K-Ar phengite geochronology of HP-UHP metamorphic rocks
-An in-depth review-

Tetsumaru ITAYA*,**,***
*Institute of Geohistory, Japan Geochronology Network, Akaiwa 701-2503, Japan
**Engineering Geology Center, Hiruzen Institute for Geology & Chronology, Okayama 703-8252, Japan
***IFST, Okayama University of Science, Okayama 700-0005, Japan

The reported discordant and anomalously old K-Ar (40Ar/39Ar) phengitic white mica ages from collisional orogenic belts are due to the fact that white micas in continental lithologies are not reset completely during high- to ultrahigh-pressure (HP-UHP) metamorphism because the closure temperature of white micas is much higher than the generally accepted value, approximately 600 °C. On the other hand, phengites in HP-UHP schists experience deformation-induced recrystallization during exhumation of the host lithology. The radiogenic argon is released from the deformed phengite, as documented by comparison of the in situ 40Ar/39Ar dating of phengite included in rigid garnet and of stretched phengite in the matrix. These non-resetting and argon-release phenomena give inconsistent phengitic white mica ages in metamorphosed continental lithologies. The heterogeneity in the deformational process due to differences in lithological compositions, local domains or even within single mica crystals results in inconsistent ages, as documented from the in situ 40Ar/39Ar dating of the deformed micas. The Sanbagawa HP schist belt and Lago di Cignana HP-UHP units both consist of metamorphosed oceanic lithologies that usually record only a single metamorphic cycle and have phengites without any inherited excess argon. The duration of deformation during exhumation spans from the peak metamorphism to the end of deformation in the crust, making it possible to estimate the exhumation rates of the metamorphic sequences. The low exhumation rates (<6 mm/y) of the Sanbagawa belt suggest a slow strain rate during rock deformation, resulting in a ‘slow schist’ sequence with a recumbent fold structure. The rapid exhumation rates (<26 mm/y) of Lago di Cignana suggest a high strain rate during rock deformations, resulting in a ‘fast schist’ sequence consisting of several units with fault-bounded contacts. The Lago di Cignana UHP unit, which underwent the highest exhumation rate, could indicate a subsequent continental collision event, whereas the Sanbagawa belt did not experience a subsequent continental collision event.

Keywords: Pacific type HP-UHP metamorphism, Phengite K-Ar (40Ar/39Ar) age, Argon release mechanism, Deformation-induced recrystallization, Effective diffusion length scale, Slow and fast schists

INTRODUCTION

Radiogenic 40Ar was discovered from natural minerals by Aldrich and Nier (1948), and the K-Ar dating method was put into practice in the 1950s (Wasserburg and Hayden, 1955). Later, this method was applied to the petrology and chronology of igneous and metamorphic rocks, and the modified 40Ar/39Ar method was established in the 1960s (cf. Merrihue and Turner, 1966). Later, workers further improved the method to include in situ dating (e.g., Megruée, 1973). The measured age values of plutonic and metamorphic rocks with slow cooling were assumed to be the cooling ages when the radiogenic 40Ar diffusion was closed. The temperature at which diffusion decreases has been termed the ‘blocking temperature’ commonly used in palaeomagnetism until Dodson (1973) formulated the closure temperature based on the thermally activated diffusion model (see the Appendix for the relation between the blocking and closure temperatures). The blocking temperature of white mica (phengite) was considered to be 350 °C, proposed first by a research group of Bern University (Villa, 1998). The abovementioned value is referenced in textbooks on absolute age determination and numerical dating (cf. Geyh and Schleicher, 1990; Kaneoka, 1998) and has been applied by many geologists.
and petrologists for a long time. The K–Ar ($^{40}$Ar/$^{39}$Ar) method has often provided discordant and anomalously old ages when phengite from high-pressure (HP) and ultra-high pressure (UHP) metamorphic rocks in collisional orogenic belts was measured (e.g., Chopin and Maluski, 1980; Scaillet et al., 1990; Monié and Chopin, 1991; Scaillet et al., 1992; Arnaud and Kelley, 1995; Hammerschmidt et al., 1995; Scaillet, 1996; Di Vincenzo et al., 2006; Beltrando et al., 2013; Halama et al., 2014). Such anomalously old and heterogeneous age values seriously confused the readers. These results were discussed to be the effect of ‘excess argon’ (cf. Kelly, 2002), and the argument to explain the excess argon inherited from the host lithologies remains vague.

Generally, HP–UHP metamorphic rocks have experienced severe ductile deformation during their exhumation, as evidenced by strong stretching mineral lineation and sheath folding (e.g., Faure, 1983, 1985; Wallis, 1990; Wallis et al., 1992). The stretched phengite in the matrix has heterogeneous Si values and Mg/Fe and Na/K ratios compared with the values/ratios of phengite included in garnet and albite (e.g., Hirajima et al., 1992; Itaya and Fujino, 1999; Gouzu et al., 2006a, 2016). Itaya et al. (2011) reviewed chemistries and K–Ar ($^{40}$Ar/$^{39}$Ar) ages of phengite in HP–UHP metamorphic rocks and described the radiogenic argon release from phengite that experienced deformation-induced (dynamic) recrystallization and chemical change, depending on the local bulk chemistry that varies under different pressure–temperature ($P$–$T$) conditions during exhumation. This argon release hypothesis was first proposed by Itaya and Takasugi (1988) to understand the relationship between age and metamorphic grade in the Sanbagawa metamorphic belt, central Shikoku, SW Japan. Their hypothesis was not accepted for 20 years, until Nuong et al. (2008) described the age (K–Ar phengite)–temperature–structure relations in the Ishigaki high-pressure schist belt, southern Ryukyu Arc, Japan.

In this paper, the author first discusses the concept of closure temperature in the K–Ar phengite system and the mechanism of argon release from phengite crystals with deformation-induced (dynamic) recrystallization to explain why HP–UHP metamorphic rocks often provide discordant and anomalously old ages in K–Ar ($^{40}$Ar/$^{39}$Ar) dating and then discusses exhumation rate estimation. The author considers that HP–UHP metamorphic rocks with oceanic host lithologies never have excess argon problems and thus give consistent ages (e.g., Itaya and Takasugi, 1988; Nishimura et al., 1989, 2000; Miyashita and Itaya, 2002; Gouzu et al., 2006a; Nuong et al., 2008, 2011; Itaya et al., 2011; Gouzu et al., 2016). Therefore, K–Ar ($^{40}$Ar/$^{39}$Ar) phengite geochronology in metamorphic belts of oceanic lithologies makes it possible to precisely estimate their exhumation rates. Two example areas (Sanbagawa HP metamorphic belt, central Shikoku, SW Japan and Lago di Cignana HP–UHP units, Western Alps, Italy) are discussed in this study to describe the K–Ar ($^{40}$Ar/$^{39}$Ar) phengite geochronology, and then their exhumation rates are proposed. The former exhibits a slow exhumation rate, whereas the latter exhibits a fast rate, creating ‘slow’ and ‘fast’ schist metamorphic sequences, respectively.

**CLOSEURE TEMPERATURE OF K–AR PHENGITE SYSTEM**

The blocking temperature at which the diffusion of radiogenic argon in phengite closes and deceases during cooling and exhumation of its host rocks was used until Dodson (1973) formulated the closure temperature based on a thermally activated diffusion model. The closure temperature of the K–Ar phengite system is believed to be 350 °C, which was originally proposed by the Bern Group as the blocking temperature (cf. Villa, 1998) because the value has been referred in textbooks on absolute age determination or numerical dating (cf. Geyh and Schleicher, 1990; Kaneoka, 1998). Chopin and Maluski (1980) carried out $^{40}$Ar/$^{39}$Ar analyses on phengite separates from the HP metamorphic rocks of the Gran Paradiso Massif in the western Alps, Italy. Their age data were inconsistent and significantly older than the commonly reported age values for the Alpine metamorphism, even for the host rocks with eclogite facies. Chopin and Maluski (1980) wrote that ‘This implies that thermally activated diffusion processes (volume diffusion …) cannot be geologically significant. Consequently, the blocking temperature concept which rests on the opposite assumption now appears questionable.’ Although these inconsistent ages were realized, many argon geochronologists carried out $^{40}$Ar/$^{39}$Ar analyses of phengitic white micas from HP–UHP metamorphic rocks of the Dora–Maira Massif (Western Alps, Italy), providing discordant and geologically meaningless ages ranging from 25 to 320 Ma (cf. Scaillet et al., 1990; Monié and Chopin, 1991; Scaillet et al., 1992; Arnaud and Kelley, 1995; Hammerschmidt et al., 1995; Scaillet, 1996; Di Vincenzo et al., 2006; Schertl and Hammerschmidt, 2016). Discordant and anomalously old ages have also been reported from other HP–UHP metamorphic rocks in many collisional setting metamorphic belts, including the Gran Paradiso Massif and the Sesia–Lanzo Zone of the western Alps, Italy (Ruffet et al., 1995, 1997; Beltrando et al., 2013; Halama et al., 2014), the Su–Lu and Dabies terranes, China (Li et al., 1994; Giogis et al., 2000), the Kaghan Valley, Pakistan.
(Tonarini et al., 1993), the Tso Morari Complex of Himalaya, India (Gouzu et al., 2006b), the Gourma, Mali (Jahn et al., 2001), the Tavsanli Zone, Turkey (Sherlock and Arnaud, 1999), and the Betic Zone, Spain (De Jong et al., 2001). These results were considered to be affected by excess argon (cf. Kelly, 2002), but the explanation for the excess argon that is inherited from the host lithologies remained vague until now.

In this context, the author insists that the closure temperature of 350 °C proposed by the Bern group is too low because the detrital muscas in the metasedimentary rocks were not reset by Alpine metamorphism (Takeshita et al., 1994). Takeshita et al. (1994) carried out K–Ar analyses of phengite separates from Piemonte calcscists of the western Alps. The data yielded variable ages older than Alpine metamorphism in the chlorite and chloritoid zones, proving consistent ages in the rutile zone higher than 450 °C. Villa (1998) examined Jäger’s calibration for the blocking temperatures and refined the closure temperature for the muscovite K–Ar system to 500 °C. Itaya et al. (2009) carried out laser step-heating 40Ar/39Ar analyses of biotite and muscovite crystals from the Barrovian pelitic schist in the eastern Tibetan Plateau, of which the host lithologies have experienced poly-metamorphism, as suggested by multi-chronological studies by Huang et al. (2003) and Wallis et al. (2003). The coexisting biotite and muscovite in sillimanite-grade pelitic schist (T > 600 °C) suggests consistent cooling ages of ~ 40 Ma. On the other hand, biotite and muscovite in the zones of lower grade (T < 500 °C) yield discordant ages due to the excess argon that was likely inherited from pre-metamorphic phases. The above authors suggested that muscovite and biotite in polymetamorphic terranes require higher metamorphic temperatures than are generally accepted to completely reset the Ar isotopic system. Beltrando et al. (2013) carried out in situ 40Ar/39Ar analyses of biotite and muscovite from meta-granites that experienced eclogite facies metamorphism (T = 550 °C) in the Grand Paradiso Massif studied by Chopin and Maluski (1980). The muscovite with typical igneous shape and chemical composition yielded heterogeneous age values, giving an age ranging from 54 to 215 Ma within a single muscovite crystal of a size of approximately 1.2 mm. The author strongly emphasizes that the closure temperature is higher than 550 °C because the Ar isotopic system in muscovite was not reset in the eclogite facies metamorphism, although Beltrando et al. (2013) concluded that ‘None of these age patterns should be interpreted as resulting from volume diffusion alone’. This type of inherited excess argon is discussed in the literature mentioned above because white muscas in continental lithologies, consisting of precursor older rocks, are not reset completely during HP–UHP metamorphism, including the Barrovian type of metamorphism. This is because the closure temperature of white mica is much higher than that generally accepted, being approximately 600 °C (cf. Gouzu et al., 2016) or possibly higher. The problem is to understand why the in situ 40Ar/39Ar ages are heterogeneous in muscovite crystals within a meta-granite that has been metamorphosed under eclogite facies conditions, such as those observed in the Grand Paradiso Massif (see Fig. 8 in Beltrando et al., 2013). Moreover, why is the inherited excess argon amount significantly variable among the phengite crystals from the eclogite, marble and orthogneiss in the UHP unit of the Dora-Maira Massif (see Fig. 10 in Di Vincenzo et al., 2006)? The answer will be described in the later sections on the argon release from phengite with deformation-induced recrystallization and on the argon release mechanism.

ARGON RELEASE FROM PHENGITE BY DEFORMATION-INDUCED RECRYSTALLIZATION

The presence of discordant and anomalously old K–Ar (40Ar/39Ar) phengitic white mica ages in metamorphic rocks has been widely reported in collisional orogenic belts in which lithologies have experienced poly-metamorphism, as described above. These results are likely due to the presence of excess 40Ar trapped in the metamorphic minerals during recrystallization. The author has long considered that no significant amount of excess argon formed in metamorphosed oceanic materials in the Pacific type HP metamorphic belts. This hypothesis was confirmed from systematic phengite K–Ar dating in the metamorphic belts in Japan and New Zealand, which yielded a continuous age spectrum with increasing metamorphic temperatures since the first report by Itaya and Takasugi (1988) (Nishimura et al., 1989, 2000; Miyashita and Itaya, 2002; Nuong et al., 2008, 2011). Gouzu et al. (2006a) showed that most of the phengite in the ocean-derived metamorphic sequence of the Lago di Cignana, Western Alps, Italy (Compagnoni and Rolfo, 2003), is free of excess argon when these lithologies were metamorphosed under UHP conditions. These observations were further confirmed by Gouzu et al. (2016), who carried out systematic K–Ar dating on phengite separates from the Lago di Cignana UHP unit and the adjoining HP meta-ophiolitic lower and upper units, as well as from the blueschist facies calcscists from the Combin unit. Based on the above works, it is clear that phengite in HP–UHP metamorphic sequences such as Sanbagawa and Lago di Cignana are free of excess argon, indicating that phengite K–Ar (40Ar/39Ar) ages are plausible and
useful for understanding regional tectonics.

Itaya and Takasugi (1988) obtained K–Ar analyses of 70 phengite separates from Sanbagawa schists in the chlorite, garnet and biotite zones along a N–S traverse including the Asemi and Saruta areas in central Shikoku, SW Japan (Fig. 1). They found that phengite K–Ar ages are older in zones of rocks of higher grade in the Sanbagawa belt. A similar age–T relation has also been observed in the Suo HP belt of the Nishiki area (Fig. 2B), the Shimanto HP belt in the Kanto Mountains (Fig. 2C) and the Otago schist sequence in New Zealand (Fig. 2D). Considering all regional-scale age-metamorphic gradient relationships, the author concludes...
that the K–Ar phengite ages of the HP schists may have been reset to the closure temperature based on thermally activated diffusion model by Dodson (1973) and may have undergone other resetting–induced processes. Since the closure temperature depends on the radius of diffusion (Dodson, 1973), the closure temperature for phengite may be lower in lower grade schists. This hypothesis, however, was not suitable for the case in the Sanbagawa metamorphic sequence of central Shikoku because phengite from the Chlorite zone, yielding the youngest age, was not always significantly finer compared with those found in the biotite zone where phengite was composed of fine–grained aggregates (0.02–0.06 mm in width and 0.4–1.0 mm in length; Itaya and Fujino, 1999). Figure 1 shows photomicrographs of representative pelitic schists from the chlorite, garnet, albite–biotite, and oligoclase–biotite zones, whose locations are shown in the cross section along a N–S traverse. As evidenced from the photomicrographs (Fig. 1), most of the phengite crystals (in the mica layer) are similar in size irrespective of their occurrence in the garnet and biotite zones, although the former zone is younger than the latter zone according to the K–Ar age. For the cases of the metamorphic sequences shown in Figures 2B–2D, older ages are observed in the lower grade schists. As described above, the closure temperatures of the phengite K–Ar system are approximately 600 °C or higher, suggesting that the schists in all the metamorphic zones shown in Figures 1 and 2 formed at temperatures lower than the closure temperature. This fact makes it difficult to explain the age–metamorphic temperature relations by the theoretical closure temperature model of Dodson (1973). In fact, the radiogenic argon in phengite becomes depleted with deformation depending on the intensity and duration of the deformation. This observation is consistent with the discussion described by Itaya and Takasugi (1988). Although not accepted by scientists who consider only the theoretical closure temperature of Dodson (1973), the author insists that argon depletion from phengite during deformation is a common phenomenon in foliated HP–UHP rocks.

The Sanbagawa HP schists have been strongly deformed, as evidenced by microstructural features such as strong stretching mineral lineation and sheath folding (Faure, 1983, 1985; Wallis, 1990). Wallis et al. (1992) identified the microstructures that were a result of the post-metamorphic stage, and the ductile deformation was interpreted to have occurred during the exhumation and cooling of the HP metamorphic belt. Itaya and Fujino

Figure 2. Age–temperature relations of the Ishigaki (A) and Nishiki (B) metamorphic sequences of the Suo HP schist belt (Nuong et al., 2008), the Shimanto HP metamorphic sequence in the Kanto Mountains (C) (Miyashita and Itaya, 2002) and the Otago schist sequence in New Zealand (D) (Nishimura et al., 2000). The Ishigaki metamorphic sequence indicates that the age becomes progressively older with increasing metamorphic temperature, and the thermal structure is inverted so that the highest–grade zone occurs in the uppermost parts of the apparent stratigraphic succession. The Nishiki, Kanto Mountains and Otago schist metamorphic sequences display younger ages in higher–grade metamorphic rocks. Note that the higher–grade zones occupy a structurally lower portion in the Kanto Mountains.
observed that most phengites in pelitic schists from the biotite zone are fine-grained aggregates in the matrix (0.02–0.06 mm in width and 0.4–1.0 mm in length), as seen in Figure 1, and the size is extremely fine along the domains close to the rigid garnet (Fig. 3A). These microstructures indicate that the size reduction of phengite occurred by strain-induced recrystallization or dynamic recrystallization during deformation accompanied by exhumation. Strain-induced recrystallization promotes the retrograde reaction of phengite because matrix phengite is different in chemistry from that included in garnet, the former having a wide range of Si contents and higher Mg/Fe and Na/K ratios in comparison with the latter (Fig. 4). The heterogeneous chemical features of matrix phengite have also been documented in the UHP rocks of Lago di Cignana, Western Alps (Gouzu et al., 2006a, 2016). Table 1 shows the phengite chemistry of the garnet-phengite schist (Cig02A) from the UHP unit of Lago di Cignana.

Recrystallization with significant re-arrangement of major elements such as Al and Si in phengite crystals should involve argon release from phengite, as trapped argon is not favoured at the K site of phengite and easily diffuses out of the crystal structure. In contrast, phengite inclusions in rigid garnet do not release argon, as documented by Gouzu et al. (2006a). Phengite in the matrix

Figure 3. Photomicrographs under crossed polarized light [(A) and (C)] and plane polarized light [(B) and (D)]. (A) and (B) show pelitic schist (302P) from the albite-biotite zone in the Asemi-gawa unit of the Sanbagawa metamorphic belt, central Shikoku, SW Japan. (C) shows a Sanbagawa amphibolite clast (118955) from the Kuma Group, central Shikoku. (D) show a garnet-phengite schist (Cig02A) from the UHP Lago di Cignana unit, Western Alps. (A) shows that extremely fine-grained phengite occurs close to rigid garnet. (B) shows fine-grained phengite is included in garnet. The phengite separate from sample 302P yielded a K-Ar age of 82.5 ± 1.8 Ma (Itaya and Fujino, 1999). Amphibolite (C) contains coarse-grained phengite, which yielded a laser-probe ⁴⁰Ar/³⁹Ar plateau age of 117.2 ± 1.6 Ma (Nuong et al., 2009). Garnet-phengite schist (D) shows coarse-grained phengite with an equant shape included in garnet and stretched phengite in the matrix. The in situ ⁴⁰Ar/³⁹Ar analyses suggest an age of 36.4 ± 1.4 Ma for the matrix phengite and 43.2 ± 1.1 and 44.4 ± 1.5 Ma ages for the phengite included in garnet (Gouzu et al., 2006a). Grt, garnet; Phe, phengite; Rt, rutile; Hbl, hornblende; Coe, coesite. Color version is available online from https://doi.org/10.2465/jmps.190123.
and as inclusions in garnet show different crystal habits. The former was stretched by deformation during exhumation, whereas the latter (equant shape inclusion) was protected from ductile deformation experienced by the host rock (Fig. 3D). Gouzu et al. (2006a) dated phengite from the matrix and as inclusion in garnet in coesite-bearing garnet gite from the matrix and as inclusion in garnet in coesite the host rock (Fig. 3D). Several types of phengites are distinguished by their fabric. In the histograms, 'G' and 'A' show the phengites included in garnet and albite, respectively. Blank boxes are matrix phengites.

### ARGON RELEASE MECHANISM

Di Vincenzo et al. (2006) carried out in situ $^{40}$Ar/$^{39}$Ar
analyses of phengite from marble, eclogite, and orthogneiss in the UHP unit of the Dora–Maira Massif, Western Alps. They provided in situ ages of phengitic mica flakes cut parallel and perpendicular to the basal cleavage plane (Table 2 and Fig. 5). The eclogite gives an age cluster that is significantly older than those of the marble and orthogneiss, suggesting that the phengites in the rigid eclogite have been protected from deformation and that its argon release was restricted in comparison with that of the phengite in the marble and orthogneiss during the exhumation of the UHP unit. Similar features were observed in mafic rocks (such as amphibolites) in the Sanbagawa HP belt (Fig. 3C). This type of argon release is due to strain–induced recrystallization of phengite during the exhumation of host rocks, as described above. Kramar et al. (2001) carried out in situ Ar–Ar analyses (170 points in total) of deformed muscovite (a coarse mica fish of 3 × 5 mm) from a Variscan granitic pegmatite that experienced greenschist facies metamorphism from the Siviez–Mischabel Nappe, western Swiss Alps. The above authors interpreted those intragrain age variations to be associated with the partial loss of radiogenic argon due to volume diffusion in mica during the Alpine greenschist facies metamorphism (~ 400 °C), and the incipient shear bands enhanced the intragrain loss of radiogenic argon. Kramar et al. (2003) described that the stacking fault enhanced argon diffusion in naturally deformed muscovite. Mulch and Cosca (2004) carried out in situ UV–laser Ar–Ar analyses of deformed muscovite from the Pogallo Shear Zone (Ivrea zone, southern Alps, Italy), indicating that the strongly deformed muscovite porphyroclasts and shear band muscovite display ages consistent with significant argon loss. Cosca et al. (2011) described the effect of deformation on radiogenic argon retention from high-pressure experiments (10 kb and 600 °C over a period of 29 hours, resulting in approximately 10% shortening) performed on rock samples of peraluminous granite containing euhedral muscovite and biotite. Intragrain in situ 40Ar/39Ar analyses on deformed muscovite provided ages from 309 to 264 Ma, consistent with a 0–16% argon loss relative to undeformed muscovite (311 Ma). Cosca et al. (2011) interpreted that the reduction in the effective diffusion length scale in naturally deformed rocks (such as the Variscan granitic pegmatite studied by Kramar et al., 2001) most likely occurs through the production of mesoscopic and submicroscopic defects such as stacking faults. As mentioned above, muscovite in the meta–granitoid in the Grand Paradiso Massif yielded heterogeneous

### Table 2. The in situ 40Ar/39Ar ages of phengites from marble, eclogite, and orthogneiss

|          | Marble       | Eclogite     | Orthogneiss |
|----------|--------------|--------------|-------------|
|          | Parallel     | Perpendicular| Parallel (a) | Parallel (b) | Perpendicular (a) | Perpendicular (b) |                          |
|          | 35.7-62.3 Ma | 35.0-53.3 Ma | 131-155 Ma  | 122-146 Ma  | 94-167 Ma         | 34.8-41.7 Ma         |                          |
|          | (15 points)  | (9 points)   | (9 points)  | (10 points) | (9 points)        | (9 points)          |                          |
|          | total gas age | total gas age | total gas age | total gas age | total gas age | total gas age |                          |
|          | 50.89 ± 0.35 Ma | 45.34 ± 0.33 Ma | 142.6 ± 0.9 Ma | 130.8 ± 0.9 Ma | 134.2 ± 1.0 Ma | 38.52 ± 0.28 Ma |                          |
|          | Ma           | Ma           | Ma           | Ma           | Ma              | Ma             |                          |
| Two types of samples were prepared for in situ dating: phengitic mica flakes cut parallel and perpendicular to the basal cleavage plane.
age values, suggesting 54 to 218 Ma in a muscovite crystal of approximately 1.2 mm in size (see Fig. 8c in Beltrando et al., 2013; Fig. 5). Moreover, the muscovite crystals retain igneous chemistry (low Si: 3.05–3.10 apfu; Ti: 0.02–0.03 apfu) despite having experienced eclogite facies metamorphism at $T = 550 \, ^\circ\text{C}$. The age variation is due to heterogeneous deformation, as evidenced by the presence of submicron–scale defects in the mica of the Variscan granitic pegmatite; these defects could have caused the reduction in the effective diffusion length scale (Cosca et al., 2011). The dated points at the crystal edge are significantly younger than the ages of the portions far from the edge, as seen in Figure 5. These features suggest that the submicroscopic defects occurring near the crystal edges were affected by rubbing with other phases, preferentially enhancing argon release.

The extreme size reduction in phengite observed at domains close to the rigid garnet (Fig. 3A) in the pelitic schists of the Sanbagawa belt is identical to the reduction in the effective diffusion length scale interpreted by Cosca et al. (2011), likely enhancing argon release. The Sanbagawa pelitic schists experienced long-term deformation (6–17 million years) during exhumation and had a slow exhumation rate (lower than 6 mm/y), as described below. In this case, the phengite could have grown with the ‘Ostwald ripening phenomenon’, consuming the extremely fine-grained phengite close to the rigid garnet. The size reduction and ‘Ostwald ripening’ growth could have continued to the final stage of a static phengite crystal size (0.02–0.06 mm in width and 0.4–1.0 mm in length; Itaya and Fujino, 1999) observed in the matrix (Fig. 3A). During these processes, phengite could have experienced chemical changes depending on the local bulk chemistry under $P$–$T$ conditions, changing progressively during exhumation and resulting in a heterogeneous chemistry (Fig. 4). On the other hand, the Lago di Cignana UHP unit experienced relatively quick deformation (shorter than 5 million years) during exhumation and had an extremely fast exhumation rate (15–26 mm/y), as described below. In this case, the phengite crystals could record heterogeneously deformed domains in a crystal as well as among the grains. In fact, the laser step heating $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of a single phengite crystal in the UHP schists of Lago di Cignana provided a significantly irregular age spectrum (Gouzu et al., 2006a) in comparison with the phengite from the Sanbagawa schists, whose age spectra show the perfect plateau for both the phengite separates (Takasu and Dallmeyer, 1990) and a single phengite crystal (Nuong et al., 2009). Figure 6 shows the histogram of the $^{40}\text{Ar}/^{39}\text{Ar}$ ages calculated using each argon release fraction by the laser step-heated $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of the phengite crystals from the garnet–phengite schists (6 crystals), the zoisite–clinozoisite schist (9 crystals) and the piemontite schist (3 crystals) in the Lago di Cignana UHP unit (Gouzu et al., 2006a). The ages with errors larger than ±2 Ma (approximately 5%), due to the extremely small amount of argon extraction during heating, were not used in the diagram. The figure also shows the K–Ar ages of phengite separates (meaning the average of the heterogeneous crystal ages) from the pelitic schists, Mn-rich meta-sediment, piemontite schist and eclogite collected from the same UHP unit by Gouzu et al. (2016).

Figure 6. Histogram of the $^{40}\text{Ar}/^{39}\text{Ar}$ ages calculated using each argon release fraction by the laser step-heated $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of the phengite crystals from the garnet–phengite schist (6 crystals), the zoisite–clinozoisite schist (9 crystals) and the piemontite schist (3 crystals) of the Dora Maira Massif in the Western Alps, and from the same UHP unit by Gouzu et al. (2016).

**EXHUMATION TECTONICS FORMING ‘SLOW’ AND ‘FAST’ SCHISTS**

Multi-stage exhumation models have been proposed for UHP metamorphic sequences in continental collision belts such as the Dora–Maira Massif in the Western Alps,
the Kokchetav massif in Kazakhstan and the Dabie-Sulu Belt in China (cf. Rubatto and Hermann, 2001; Katayama et al., 2001; Hacker et al., 2003; Liu and Liou, 2011). The models consider that the exhumation rates were high from the deepest level to the lower crust but decreased to shallow crustal levels. It has been considered that the Sanbagawa HP belt in central Shikoku consists of rocks of the Early Cretaceous accretionary complex that were metamorphosed at P–T conditions of the pumpellylite–actinolite through epidote–blueschist to epidote-amphibolite facies and up to the eclogite facies during a prograde stage in a subduction zone (cf. Itaya et al., 2011). Recent geochronological data have revealed that this belt consists of three units, Besshi, Asemi–gawa and Oboke, which have significantly different accretional stages and prograde metamorphic stages (cf. Aoki et al., 2019a). The eclogite facies metamorphism of the Besshi and Asemi–gawa units took place at ~130–90 and ~90 Ma, respectively (cf. Aoki et al., 2019b). The Iratsu quartz eclogite in the Besshi unit gives the zircon U–Pb age and garnet–omphacite–whole rock Sm–Nd age of ~120 Ma (cf. Itaya et al., 2011), and the Seba eclogite in the Asemi–gawa unit gives a zircon U–Pb age of ~90 Ma (Aoki et al., 2009). The biotite zone schists in the Asemi–gawa unit and the Iratsu quartz eclogite have recorded the epidote–amphibolite facies overprint at 86 Ma (Aoki et al., 2009) and the amphibolite facies overprint at 109 Ma (Itaya et al., 2011), respectively. The exhumation rates from the deepest level to the lower crust were 6 mm/y for the Asemi–gawa unit and 4.5 mm/y for the Iratsu quartz eclogite, which are calculated from the peak P–T conditions estimated by Aoki et al. (2009) and by Miyamoto et al. (2007), respectively (Fig. 7A). The exhumation rates of the garnet and chlorite zones were less than 6 mm/y, as deduced from the long-term deformation during the exhumation; in particular, the exhumation rate was extremely low in the chlorite zone. These low exhumation rates suggest a slow strain rate during rock deformation, resulting in the ‘slow schist’ sequence with the recumbent fold structure proposed by Hide (1954), Higashino (1975, 1990), and Banno et al. (1978) followed by Itaya and Takasugi (1988) and Itaya et al. (2011).

In the Lago di Cignana HP–UHP metamorphic sequence in the western Alps, the UHP unit and the adjoining HP meta–ophiolitic lower (LU) and upper (UU) units, as well as the blueschist facies calc-schists from the Combina unit (CU), yielded similar ages (Gouzu et al., 2016; Fig. 7B). This makes it possible to interpret that these units formed as a series of metamorphic sequences in the Piemonte–Liguria paleo–subduction zone and first exhumed together, but then the UHP unit exhumed more rapidly in comparison to the UU, LU, and CU to create the present structural sequence. The differences between the K–Ar phengite ages of each unit and the peak age (44 Ma) deduced from SHRIMP U–Pb zircon analyses (Rubatto et al., 1998) and from the in situ 40Ar/39Ar analyses of the phengite included in garnet (Gouzu et al., 2006a) are 3–5, 6–7, 3–6, and 4–8 Myr for the UH,P, LU, and CU units, respectively. This indicates that the duration of deformation was significantly shorter than that (6–17 Myr: Fig. 7A) of the Asemi–gawa unit of the Sanbagawa HP belt in SW Japan, suggesting high exhumation rates for the Lago di Cignana HP–UHP units. The exhumation rates from the deepest level deduced from the peak P–T conditions by Groppo et al. (2009) to the lower crust level are 15–26, 9–11, and 8–16 mm/y for the UH,P, LU, and CU units, respectively (Fig. 7B). The rate of the CU unit deduced from the peak P–T condition suggested by Cartwright and Barnicoat (2002) is 1.3–2.5 mm/y. These high exhumation rates, consistent with the rapid exhumation described by Amato et al. (1999), suggest a high strain rate during rock deformations, making the ‘fast schist’ sequence composed of several units of which the boundaries are distinct faults (Fig. 7B). The Lago di Cignana HP–UHP units and Sanbagawa HP schist belt both consist of metamorphosed oceanic lithologies that usually record only a single metamorphic cycle, although the former has been considered to be part of a collisional orogeny. Thus, these metamorphic belts also have experienced a multi-stage exhumation process, although early-stage exhumation rates varied significantly. The high exhumation rate of the Lago di Cignana HP–UHP units may be due to the subsequent continental collision event because the Sanbagawa HP schist belt in central Shikoku, SW Japan, did not experience this subsequent continental collision event.

**SUMMARY**

The presence of discordant and anomalously old K–Ar (40Ar/39Ar) phengitic white mica ages in metamorphic rocks has been widely reported in collisional orogenic belts. These results are likely due to the presence of excess 40Ar trapped in the metamorphic minerals during recrystallization. This type of inherited excess argon is due to the fact that white micas in continental lithologies derived from precursor older rocks were not reset completely during HP–UHP metamorphism because the closure temperature of white mica is much higher than that generally accepted, approximately 600 °C. On the other hand, HP–UHP metamorphic rocks commonly experienced severe ductile deformation during their exhumation. The phengite in the HP–UHP schists also experienced deformation–induced (dynamic) recrystallization.
and chemical change depending on the local bulk chemistry under the progressively changing $P$-$T$ conditions during exhumation. Radiogenic argon is released from deformed phengite, as documented by a comparison of the in situ $^{40}$Ar/$^{39}$Ar dating of phengite with equant shapes included in rigid garnet and stretched phengite in the matrix. The inconsistent ages observed among the rock samples with the same $P$-$T$-$t$ history and in a single phengite crystal are due to the heterogeneous deformation among the samples and the crystal domains. The duration of deformation during exhumation spans a period from the peak metamorphism to the end of deformation in the crust, making it possible to calculate the exhumation rates of HP-UHP metamorphic belts consisting of metamorphosed oceanic lithology without excess argon. The Sanbagawa belt, SW Japan, experienced exhumation rates from the deepest level to the lower crust of 4.5 mm/y for the Iratsu quartz eclogite in the Besshi unit and 6 mm/y for the biotite zone in the Asemi-gawa unit, and the exhumation rates were less than 6 mm/y for the lower grade zones. In the Lago di Cignana of the Western Alps, Italy, the early stage of exhumation from the deepest level to the lower crust level had exhumation rates of 15–26, 8–16, and 1.3–2.5 mm/y for the UHP rock...
and the adjoining HP meta-ophiolitic and blue schist units, respectively. The slow exhumation rates of the Sanbagawa belt suggest a low strain rate during rock deformation, resulting in the ‘slow schist’ sequence with recumbent fold structures. The high rates of exhumation in Lago di Cignana suggest a high strain rate during rock deformation, resulting in the ‘fast schist’ sequence consisting of several units of which the boundaries are distinct faults. The high exhumation rates in Lago di Cignana HP-UHP units could be attributed to the continental collision event that is not observed in the Sanbagawa HP schist belt.

ACKNOWLEDGMENTS

The author sincerely thanks his colleagues (Takasugi, H., Hyodo, H., Takeshita, H., Okada, T., Fukui, S., Fujino, M., Shimoya, H., Kim, S.W., Gouzu, C., Yagi, K., Nuong, N.D., Thanh, N.X.) who helped him in the field survey, thin section preparation, Electron Micro Probe analyses, and K-Ar (40Ar/39Ar) dating, and gave valuable comments and kind advice during his long research work. Compagnoni, R. and Rehman, H.U. read carefully the early version of the manuscript and gave the nice comments and suggestions that improved the manuscript. Higashino, T. and Enami, M. provided thin sections from their collection of the Sanbagawa schists in the Asemi area of central Shikoku, SW Japan. The author thanks them. This research was financially supported by the JSPS KAKENHI Grant Numbers JP20244087, JP06554022, and JP63540616. The author acknowledges JSPS KAKENHI Grant Numbers JP20244087, and JP63540616. The author acknowledges a reviewer who critically reviewed the manuscript and is also grateful for M. Satish Kumar and Zähringer, J. Eds.). Springer, 117 – 133.

SUPPLEMENTARY MATERIAL

Color version of Figures 1 and 3 is available online from https://doi.org/10.2465/jmps.190123.

REFERENCES

Aldrich, L.T. and Nier, A.O. (1948) Argon-40 in potassium minerals. Physical Review 74, 876 – 877.
Armstrong, R.L. (1966) K-Ar dating of plutonic and volcanic rocks in orogenic belts. In Potassium–Argon Dating (Schaeffer, O.A. and Zähringer, J. Eds.). Springer, 117 – 133.
Aoki, K., Kitajima, K., Masago, H., Kon, Y., et al. (2009) Metamorphic P-T-time history of the Sanbagawa belt in central Shikoku, Japan and implication for retrograde metamorphism during exhumation. Lithos, 113, 393–407.
Aoki, K., Seo, Y., Sakata, S., Obayashi, H., et al. (2019a) U-Pb zircon dating of the Sanbagawa metamorphic rocks in the Besshi-Asemi-gawa region, central Shikoku, Japan, and tecotonostro-stratigraphic consequences. Journal of Geological Society of Japan, 125, 183–194.
Aoki, S., Aoki, K., Tsueihiya, Y. and Kato, D. (2019b) Constraint on the eclogite age of the Sanbagawa metamorphic rocks in central Shikoku, Japan. International Geology Review, DOI: 10.1080/00206814.2019.1581997.
Amato, J.M., Baumgartner, L. and Beard, B. (1999) Rapid exhumation of the Zermatt-Sass ophiolite deduced from high-precision Sm-Nd and Rb-Sr geochronology. Earth and Planetary Science Letters, 171, 425–438.
Arnaud, N.O. and Kelley, S. (1995) Evidence for excess Ar during high pressure metamorphism in the Dora Maira (western Alps, Italy), using a Ultra-Violet Laser Ablation Microprobe 40Ar-39Ar technique. Contributions to Mineralogy and Petrology, 121, 1–11.
Banno, S., Higashino, T., Otsuki, M., Iiwa, T. and Nakajima, T. (1978) Thermal structure of the Sanbagawa metamorphic belt in central Shikoku. Journal of Physics of Earth, 26 (Suppl.), S345–S356.
Beltran, M., Di Vincenzo, G. and Ferraris, C. (2013) Preservation of sub-microscopic structural relics in micas from the Gran Paradiso Massif (Western Alps): Implications for 40Ar-39Ar geochronology. Geochimica et Cosmochimica Acta, 119, 359–380.
Cartwright, I. and Barnicoat, A.C. (2002) Petrology, geochronology, and tectonics of shear zones in the Zermatt–Saas and Combini zones of the Western Alps. Journal of Metamorphic Geology, 20, 263–281.
Chopin, C. and Maluski, H. (1980) 40Ar-39Ar dating of high pressure metamorphic micas from the Gran Paradiso area (Western Alps): Evidence against the blocking temperature concept. Contributions to Mineralogy and Petrology, 74, 109–122.
Compagnoni, R. and Rolfo, F. (2003) UHPM units in the Western Alps. In Ultrahigh Pressure Metamorphism (Carswell, D.A. and Compagnoni, R. Eds.). EMU Notes in Mineralogy, 5, 13–49. Eötvös University Press, Budapest.
Cosca, M.A., Sunitiz, H., Bourgeois, A.-L. and Lee, J.P. (2011) 40Ar* loss in experimentally deformed muscovite and biotite with implications for 40Ar/39Ar geochronology of naturally deformed rocks. Geochimica et Cosmochimica Acta, 75, 7759–7778.
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, 178, 159–195.
Di Vincenzo, G., Tonarini, S., Lombardo, B., Castelli, D. and Ortolini, L. (2006) Comparison of 40Ar-39Ar and Rb-Sr data on phengites from the UHP Brossasco-Iasaca Unit (Dora Maira Massif, Italy): Implications for dating white mica. Journal of Petrology, 47, 1439–1465.
Dodson, M.H. (1973) Closure temperature in cooling geochronological and petrological systems. Contributions to Mineralogy and Petrology, 40, 259–274.
Faure, M. (1983) Eastward ductile shear during the early tectonic phase in the Sanbagawa belt. Journal of Geological Society of Japan, 89, 319–329.
Faure, M. (1985) Microtectonic evidence for eastward ductile shear in the Jurassic orogen of S. W. Japan. Journal of Structural Geology, 7, 175–186.
Geyh, M.A. and Schleicher, H. (1990) Absolute Age Determina-
Halama, R., Cosca, M. and Li, S. (2000) Distribution and significance of extraneous argon in UHP eclogite (Sulu terrain, China): insight from in situ $^{40}\text{Ar}/^{39}\text{Ar}$ UV laser ablation analysis. Earth and Planetary Science Letters, 181, 605–615.

Gouzu, C., Itaya, T., Hyodo, H. and Matsuda, T. (2006a) Excess $^{40}\text{Ar}$-free phengite in ultrahigh-pressure metamorphic rocks from the Lago di Cignana area, Western Alps. Lithos, 92, 418–430.

Gouzu, C., Itaya, T., Hyodo, H. and Ahmad, A.T. (2006b) Cretaceous isochron ages from K–Ar and Ar–Ar dating of eclogitic rocks in the Tso Moriri complex, western Himalaya, India. Gondwana Research, 9, 426–440.

Hirajima, T., Isono, T. and Itaya, T. (1992) K-bagawa schists, Japan and argon depletion during cooling and deformation. Contributions to Mineralogy and Petrology, 100, 281–290.

Itaya, T. and Fujino, M. (1999) K–Ar age-chemistry–fabric relations of phengite from the Sanbagawa high-pressure schists, Japan. Island Arc, 8, 523–536.

Itaya, T., Hyodo, H., Tsujimori, T., Wallis, S., et al. (2009) Regional-Scale Excess Ar wave in a Barrovian type metamorphic belt, eastern Tibetan Plateau. Island Arc, 18, 293–305.

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, 42, 1075–1090.

Jahn, B.M., Caby, R. and Monié, P. (2001) The oldest UHP eclogites of the World: age of UHP metamorphisim, nature of protoliths and tectonic implications. Chemical Geology, 178, 143–158.

Kaneoka, I. (1998) Numerical dating: From a decade to 46 hundred million years ago. pp. 315, University of Tokyo Press (ISBN4-13-060722-7).

Katayama, I., Maruyama, S., Parkinson, C.D., Terada, K. and Sano, Y. (2001) Ion microprobe U-Pb zircon geochronology of peak and retrograde stages of ultrahigh-pressure metamorphic rocks from the Kokchetav Massif, northern Kazakhstan. Earth and Planetary Science Letters, 188, 185–198.

Kelly, S. (2002) Excess argon in K–Ar and Ar–Ar geochronology. Chemical Geology, 188, 1–22.

Kramar, N., Cosca, M.A. and Hunziker, J.C. (2001) Heterogeneous $^{40}\text{Ar}$ distributions in naturally deformed muscovite: in situ UV laser ablation evidence for microstructurally controlled intragrain diffusion. Earth and Planetary Science Letters, 192, 377–388.

Kramar, N., Cosca, M.A., Buffat, P.-A. and Baumann, L.P. (2003) Stacking fault-enhanced argon diffusion in naturally deformed muscovite. Geological Society, London, Special Publications, 220, 249–260.

Li, S., Wang, S., Chen, Y., Liu, D., et al. (1994) Excess argon in phengite from eclogite: Evidence from dating of eclogite minerals by Sm-Nd, Rb-Sr and $^{40}\text{Ar}/^{39}\text{Ar}$ methods. Chemical Geology, 112, 343–350.

Liu, F.L. and Liou, J.G. (2011) Zircon as the best mineral for $P$–$T$ history of UHP metamorphism: a review on mineral inclusions and U-Pb SHRIMP ages of zircons from the Dabie–Sulu UHP rocks. Journal of Asian Earth Sciences, 40, 1–39.

McDonald, C.S., Warren, C.J. and Hanke, F. (2019) Determining cooling rates from Ar/Ar thermochronology data: Effect of cooling path shape. Terra Nova, 31, 234–246.

Megrue, G.H. (1973) Spatial distribution of $^{40}\text{Ar}/^{39}\text{Ar}$ ages in the Dora Maira massif, western Alps. European Journal of Mineralogy, 3, 239–262.

Mulch, A. and Cosca, M.A. (2004) Recrystallization or cooling
ages: in situ UV-laser $^{40}\text{Ar}^{39}\text{Ar}$ geochronology of muscovite in mylonitic rocks. Journal of the Geological Society, 161, 573–582.

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

Nishimura, Y., Coombs, D.S., Landis, C.A. and Itaya, T. (2000) Continuous metamorphic gradient documented by graphitic zircon and K–Ar age, southeast Otago, New Zealand. American Mineralogist, 85, 1625–1636.

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, 145, 677–684.

Nuong, N.D., Itaya, T., Hyodo, H. and Yokoyama, K. (2009) K–Ar and Ar/Ar phengite ages of Sanbagawa schist clasts from the Kuma Group, central Shikoku, southwest Japan. Island Arc, 18, 282–292.

Nuong, N.D., Than, N.X., Gouzu, C. and Itaya, T. (2011) Phengite geochronology of the crystalline schists in the Sakumatenryu district, central Japan. Island Arc, 20, 401–410.

Rubatto, D., Gehauer, D. and Fanning, M. (1998) Jurassic formation and Eocene subduction of the Zermatt-Saas-Fee ophiolites: implications for the geodynamic evolution of the Central and Western Alps. Contributions to Mineralogy and Petrology, 132, 269–287.

Rubatto, D. and Hermann, J. (2001) Exhumation as fast as subduction? Geology, 29, 3–6.

Ruffet, G., Féraud, G., Ballèvre, M. and Kienast, J.R. (1995) Plateau ages and excess argon in phengites: an $^{40}\text{Ar}^{39}\text{Ar}$ laser probe study of Alpine micas (Sessa zone, Western Alps, northern Italy). Chemical Geology, 121, 327–343.

Ruffet, G., Gruau, G., Ballèvre, M., Féraud, G. and Philippot, P. (1997) Rb-Sr and $^{40}\text{Ar}^{39}\text{Ar}$ 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, 141, 1–18.

Scaillet, S., Féraud, G., Lagabrielle, Y., Ballèvre, M. and Ruffet, G. (1990) $^{40}\text{Ar}^{39}\text{Ar}$ laser–probe dating by step-heating and spot-fusion of phengites from the Dora Maira nappe of the western Alps, Italy. Geology, 18, 741–744.

Scaillet, S., Féraud, G., Ballèvre, M. and Amourie, M. (1992) Mg/Fe and [(Mg,Fe)Si]–Al2 complex compositional control on Ar behaviour in high-pressure white micas: a $^{40}\text{Ar}^{39}\text{Ar}$ continuous laser probe study from the Dora-Maira nappe of the internal western Alps, Italy. Geochimica et Cosmochimica Acta, 56, 2851–2872.

Scaillet, S. (1996) Excess $^{40}\text{Ar}$ 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, 60, 1075–1090.

Schertl, H.-P. and Hammerschmidt, K. (2016) Tracking the incidence of excess argon in white mica Ar–Ar data from UHP conditions to upper crustal levels in the Dora-Maira Massif, Western Alps. European Journal of Mineralogy, 28, 1255–1275.

Sherlock, S.C. and Arnaud, N.O. (1999) Flat plateau and impos-sible isochrons: Apparent $^{40}\text{Ar}^{39}\text{Ar}$ geochronology in a high-pressure terrain. Geochimica et Cosmochimica Acta, 63, 2835–2838.

Takasu, A. and Dallmeyer, R.D. (1990) $^{40}\text{Ar}^{39}\text{Ar}$A mineral age constraints for the tectonothermal evolution of the Sanbagawa metamorphic belt, central Shikoku, Japan: A Cretaceous accretionary prism. Tectonophysics, 185, 111–139.

Takeshita, H., Shimoya, H. and Itaya, T. (1994) White mica K–Ar ages of blueschist-facies rocks from the Piemeonte “calcschists” in the western Italian Alps. The Island Arc, 3, 151–162.

Takeshita, T., Yagi, K., Gouzu, C., Hyodo, H. and Itaya, T. (2015) Extensive normal faulting during exhumation revealed by the spatial variation of phengite K–Ar ages in the Sambagawa metamorphic rocks, central Shikoku, SW Japan. Island Arc, 24, 245–262.

Tonarini, S., Villa, I.M., Oberti, F., Meier, M., et al. (1993) Eocene age of eclogite metamorphism in Pakistan Himalaya: Implications for India-Eurasia collision. Terra Nova, 5, 13–20.

Villa, I.M. (1998) Isotopic closure. Terra Nova 10, 42–47.

Wallis, S.R. (1990) The timing of folding and stretching in the Sanbagawa belt: the Asemigawa region, central Shikoku. Journal of Geological Society of Japan, 96, 345–352.

Wallis, S.R., Banno, S. and Radvanec, M. (1992) Kinematic, structural and relationship to metamorphism of the east-west flow in the Sanbagawa belt, south-west Japan. Island Arc, 1, 176–185.

Wallis, S., Tsujimori, T., Aoya, M., Kawakami, T., et al. (2003) Cenozoic and Mesozoic metamorphism in the Longmenshan orogen: Implications for geodynamic models of eastern Tibet. Geology, 31, 745–8.

Warren, C.J., Hanke, F. and Kelley, S.P. (2012) When can muscovite $^{40}\text{Ar}^{39}\text{Ar}$ dating constrain the timing of metamorphic exhumation? Chemical Geology, 291, 287–292.

Wasserburg, G.J. and Hayden, R.J. (1955) $^{40}\text{Ar}^{39}\text{Ar}$ geochronology in a high-pressure terrain. Geochimica et Cosmochimica Acta, 7, 51–60.

Manuscript received January 23, 2019
Manuscript accepted February 1, 2020

Manuscript handled by M. Satish-Kumar
APPENDIX

BLOCKING AND CLOSURE TEMPERATURES OF WHITE MICA K–Ar SYSTEM

The concept of ‘closure temperature’ was first examined by Armstrong (1966). The basic idea is that when a rock cools to a particular temperature, the diffusion of radiogenic isotopes will cease. On the other hand, researchers at Bern proposed a ‘blocking temperature’ for isotopic closure ages, as hypothesized by Villa (1998), although the present author could not find their original description in the literature. According to the review comments by an argon geochronologist (anonymous), the blocking temperature was defined by the Bern Group by considering the magnetic blocking in minerals and calibrated using the combined method of the K–Ar analyses and metamorphic petrology in the central Alps where the pre-Alpine ages were reset due to an increase in the overprinting temperatures. The blocking temperature of the K–Ar muscovite system was proposed to be 350 °C. This blocking temperature can be considered to be an empirical closure temperature, although the reviewer emphasized that the blocking temperature and the closure temperature are fundamentally different in definition and boundary conditions and should not be compared. In fact, later studies and textbooks referred to 350 °C as the closure temperature of the K–Ar muscovite system, as described in this paper. However, this value is not consistent with the recent geochronological results and metamorphic conditions for the western Alps, as described in this paper.

Dodson (1973) formulated the closure temperature based on a thermally activated diffusion model. The following equations are given from Dodson’s model.

\[ D = D_0 \exp\left(-\frac{E}{R T}ight), \quad \frac{E}{R T_c} = \ln\left(\frac{A D_0}{a^2}\right), \quad \tau = -\frac{R T_c^2}{E} \left(\frac{dT}{dt}\right), \]

where \( D \) is the diffusion coefficient, \( D_0 \) is the diffusion pre-exponential factor, \( R \) is the gas constant, \( E \) is the activation energy, \( a \) is the diffusion (or grain) radius, \( A \) is a grain-shape-related constant, \( T_c \) is Dodson’s closure temperature, and \( \tau \) relates \( T_c \) to the cooling rate \( (dT/dt) \).

The Dodson \( T_c \) formulation is underpinned by the several important assumptions and approximations provided below (McDonald et al., 2019).

1. Thermally activated volume diffusion was the only mechanism by which the daughter isotope was mobilized within the mineral.
2. The mineral crystallized with no inherited daughter isotope.
3. A daughter isotope concentration of zero was maintained at the mineral grain boundary throughout cooling.
4. The starting temperature was high enough for diffusion of the daughter isotope to be efficient and for removal from the grain to be geologically instantaneous.
5. The cooling path from the time of crystallization to the time of closure conformed to a \( 1/t \) shape (where \( t \) is time).

The above three equations suggest that Dodson’s closure temperature depends on the diffusion radius \( a \) and the cooling rate \( (dT/dt) \), even if other parameters such as the diffusion coefficient and activation energy were constrained well by the experiments (cf. Harrison et al., 2009), and the assumptions and approximations mentioned above were reasonable. These assumptions lead to difficulties in estimating the cooling rates and exhumation history of metamorphic rocks, although some recent studies have attempted to do so (cf. Warren et al 2012; McDonald et al., 2019). In addition, other difficulties arise when applying Dodson’s closure temperature model in metamorphic systems. For example, the second assumption (the mineral crystallized with no inherited daughter isotope) is not valid because the HP–UHP metamorphic rocks in the collisional setting of the metamorphic belts commonly give discordant and anomalously old (meaningless) ages in K–Ar \(^{40}\text{Ar}/^{39}\text{Ar} \) dating, as described in this paper. This issue is due to the excess argon inherited from white micas in continental lithologies consisting of precursor older rocks that have not been reset completely during metamorphism. Another problem is the radiogenic argon release from the phengite that experienced deformation–induced recrystallization during the exhumation of the HP–UHP metamorphic rocks. This paper focuses mainly on this problem, which should be examined in detail to accurately determine the exhumation history.