason why the eclogite shows the old age. The rigid meta-peridotite would have prevented a ductile shear deformation of the Gongen eclogite, and consequently, mantle-derived Ar gained from the Higashi-Akaishi peridotite in the eclogite was inherited by the limited-Ar-depletion due to less deformation.

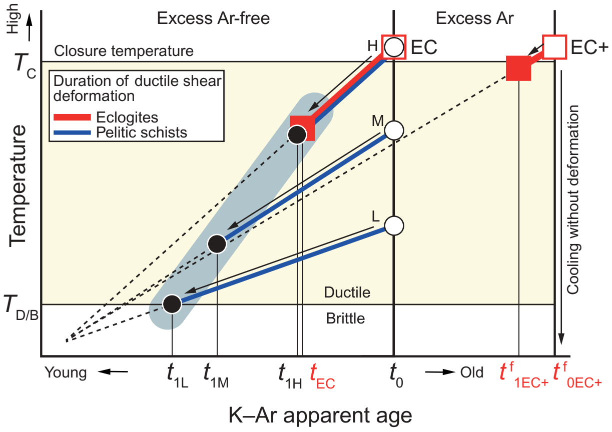

Figure 4. Generalized temperature–age diagram showing a possible mechanism to explain white mica K–Ar ages of Sanbagawa eclogites and surrounding pelitic schists. Squares represent eclogite; EC, eclogites without excess ^{40}Ar (Seba, Nishi-Iratsu, and Kotsu/Bizan); EC+, eclogite with excess ^{40}Ar (Gongen). Solid square represents timings of K–Ar system reset in white micas from eclogites; t^f, 'false' age of Gongen eclogite due to excess ^{40}Ar. Circle represents pelitic schists of coherent Sanbagawa metamorphic sequence; L, low-grade; M, middle-grade; and H, high-grade zones. T_C, closure temperature of white mica; $T_{D/B}$, temperature of ductile/brittle boundary; t_0, beginning of exhumation; and t_1, resetting of K–Ar system. A positive age-metamorphic grade correlation in pelitic schists suggests a long duration of deformation during exhumation (Itaya and Takasugi 1988; Itaya *et al.* 2011).

5.2. *Excess ^{40}Ar*

Anomalously old white mica K–Ar and Ar/Ar ages due to excess ^{40}Ar are not common in Pacific-type H*P* metamorphic rocks. This is a consequence of the protoliths, simple metamorphic histories, and a water-saturated environment of metamorphism. However, old ages due to excess ^{40}Ar have been reported from collision zone M*P*–H*P*–UH*P* metamorphic rocks of various localities, including the Dora Maira massif, Italy (Arnaud and Kelly 1995; Scaillet 1996); the Su-Lu and Dabie terranes, China (Li *et al.* 1994; Giorgis *et al.* 2000); the Kaghan Valley, Pakistan (Tonarini *et al.* 1993); the Tso Morari Complex of Himalaya, India (Gouzu *et al.* 2006a); the Gourma, Mali (Jahn *et al.* 2001); the Sesia-Lanzo Zone, Italy (Ruffet 1995; Inger *et al.* 1996; Ruffet *et al.* 1997; Halama *et al.* 2014); the Gran Paradiso, Italy (Chopin and Maluski 1980; Beltrando *et al.* 2013); the Tavsanli Zone, Turkey (Sherlock and Arnaud 1999); the Betic

Zone, Spain (De Jong *et al.* 2001); and the Longmenshan, China (Itaya *et al.* 2009).

Recently, Beltrando *et al.* (2013) conducted Ar/Ar *in-situ* and stepwise heating analyses for white mica and biotite from eclogite-facies (T = ~550°C) meta-granitoids in the Gran Pradiso massif (western Alps). They showed that white mica from the partially deformed meta-granitoid that preserved abundant granitic mineral assemblages yielded an age range from 230 (protolith age) to 45 Ma (HP metamorphic event). These observations suggest that white mica (muscovite) in polymetamorphic terranes requires much higher metamorphic temperatures to completely reset the Ar isotopic system than generally thought. Moreover, the data suggest that deformation plays a critical role in reducing excess ^{40}Ar.

Another excess ^{40}Ar scenario in mica is uptake through argon diffusion. For example, Hyodo and York (1993) found significantly old 'discordant' mica ages in a narrow zone of a contact aureole; they called this phenomenon the 'Excess-Argon Wave' (EAW). The EAW has been also found in regional metamorphic sequences. In the Barrovian-type metamorphic complex of the Longmenshan orogen (eastern Tibet), the upper kyanite-grade metapelite yielded biotite Ar/Ar ages 4 to 5 times older than those in the sillimanite grade (Itaya *et al.* 2009); the excess ^{40}Ar was gained in mica by diffusion, possibly through a breakdown reaction of muscovite with a significant amount of radiogenic argon.

The old excess ^{40}Ar ages from Gongen eclogite in this study may suggest a phenomenon similar to an EAW. We consider that the excess ^{40}Ar was not inherited from precursor older rocks as many cases in metamorphic rocks from collision zones. We interpret that excess ^{40}Ar preserved in the Gongen eclogite formed by an interaction between the metagreywacke and the meta-peridotite with mantle-derived noble gas (very-high ^{40}Ar/^{36}Ar ratio) at eclogite-facies depth. Fluid exchange between deep-subducted sediments and mantle material might have enhanced the gain of mantle-derived extreme ^{40}Ar in the meta-sediment. A high argon pressure environment that formed through a slab–peridotite–fluid interaction would allow the trapping of a large amount of excess argon within phengitic micas. To justify this model, further understanding of multiple noble gas isotopes such as He, Ne, Kr, and Xe is required than that documented in previous Ar studies.

Acknowledgements

The investigated samples were provided by M. Aoya, S. Wallis, and M. Enami. We thank T. Okada for his laboratory assistance. We are also grateful for James Brophy's efforts editing a first draft for clarity. We acknowledge W.G. Ernst and J. Wakabayashi who critically reviewed this manuscript.

References

Aoki, K., Itaya, T., Shibuya, T., Masago, H., Nishizawa, M., Terabayashi, M., Omori, S., Yokoyama, T., Takahara, N., Sano, Y., and Maruyama, S., 2008, The youngest blueschist belt in SW Japan: Implication for the exhumation of the Cretaceous Sanbagawa high-P/T metamorphic belt: Journal of Metamorphic Geology, v. 26, p. 583–602. doi:10.1111/j.1525-1314.2008.00777.x

Aoki, K., Maruyama, S., Isozaki, Y., Otoh, S., and Yanai, S., 2011, Recognition of the Shimanto HP metamorphic belt within the traditional Sanbagawa HP metamorphic belt: New perspectives of the Cretaceous-Paleogene tectonics in Japan: Journal of Asian Earth Sciences, v. 42, p. 355–369. doi:10.1016/j.jseaes.2011.05.001

Aoya, M., 2001, P-T-D path of eclogite from the Sambagawa belt deduced from combination of petrological and microstructural analyses: Journal of Petrology, v. 42, p. 1225–1248. doi:10.1093/petrology/42.7.1225

Arakawa, M., Okamoto, K., Yi, K., Terabayashi, M., and Tsutsumi, Y., 2013, SHRIMP U–Pb dating of zircons related to the partial melting in a deep subduction zone: Case study from the Sanbagawa quartz-bearing eclogite: Island Arc, v. 22, p. 74–88. doi:10.1111/iar.12012

Arnaud, N.O., and Kelly, S., 1995, Evidence for excess argon during high pressure metamorphism in the dora maira massif (Western Alps, Italy), using an ultra-violet laser ablation microprobe ^{40}Ar-^{39}Ar technique: Contributions to Mineralogy and Petrology, v. 121, p. 1–11. doi:10.1007/s004100050086

Banno, S., 1964, Petrological studies on Sanbagawa crystalline schists in the Bessi-Inno district, central Shikoku, Japan: Journal of Faculty of Science, University of Tokyo, v. II-15, p. 203–319.

Banno, S., and Sakai, C., 1989, Geology and metamorphic evolution of the Sanbagawa metamorphic belt, Japan, *in* Daly, J.S., Cliff, R.A., and Yardley, B.E.D., eds., Evolution of metamorphic belts: Geological Society, Special Publication 47, p. 519–532.

Beltrando, M., Di Vincenzo, G., and Ferraris, C., 2013, Preservation of sub-microscopic structural relicts in micas from the Gran Paradiso Massif (Western Alps): Implications for ^{40}Ar–^{39}Ar geochronology: Geochimica Et Cosmochimica Acta, v. 119, p. 359–380. doi:10.1016/j.gca.2013.05.043

Burnard, P.G., Stuart, F.M., Turner, G., and Oskarsson, N., 1994, Air contamination of basaltic magmas: Implications for high ^{3}He/^{4}He mantle Ar isotopic composition: Journal of Geophysical Research, v. 99, no. B9, p. 17709–17715. doi:10.1029/94JB01191

Chopin, C., and Maluski, H., 1980, ^{40}Ar-^{39}Ar dating of high pressure metamorphic micas from the Gran Paradiso area (Western Alps): Evidence against the blocking temperature concept: Contributions to Mineralogy and Petrology, v. 74, p. 109–122. doi:10.1007/BF01131997

Dallmeyer, R.D., and Takasu, A., 1991, Tectonometamorphic evolution of the Sebadani eclogitic metagabbro and the Sambagawa schists, central Shikoku, Japan: ^{40}Ar/^{39}Ar mineral age constraints: Journal of Metamorphic Geology, v. 9, p. 605–618. doi:10.1111/j.1525-1314.1991.tb00551.x

De Jong, K., Féraud, G., Ruffet, G., Amouric, M., and Wijbrans, J.R., 2001, Excess argon incorporation in phengite of the Mulhacén Complex: Submicroscopic illitization and fluid ingress during late Miocene extension in the Betic Zone, south-eastern Spain: Chemical Geology, v. 178, p. 159–195. doi:10.1016/S0009-2541(00)00411-3

Enami, M., 1983, Petrology of pelitic schist's in the oligoclase-biotite zone of the Sanbagawa metamorphic terrain, Japan: Phase equilibria in the highest grade zone of a high-pressure intermediate type of metamorphic belt: Journal of Metamorphic Geology, v. 1, p. 141–161. doi:10.1111/j.1525-1314.1983.tb00269.x

Endo, S., Wallis, S., Hirata, T., Anczkiewicz, R., Platt, J., Thirlwall, M., and Asahara, Y., 2009, Age and early metamorphic history of the Sanbagawa belt: Lu-Hf and P-T constraints from the Western Iratsu eclogite: Journal of Metamorphic Geology, v. 27, p. 371–384. doi:10.1111/j.1525-1314.2009.00821.x

Farley, K.A., and Poreda, R.J., 1993, Mantle neon and atmospheric contamination: Earth and Planetary Science Letters, v. 114, p. 325–339. doi:10.1016/0012-821X(93)90034-7

Faure, M., 1983, Eastward ductile shear during the early tectonic phase in the Sanbagawa belt: The Journal of the Geological Society of Japan, v. 89, p. 319–329. doi:10.5575/geosoc.89.319

Faure, M., 1985, Microtectonic evidence for eastward ductile shear in the Jurassic orogen of S.W. Japan: Journal of Structural Geology, v. 7, p. 175–186. doi:10.1016/0191-8141(85)90130-0

Giorgis, D., Cosca, M., and Li, S.-G., 2000, Distribution and significance of extraneous argon in UHP eclogite (Sulu terrain, China): Insight from in situ 40Ar/39Ar UV laser ablation analysis: Earth and Planetary Science Letters, v. 181, p. 605–615.

Gouzu, C., Itaya, T., Hyodo, H., and Ahmad, T., 2006a, Cretaceous isochron ages from K–Ar and ^{40}Ar/^{39}Ar dating of eclogitic rocks in the Tso Morari Complex, western Himalaya, India: Gondwana Research, v. 9, p. 426–440. doi:10.1016/j.gr.2006.01.002

Gouzu, C., Itaya, T., Hyodo, H., and Matsuda, T., 2006b, Excess 40Ar-free phengite in ultrahigh-pressure metamorphic rocks from the Lago di Cignana area, Western Alps: Lithos, v. 92, p. 418–430. doi:10.1016/j.lithos.2006.03.056

Halama, R., Konrad-Schmolke, M., Sudo, M., Marschall, H.R., and Wiedenbeck, M., 2014, Effects of fluid-rock interaction on 40Ar/39Ar geochronology in high-pressure rocks (Sesia-Lanzo Zone, Western Alps): Geochimica Et Cosmochimica Acta, v. 126, p. 475–494. doi:10.1016/j.gca.2013.10.023

Hara, I., Shiota, T., Hide, K., Kanai, K., Goto, M., Seki, S., Kaikiri, K., Takeda, K., Hayasaka, Y., Miyamoto, T., Sakurai, Y., and Ohtomo, Y., 1992, Tectonic evolution of the Sanbagawa schists and its implications in convergent margin process: Journal of Science Hiroshima University Series, ser. C, v. 9, p. 495–595.

Higashino, T., 1975, Biotite zone of Sanbagawa metamorphic terrain in the Siragayama area, central Shikoku, Japan: The Journal of the Geological Society of Japan, v. 81, p. 653–670. doi:10.5575/geosoc.81.653

Higashino, T., 1990, The higher grade metamorphic zonation of the Sambagawa metamorphic belt in central Shikoku, Japan: Journal of Metamorphic Geology, v. 8, p. 413–423. doi:10.1111/j.1525-1314.1990.tb00628.x

Hyodo, H., and York, D., 1993, The discovery and significance of a fossilized radiogenic argon wave (argonami) in the earth's crust: Geophysical Research Letters, v. 20, p. 61–64. doi:10.1029/92GL02675

Inger, S., Ramsbotham, W., Cliff, R.A., and Rex, D.C., 1996, Metamorphic evolution of the Sesia-Lanzo zone, Western Alps: Time constraints from multi-system geochronology: Contributions to Mineralogy and Petrology, v. 126, p. 152–168. doi:10.1007/s004100050241

Isozaki, Y., and Itaya, T., 1990, Chronology of Sanbagawa metamorphism: Journal of Metamorphic Geology, v. 8, p. 401–411. doi:10.1111/j.1525-1314.1990.tb00627.x

Itaya, T., Hyodo, H., Tsujimori, T., Wallis, S., Aoya, M., Kawakami, T., and Gouzu, C., 2009, Regional-scale excess Ar wave in a Barrovian type metamorphic belt, eastern Tibetan Plateau: Island Arc, v. 18, p. 293–305. doi:10.1111/j.1440-1738.2009.00668.x

Itaya, T., Nagao, K., Inoue, K., Honjou, Y., Okada, T., and Ogata, A., 1991, Argon isotope analysis by a newly developed mass spectrometric system for K-Ar dating: Mineralogical Journal, v. 15, p. 203–221. doi:10.2465/minerj.15.203

Itaya, T., and Takasugi, H., 1988, Muscovite K-Ar ages of the Sanbagawa schists, Japan and argon depletion during cooling and deformation: Contributions to Mineralogy and Petrology, v. 100, p. 281–290. doi:10.1007/BF00379739

Itaya, T., Tsujimori, T., and Liou, J.G., 2011, Evolution of the Sanbagawa and Shimanto high-pressure belts in SW Japan: Insights from K-Ar (Ar-Ar) geochronology: Journal of Asian Earth Sciences, v. 42, p. 1075–1090. doi:10.1016/j.jseaes.2011.06.012

Jahn, B.-M., Caby, R., and Monie, P., 2001, The oldest UHP eclogites of the World: Age of UHP metamorphism, nature of protoliths and tectonic implications: Chemical Geology, v. 178, p. 143–158. doi:10.1016/S0009-2541(01)00264-9

Kaneoka, I., and Takaoka, N., 1980, Rare gas isotopes in Hawaiian ultramafic nodules and volcanic rocks: Constraint on genetic relationships: Science, v. 208, p. v. 1366–1368. doi:10.1126/science.208.4450.1366

Kelley, S., 2002, Excess argon in K–Ar and Ar–Ar geochronology: Chemical Geology, v. 188, p. 1–22. doi:10.1016/S0009-2541(02)00064-5

Kugimiya, Y., and Takasu, A., 2002, Geology of the Western Iratsu mass within the tectonic melange zone in the Sambagawa metamorphic belt, Besshi district, central Shikoku, Japan: The Journal of the Geological Society of Japan, v. 108, p. 644–662. doi:10.5575/geosoc.108.10_644

Kurata, H., and Banno, S., 1974, Low-grade Progressive Metamorphism of Pelitic Schists of the Sazare area, Sanbagawa Metamorphic Terrain in central Sikoku, Japan: Journal of Petrology, v. 15, p. 361–382. doi:10.1093/petrology/15.2.361

Li, S., Wang, S., Chen, Y., Liu, D., Qiu, J.I., Zhou, H., and Zhang, Z., 1994, Excess argon in phengite from eclogite: Evidence from dating of eclogite minerals by Sm-Nd, Rb-Sr and ^{40}Ar/^{39}Ar methods: Chemical Geology, v. 112, p. 343–350. doi:10.1016/0009-2541(94)90033-7

Matsumoto, M., Wallis, S., Aoya, M., Enami, M., Kawano, J., Seto, Y., and Shimobayashi, N., 2003, Petrological constraints on the formation conditions and retrograde P-T path of the Kotsu eclogite unit, central Shikoku: Journal of Metamorphic Geology, v. 21, p. 363–376. doi:10.1046/j.1525-1314.2003.00449.x

Minamishin, M., Yanagai, T., and Yamaguchi, M., 1979, Rb-Sr whole rock age of the Sanbagawa metamorphic rocks in central Shikoku, Japan, *in* Yamaguchi., M., ed., Isotope geosciences of Japanese Islands: Report for Scientific Research from the MEJ (No. 334054), p. 68–71.

Miyamoto, A., Enami, M., Tsuboi, M., and Yokoyama, K., 2007, Peak conditions of kyanite-bearing quartz eclogites in the Sanbagawa metamorphic belt, central Shikoku, Japan: Journal of Mineralogical and Petrological Sciences, v. 102, p. 352–367. doi:10.2465/jmps.070120

Miyashita, A., and Itaya, T., 2002, K-Ar age and chemistry of phengite from the Sanbagawa schists in the Kanto Mountains, central Japan, and their implication for exhumation tectonics: Gondwana Research, v. 5, p. 837–848. doi:10.1016/S1342-937X(05)70917-5

Nagao, K., Nishido, H., Itaya, T., and Ogata, K., 1984, An age determination by K-Ar method: Bulletin of the Hiruzen Reserch Institute, Okayama University of Science, v. 9, p. 19–38.

Nishimura, Y., Coombs, D.S., Landis, C.A., and Itaya, T., 2000, Continuous metamorphic gradient documented by graphitization and K-Ar age, southeast Otago, New Zealand: American Mineralogist, v. 85, p. 1625–1636.

Nishimura, Y., Itaya, T., Isozaki, Y., and Kameya, A., 1989, Depositional age and metamorphic history of 220Ma high P/T type metamorphic rocks: An example of the Nishiki-cho area, Yamaguchi Prefecture, Southwest Japan: Memoirs of Geological Society of Japan, v. 33, p. 143–166.

Nuong, N.D., Itaya, T., and Nishimura, Y., 2008, Age (K-Ar phengite)-temperature-structure relations: A case study from the Ishigaki high-pressure schist belt, southern Ryukyu Arc, Japan: Geological Magazine, v. 145, p. 677–684. doi:10.1017/S0016756808004998

Nuong, N.D., Thanh, N.X., Gouzu, C., and Itaya, T., 2011, Phengite geochronology of crystalline schists in the Sakuma-Tenryu district, central Japan: Island Arc, v. 20, p. 401–410. doi:10.1111/j.1440-1738.2011.00773.x

Okamoto, K., Shinjoe, H., Katayama, I., Terada, K., Sano, Y., and Johnson, S., 2004, SHRIMP U-Pb zircon dating of quartz-bearing eclogite from the Sanbagawa Belt, southwest Japan: Implications for metamorphic evolution of subducted protolith: Terra Nova, v. 16, p. 81–89. doi:10.1111/j.1365-3121.2004.00531.x

Ota, T., 2004, Thermobaric structure and metamorphic evolution of the Iratsu eclogite body in the Sanbagawa belt, central Shikoku, Japan: Lithos, v. 73, p. 95–126. doi:10.1016/j.lithos.2004.01.001

Ruffet, G., 1995, Plateau ages and excess argon in phengites: An ^{40}Ar-^{39}Ar laser probe study of Alpine micas (Sesia Zone, Western Alps, northern Italy): Chemical Geology, v. 121, p. 327–343. doi:10.1016/0009-2541(94)00132-R

Ruffet, G., Gruau, G., Ballèvre, M., Féraud, G., and Philippot, P., 1997, Rb-Sr and 40Ar-39Ar laser probe dating of high-pressure phengites from the Sesia zone (Western Alps): Underscoring of excess argon and new age constraints on the high-pressure metamorphism: Chemical Geology, v. 141, p. 1–18. doi:10.1016/S0009-2541(97)00052-1

Scaillet, S., 1996, Excess ^{40}Ar transport scale and mechanism in high-pressure phengites: A case study from an eclogitized metabasite of the Dora-Maira nappe, western Alps: Geochimica Et Cosmochimica Acta, v. 60, p. 1075–1090. doi:10.1016/0016-7037(95)00440-8

Sherlock, S., and Kelley, S., 2002, Excess argon evolution in HP-LT rocks: A UVLAMP study of phengite and K-free minerals, NW Turkey: Chemical Geology, v. 182, p. 619–636. doi:10.1016/S0009-2541(01)00345-X

Sherlock, S.C., and Arnaud, N.O., 1999, Flat plateau and impossible isochrons: Apparent 40Ar-39Ar geochronology in a high-pressure terrain: Geochimica Et Cosmochimica Acta, v. 63, p. 2835–2838. doi:10.1016/S0016-7037(99)00116-7

Steiger, R.H., and Jäger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362. doi:10.1016/0012-821X(77)90060-7

Takasu, A., 1984, Prograde and retrograde eclogites in the Sambagawa metamorphic belt, Besshi district, Japan: Journal of Petrology, v. 25, p. 619–643. doi:10.1093/petrology/25.3.619

Terabayashi, M., Okamoto, K., Yamamoto, H., Kaneko, Y., Ota, T., Maruyama, S., Katayama, I., Komiya, T., Ishikawa, A., Anma, R., Ozawa, H., Windley, B.F., and Liou, J.G., 2005, Accretionary complex origin of the mafic- ultramafic bodies of the Sanbagawa belt, Central Shikoku, Japan: International Geology Review, v. 47, p. 1058–1073. doi:10.2747/0020-6814.47.10.1058

Tonarini, S., Villa, I.M., Oberli, F., Meier, M., Spencer, D.A., Pognante, U., and Ramsay, J.G., 1993, Eocene age of eclogite metamorphism in Pakistan Himalaya: Implications for India-Eurasia collision: Terra Nova, v. 5, p. 13–20. doi:10.1111/j.1365-3121.1993.tb00221.x

Tsuchiya, S., and Hirajima, T., 2013, Evidence of the lawsonite eclogite facies metamorphism from an epidote-glaucophane eclogite in the Kotsu area of the Sanbagawa belt, Japan: Journal of Mineralogical and Petrological Sciences, v. 108, p. 166–171. doi:10.2465/jmps.121022b

Tsujimori, T., and Itaya, T., 1999, 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: The Island Arc, v. 8, p. 190–205. doi:10.1046/j.1440-1738.1999.00231.x

Wallis, R.S., 1990, The timing of folding and stretching in the Sambagawa belt: The Asemigawa region, Central Shikoku: The Journal of the Geological Society of Japan, v. 96, p. 345–352. doi:10.5575/geosoc.96.345

Wallis, S., and Aoya, M., 2000, A re-evaluation of eclogite facies metamorphism in SW Japan: Proposal for an eclogite nappe: Journal of Metamorphic Geology, v. 18, p. 653–664. doi:10.1046/j.1525-1314.2000.00285.x

Wallis, S.R., Anczkiewicz, R., Endo, S., Aoya, M., Platt, J.P., Thirlwall, M., and Hirata, T., 2009, Plate movements, ductile deformation and geochronology of the Sanbagawa belt, SW Japan: Tectonic significance of 89-88 Ma Lu-Hf eclogite ages: Journal of Metamorphic Geology, v. 27, p. 93–105. doi:10.1111/j.1525-1314.2008.00806.x

Yamamoto, H., Okamoto, K., Kaneko, Y., and Terabayashi, M., 2004, Southward extrusion of eclogite-bearing mafic–ultramafic bodies in the Sanbagawa belt, central Shikoku, Japan: Tectonophysics, v. 387, p. 151–168. doi:10.1016/j.tecto.2004.06.014