$^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock dating of metapelites from the Mikabu and Sambagawa Belts, western Kii Peninsula, Southwest Japan

Koen de Jong,
Chikao Kurimoto*
and Phil Guise***

Received October 18, 1999.

Accepted May 17, 2000.

* Geological Survey of Japan, Geology
Department Higashi 1-1-3, Tsukuba, Ibaraki
305-8567, Japan

** Department of Earth Sciences, Leeds Uni-
versity Leeds LS2 9JT, England

Abstract

$^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock age spectra have been obtained from three metapelite samples from the Mikabu and Sambagawa Belts in the western Kii Peninsula (Wakayama Prefecture) as a feasibility study. All samples yielded 2σ plateau ages and the integrated $^{40}\text{Ar}/^{39}\text{Ar}$ ages are concordant with the K-Ar ages reported by Kurimoto (1993).

A phyllite with a shear band cleavage from the spotted zone of the Sambagawa Belt (Iimori Unit) yielded a plateau age of 73.0 ± 0.8 Ma (82% ^{39}Ar release). This result is interpreted as the age of the isotopic closure of white mica during retrograde recrystallization in this greenschist facies metamorphic rock. Two slate samples from the Mikabu Belt (Kebara Unit) yielded 96.4 ± 1.0 Ma (54% ^{39}Ar release) and 102.9 ± 1.0 Ma (49% ^{39}Ar release) plateau ages. The 7 Ma age difference between the Kebara samples may be interpreted by the smaller grain size of the white mica in the youngest sample. Alternatively, the age difference indicates that the main tectono-metamorphic recrystallization in both samples did not occur at the same time. Both interpretations imply that the main tectono-metamorphic phase in the Kebara Unit occurred significantly earlier than in the Iimori Unit.

The age spectra of the Kebara samples show progressively increasing apparent ages during early incremental degassing climbing to age plateaux at intermediate- and high-temperature ^{39}Ar release. Such staircase age spectra may be interpreted by partial loss of radiogenic ^{40}Ar due to thermo-tectonic resetting related to movement along the Aridagawa Tectonic Line, that runs parallel to the Kebara Unit.

Key words: $^{40}\text{Ar}/^{39}\text{Ar}$ dating, whole-rocks, partial resetting, Sambagawa Belt, Sanbagawa Belt, Mikabu Belt, Kebara Unit, Iimori Unit, Kii Peninsula

Introduction

In order to date tectono-metamorphic processes, isotopic analysis of individual minerals is usually preferred. However, as the grain-size of (very) low-grade metapelites is too small for a successful mineral separation, K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations have to be carried out on whole-rock samples instead. Whole-rocks consist of mixed minerals, thus the application of these dating methods to such samples, clearly, is only successful if the radiogenic argon ($^{40}\text{Ar}^*$) of the original detrital minerals is completely outgassed during tectono-metamorphic processes (Dodson and Rex, 1971). Studies by Leitch and McDougall (1979) and Hunziker et al. (1986) implied that inherited argon

of detrital minerals is usually completely outgassed when rocks have been deformed and metamorphosed at temperatures above 300–350°C. McDougall and Harisson (1988) argued that it is unlikely that dating of whole-rocks will yield a unique age of a tectono-metamorphic event, even if complete outgassing of preexisting argon occurred, because the timing of closure of minerals will depend on the cooling rate of rocks, as well as on the chemical composition and grain size of minerals. Villa (1998) has stressed that isotope transport, and thus closure of radiogenic systems, is strongly dependent on fluid circulation and recrystallization and that temperature is not a rate-controlling parameter when such fast mechanisms are operative. It has been shown that chemical and struc-

Fig. 1. Geological map of the northern Wakayama Prefecture (western Kii Peninsula) with the location of the dated samples (SAM 1, KEB 1 and KEB 2). The area is characterised by major fault zones, indicated by thick lines, that separate the principal tectonic units: MTL=Median Tectonic Line, ATL=Aridagawa Tectonic Line and BTL=Butsuzo Tectonic Line. Modified from Kurimoto (1995), Kurimoto et al. (1998) and Awan and Kimura (1996).

tural recrystallization of white mica have a pronounced effect on the age of the mineral (Wijbrans and McDougall, 1986 ; Itaya and Takasugi, 1988 ; Villa, 1998 ; Itaya and Fujino, 1999 ; de Jong et al., 2000).

To enable $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating, samples are irradiated with neutrons, during which $^{39}\text{Ar}_\text{K}$, $^{38}\text{Ar}_\text{Cl}$ and $^{37}\text{Ar}_\text{Ca}$ are produced from respectively ^{39}K , ^{37}Cl and ^{40}Ca (McDougall and Harisson, 1988). The apparent age of each heating increment can be calculated from the measured $^{40}\text{Ar}^*/^{39}\text{Ar}_\text{K}$ ratio, on the assumption that the trapped argon has an atmospheric ratio. The $^{40}\text{Ar}/^{39}\text{Ar}$ technique also permits an isochron calculation, using three argon isotopes, that does not rely on this assumption (Roddick et al., 1980 ; McDougall and Harisson, 1988). In contrast to conventional K-Ar dating, the $^{40}\text{Ar}/^{39}\text{Ar}$ technique potentially permits to indicate whether or not radiogenic argon is distributed homogeneously in samples (Scaillet et al., 1990 ; de Jong et al., 1992) and to monitor partial $^{40}\text{Ar}^*$ loss that makes ages younger (McDougall and Harisson, 1988 ; Muecke et al., 1988 ; Reuter and Dallmeyer, 1989). The $^{37}\text{Ar}_\text{Ca}/^{39}\text{Ar}_\text{K}$ of each heating increment gives information on the Ca/K ratio of the degassing material. This characteristic allows in (very) low-grade whole-rock samples to evaluate the contribution of older detrital minerals, like feldspars, that degas at higher temperature than colourless mica (McDougall and Harisson, 1988 ; Reuter and Dallmeyer, 1989 ; Dallmeyer and Takasu, 1992), or chlorite that degasses at lower temperature (Muecke

et al., 1988 ; Dallmeyer and Nance, 1994) and that have different Ca/K ratios.

The geochronological database of the western part of the Kii Peninsula (Wakayama Prefecture) almost exclusively consists of K-Ar ages. To solve the potential problems related to the presence of detrital minerals and partial $^{40}\text{Ar}^*$ loss, we initiated a $^{40}\text{Ar}/^{39}\text{Ar}$ dating programme in the western Kii Peninsula. As a feasibility study we selected three whole-rock samples from the Sambagawa and Mikabu Belts that have been previously dated by the K-Ar method (Kurimoto, 1993).

Regional geology

The Sambagawa Belt occurs to the South of the Median Tectonic Line (MTL ; Fig. 1), in the so-called Outer Zone. The belt consists of a thick and coherent, laterally consistent lithological sequence of metasediments, in which metabasic rocks and serpentinite blocks occur (Fig. 1, Barber, 1982 ; Banno and Sakai, 1989 ; Takasu and Dallmeyer, 1990). The belt is generally characterised by a HP-intermediate type metamorphism of Cretaceous age (Banno, 1964 ; Hada, 1967 ; Nakajima, 1997). In the western Kii Peninsula the Sambagawa metamorphic sequence is subdivided into the Iimori and the Tomobuchi Units (Fig. 1). The former unit comprises higher grade siliceous and psammitic schists with lenses of pervasively serpentinitised ultramafic rocks. (Fig. 1, Kurimoto, 1995 ; Takasu et al., 1996 ; Kurimoto et al., 1998). The

maximum temperature of the Iimori Unit might have been about 440°C (Takasu et al., 1996). The latter unit mainly consists of a monotonous series of graphite-bearing metapelites with subordinate cherts and foliated greenstones, belonging to the chlorite zone.

The Mikabu Belt occurs discontinuously along the boundary between the Sambagawa and Northern Chichibu Belts (Kojima, 1950; Hada, 1967; Suzuki, 1967). The Mikabu Belt of the western Kii Peninsula has been subdivided into four lithological units by Kurimoto (1995). The Kebara Unit, from which samples were collected, crops out between the Sambagawa and Northern Chichibu Belts at the eastern termination of the Mikabu Belt in western Kii (Fig. 1). It consists principally of metapelites and foliated greenstones, with rare chert and limestone blocks.

The Northern Chichibu Belt, that consists of virtually unmetamorphosed to chlorite zone metapelites, has been considered as an outlier of the Jurassic accretionary complex of the Inner Zone (Barber, 1982; Faure et al., 1986; Isozaki et al., 1990). Banno (1998) and Suzuki and Ishizuka (1998) emphasize that the northernmost part of the belt contains similar metamorphic mineral assemblages as the Mikabu Belt.

The early Middle Cretaceous to early Miocene Shimanto Belt is the structurally lowest accretionary complex of the Outer Zone (Awan and Kimura, 1996; Kurimoto et al., 1998 and references therein).

In the western Kii Peninsula the boundaries between the Chichibu, Mikabu and Shimanto Belts are formed by generally steeply dipping fault zones (Fig. 1): the Aridagawa Tectonic Line (ATL) and the Butsuzo Tectonic Line (BTL), along which deformed, non-metamorphic Cretaceous sediments occur locally (Hada, 1967; Yamato Omine Res. Group, 1981; Kurimoto, 1986, 1993). The generally ENE-WSW striking and steeply northward dipping ATL is a 50-60 m wide fault zone in which fault gauges and cataclasites are locally developed (Hada, 1967; Kurimoto, 1994). The rocks close to the ATL are often strongly affected by flexural slip folds that are associated with faults.

Previous geochronology

K-Ar phengite ages in the Sambagawa Belt are confined to the 60-90 Ma range in Shikoku (Itaya and Takasugi, 1988), the Kanto Mountains (Hirajima et al., 1992) and the Kii Peninsula (Hara et al., 1992; Takasu et al., 1996). Careful petrography and electron probe micro analysis permitted Itaya and Fukui (1994) to constrain the influence of detrital muscovite on the K-Ar age of white mica concentrates. In central Shikoku $^{40}\text{Ar}/^{39}\text{Ar}$ ages have been obtained for muscovite (75-90 Ma), hornblende (78-95 Ma) and for whole-rocks (70-77 Ma) of the lower-chlorite zone (Monié et al., 1987; Takasu and Dallmeyer, 1990). $^{40}\text{Ar}/^{39}\text{Ar}$

whole-rock plateau ages of the southernmost Sambagawa Belt, adjacent to the Mikabu and Northern Chichibu Belts, are 85 to 97 Ma (Takasu and Dallmeyer, 1990; Dallmeyer et al., 1995).

In the western Kii Peninsula low-grade metapelites of the Tomobuchi unit yielded K-Ar whole-rock ages between 69 and 97 Ma, the oldest of which occur adjacent to the Mikabu Belt (Kurimoto, 1993, 1995). K-Ar whole-rock ages of the Iimori Unit are between 72 and 74 Ma (Kurimoto, 1993, 1995), consistent with 75-77 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of white mica (Takasu et al., 1996) from the unit.

Rocks of the Mikabu Belt in Kii have K-Ar ages of 89-98 Ma, except for one sample which yielded an age as old as about 125 Ma (Kurimoto, 1993, 1995). In Shikoku, two Mikabu whole-rock samples yielded 96 and 98 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages (Takasu and Dallmeyer, 1990; Dallmeyer et al., 1995).

Sample description

SAM 1 is a platy, quartz-rich albite-bearing mica schist that is derived from the Iimori Unit (Fig. 1). The principal foliation is a well expressed quartz-mica differentiated layering, that is cut by a shear band cleavage. It has a well developed stretching lineation defined by elongated quartz, white mica and albite. White mica occurs as well crystallised 200-1,000 μm long grains and finer-grained aggregates parallel to the tectonic foliation. Quartz has a well expressed lattice preferred orientation and occurs as elongated, strain-free 200-300 μm diameter grains that form an annealed structure (Hobbs et al., 1976). Adjacent to shear bands this equilibrium texture is overprinted. Quartz grains shows dynamic recrystallization and are subdivided into smaller equigranular sub grains and new grains, that define an oblique secondary fabric. White mica is strongly affected by lattice bending and boudinage. Retrograde chlorite occurs in and adjacent to the shear bands, where the mineral grew parallel to (001) of white mica, at its borders, or in boudinaged parts. Albite occurs as porphyroblasts with a straight or slightly curved internal fabric of oriented opaque minerals and epidote, as well as strain-free elongated quartz and mica. The internal fabric is oblique with respect to the main foliation. Albite shows lattice bending, kinking and occasionally boudinage, where cut by shear bands.

Two phyllites were collected from the Kebara Unit (Fig. 1) of the Mikabu Belt. Sample KEB 1 has been taken at 400 m from the ATL and KEB 2 at 200 m from this fault zone. The rocks strongly differ with respect to metamorphic grade and deformation structure.

KEB 1 is an albite-bearing metapelite with epidote, titanite and chlorite as other metamorphic minerals. The rock has a well-developed tectonic foliation with a pronounced quartz-mica differentiation, that is a

Table 1. $^{40}\text{Ar}/^{39}\text{Ar}$ analytical data of whole-rock samples from the northern Wakayama Prefecture.

Temperature (°C)	$^{39}\text{Ar}_K$ Vol ($10^{-9}\text{ cm}^3\text{ STP}$)	$^{37}\text{Ar}_{Ca}$	$^{38}\text{Ar}_{Cl}$	Ca/K	$^{40}\text{Ar}^*/^{39}\text{Ar}_K$	$^{40}\text{Ar}_{Atm}$ (%)	$^{39}\text{Ar}_K$ (%)	Age (Ma)	error (1 σ)
SAM 1 weight (g) : 0.03011 J-value: 0.004685 ± 0.5 K-Ar age: $72.8 \pm 1.6\text{ Ma}^{\#}$ %K: $7.217^{\#}$									
550	1.74	0.00	0.03	0.00	6.79	37.3	2.5	56.5	2.4
610	1.96	0.00	0.03	0.00	8.86	16.3	2.8	73.4	2.3
655	2.59	0.00	0.03	0.00	9.29	26.4	3.7	76.8	1.5
710	4.11	0.00	0.05	0.00	8.95	22.5	5.9	74.1	0.6
760	5.52	4.10	0.06	1.48	8.80	3.9	7.9	72.9	0.7
810	7.63	0.00	0.10	0.00	8.76	3.2	11.0	72.5	0.5
870	12.65	0.97	0.16	0.15	8.77	2.6	18.2	72.6	0.3
1005	27.16	0.00	0.35	0.00	8.81	3.2	39.0	73.0	0.1
1270	6.34	0.00	0.08	0.00	9.27	15.3	9.1	76.7	0.4
Total gas age: $73.0 \pm 0.4\text{ Ma}$ Plateau age: $73.0 \pm 0.8\text{ Ma}$ (2 σ) K from $^{39}\text{Ar} = 7.05\text{ wt}\%$ Inverse isochron age: $72.5 \pm 0.6\text{ Ma}$; $^{40}\text{Ar}/^{36}\text{Ar}$ intercept = 354 ± 45 ; MSWD = 3.7 Inverse isochron age of plateau: $72.3 \pm 0.5\text{ Ma}$; $^{40}\text{Ar}/^{36}\text{Ar}$ intercept = 314 ± 20 ; MSWD = 0.5									
KEB 1 weight (g) : 0.03740 J-value: 0.004681 ± 0.5 K-Ar age: $97.1 \pm 2.5\text{ Ma}^{\#}$ %K: $5.946^{\#}$									
490	1.43	0.04	0.06	0.06	7.09	95.1	1.9	58.9	3.9
550	3.47	0.06	0.06	0.04	5.60	33.1	4.5	46.7	1.1
598	5.82	0.20	0.08	0.07	10.39	4.3	7.6	85.7	0.8
647	11.29	0.34	0.14	0.06	11.66	5.8	14.8	95.9	0.3
695	13.95	0.08	0.18	0.01	12.19	4.1	18.3	100.1	0.1
725	8.46	0.05	0.11	0.01	12.49	2.0	11.1	102.5	0.5
767	7.63	0.03	0.09	0.01	12.63	2.3	10.0	103.6	0.4
825	11.07	0.06	0.14	0.01	12.53	5.6	14.5	102.8	0.4
897	10.24	0.11	0.13	0.02	12.59	4.5	13.4	103.3	0.4
1090	2.92	1.14	0.04	0.08	13.03	32.0	3.8	106.8	0.9
1290	0.08	1.37	0.00	32.72	36.61	58.5	0.1	285.4	31.7
Total gas age: $97.0 \pm 0.5\text{ Ma}$ Plateau age: $102.9 \pm 1.0\text{ Ma}$ (2 σ) K from $^{39}\text{Ar} = 6.22\text{ wt}\%$ Inverse isochron age: $100.0 \pm 4.0\text{ Ma}$; $^{40}\text{Ar}/^{36}\text{Ar}$ intercept = 291 ± 40 ; MSWD = 332 Inverse isochron age of plateau: $103.0 \pm 3.0\text{ Ma}$; $^{40}\text{Ar}/^{36}\text{Ar}$ intercept = 289 ± 462 ; MSWD = 2.1									
KEB 2 weight (g) : 0.04041 J-value: 0.004782 ± 0.5 K-Ar age: $92.0 \pm 2.3\text{ Ma}^{\#}$ %K: $4.827^{\#}$									
530	4.39	0.00	0.09	0.00	7.68	97.0	6.1	65.1	2.3
590	6.41	0.17	0.09	0.05	9.24	13.8	8.9	78.0	0.6
645	11.38	0.12	0.14	0.02	11.14	7.6	15.7	93.6	0.4
680	9.27	0.04	0.11	0.01	11.48	8.1	12.8	96.4	0.4
720	10.19	0.00	0.13	0.00	11.47	3.1	14.1	96.4	0.2
775	13.07	0.23	0.16	0.03	11.43	2.4	18.1	96.0	0.2
820	6.67	0.20	0.09	0.06	11.59	3.7	9.2	97.3	0.9
900	6.10	0.47	0.08	0.15	11.78	4.4	8.4	98.8	0.5
1100	4.64	7.36	0.06	3.15	11.83	25.3	6.4	99.3	0.6
1310	0.17	68.20	0.01	780.36	64.90	-62.3	0.2	487.6	19.5
Total gas age: $93.9 \pm 0.5\text{ Ma}$ Plateau age: $96.4 \pm 1.0\text{ Ma}$ (2 σ) K from $^{39}\text{Ar} = 5.34\text{ wt}\%$ Inverse isochron age: $96.0 \pm 3.0\text{ Ma}$; $^{40}\text{Ar}/^{36}\text{Ar}$ intercept = 292 ± 8 ; MSWD = 133 Inverse isochron age of plateau: $96.0 \pm 0.6\text{ Ma}$; $^{40}\text{Ar}/^{36}\text{Ar}$ intercept = 316 ± 50 ; MSWD = 1.1									

[#] data from Kurimoto (1993), samples R57598 (SAM 1), R57601 (KEB 1) and R57604 (KEB 2)

The temperature of the double-vacuum, resistance-heated furnace was monitored with a Minolta/Land™ Cyclops 52 infra-red optical pyrometer and is estimated to be accurate to $\pm 25^\circ\text{C}$ with reproducibility of $\pm 5^\circ\text{C}$. $^{40}\text{Ar}_{atm}$ = atmospheric ^{40}Ar ; $^{40}\text{Ar}^*$ = radiogenic ^{40}Ar . Errors are quoted at the 1 σ level, unless otherwise stated. J-value uncertainty is included in the errors quoted on the total gas and plateau ages but the individual step ages have analytical errors only. Individual step ages are corrected for irradiation-induced contaminant Ar-isotopes derived from Ca and K in the sample. Correction factors used were: $(^{36}\text{Ar}/^{37}\text{Ar})_{Ca} 0.255 \times 10^{-3}$, $(^{39}\text{Ar}/^{37}\text{Ar})_{Ca} 0.67 \times 10^{-3}$ and $(^{40}\text{Ar}/^{39}\text{Ar})_K 0.48 \times 10^{-1}$. Ages were calculated using the decay constants given by Steiger and Jäger (1977). The $^{40}\text{Ar}/^{36}\text{Ar}$ intercept and inverse isochron age are calculated from the best-fit line, using Yorkfit-1 (York, 1969) and errors are taken from the 95% confidence level values. See Roddick et al. (1983) for details on this calculation method. Data is reduced using 'Isoplot' (Ludwig, 1990). MSWD = SUMS / (n-2); with SUMS = minimum weighted sum of residuals; n = number of points fitted.

second foliation, indicated by isolated relics of fold hinges and open folded inclusion patterns in albite porphyroblasts. White mica occurs as well crystallised 50-200 μm diameter grains and crystal aggregates that have a well developed shape preferred orientation parallel to the cleavage septa. Chlorite is less than 50 μm in diameter. Quartz aggregates have a strain-free texture with straight grain boundaries. Albite is wrapped and truncated by the cleavage and crystals are boudinaged in the fold limbs and the mineral shows lattice deformation, kinking and fracturing. This points to an early syn- D_2 growth of the mineral.

KEB 2 is a tightly folded metapelite with a well developed, anastomosing axial planar cleavage, that is accentuated by seams rich in opaque minerals. Fold hinges of quartz-rich layers are wrapped by the cleavage and are often disconnected from the limbs. These microstructures imply (Hobbs et al., 1976) that pressure solution was an important deformation mechanism. Quartz shows abundant lattice bending but, despite the strong deformation, limited dynamic recrystallization. Lattice bending of white mica is also striking. Pale green metamorphic mica grains are between 40-100 μm in diameter. Such mica does not have a strong preferred orientation and growth parallel to the cleavage is limited. The sample contains fairly abundant chlorite, that is less than 50 μm in diameter. KEB 2 is the only sample that contains detrital minerals: white mica that is up to 500 μm in diameter and abundant rounded to angular quartz and plagioclase. The petrography implies that the metamorphic temperature was relatively low.

XRD analyses confirmed the main mineral composition based on petrographic microscopy and underlined the abundance of chlorite in all samples. The relative peak intensities of mica and chlorite imply that KEB 2 is the most chlorite-rich sample and SAM 1 the chlorite-poorest.

Analytical methods

Between 0.03 and 0.04 g of sample (Table 1) in the 75-100 μm size fraction, wrapped in high purity aluminum foil and loaded into a Spectrosil phial, was irradiated for 10 hours at the Risø facility, Roskilde (Denmark). They received a fast neutron dose of approximately 9×10^{17} neutron/ cm^2 that was monitored by co-irradiated aliquots of Leeds biotite standard Tinto (K-Ar age: 409.2 Ma, Rex and Guise, 1986) and hornblende HB3gr (Turner et al., 1971). Tinto has been cross calibrated against LP-6 (Engels and Ingamells, 1971), Fy12a (Roddick, 1983) and MMHb-1 (Alexander et al., 1978); ages used for each of these standards as given in Roddick (1983). Flux variation over the length of the canister was of the order of 5-6%. The irradiation parameter J was obtained from the $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ of the monitors using a polynomial fit

according to Dodson et al. (1996).

Argon was extracted from each sample in a double-vacuum, resistance-heated furnace with a tantalum crucible and liner. Samples were loaded into the arms of a glass storage tree above the furnace and the entire system baked overnight at 125°C under vacuum. A sample was dropped into the crucible and incremental heating commenced. The furnace was allowed to cool for 5 minutes after each 30 minute heating step. The extracted gas was purified over two successive getters (mixtures of Ti-Zr metal shavings and Ti sponge) heated to 800°C for 5 minutes and then allowed to cool, for another 5 minutes. The gas was then transferred to a small volume inlet section by absorption on charcoal at liquid nitrogen temperature during 10 minutes. Subsequently, the gas was expanded into the mass spectrometer for 120 seconds. Argon isotope analyses were performed using a modified Associated Electrical Industries MS 10 mass spectrometer with a 4.2 kGauss magnet and voltage peak jumping under computer control. Mass selection was achieved by variation of the acceleration voltage. Ion beams were detected by a VG pre-amplifier with $4 \times 10^{10} \Omega$ resistor, digitised with a Keithley™ 2000 voltmeter.

Measured mass spectrometer peak intensities were corrected for the following: amplifier response and non-linearity; linear extrapolation to gas inlet time; spectrometer mass discrimination; and radioactive decay of ^{39}Ar and ^{37}Ar . Atmospheric ^{40}Ar extraction blanks, mainly dominated by the contribution from the Al sample packet, were $5 \times 10^{-9} \text{ cm}^3 \text{ STP}$ at 660°C (when the Al melts), 3×10^{-10} at 900°C and 2×10^{-9} at 1,350°C.

The mass spectrometer discrimination and sensitivity were monitored by analysing atmospheric argon from a pipette system. The measured atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ was 289.2 ± 0.2 for these analyses and the sensitivity $1.4 \times 10^{-7} \text{ V cm}^{-3} \text{ STP}$. The $^{40}\text{Ar}/^{39}\text{Ar}$ ratio, age and errors for each gas fraction were calculated using formulae similar to those given by Dalrymple and Lanphere (1971). Errors in these ratios were evaluated by numerical differentiation of the equation used to determine the isotope ratios and quadratically propagating the errors in the measured ratios. Additional analytical details are given in the footnote of Table 1.

To identify the main minerals and their relative abundance < 2 μm ground samples were analysed with a computer-controlled Jeol 8030 powder diffractometer, using Cu $K\alpha$ radiation operated at 40 kV and 40 mA with a rate of $0.01^\circ 2\theta/\text{sec}$. Two slides of each sample were scanned between 0 and $50^\circ 2\theta$.

Results

The $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock analytical data are listed in Table 1 and portrayed as age spectra in Fig. 2.

Fig. 2. a-c $^{40}\text{Ar}/^{39}\text{Ar}$ resistance furnace step heating age spectra and an isotope correlation plot of whole-rock samples of the western Kii Peninsula. The error bars are at the 2σ level and do not include the error in J and the sections that yielded plateau ages are indicated. a: Iimori Unit (Sambagawa Belt). b: Kebara Unit (Mikabu Belt). c: $^{39}\text{Ar}/^{40}\text{Ar}$ versus $^{36}\text{Ar}/^{40}\text{Ar}$ isotope correlation plot for KEB 2. The step numbers are indicated; the fusion step is omitted from calculation. For details on the $^{40}\text{Ar}/^{36}\text{Ar}$ intercept, inverse isochron age and M.S.W.D., see footnote of Table 1.

The integrated $^{40}\text{Ar}/^{39}\text{Ar}$ ages of the three samples are concordant with the K-Ar ages reported by Kurimoto (1993) and the K content calculated from the measured $^{39}\text{Ar}_\text{K}$ is similar to the K data by Kurimoto (1993) (Table

1). All samples yielded plateau ages at the 2σ level. The elevated $^{40}\text{Ar}_\text{atm}$ release during the first steps (Table 1) is probably related to slight weathering of the samples.

About 82% of the spectrum of SAM 1 from the Iimori Unit yielded a plateau age of 73.0 ± 0.8 Ma (Fig. 2a), that is concordant to the total gas age, the inverse isochron age and to the K-Ar age of the sample (Table 1). The inverse isochron age of the plateau steps is 72.3 ± 0.5 Ma (Table 1).

Both Kebara Unit samples yielded disturbed age spectra that show progressively increasing apparent ages during the first 30-40% of ^{39}Ar release, rising to a plateau at intermediate- and high-temperature, whereas the last increments show slightly older apparent ages (Fig. 2b). The plateau ages are 96.4 ± 1.0 Ma and 102.9 ± 1.0 Ma for KEB 2 and KEB 1, respectively, and they are concordant to the 96.0 ± 0.6 and 103.0 ± 3.0 Ma inverse isochron ages of the steps that define the plateaux (Table 1). The isotope correlation plots for the Kebara samples are based on a small amount of fitted points, accordingly the errors in the $^{40}\text{Ar}/^{36}\text{Ar}$ intercept are large (Table 1). The total gas ages of 97.0 ± 0.5 (KEB 1) and 93.9 ± 0.5 Ma (KEB 2) are concordant with the inverse isochron ages of 100.0 ± 4.0 and 96.0 ± 3.0 Ma of both samples (Fig. 2c; Table 1).

Discussion

Neutron irradiation of samples induces the possibility of $^{39}\text{Ar}_\text{K}$ recoil, i.e. the displacement of the formed nuclide by the kinetic energy of the incoming neutron. Recoil can be important for fine-grained and multiminerale samples, like whole-rocks. In general, agreement between $^{40}\text{Ar}/^{39}\text{Ar}$ total gas ages and K-Ar ages is used as indication that there has been no overall loss of $^{39}\text{Ar}_\text{K}$ by recoil (Hunziker et al., 1986; Muecke et al., 1988; Reuter and Dallmeyer, 1989; Dong et al., 1995; Merriman et al., 1995). This can similarly be inferred from our data (Table 1). In addition, the white mica crystals in the finest-grained sample KEB 2 are orders of magnitude larger than the grain size for which the effects of $^{39}\text{Ar}_\text{K}$ recoil loss may become seriously disturbing (Hunziker et al., 1986; Reuter and Dallmeyer, 1989; Dong et al., 1995). This means that the progressively increasing apparent ages for the low-temperature gas fractions for the two Kebara unit samples (Fig. 2b) may be geologically significant. Such staircase-shaped age spectra of whole-rock samples have been interpreted by partial $^{40}\text{Ar}^*$ loss of the finer grained white mica component that is related to thermo-tectonic resetting (Dallmeyer and Takasu, 1992; Dallmeyer and Nance, 1994). The position of the two samples close to the ATL makes a post peak metamorphic disturbance of the isotopic system likely.

In all samples the $^{39}\text{Ar}_\text{K}$ release is well correlated with that of $^{38}\text{Ar}_\text{Cl}$ (corrected for atmospheric compo-

Fig. 3. a-d Degassing characteristics of the samples. a-c : Gas release plotted as the signal in volume normalised by the temperature intervals between two successive steps, versus temperature during furnace step heating. d : log Ca/K ratio plot versus analytical temperature.

ment) and $^{40}\text{Ar}^*$ and is unrelated to the $^{37}\text{Ar}_{\text{Ca}}$ release (Table 1, Fig. 3a-c). This is consistent with degassing of white mica as main component of the whole-rock samples and agrees with the petrography and XRD data. Cl can replace OH in the O-OH octahedrons of the white mica lattice, whereas K is located in the 12-coordinated interlayer (de Jong et al., 2000, and references therein). The degassing peaks for the 40, 39 and 38 isotopes are rather broad and the main degassing of SAM 1 took place close to 900°C, whereas for the Kebara samples it occurred around 700°C (Fig. 3a-c). This difference in main degassing temperature reflects the larger size and better ordered crystal lattice of white mica in the Sambagawa sample, compared to the Kebara samples.

The Sambagawa sample has no $^{37}\text{Ar}_{\text{Ca}}$ release for most steps (Table 1, Fig. 3d). Both Kebara samples have similar Ca/K ratio spectra, that show high values at temperatures between 550 and 700°C and maxima above 900°C (Fig. 3d). Lo and Onstott (1989) showed that degassing of chlorite is important around 650°C and is characterised by a high Ca/K ratio. The high Ca/K ratios at low-temperature (Fig. 3) are,

hence, interpreted by the degassing of chlorite. The high-temperature main $^{37}\text{Ar}_{\text{Ca}}$ release is probably related to degassing of plagioclase. Absence of old apparent ages for the gas released above 900°C implies that the Ar-isotopic system of the detrital feldspar present in KEB 2 has been completely reset during metamorphism.

Meaning of plateau ages

The 72-73 Ma plateau and inverse isochron ages of sample SAM 1 agree well with K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of the Imori Unit in the same area (Kurimoto, 1993; Takasu et al., 1996). The ages are comparable to K-Ar ages obtained by Itaya and Fujino (1999) for strongly dynamically recrystallized samples from central Shikoku, that are significantly younger than not recrystallised samples from the same outcrop. SAM 1 has been affected by dynamic recrystallization too. The 72-73 Ma age may therefore be interpreted to date the isotopic closure of white mica during retrograde recrystallization of the rock.

The 96 and 103 Ma plateau and inverse isochron ages of the Kebara Unit samples are comparable to

$^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock ages of the Mikabu Belt in central Shikoku. On the basis of a detailed study of mineral assemblages Suzuki and Ishizuka (1998) estimated that the metamorphic temperature of the Mikabu Belt in Shikoku was in the 300–400°C range. Absence of prehnite-chlorite assemblages in the KEB samples implies that the metamorphic temperature was not below 300°C. Pumpellyite-bearing mineral assemblages are widespread in basic rocks of the Kebara Unit (Kurimoto, 1986). Banno (1998) argued that the pumpellyite-out isograd was located at about 350°C, for rocks of the upper chlorite zone of the Sambagawa Belt in central Shikoku. Clinopyroxene and lawsonite-actinolite assemblages of the Mikabu Belt in Shikoku, however, indicate a lower temperature than the pumpellyite-actinolite assemblage of the Sambagawa Belt (Banno, 1998; Suzuki and Ishizuka, 1998). Taken together, this implies that temperatures below 350°C can be assumed for the Kebara Unit. The age difference between both Kebara samples might reflect their difference in grain size, as smaller grains of KEB 2 (96 Ma) have shorter argon diffusion paths and thus became closed systems later than larger grains of KEB 1 (103 Ma), following Dodson's (1973) cooling theory. It is also possible that the main tectono-metamorphic recrystallization in both samples did not occur at the same time.

The plateau ages indicate that the main tectono-metamorphic phase in the Kebara Unit significantly predates the recrystallization phase in the Iimori Unit. The 20–30 Ma age difference seems too large to be explained by differential cooling of units accreted at the same time in a tectonically active belt. Hence, it may be inferred from this that the Kebara and Iimori Units were accreted at different times.

Conclusions

$^{40}\text{Ar}/^{39}\text{Ar}$ dating of whole-rock samples from the Mikabu and Sambagawa Belts of the western Kii Peninsula gave coherent results and regular and meaningful age spectra. All samples yielded plateau ages at the 2σ level. The metamorphic temperature of 300–350°C in the lowest grade sample (KEB 2) was high enough to have reset the Ar-isotopic system of detrital feldspar in the rock.

The 72–73 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age of the sample of the Iimori unit is regarded as dating the isotopic closure of white mica during retrograde recrystallization concomitant with exhumation of these greenschist-facies metamorphic rocks of the Sambagawa Belt. The 96 and 103 Ma plateau ages of the Kebara Unit of the Mikabu Belt are also interpreted as the timing of the isotopic closure of white mica. The 7 Ma age difference may indicate that the finer grained white mica of sample KEB 2 (96 Ma) closed later. It is also possible that the main tectono-metamorphic recrystallization in both samples did not occur at the same time. In

either case, the $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages show that the main tectono-metamorphic phase in the Kebara Unit is significantly older than in the higher grade Iimori Unit.

The staircase spectra of the Kebara samples may be due to a partial thermo-tectonic resetting of the isotopic system, in accordance with their proximity to the ATL.

Acknowledgments

We would like to thank Mr. Dave Rex (University of Leeds) for his accord to undertake this study and his advice. Stimulating discussion with Drs. Gilbert Féraud and Gilles Ruffet clarified our way of thinking. Drs. Hidetoshi Hara's and Katsumi Kimura's help with XRD analyses is greatly appreciated. Last but not least, an anonymous reviewer and Drs. Noriko Hasebe and Akira Ishiwatari are thanked for their thoughtful comments, suggestions and improvements of the text.

References

- Alexander, E.C., Jr, Michelson, G.M. and Lanphere, M.A., 1978, A new $^{40}\text{Ar}/^{39}\text{Ar}$ dating standard. In Zartman, R.E., ed., *Short Pap. Int. Conf. Geochronology, Cosmochronology and Isotope Geology*; 4th U.S. Geol. Surv. Open-File Rep., 78-701, 6–8.
- Awan, M.A. and Kimura, K., 1996, Thermal structure and uplift of the Cretaceous Shimanto Belt, Kii Peninsula, Southwest Japan: An illite crystallinity and b_0 lattice spacing study. *The Island Arc*, 5, 69–88.
- Banno, S., 1964, Petrologic studies on the Sanbagawa crystalline schists in the Bessi-Ino district, central Shikoku Japan. *Tokyo Univ. Fac. Sci. J. Sec. II*, 15, 203–319.
- Banno, S., 1998, Pumpellyite-actinolite facies of the Sanbagawa metamorphism. *Jour. Metamorphic Geol.*, 16, 117–128.
- Banno, S. and Sakai, S., 1989, Geology and metamorphic evolution of the Sanbagawa metamorphic belt, Japan. In Daly, J.S., Cliff, R.A. and Yardley, B.W.D., eds., *Evolution of Metamorphic Belts. Geol. Soc. Spec. Publ.*, 43, 519–532.
- Barber, A.J., 1982, Interpretations of the tectonic evolution of Southwest Japan. *Proc. Geol. Ass.*, 93, 131–145.
- Dallmeyer, R.D. and Nance, R.D., 1994, $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock phyllite ages from late Precambrian rocks of the Avalon composite terrane, New Brunswick: evidence of Silurian-Devonian thermal rejuvenation. *Can. Jour. Earth Sci.*, 30, 818–824.
- Dallmeyer, R.D. and Takasu, A., 1992, $^{40}\text{Ar}/^{39}\text{Ar}$ ages of detrital muscovite and whole-rock slate/phyllite, Narragansett Basin, RI-MA, USA: implications for rejuvenation during very low-grade metamorphism. *Contrib. Mineral. Petrol.*, 110, 515–527.
- Dallmeyer, R.D., Takasu, A. and Yamaguchi, K., 1995, Mesozoic tectonothermal development of the Sambagawa, Mikabu and Chichibu belts, south-west Japan: evidence from $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock phyllite age. *Jour. Metamorphic Geol.*, 13, 271–286.
- Dalrymple, G.B. and Lanphere, M.A., 1971, $^{40}\text{Ar}/^{39}\text{Ar}$ technique of K-Ar dating: a comparison with the conventional technique. *Earth Planet. Sci. Lett.*, 12, 300–315.
- de Jong, K., Féraud, G., Ruffet, G., Amouric, M. and Wijbrans, J.R., 2000, 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. *Chem. Geol. (Isotope Geosci. Sect.)*, (in press).
- de Jong, K., Wijbrans, J.R. and Féraud, G., 1992, Repeated thermal resetting of phengites in the Mulhacen Complex (Betic Zone, southeastern Spain) shown by $^{40}\text{Ar}/^{39}\text{Ar}$ stepheating and single grain laser probe dating. *Earth Planet. Sci. Lett.*, **110**, 173–191.
- Dodson, M.H., 1973, Closure temperatures in cooling geochronological and petrological systems. *Contrib. Mineral. Petrol.*, **40**, 259–274.
- Dodson, H. and Rex, D.C., 1971, Potassium-argon ages of slates and phyllites from south-west England. *Geol. Soc. Lond. Q. J.*, **126**, 465–499.
- Dodson, H., Rex, D.C. and Guise, P.G., 1996, The multi-standard approach to accuracy in $^{40}\text{Ar}/^{39}\text{Ar}$ dating. *Jour. Conferences Abstracts*, **1**, 134.
- Dong, H., Hall, C.M., Peacor, D.R. and Halliday, A.N., 1995, Mechanisms of argon retention in clays revealed by laser ^{40}Ar - ^{39}Ar dating. *Science*, **267**, 355–359.
- Engels, J.C. and Ingamells, C.O., 1971, Information Sheets 1 and 2, LP-6 Biotite 40–60 mesh. *U.S.G.S. Menlo Park, Calif. U.S.A.*
- Faure, M., Caridroit, M. and Charvet, J., 1986, The Late Jurassic orogen of S.W. Japan—new structural data and synthesis. *Tectonics*, **5**, 1089–1114.
- Hada, S., 1967, Geology of the middle-Aritagawa district, Wakayama Prefecture, with special reference to the relationship between the Chichibu Belt and the Sambagawa Belt. *Bull. Osaka Museum of Nat. Hist.*, **20**, 39–60.
- Hara, I., Shiota, T., Hide, K., Kanai, K., Goto, M., Seki, S., Kaikiri, K., Takeda, K., Hayasaka, Y., Miyamoto, T., Sakurai, M. and Ohtomo, Y., 1992, Tectonic evolution of the Sambagawa Schists and its implications in convergent margin processes. *Jour. Sci. of the Hiroshima Univ., Ser. C*, **9**, 495–595.
- Hirajima, T., Isono, T. and Itaya, T., 1992, K-Ar ages and chemistry of white mica in the Sanbagawa metamorphic rocks in the Kanto Mountains, central Japan. *Jour. Geol. Soc. Japan*, **98**, 445–455.
- Hobbs, B.E., Means, W.D. and Williams, P.F., 1976, *An outline of structural geology*. John Wiley & sons, Inc., New York, 571 p.
- Hunziker, J.C., Frey, M., Clauer, N., Dallmeyer, R.D., Friedrichsen, H., Flemig, W., Hochstrasse, K., Roggwiler, P. and Schwander, H., 1986, The evolution of illite to muscovite: mineralogical and isotopic data from the Glarus Alps, Switzerland. *Contrib. Mineral. Petrol.*, **92**, 157–180.
- Isozaki, Y., Itaya, T. and Kawato, K., 1990, Pre-Jurassic klippe in Northern Chichibu belt in west central Shikoku, Southwest Japan—Kurosegawa terrane as a tectonic outlier of the pre-Jurassic rocks of the Inner zone. *Jour. Geol. Soc. Japan*, **97**, 431–450.
- Itaya, T. and Fujino, M., 1999, K-Ar age-chemistry-fabric relations of phengite from the Sanbagawa high-pressure schists, Japan. *The Island Arc*, **8**, 523–536.
- Itaya, T. and Fukui, S., 1994, Phengite K-Ar ages of schists from the Sanbagawa southern marginal belt, central Shikoku, southwest Japan: Influence of detrital mica and deformation on age. *The Island Arc*, **3**, 48–58.
- Itaya, T. and Takasugi, H., 1988, Muscovite K-Ar ages of the Sanbagawa schists, Japan, and argon depletion during cooling and deformation. *Contrib. Mineral. Petrol.*, **100**, 281–290.
- Kojima, G., 1950, On the so-called Mikabu system in the outer zone of South-western Japan. *Jour. Geol. Soc. Japan*, **56**, 339–344.
- Kurimoto, C., 1986, Kebara Formation in the Misato area, Wakayama Prefecture, Southwest Japan—with reference to the relationship of the Sambagawa and Chichibu Belts. *Bull. Geol. Surv. Japan*, **37**, 381–389.
- Kurimoto, C., 1993, K-Ar ages of the rocks of the Sambagawa, Kurosegawa and Shimanto Terranes in the northwestern part of Wakayama Prefecture, Southwest Japan. *Bull. Geol. Surv. Japan*, **44**, 367–375.
- Kurimoto, C., 1994, Geology of the Kudoyama area in the western Kii Peninsula, Southwest Japan, with reference to disappearance of the Chichibu terrane. *Bull. Geol. Surv. Japan*, **45**, 235–255.
- Kurimoto, C., 1995, K-Ar ages of the Sambagawa metamorphic rocks in the northern part of Wakayama Prefecture, Southwest Japan. *Bull. Geol. Surv. Japan*, **46**, 517–525.
- Kurimoto, C., Makimoto, H., Yoshida, F., Takahashi, Y. and Komazawa, M., 1998, *Geological map of Japan 1 : 200/000, Wakayama*. Geol. Surv. Japan.
- Leitch, E.C. and McDougall, I., 1979, The age of orogenesis in the Nambucca Slate belt: K-Ar study of low-grade regional metamorphic rocks. *Geol. Soc. Aust. J.*, **26**, 111–119.
- Lo, C.-H., and Onstott, T.C., 1989, ^{39}Ar recoil artifacts in chloritized biotite. *Geochim. Cosmochim. Acta*, **53**, 2697–2711.
- Ludwig, K.R., 1990, A plotting and regression program for radiogenic-isotope data, for IBM-PC compatible computers. *U.S.G.S. Open-File Report*, 88–557.
- McDougall, I. and Harisson, T.M., 1988, *Geochronology and Thermogeochronology by the $^{40}\text{Ar}/^{39}\text{Ar}$ method*. Oxford University Press, Oxford, New York, 195 p.
- Merriman, R.J., Rex, D.C., Soper, N.J. and Peacor, D.R., 1995, The age of Acadian cleavage in northern England, UK: K-Ar and TEM analysis of a Silurian metabentonite. *Proc. Yorkshire Geol. Soc.*, **50**, 255–265.
- Monié, P., Faure, M. and Maluski, H., 1987, Isotopic geochemistry and geochronology—First $^{39}\text{Ar}/^{40}\text{Ar}$ dating of high-pressure Mesozoic metamorphism of Sanbagawa (SW Japan). *Comptes R. Acad. Sci., Paris*, **304**, 1221–1225.
- Muecke, G.K., Elias, P. and Reynolds, P.H., 1988, Hercynian/Alleghenian overprinting of an Acadian terrane: $^{40}\text{Ar}/^{39}\text{Ar}$ studies in the Meguma zone, Nova Scotia, Canada. *Chem. Geol. (Isot. Geosci. Sect.)*, **73**, 153–167.
- Nakajima, T., 1997, Regional metamorphic belts of the Japanese islands. *The Island Arc*, **6**, 69–90.
- Reuter, A. and Dallmeyer, R.D., 1989, K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of cleavage formed during very low-grade metamorphism: a review. In Daly, J.S., Cliff, R.A. and Yardley, B.W.D., eds., *Evolution of Metamorphic Belts*. *Geol. Soc. Spec. Publ.*, **43**, 161–171.
- Rex, D.C. and Guise, P.G., 1986, Age of the Tinto felsite, Lanarkshire: a possible $^{40}\text{Ar}/^{39}\text{Ar}$ monitor. *Bull. Liaison and Informations, IGCP Project 196*, **6**, 8–9.
- Roddick, J.C., 1983, High precision intercalibration of ^{40}Ar - ^{39}Ar standards. *Geochim. Cosmoch. Acta*, **47**, 887–898.
- Roddick, J.C., Cliff, R.A. and Rex, D.C., 1980, The evolution of excess argon in Alpine biotites—A $^{40}\text{Ar}/^{39}\text{Ar}$ analysis. *Earth Planet. Sci. Lett.*, **48**, 185–208.
- Scaillet, S., Féraud, G., Lagabriele, Y., Ballèvre, M. and Ruffet, G., 1990, $^{40}\text{Ar}/^{39}\text{Ar}$ dating by step heating and spot fusion of phengites from the Dora Maira nappe of the western Alps, Italy. *Geology*, **18**, 741–744.
- Steiger, R.H. and Jäger, E., 1977, Subcommission on geochronology: convention on the use of decay constants in geo- and cosmology. *Earth Planet. Sci. Lett.*, **36**, 359–362.
- Suzuki, T., 1967, The Mikabu green rocks in Shikoku. *Jour. Geol. Soc. Japan*, **73**, 207–216.
- Suzuki, S. and Ishizuka, H., 1998, Low-grade metamorphism of the Mikabu and northern Chichibu belts in central Shikoku, SW Japan: implications for the areal extent of

- the Sanbagawa low-grade metamorphism. *Jour. Metamorphic Geol.*, **16**, 107–1216.
- Takasu, A. and Dallmeyer, R.D., 1990, ^{40}Ar - ^{39}Ar age constraints for the tectono-thermal evolution of the Sambagawa metamorphic belt, central Shikoku, Japan: a Cretaceous accretionary prism. *Tectonophysics*, **185**, 303–324.
- Takasu, A., Dallmeyer, R.D. and Hiroi, I., 1996, ^{40}Ar - ^{39}Ar muscovite ages of the Sambagawa schists in the Imori district, Kii Peninsula, Japan: Implications for orogen-parallel diachronism. *Jour. Geol. Soc. Japan*, **102**, 406–418.
- Turner, G., Huneke, J.C., Podosek, F.A. and Wasserburg, G.J., 1971, ^{40}Ar - ^{39}Ar ages and cosmic ray exposure ages of Apollo 14 samples. *Earth Planet. Sci. Lett.*, **12**, 19–35.
- Villa, I.M., 1998, Isotopic closure. *Terra Nova*, **10**, 42–47.
- Wijbrans, J.R. and McDougall, I., 1986, ^{40}Ar - ^{39}Ar dating of white micas from an Alpine high-pressure metamorphic belt on Naxos (Greece): the result of resetting of the argon isotopic system. *Contrib. Mineral. Petrol.*, **93**, 187–194.
- Yamato Omine Research Group, 1981, *Paleozoic and Mesozoic systems in the central area of the Kii Mountains, Southwest Japan*. Guide book for the excursion for 35th Ann. Meeting of Assoc. Geol. Coll. Japan, 88 p.
- York, D., 1969, Least squares fitting of a straight line with correlated errors. *Earth Planet. Sci. Lett.*, **5**, 324–324.

(要 旨)

de Jong, K., Kurimoto, C. and Guise, P., 2000, $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock dating of metapelites from the Mikabu and Sambagawa Belts, western Kii Peninsula, Southwest Japan. *Jour. Geol. Soc. Japan*, **106**, 703–712. (ド・ヨング, K.・栗本史雄・ガイザ, P., 2000, 紀伊半島西部の御荷鉾帯および三波川帯泥質片岩の $^{40}\text{Ar}/^{39}\text{Ar}$ 全岩年代. 地質雑, **106**, 703–712.)

三波川帯飯盛ユニット (点紋帯) から得られた $^{40}\text{Ar}/^{39}\text{Ar}$ 年代 $73.0 \pm 0.8 \text{ Ma}$ (2σ) は, 緑色片岩相の岩石が白雲母の閉鎖温度を通過した冷却時期に相当する. 一方, 御荷鉾帯の2試料の $^{40}\text{Ar}/^{39}\text{Ar}$ 年代は, $96.4 \pm 1.0 \text{ Ma}$ と $102.9 \pm 1.0 \text{ Ma}$ (いずれも 2σ) を示し, 両者には700万年の差がある. その理由として, 前者がより細粒な変成白雲母から構成されること, あるいは両者の主たる変成時期が異なっていたこと, などが考えられる. いずれにしても毛原ユニットと飯盛ユニットの主たる変成作用の時期は明らかに異なっていたと考えられる. 毛原ユニットの年代スペクトラムは, 増大する脱ガスの間に見かけの年代が増大する特徴を示す. このような階段状の年代スペクトラムは, 放射起源の ^{40}Ar が一部損失したことを示すと解釈され, 毛原ユニットから200~400 m 離れて通過する有田川構造線の構造運動に影響を受けた結果とみなすことができる.