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Metamorphic Ages of the Jurassic Accretionary Complexes in the Kanto Mountains, Central Japan, Determined by K–Ar Dating of Illite: Implications for the Tectonic Relationship between the Chichibu and Sanbagawa Belts

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Abstract: To determine the metamorphic ages of the accretionary complexes in the Northern Chichibu Belt in SW Japan, K–Ar dating was conducted using weakly metamorphosed sedimentary rocks collected from the Kanto Mountains, Central Japan. Whole-rock ages were obtained for chert and red shale samples, and the mineral ages of fine-grained illite with a grain size of less than 4 μm were obtained for chert, red shale, mudstone, acidic tuff, and basic tuff. The K–Ar ages of chert and red shale presented large variations, with systematically older ages compared to those of mudstone and tuff in the same strata. The influence of submarine hydrothermal activities on chert and red shale before subduction is a possible cause of this deviation. The illite samples, which were fractionated into four grain-size classes using a suspension method, yielded older ages and higher illite crystallinity (i.e., smaller values of Kübler's crystallinity index) for larger grain-size classes. The peak metamorphic ages were determined from the K–Ar ages of the 3–4 μm class illite in mudstone and tuff. The Late Jurassic to the Earliest Cretaceous accretionary complex of the lowest structural unit (Kashiwagi Unit) was dated within a small range between 117–110 Ma, which is distinctly older than the K–Ar ages of white mica reported from the Sanbagawa Belt. The peak metamorphic age of acidic tuff (113 Ma) at the type locality of the Mikabu Greenstones indicates that the subducted Mikabu seamount is a constituent of the Kashiwagi Unit. The peak metamorphic ages of the Manba and Kamiyoshida Units were obtained as 132–107 Ma and 163–144 Ma, respectively. Major structural discontinuity is suggested within the Middle Jurassic accretionary complexes.

Keywords: K–Ar dating; illite crystallinity; Northern Chichibu Belt; Mikabu Greenstones; Sanbagawa (Sambagawa) metamorphism; accretionary complex

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1. Introduction

The Chichibu Belt, which is located to the south of the Sanbagawa (or Sambagawa) Belt in the Outer Zone of SW Japan (Figure 1), is constituted of coherent or chaotic units of the Jurassic to Early Cretaceous accretionary complex. The rocks in the Northern Chichibu Belt are weakly metamorphosed up to pumpellyite–actinolite facies in the northern areas, and it was traditionally treated as a southern extension of the 'Sanbagawa metamorphic belt' [1], whereas the 'Sanbagawa Belt' has been used for tectonic division in a narrower sense, wherein crystalline schists are exposed. In the 1980s, a different view on the tectonic relationships between the Sanbagawa and Chichibu Belts was presented by Faure and coworkers [2–4] in Shikoku, SW Japan. They considered that the Northern Chichibu complex is a superficial nappe emplaced on the crystalline schists of the Sanbagawa Belt after syn-metamorphic deformation. Guidi and coworkers [5–7] have applied a similar nappe model to the type localities of the Sanbagawa and Chichibu Belts in the Kanto Mountains, Central Japan.

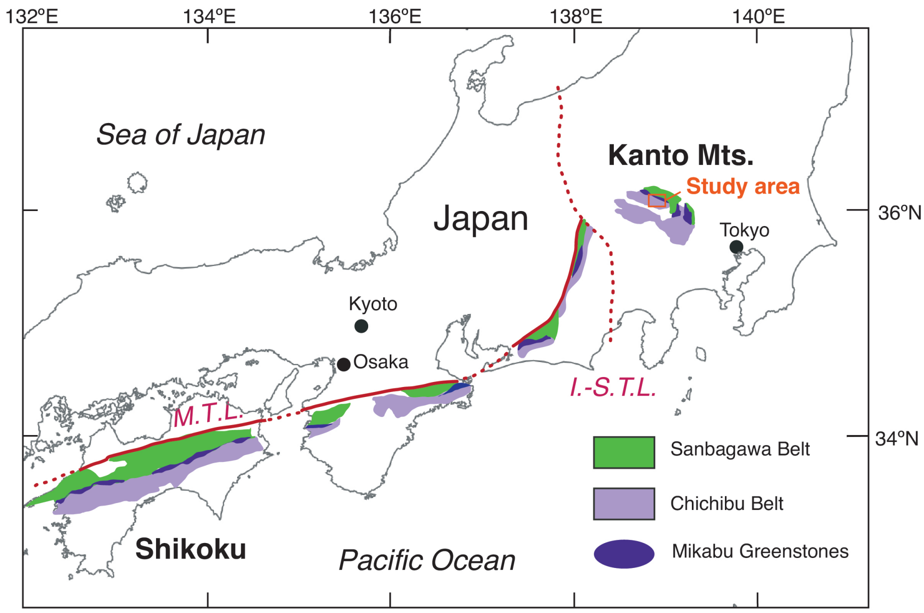

Figure 1. An index map showing the tectonic division of the Chichibu and Sanbagawa Belts and distribution of the Mikabu Greenstones. The study area is indicated by an orange rectangle. The Median Tectonic Line (M.T.L.) and the Itoigawa–Shizuoka Tectonic Line (I.-S.T.L.) are denoted by a red line and a red dotted line, respectively.

In central Shikoku, where high-grade metamorphic rocks of the Sanbagawa Belt are largely exposed, K–Ar and Ar–Ar dating methods have been extensively used to determine the muscovite cooling ages and subduction–uplifting histories of the Sanbagawa schists, as has been previously discussed [8–10]. These dating methods have also been applied to fine-grained white mica in weakly metamorphosed sedimentary rocks in the Northern Chichibu Belt, and a systematic change in the metamorphic ages from the northern to the southern parts of the belt was recognized [10–12]. Isozaki and Itaya [11] have considered that the northern unit (ca. 115 Ma, according to K–Ar dating of white mica) was metamorphosed contemporaneously with the main suite of the Sanbagawa Belt, whereas the southern unit (ca. 140 Ma) is a nappe rooted in the Mino–Tanba Belt in the Inner Zone of SW Japan. According to this model, the actual boundary between the Sanbagawa metamorphic belt and the 'Chichibu belt', which is free from the Cretaceous Sanbagawa metamorphism, can be drawn within the 'traditional' Chichibu Belt [13,14]. The basic assumption of this tectonic model is that the deposition and accretion ages of the host rocks of the Sanbagawa schists and those of the northern unit of the Chichibu Belt were contemporaneous (from the Late Jurassic to Early Cretaceous). However, U–Pb dating of detrital zircons in the past decade has revealed that the protoliths of the Sanbagawa Belt were deposited in the Late Cretaceous, which overlaps with the sedimentation ages in the Northern Shimanto Belt [15–17]. Accordingly, the tectonic model of the Sanbagawa and Chichibu Belts must be revised.

The Mikabu Greenstones (or Mikabu greenrocks) [18] is a volcanic complex with a distinct lithology, including pillow lava and breccia, hyaloclastite, dolerite, gabbro, and ultramafic cumulates, that is exposed at the boundary region between the Sanbagawa and Chichibu Belts. The Mikabu Greenstone and surrounding meta-sedimentary rocks have been treated as an independent tectonic division, with names such as the 'Mikabu belt', 'Mikabu greenstone belt' [10], and 'Mikabu unit' [19]; a sub-unit of the Sanbagawa Belt [20]; or a member or sub-unit of the Northern Chichibu Belt [5,21,22]. The origin of the Mikabu Greenstones is considered as a seamount chain [23] or an oceanic plateau [24], which records volcanic activity from the Early Jurassic (ca. 200 Ma, based on K–Ar dating of hornblende) [25] to Late Jurassic (155 Ma for basalt [26] and 157 Ma for anorthosite, based on U–Pb dating of igneous zircon [24]). Here, the term 'Mikabu seamount' is conventionally used for the original volcanic bodies of the Mikabu Greenstones. Determining the subduction history of the Mikabu seamount is the key to understanding the tectonic evolution of the Mesozoic accretionary complex in the Chichibu–Sanbagawa Belts. Previously, white mica K–Ar ages of 124 Ma [27], 110 Ma [24], and 82 Ma [20], as well as whole-rock Ar–Ar ages of 98–96 Ma [10], have been reported from mudstone and tuff (including phyllite, tuffaceous phyllite, and pelitic schist) in the 'Mikabu greenstone belt' or 'Mikabu unit'. However, their geotectonic meanings were not clear, as these rock types are not characteristic of the Mikabu Greenstones.

In this paper, we applied the K–Ar dating method to weakly metamorphosed accretionary complexes in the northern Kanto Mountains, central Japan, where the original structural sequence of the Sanbagawa–Chichibu Belts is well-preserved. The K–Ar ages of white mica in the Sanbagawa schists have been previously reported in this area [20,28], but little is known about metamorphic ages in the Northern Chichibu Belt and the Mikabu Greenstones. One of the problems when conducting K–Ar dating using low-grade metasedimentary rocks is the sample heterogeneity due to incomplete recrystallization. For example, remnants of detrital mica in mudstones, which inherited the crystallization age at the igneous event, could result in grain-size-dependent K–Ar age distributions and apparently old ages as a whole [29]. In contrast, almost flat K–Ar age spectra with respect to grain size had been reported for white mica in detritus-free meta-volcaniclastic rocks [30]. To establish a reliable dating method for weakly metamorphosed materials, we measured whole-rock and white mica mineral ages for samples of various lithologic types, including mudstone, tuff, and chert. In low-grade metasedimentary rocks, illite is generally the most dominant phase of white mica, and its crystallinity has been used to estimate the maximum temperature that they attained [31–35]. In this study, we quantified the illite crystallinity of the dated samples in order to constrain their thermal histories and factors affecting the illite K–Ar ages. Finally, we estimated the peak metamorphic age of each geological unit based on an interpretive framework of the K–Ar ages, and discuss the tectonic evolution of the Sanbagawa–Chichibu Belts.

2. Outline of Geology

The Northern Chichibu Belt in the study area (Figure 2) comprises three lithologically distinct units: the Kashiwagi, Manba, and Kamiyoshida Units, in ascending order of structural level [22,36,37].

The Kashiwagi Unit is characterized by coherent layers of red chert, red shale, and basic tuff in the lower sub-unit, and by the alteration of acidic tuff, mudstone, and sandstone in the upper sub-unit [36]. Upper Triassic limestone occasionally occurs as lenses and beds [38]. Based on the radiolarian assemblages in mudstone, the sedimentation age of the upper sub-unit of the Kashiwagi Unit has been constrained to during the Late Jurassic and the Early Cretaceous [39–41]. The Manba and Kamiyoshida Units are considered as Middle Jurassic accretionary complexes characterized by block-in-matrix structures. The Manba Unit comprises chaotic blocks of pillow lava, pillow breccia, and basic tuff associated with Carboniferous–Permian limestone [37,42], as well as chert blocks of the Middle Triassic age [43]. Early to Middle Jurassic radiolaria have been reported from mudstone (shale) in the outcrops to the south-east [41,43,44] and to the west of the study area [43]. The Kamiyoshida Unit consists of mudstone of the early Middle Jurassic age [41,45,46], sandstone, siliceous shale, and chert of the Triassic age, as well as Permian limestone [42,43]. The type locality of the Mikabu Greenstones [18,47] is located at Mts. Mikabu (Mikabo, including Mts. Nishi- and Higashi-Mikabo and Mt. Odokeyama), where the meta-basaltic body associated with pillow lava, hyaloclastite, and doleritic intrusives is exposed. The red shale on the top of hyaloclastite comprises late Middle Jurassic to Late Jurassic radiolaria [48].

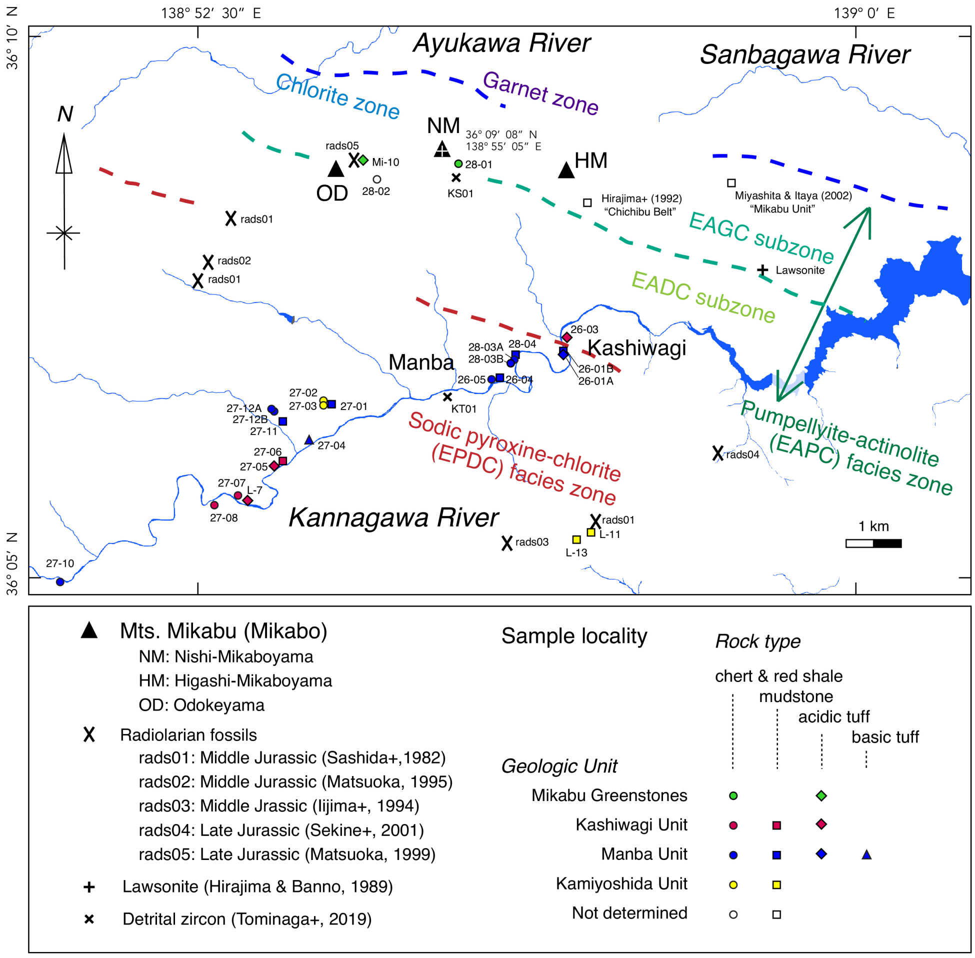

Figure 2. Sampling localities for K–Ar dating in the study area in the Northern Kanto Mountains. The localities of radiolarian fossils in literature (Sashida et al. [42], Matsuoka [48,49], Iijima et al. [46], Sekine et al. [39]), and the sampling localities for the K–Ar dating in the 'Chichibu Belt' by Hirajima et al. [28] and 'Mikabu Unit' by Miyashita and Itaya [20] (open squares), and, for zircon, U–Pb dating by Tominaga et al. [50] (cross), are also marked. The metamorphic zonations follow Hirajima and Banno [51] and Tagiri et al. [52]. Blue dashed lines show the isograd between the chlorite and garnet zones in pelitic schists. Metamorphic grades in basic rocks are represented by critical mineral assemblages in terms of E (epidote), A (actinolite), D (sodic pyroxene), and C (chlorite). Red dashed line bounds the pumpellyite–actinolite (EAPC) facies zone and the sodic-pyroxine–chlorite (EPDC) facies zone in basic schists, and green dashed lines bounds the EAGC and EADC subzones in the pumpellyite–actinolite (EAPC) facies zone. The outcrop comprising the lawsonite-bearing schist [51] is also indicated (T. Hirajima, personal comm.). The geographical information is based on the digital topographic map 25,000 published by Geospatial Information Authority of Japan [53].

The metamorphic grade of the basic rocks in the Northern Chichibu Belt and the Mikabu Greenstones increases toward the north (i.e., toward the lower structural level) up to the pumpellyite–actionlite facies zones [51,52] (Figure 2). The metamorphic grade of the Kamiyoshida Unit remains undetermined due to a lack of basic rocks. Magnitudes of strain measured by the shapes of radiolarian fossils and amygdules in pillow lava increase toward higher metamorphic grade zones [22,36].

The Manba and Kamiyosida Units are sometimes treated as a single stratigraphic unit, re-defined together as the 'Kamiyoshida Unit' [50,54], which is supposed to overlie the Kashiwagi Unit with a fault contact [55,56]. Guidi and coworkers [5,7] have considered that the Manba and Kamiyosida Units, together with the Mikabu Greenstones around Mts. Mikabu, constitute a superficial nappe that covers the Sanbagawa Belt and the Kashiwagi

Unit. However, Hirajima and Banno [51] have contradicted this idea, based on the findings of high-pressure minerals such as sodic-amphiboles and lawsonite in the region where the superficial nappe was postulated. Shimizu [36] has considered that the Kamiyoshida Unit constitutes a post-metamorphic nappe that overlies both the Manba and Kashiwagi Units. Herein, we follow the classical division of the Manba and Kamiyoshida Units and investigate the relationships between each structural unit.

3. Samples

Rock samples of mudstone, acidic tuff, basic tuff, chert, and red shale were collected from the outcrops shown in Figure 2. The list of samples is given in Table A1 in Appendix A. Mudstone includes black shale (in the Manba and Kamiyoshida Units) and phyllite (in the Kashiwagi Unit). As most researchers postulate the major structural discontinuity between the Manba and Kashiwagi Units [5,24,41,55], samples were collected across the boundary region of the Manba–Kashiwagi Units in two outcrops along the Kannagawa River. Because the exact location of the boundary between the two units is controversial [55], the samples taken from the boundary zone between the Manba and Kashiwagi Units are marked with asterisks (*) in Table A1. Shimizu [36] considered that the Manba and Kamiyoshida Units are bounded by a basal thrust fault of the post-metamorphic nappe as mentioned above. Sample 27-01 and 27-02 are mudstone (black shale) of the Manba Unit and bedded chert of the Kamiyoshida Unit taken from the hanging wall and the footwall sides of the thrust fault (Figure 5 of Shimizu [36]), respectively.

At the type locality of the Mikabu Greenstones around Mt. Nishi-Mikaboyama, basic lava and pyroclastic rocks are conformably overlain by red shale with a thickness of more than 20 m, containing a large number of deformed radiolarian fossils [36]. Sample 28-01 was collected from the roadside outcrop of this red shale. The red shale layer extends to the west around Mt. Odokeyama [5], where Middle Jurassic to Late Jurassic radiolaria have been reported [48]. In this outcrop, red shale was intercalated with a whitish acidic tuff layer with a thickness of 30 cm. The sample Mi-10 of acidic tuff was taken from this outcrop (Figure 3).

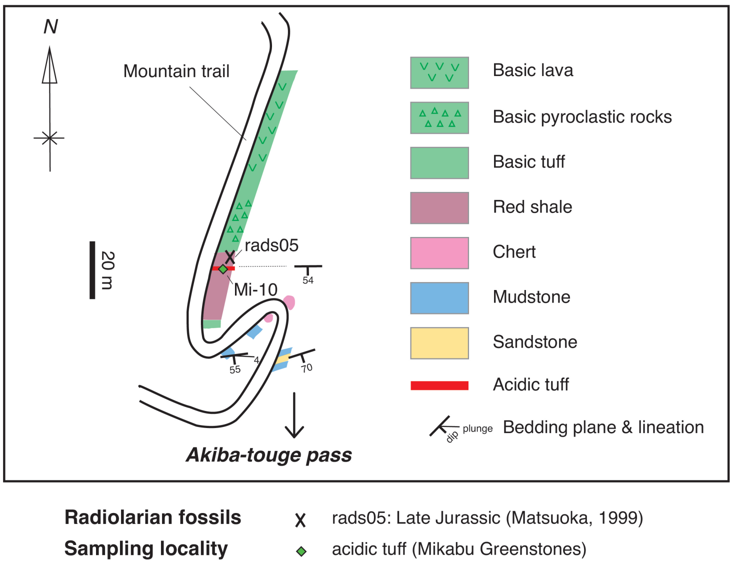

Figure 3. A route map to the north-east of Mt. Odokeyama (Figure A1 in Appendix A) showing the detailed sampling locality of acidic tuff (Mi-10) deposited on the top of the Mikabu Greenstones. The sampling locality of the radiolarian fossils in literature [48] is also plotted.

All of the samples contained quartz, white mica, and chlorite in thin sections. White mica and chlorite grains with lengths of approximately a few microns constitute slaty cleavage or schistosity planes. In mudstones, detrital mica with larger grain sizes (20–50 μm) was also observed. No detrital mica was identified in chert and red shale under an optical microscope. Acidic tuff was found to contain larger feldspar grains in fine-grained quartz matrix.

4. Analytical Methods

Rock samples were broken into fragments and powders using a jaw crusher and a mortar mill, and then washed with ion-exchanged water several times. Rock fragments of ca. 2 mm size were separated by hand-picking and used for the whole-rock analysis. White mica was extracted from crushed samples in ion-exchanged water using supersonic waves and fractionated into four grain-size classes using a centrifuge (0.5–1 μm, 1–2 μm, 2–3 μm, and 3–4 μm, according to Stokes law) and then freeze-dried. In this paper, white mica separated in this way are conventionally referred to as 'illite', although other mica species of detrital origin might have been included in the powders.

K–Ar dating was conducted with a mass spectrometer and associated analytical system at the Research Institute of Natural Sciences, Okayama University of Science [57]. An argon 38 spike was used in the isotopic dilution method. The K-content was determined by flame photometry (HITACHI130-80), where Cs was added as a buffer to reduce interference from other elements. The standard sample was a weakly metamorphosed rock, named 82A, whose potassium contents were previously measured in the same laboratory. As the K-contents of some samples are very low, the potassium weight percent was analyzed using ultra-low blank chemical lines [58]. The radiometric ages were calculated using the decay constants given by Steiger and Jağer [59].

The illite crystallinity was investigated using the Mac Science MXP3 X-ray diffractometer (XRD) at the University of Tokyo. All X-ray scans were conducted with CuKα radiation at 40 kV and 20 mA under the following machine settings: divergent slit angle of 1°, scan range of 7.5–10°2θ, step size ($\Delta 2\theta$) of 0.02°, and 2θ scan rate of 1.2° per minute. The illite crystallinity index, CI, is defined by a full width at half maximum (FWHM) of an X-ray diffraction peak for the basal (001) plane of illite with 10Å spacing [31]. Large CI indicates low crystallinity of the illite. The FWHM values were determined after smoothing and background correction of the diffraction data.

5. Results

5.1. K–Ar Ages

5.1.1. Chert and Red Shale

The results of K–Ar dating for the chert and red shale are summarized in Table 1 and Figure 4. The measurement errors in each sample were approximately ±3 Ma with a 2σ confidence level. Hereafter, we describe the K–Ar age data in terms of the average values. The whole-rock ages of chert and red shale in the Kashiwagi Unit were 133 Ma and 115 Ma, respectively. The red shale on the top of the Mikabu Greenstones yielded a whole-rock age of 124 Ma. The whole-rock ages of chert varied from 168 Ma to 121 Ma in the Manba Unit, and from 156 Ma to 125 Ma in the Kamiyoshida Unit. The Illite K–Ar ages of chert and red shale yielded younger ages for smaller grain-size classes, most of which were younger than the whole-rock age of the same sample. The mineral ages of illite in chert and red shale varied in the ranges of 165–107 Ma in the Kshiwagi Unit, 154–127 Ma in the Manba Unit, and 150–120 Ma in the Kamiyoshida Unit. The ages obtained for smaller grain-size classes yielded systematically younger ages.

5.1.2. Mudstone and Tuff

The results of the K–Ar dating of mudstone, acidic tuff, and basic tuff are summarized in Table 2 and Figure 5. The measurement errors for each fractionated sample were within ±3 Ma with a 2σ confidence level. All data, obtained for fractionated illite samples, indicated younger ages for a decreasing grain size (as observed for chert and red shale). The illite ages of the acidic tuff associated with the Mikabu Greenstones were obtained as 113–89 Ma. The illite K–Ar ages of the Kashiwagi and Manba Units were determined in small ranges for each sample (within 20 My). Overall, the mudstone and acidic tuff in the Kashiwagi Unit were dated as 117–100 Ma, and mudstone, acidic tuff, and basic tuff in the Manba Unit were dated as 132–97 Ma. The two mudstone samples taken from the Kamiyoshida Unit exhibited larger age variations (up to 33 My), ranging from 163 Ma to 121 Ma.

Table 1. The K–Ar ages of whole-rock samples and fractionated illite samples from chert and red shales. The crystallinity index (CI) of illite and the apparent temperature calculated from the CI are also listed. The measurement errors are shown with 2σ confidence level.

Geologic Unit	Sample	Rock Type	Grain Size (μm)	K (wt.%)	Rad. ^{40}Ar (10^{-8} cc STP/g)	Age (Ma)	CI (°Δ2θ)	T_{CI} (°C)
Mikabu Greenstones	28-01	red shale	whole rock	0.43 ± 0.02	216 ± 2	123.6 ± 2.6		
Kashiwagi Unit	27-07	red shale	whole rock	0.60 ± 0.02	277 ± 3	115.3 ± 2.3		
			0.5–1	6.03 ± 0.12	2641 ± 26	106.9 ± 2.3	0.474	249.2
			1–2	5.26 ± 0.11	2574 ± 25	121.8 ± 2.5	0.452	257.1
			2–3	3.46 ± 0.07	1978 ± 17	129.3 ± 2.6	0.456	255.7
			3–4	1.95 ± 0.03	1304 ± 14	164.7 ± 3.3	0.422	267.4
	27-08	chert	whole rock	0.14 ± 0.01	75 ± 1	133.2 ± 2.7		
			0.5–1	1.35 ± 0.03	617 ± 18	114.4 ± 2.3	0.441	260.6
			1–2	1.46 ± 0.03	705 ± 15	120.5 ± 2.4	0.407	272.5
			2–3	1.54 ± 0.03	747 ± 16	121.2 ± 2.4	0.389	278.6
			3–4	1.09 ± 0.02	632 ± 8	143.3 ± 2.9	0.372	284.3
Manba Unit	26-05	chert	whole rock	0.17 ± 0.01	94 ± 1	141.3 ± 2.8		
	27-10	chert	whole rock	0.22 ± 0.01	116 ± 2	130.6 ± 2.6		
	27-12B	chert	whole rock	0.12 ± 0.01	60 ± 1	120.8 ± 2.4		
	28-03A	chert	whole rock	0.24 ± 0.01	163 ± 2	168.2 ± 3.8		
			0.5–1	4.82 ± 0.09	2495 ± 25	128.7 ± 2.5	0.411	270.9
			1–2	4.27 ± 0.08	2206 ± 22	128.5 ± 2.5	0.422	267.2
			2–3	3.09 ± 0.06	1782 ± 17	142.8 ± 2.8	0.455	256.0
			3–4	1.28 ± 0.03	787 ± 8	152.5 ± 3.1	0.421	267.7
	28-03B	chert	whole rock	0.35 ± 0.01	212 ± 2	148.4 ± 2.9		
			0.5–1	5.91 ± 0.18	3019 ± 31	127.1 ± 2.5	0.467	251.8
			1–2	5.6 ± 0.12	2997 ± 29	132.9 ± 2.6	0.389	278.6
			2–3	4.3 ± 0.08	2477 ± 24	142.4 ± 2.8	0.377	282.6
			3–4	2.38 ± 0.06	1483 ± 15	154.1 ± 3.1	0.372	284.4
Kamiyoshida Unit	27-02	chert	whole rock	0.33 ± 0.02	205 ± 2	152.7 ± 3.1		
			0.5–1	5.81 ± 0.12	2787 ± 27	119.6 ± 2.4	0.419	268.2
			1–2	5.30 ± 0.11	2860 ± 27	128.8 ± 2.5	0.388	278.9
			2–3	3.81 ± 0.07	2119 ± 21	136.3 ± 2.7	0.395	276.6
			3–4	1.64 ± 0.03	1003 ± 10	149.6 ± 2.9	0.375	283.5
	27-03	chert	whole rock	0.25 ± 0.01	161 ± 0.1	155.9 ± 3.1		
Unknown	28-02	chert	whole rock	0.13 ± 0.01	65 ± 0.9	124.7 ± 2.4		

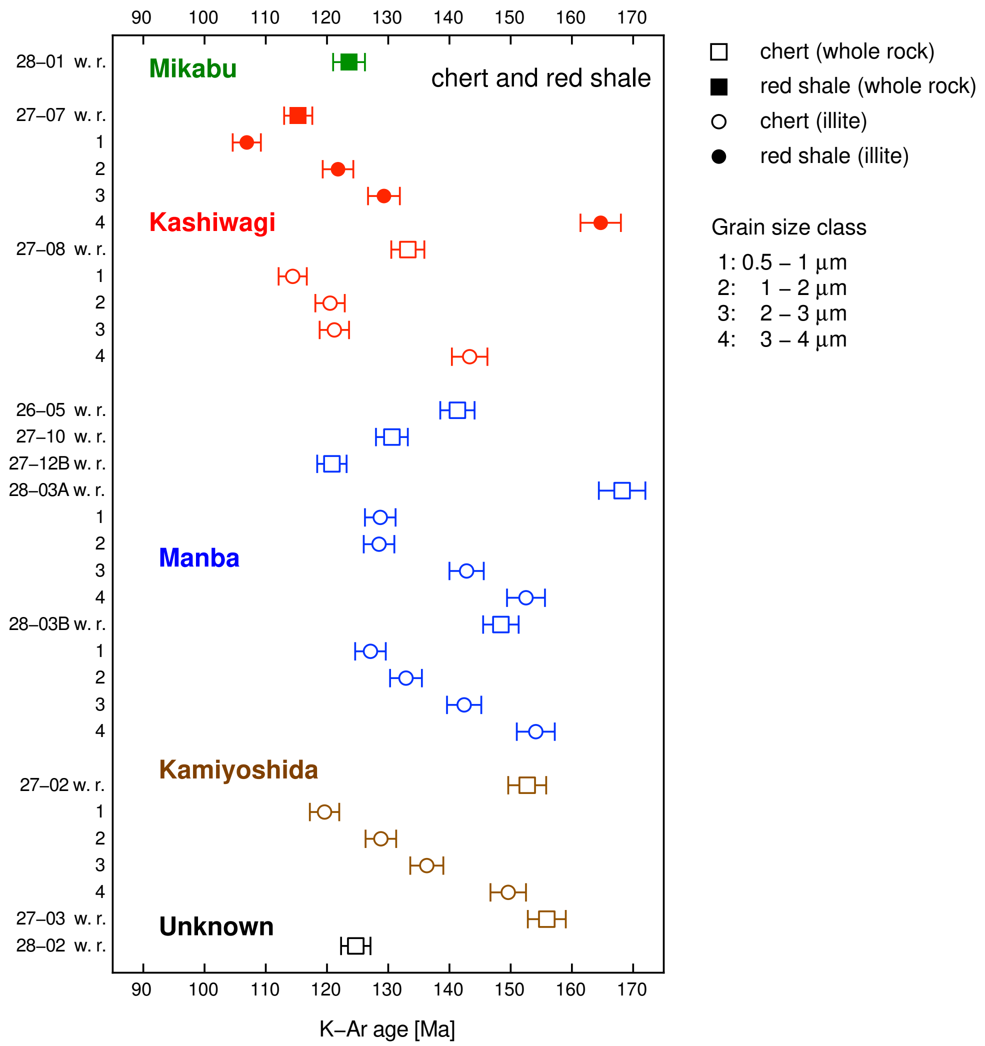

Figure 4. The peak metamorphic ages determined from the bulk and fractionated illite samples of chert and red shale (Table 1). Green, red, blue, and brown symbols indicate the Mikabu Greenstones and the Kashiwagi, Manba, and Kamiyoshida Units, respectively. Bars show the measurement errors with 2σ confidence level.

Table 2. The K–Ar ages of fractionated illite samples of mudstone and tuff. The crystallinity index (CI) of illite and the apparent temperature T_{CI} calculated from the CI are also listed. * Samples taken from the boundary zone between the Kashiwagi and Manba Units. † Sample for the crushing test. The measurement errors are shown with 2σ confidence level.

Geologic Unit	Sample	Rock Type	Grain Size (µm)	K (wt.%)	Rad. ^{40}Ar (10^{-8} cc STP/g)	Age (Ma)	CI (°Δ2θ)	T_{CI} (°C)
Mikabu Greenstones	Mi-10	acidic tuff	0.5–1	4.62 ± 0.10	1639 ± 17	89.2 ± 2.0	0.312	305.3
			1–2	4.92 ± 0.10	1889 ± 20	96.4 ± 2.1	0.305	307.4
			2–3	4.83 ± 0.10	2050 ± 21	106.2 ± 2.5	0.287	313.7
			3–4	3.48 ± 0.07	1582 ± 17	113.4 ± 2.5	0.256	324.6
Kashiwagi Unit	26-03	acidic tuff	0.5–1	6.61 ± 0.13	2763 ± 29	104.0 ± 2.1	0.403	273.8
			1–2	6.75 ± 0.13	3032 ± 30	111.7 ± 2.2	0.297	310.3
			2–3	6.21 ± 0.12	2863 ± 28	114.1 ± 2.3	0.294	311.3
			3–4	5.38 ± 0.11	2356 ± 23	109.8 ± 2.2	0.255	324.9

Table 2. *Cont.*

Geologic Unit	Sample	Rock Type	Grain Size (μm)	K (wt.%)	Rad. ^{40}Ar (10^{-8} cc STP/g)	Age (Ma)	CI (°Δ2θ)	T_{CI} (°C)
	27-05	acidic tuff	0.5–1	6.16 ± 0.12	2455 ± 32	99.9 ± 2.0	0.321	302.2
			1–2	6.11 ± 0.12	2515 ± 25	103.0 ± 2.1	0.297	310.3
			2–3	5.53 ± 0.11	2326 ± 23	105.3 ± 2.1	0.281	315.8
			3–4	3.97 ± 0.08	1727 ± 17	108.9 ± 2.2	0.362	287.9
	27-06	mudstone	0.5–1	6.69 ± 0.13	2912 ± 28	108.8 ± 2.2	0.460	254.1
			1–2	5.88 ± 0.11	2604 ± 26	110.7 ± 2.2	0.453	256.5
			2–3	4.66 ± 0.10	2116 ± 21	113.5 ± 2.3	0.444	259.7
			3–4	3.63 ± 0.07	1700 ± 17	116.8 ± 2.3	0.436	262.4
	L-7	acidic tuff	0.5–1	6.75 ± 0.13	2853 ± 30	105.8 ± 2.1	0.406	272.7
			1–2	6.86 ± 0.14	3120 ± 32	111.9 ± 2.2	0.342	294.7
			2–3	6.38 ± 0.13	2901 ± 29	113.5 ± 2.3	0.312	305.1
			3–4	5.23 ± 0.11	2522 ± 25	116.2 ± 2.3	0.337	296.5
	L-7R †	acidic tuff	1-2	6.86 ± 0.14	3173 ± 33	115.4 ± 2.5	0.333	
			2–3	6.33 ± 0.13	3085 ± 31	119.1 ± 2.6	0.329	
			3–4	4.87 ± 0.10	2302 ± 24	118.0 ± 2.6	0.314	
Manba Unit	27-01	mudstone	0.5–1	7.08 ± 0.14	2883 ± 30	100.5 ± 2.0	0.470	250.7
			1–2	7.04 ± 0.14	3116 ± 32	110.6 ± 2.2	0.415	269.7
			2–3	6.77 ± 0.13	3006 ± 31	111.0 ± 2.2	0.390	278.2
			3–4	4.75 ± 0.09	2192 ± 22	115.2 ± 2.3	0.399	275.3
	26-01A *	acidic tuff	0.5–1	6.88 ± 0.13	2832 ± 28	103.1 ± 2.0	0.426	266.0
			1–2	6.92 ± 0.14	2928 ± 28	105.9 ± 2.1	0.421	267.6
			2–3	6.12 ± 0.12	2743 ± 26	111.9 ± 2.2	0.424	266.5
			3–4	4.33 ± 0.09	1966 ± 19	113.4 ± 2.2	0.320	302.5
	26-01B *	mudstone	27-01	6.67 ± 0.14	2407 ± 27	97.0 ± 1.9	0.456	255.5
			1–2	6.26 ± 0.12	2537 ± 35	101.3 ± 2.0	0.447	258.5
			2–3	5.02 ± 0.11	2172 ± 21	107.6 ± 2.1	0.422	267.1
			3–4	4.49 ± 0.09	1915 ± 18	106.6 ± 2.1	0.431	264.2
	26-04	mudstone	0.5–1	6.88 ± 0.14	3334 ± 35	120.8 ± 2.4	0.452	256.9
			1–2	6.40 ± 0.12	3204 ± 33	124.7 ± 2.5	0.439	261.3
			2–3	5.21 ± 0.10	2724 ± 28	129.9 ± 2.6	0.398	275.7
			3–4	3.28 ± 0.06	1743 ± 18	132.2 ± 2.6	0.428	265.3
	27-04	basic tuff	0.5–1	7.59 ± 0.15	3775 ± 36	123.8 ± 2.7	0.468	251.6
			1–2	7.20 ± 0.14	3684 ± 40	127.3 ± 2.6	0.429	264.9
			2–3	6.92 ± 0.14	3563 ± 34	128.1 ± 2.6	0.385	279.9
			3–4	6.67 ± 0.13	3466 ± 33	129.1 ± 2.7	0.398	275.7
	27-11	mudstone	0.5–1	6.44 ± 0.12	3225 ± 25	121.4 ± 2.4	0.443	259.9
			1–2	6.35 ± 0.12	3149 ± 23	123.5 ± 2.6	0.394	277.0
			2–3	5.24 ± 0.10	2796 ± 19	127.7 ± 2.5	0.385	279.9
			3–4	4.78 ± 0.09	2484 ± 25	129.1 ± 2.6	0.363	287.6
	28-04	mudstone	0.5–1	5.60 ± 0.11	2311 ± 24	103.4 ± 2.1	0.425	266.3
			1–2	4.98 ± 0.10	2153 ± 22	108.1 ± 2.2	0.402	274.2
			2–3	3.80 ± 0.07	1684 ± 17	110.9 ± 2.2	0.394	277.0
			3–4	2.47 ± 0.05	1126 ± 12	113.8 ± 2.4	0.368	285.8
Kamiyoshida Unit	L-11	mudstone	0.5–1	6.71 ± 0.13	3219 ± 34	129.6 ± 2.6	0.464	252.6
			1–2	5.34 ± 0.10	2948 ± 30	136.9 ± 2.8	0.454	256.2
			2–3	3.95 ± 0.08	2363 ± 24	148.1 ± 2.9	0.436	262.6
			3–4	2.75 ± 0.05	1814 ± 19	162.7 ± 3.1	0.440	260.9
	L-13	mudstone	0.5–1	6.11 ± 0.12	2969 ± 31	121.1 ± 2.4	0.455	255.9
			1–2	5.56 ± 0.12	2911 ± 30	130.1 ± 2.6	0.444	259.8
			2–3	4.26 ± 0.08	2303 ± 24	134.2 ± 2.7	0.420	268.0
			3–4	3.09 ± 0.06	1797 ± 19	144.1 ± 2.8	0.440	261.0

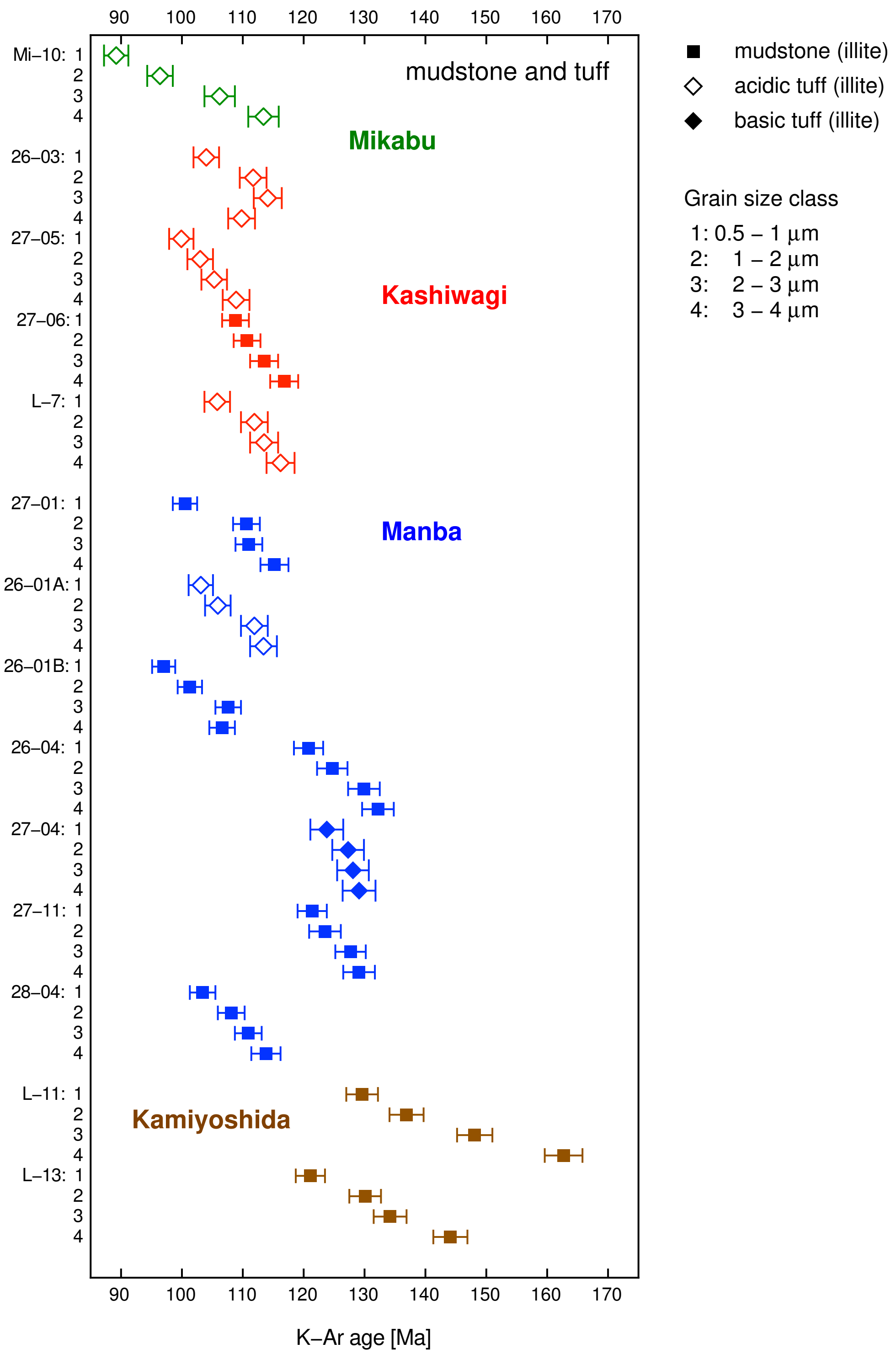

Figure 5. The peak metamorphic ages determined from the fractionated illite samples of mudstone, acidic tuff, and basic tuff (Table 2). Green, red, blue, and brown symbols indicate the Mikabu Greenstones and the Kashiwagi, Manba, and Kamiyoshida Units, respectively. Bars show the measurement errors with 2σ confidence level.

5.2. Illite Crystallinity

The CI values were determined for all fractionated samples of illite (Tables 1 and 2). Each sample exhibited smaller CI for larger grain size classes (Figure 6), although there were some exceptions. The minimum CI in each sample was mostly around 0.4, but acidic tuff samples taken from the Mikabu Greenstones and the Kashiwagi Unit displayed smaller values (i.e., high crystallinity) of around 0.3. No remarkable difference was found between the CI values obtained for mudstone and chert.

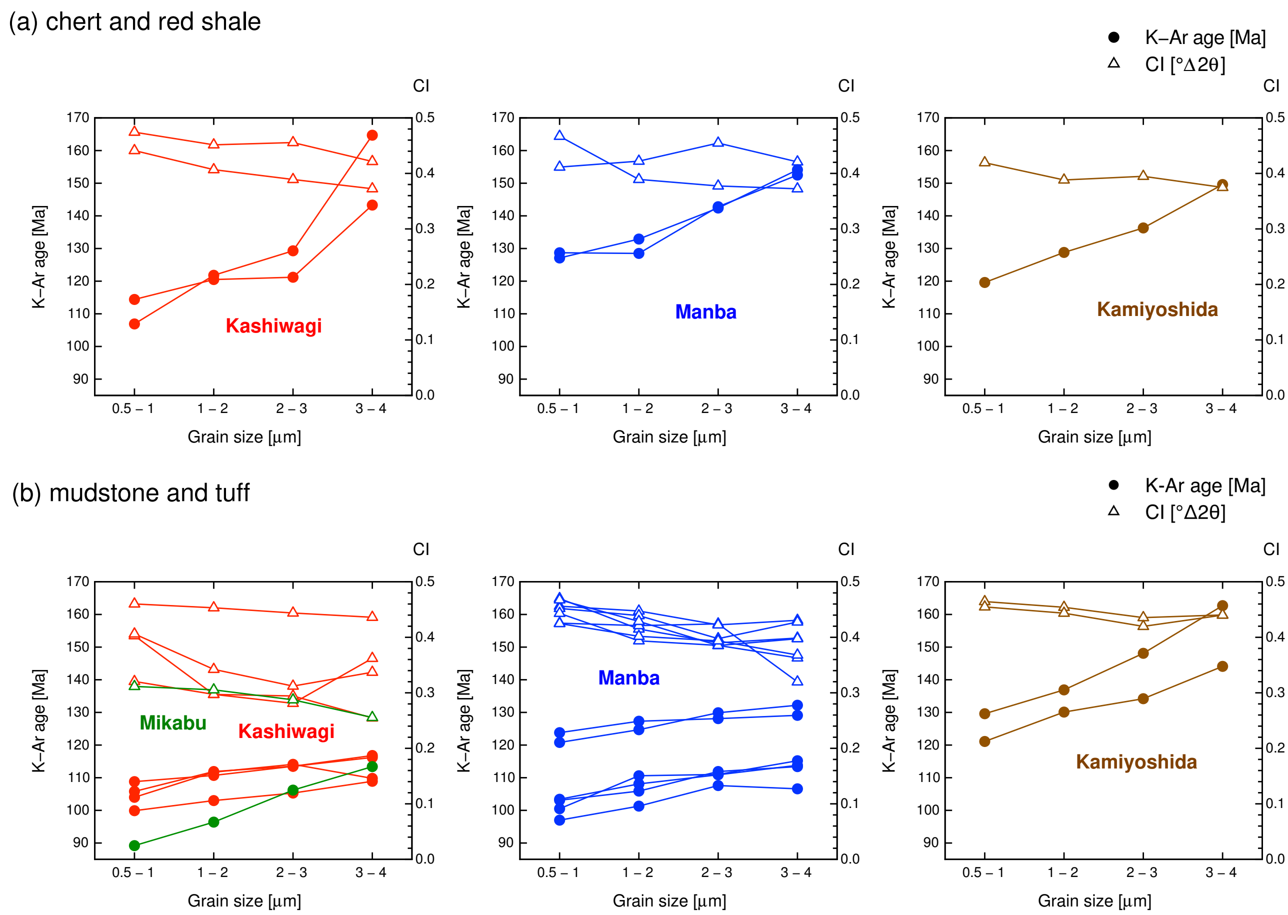

Figure 6. The K–Ar ages and crystallinity index (CI) of illite in chert and red shale plotted from Table 1 (**a**), and in mudstone, acidic tuff, and basic tuff plotted from Table 2 (**b**), determined for each grain-size class. Green, red, blue, and brown symbols indicate the data of the Mikabu Greenstones and the Kashiwagi, Manba, and Kamiyoshida Units, respectively.

5.3. Mechanical Crushing Test

To examine possible effects of Ar-loss during sample preparation, we conducted a mechanical crushing test on a powdered and fractionated sample of acidic tuff (L-7). The illite sample of the 3–4 µm class, which originally yielded a K–Ar age of 116 Ma, was ground with an agate mortar, then fractionated into 1–2 µm, 2–3 µm, and 3–4 µm size classes. The results of the K–Ar dating and the CI measurement are listed as L-7R in Table 2. Figure 7 compares the K–Ar ages and CI values of illite before and after refinement. Notably, no significant loss of Ar was detected in this test. Hence, the possibility of Ar loss and change in illite crystallinity during mechanical crushing and gliding in the laboratory are not considered in the following discussion.

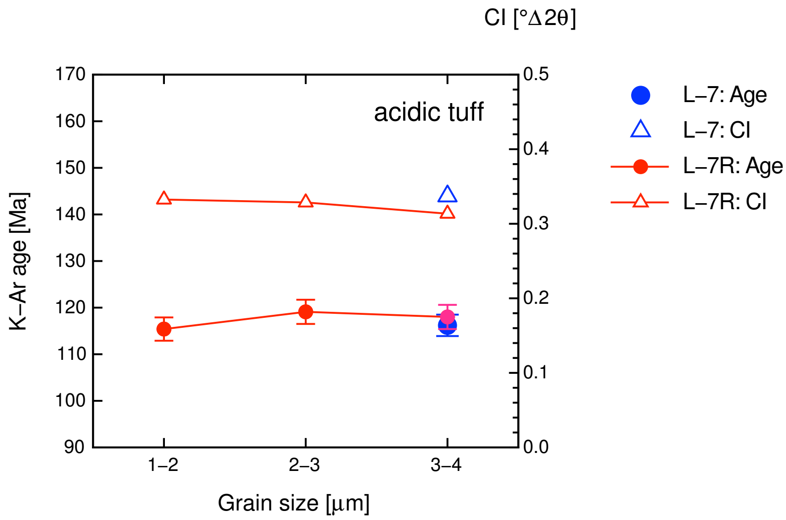

Figure 7. The illite K–Ar ages and CI values of a sample (L-7) of acidic tuff before (blue) and after (red) the crushing test. See text for details.

6. Discussion

6.1. Interpretation of K–Ar Ages

6.1.1. Chert and Red Shale

The K–Ar ages of chert and red shale exhibited a large variation (Table 1). The chert and red shale originated from pelagic sediments, which are expected to be almost free from terrestrial materials. Hence, the contamination of detrital mica would not have seriously affected the K–Ar dating of these rocks. Nevertheless, the whole-rock ages of chert in the Kamiyoshida and Manba Units showed a large variation, and the oldest age obtained from the Manba Unit (168 Ma) was very close to the timing of accretion at the Middle Jurassic (>165 Ma; Figure 4). The illite samples separated from chert and red shale also showed large variations, and the whole-rock measurements yielded relatively old ages compared with the illite mineral ages of the same sample (Figure 6a). The K–Ar ages determined for chert and red shale in the Kashiwagi Unit also presented large variations. The oldest one obtained for the largest grain-size class of illite yielded an age before the Late Jurassic accretion age. The mineral ages of illite determined for chert blocks (28-03A, 28-03B) in the Manba Unit were older than those of the surrounding mudstone matrix (28-04) at the same outcrop (Figure 8a). Similarly, the mineral ages for the largest grain size group of illite separated from red shale (27-07) displayed older ages than those separated from acidic tuff (L-7) in the same outcrops (Figure 8b).

The micro-fossil data in chert blocks of the Kashiwagi, Manba, and Kamiyoshida Units indicate deposition ages from Carboniferous to Triassic, whereas those in mudstone indicated younger ages of accretion, during the Middle to Late Jurassic, as summarized in the previous section. One possible explanation is that the K–Ar ages were affected by submarine processes at the time of deposition; for example, hydrothermal activity and submarine metasomatism-associated volcanism of ridges or seamounts may lead to the precipitation of illite or its precursor K-bearing minerals.

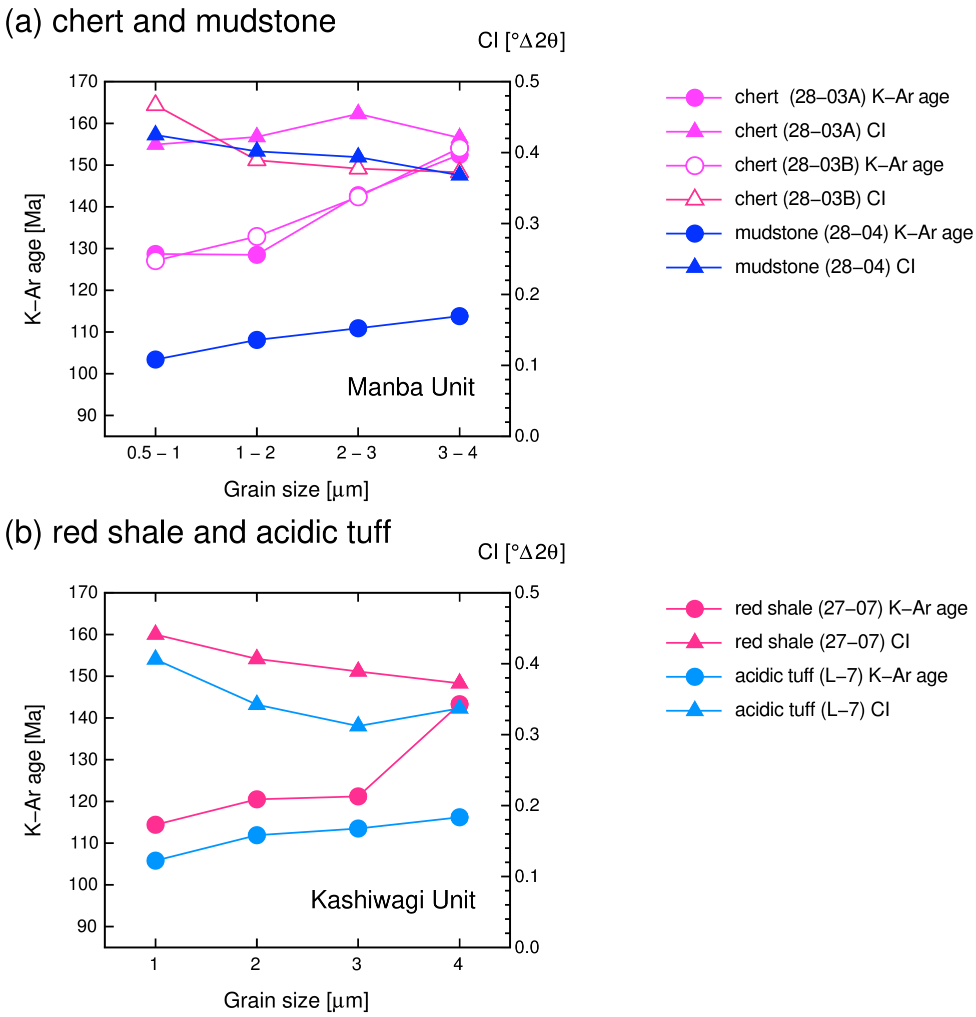

Figure 8. The illite K–Ar ages (circles) and CI (triangle) of selected samples. (**a**) Comparison between chert blocks and the surrounding mudstone matrix in the Manba Unit. (**b**) Comparison between red shale and acidic tuff in the same outcrop of the Kashiwagi Unit.

6.1.2. Mudstone and Tuff

Compared with the ranges of K–Ar ages for chert and red shale, the illite ages of mudstone, acidic tuff, and basic tuff in each samples, and for each structural unit (Figure 5), were concentrated in narrow ranges (except for mudstone in the Kamiyoshida Unit). In the following discussion, we focus on the illite ages obtained from these rocks. Among the illite ages determined for different grain-size classes of the same rock sample, larger illite grains yielded older ages and smaller CI values, although there were some exceptions (Figure 6b). The contamination of detrital mica, formation of new clay minerals, and brittle deformation in the retrograde stages are possible causes of the systematic changes in the K–Ar ages and illite crystallinity. In the present case, the mechanical crushing test exhibited no detectable changes in the K–Ar ages and CI values (Figure 7). Furthermore, the illite ages and CI values of the mudstone of the Manba Unit beneath the fault boundary (27-01) were similar to those obtained from other mudstone samples of the Manba Unit. Thus, we consider that the K–Ar age data and CI values were not strongly affected by brittle deformation in the retrograde stages. A grain-size dependence of the illite K–Ar ages and CI was observed not only in mudstone, but also in pelagic sediments (chert and red shale) and tuffs. The acidic tuff of the Kashiwagi Unit and Mikabu Greenstones had illite grains with small CI (i.e., high crystallinity), which are thought to have crystallized from volcanic glass and feldspars during metamorphism. The illite K–Ar ages determined for mudstone and acidic tuff in the same outcrops (26-01A and 26-01B; 27-05 and 27-06) yielded similar age distributions. This suggests that the influence of detrital mica on the K–Ar dating was negligible.

The white mica in the low-grade metamorphic rocks was actually illite–smectite interstratified clay minerals, with CI values mainly controlled by the layer thickness of illite crystallite domains and the percentage of the smectite layers [60]. Kübler [31] has proposed using the CI of the <2 μm sized fraction of clay samples as an indicator of metamorphic grade. Although illite crystallinity could be affected by many kinetic factors other than temperature, such as the duration of metamorphism and chemical environment of the host rock, Kübler's index has been widely applied to estimate the grade of the incipient to low-grade metamorphic rocks, which have traditionally been divided into three zones: the diagenetic zone, anchizone, and epizone. While the CI values of 0.42 and 0.25 have been frequently used for the diagenetic/anchizone and anchizone/epizone boundaries, respectively, the standardization between different laboratories has long been discussed [61–63]. Underwood et al. [64] have measured the Kübler's CI in the Cretaceous accretionary complex of the Shimanto Belt, SW Japan, and correlated CI and the peak metamorphic temperature T_{vtr} (°C), quantified by the vitrinite reflectance as

$$\mathrm{CI} = 1.197 - 0.0029\ T_{vtr}. \quad (1)$$

Underwood et al. [64] suggested that errors in determining T_{vtr} were at least ±50°C. We use the above equation to define the apparent metamorphic temperature T_{CI} (°C) as

$$T_{CI} = (4.13 - 3.45\ \mathrm{CI}) \times 10^2. \quad (2)$$

The T_{CI} values calculated for each fractionated samples of illite are also listed in Tables 1 and 2. Taking the 1–2 μm size class illite samples, the CI values of mudstone in the Kamiyosida Unit (0.44–0.45 in the diagenetic zone) corresponded to a T_{CI} of 256–260 °C, whereas those of the Manba Unit (0.40–0.45 from the diagenetic to anchizone) corresponded to 259–277 °C. Mudstone at the uppermost part of the Kashiwaki Unit yielded a relatively large CI (0.45 in the diagenetic zone), corresponding to 257 °C, whereas acidic tuff in the Kashiwagi Unit (CI = 0.30–0.34 in the anchizone) and the Mikabu Greenstones (CI = 0.31 in the anchizone) yielded a T_{CI} of 295–310 °C. These results are roughly consistent with the mineral assemblages of the Kashiwagi Unit and the Mikabu Greenstones, which belong to the pumpellyite–actinolite facies zone (ca. 250–350°C) [51]. The peak metamorphic temperatures of mudstones in the eastern area of the Kanto Mountains estimated by the Raman spectroscopy of carbonaceous materials (315 °C for the Mikabu Greenstones, 252–268 °C for the Kashiwagi Unit, and ca. 260 °C for the Kamiyoshida Unit) [65] are in reasonable agreement with the T_{CI} values of each units. In the south-east extension of the Kashiwagi Unit (Hashidate Unit), CI values of 0.23–0.33, corresponding to a T_{CI} of 299–334 °C, have been reported from mudstone [34]. In the XRD measurements, we directly used the powdered samples of illite, whereas the preparation of sedimentated slides was recommended for Kübler's index [62]. The relatively smaller values of CI in our results might be partly due to the difference in sample preparation method.

As discussed above, the grain-size dependence of the K–Ar ages and CI observed in the samples of various lithologies was not attributable to the contamination of detrital muscovite. The younger ages and larger CI values observed for fine-grained illite would be more reasonably explained by their formation in the retrograde stages. The ranges of the illite ages in each sample possibly reflect the cooling history of each structural unit. Figure 9 tentatively plots the change in the apparent metamorphic temperature of each fractionated sample of illite against its K–Ar age. It should be noted that kinetic factors other than temperature, such as the duration of metamorphism and chemical environments, might have been affected the CI values. The illite K–Ar ages of acidic tuff (Mi-10) at the type locality of the Mikabu Greenstones showed a deviation toward younger ages in the small grain-size classes (<2 μm). As the sample was located at a small outcrop along a mountain pass, small illite grains might have been influenced by Ar loss due to weathering on the ground surface.

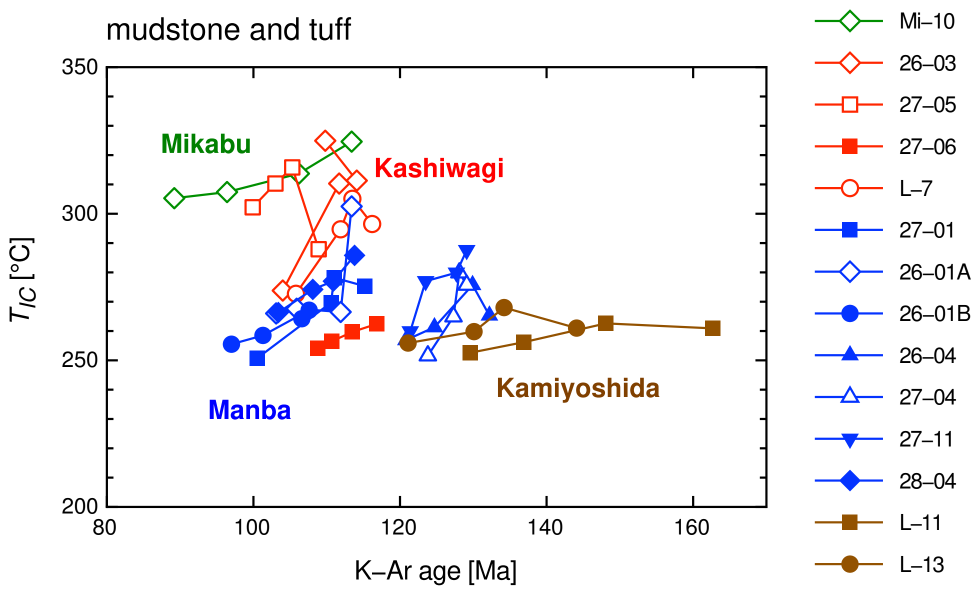

Figure 9. Relationship between the K–Ar age and the apparent metamorphic temperature T_{CI}, determined for each fractionated sample of illite. Green, red, blue, and brown symbols indicate the data of the Mikabu Greenstones and the Kashiwagi, Manba, and Kamiyoshida Units, respectively.

6.1.3. Peak Metamorphic Ages

In the previous chronological studies of the Sanbagawa Belt, the K–Ar and Ar–Ar ages of white mica have been generally interpreted as the cooling ages in uplifting stages [9,11,66], which correspond to the timing of the closure of Ar isotopic systems within muscovite grains [67]. However, in the Northern Chichibu Belt, the metamorphism temperatures were close to or lower than the conventionally used values of closure temperatures in Ar–muscovite systems (ca. 350 °C [68]). The closure temperature of Ar in fine-grained illite has been estimated to be in a range between 250–350 °C, which overlaps with the temperatures of illite crystallization [30]. Hence, the illite K–Ar ages obtained from the Northern Chichibu Belt have been understood as the illite crystallization ages at the peak metamorphism rather than cooling ages [11]. The illite ages of the Mikabu Greenstones, which belong to the pumpellyite–actinolite facies zone (ca. 250–350 °C), have also been considered as the peak metamorphic ages. In the present study, however, different K–Ar ages were obtained for illite in different size classes. The variation in the K–Ar age likely reflects the cooling history of each structural unit, as discussed above. Hence, the illite ages obtained for the 3–4 µm class were taken to determine the timing of peak metamorphism (Figure 10).

Using the illite mineral ages obtained from mudstone, acidic tuff, and basic tuff, the Kashiwagi Unit was dated to 117–110 Ma, and the Manba Unit was dated to 132–107 Ma. The age of mudstone previously reported from the low-grade sub-zone of the pumpellyite–actinolite facies zone (117 Ma) using a conventional K–Ar dating method [28] is consistent with the determined peak metamorphic ages of the Kashiwagi Unit. The K–Ar age of tuffaceous phyllite (110 Ma) in the 'Mikabu Unit' in the eastern area of the Kanto Mountains [24] can be correlated with the ages of acidic tuff in the Kashiwagi Unit determined in the present study. The peak metamorphic age of the red shale on the top of the ancient Mikabu seamount is 113 Ma according to the K–Ar dating of the intercalation of acidic tuff.

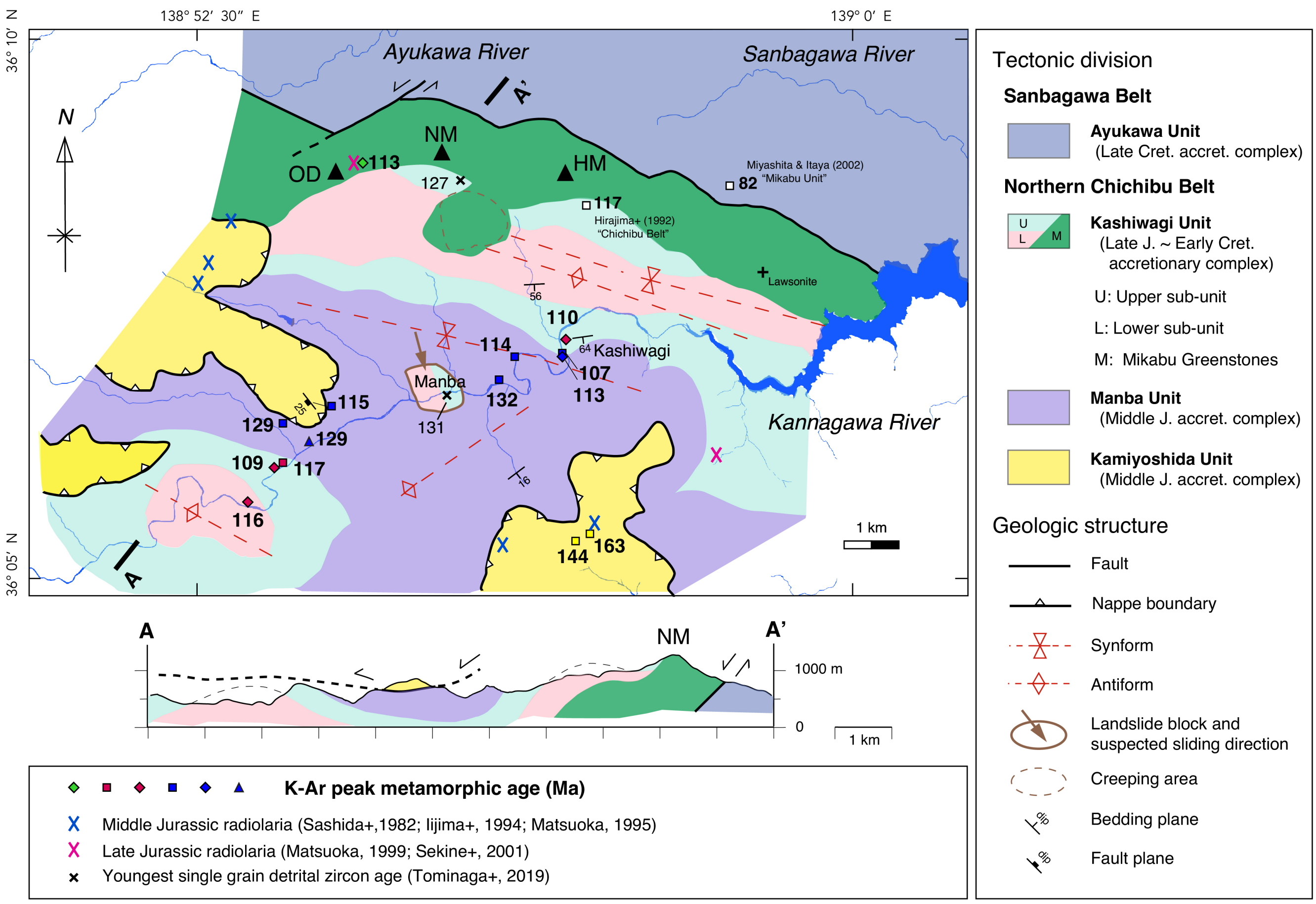

Figure 10. The geological map of the Northern Chichibu Belt in the study area plotted with the peak metamorphic ages of mudstone, acidic tuff, and basic tuff, determined from the K–Ar dating of 3–4 µm fractionated samples of illite. Symbols of sampling localities are the same as those in Figure 2. The geologic cross section along A–A' shows the upper and lower sub-units of the Kashiwagi Unit that are exposed around Mt. Nishi-Mikaboyama about the Mikabu Greenstones. The localities of radiolarian fossils in literature (Sashida et al. [42], Matsuoka [48,49], Iijima et al. [46], Sekine et al. [39]), and the sampling localities for the K–Ar dating in the 'Chichibu Belt' by Hirajima et al. [28] and 'Mikabu Unit' by Miyashita and Itaya [20] (open squares), and, for zircon, U–Pb dating by Tominaga et al. [50] (cross), are also marked. NM: Mt. Nishi-Mikaboyama; HM: Mt. Higashi-Mikaboyama; OD: Mt. Odokeyama.

Two mudstone samples taken from the Kamiyoshida Unit were dated to 163 Ma and 144 Ma, based on the illite ages of the 3–4 µm class. These ages were remarkably older than the illite ages of the Kashiwagi and Manba Units. This supports the tectonic interpretation of Shimizu [36] that the Kamiyoshida Unit is a different tectonic unit covering the Kashiwagi and Manba Units with a major discontinuity. It should be noted, however, that the illite ages presented a very large variation depending on the grain size, and that the oldest age (163 Ma) was very close to the accretion age of the early Middle Jurassic [43] (Figure 11). The influence of contamination of older white mica might be relatively important in these very low-grade sedimentary rocks, but the CI values of these samples did not show markedly different values for different grain sizes (Figure 6b). As the rock samples of mudstone taken from the Kamiyoshida Unit comprised small fragments of chert breccia, the contamination of older materials of chert fragments possibly affected the K–Ar ages. Thus, more detailed studies with additional sampling and methodologies (e.g., illite polytype quantification [30,69]) are required to specify the peak metamorphic age of the Kamiyoshida Unit.

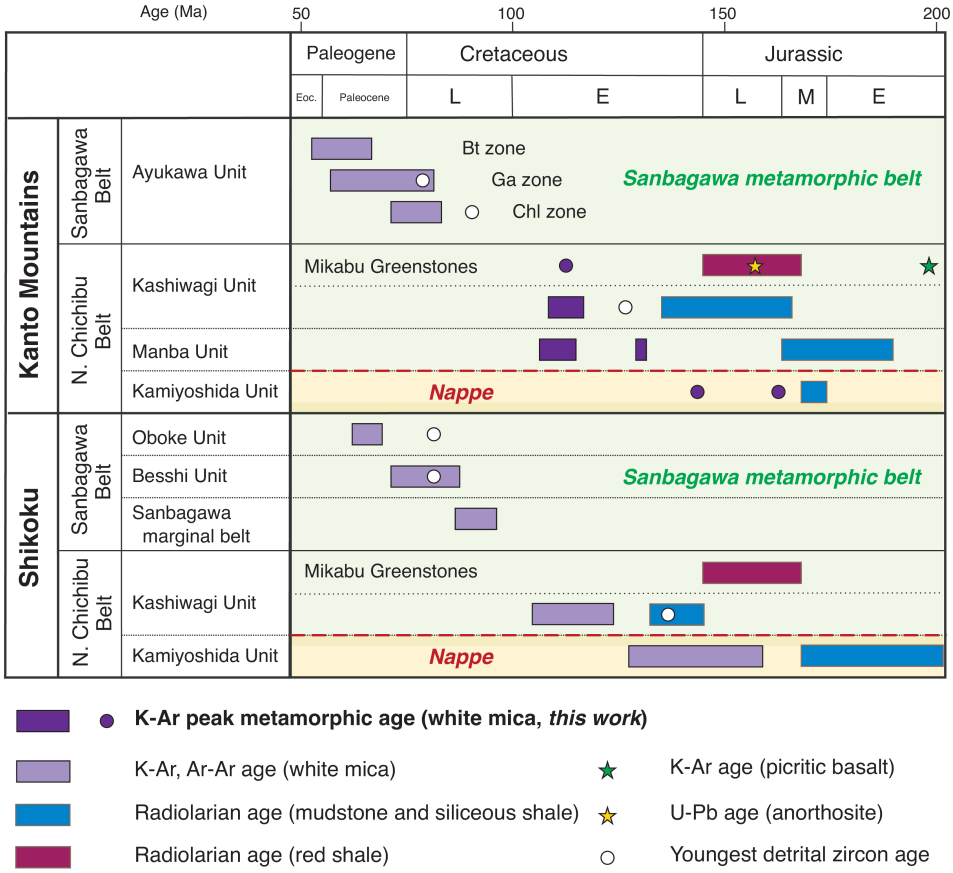

Figure 11. Sedimentation, accretion, and metamorphic histories of the Sanbagawa and Chichibu Belts in the Kanto Mountains and Shikoku. Rectangular areas and symbols show the ranges and individual age data, respectively. The K–Ar and Ar–Ar ages in the Sanbagawa Belt after [20,28] (Kanto Mountains) and [9,11] (Shikoku). K–Ar ages in the Northern Chichibu Belt in Shikoku after [12]. Radiolarian ages of mudstone and siliceous shales in the Kanto Montains are based on [39,40] (Kashiwagi Unit), [43,44] (Manba Unit), and [45,46] (Kamiyoshida Unit), with re-interpretation by [41], and those in Shikoku are based on [41]. Radiolarian ages of red shale are based on [48] (Kanto Mountains) and [70] (Shikoku). The volcanic ages of the Mikabu Greenstones refer to [25] (K–Ar age) and [24] (U–Pb age). The youngest detrital zircon ages refer to [71] (Ayukawa Unit) and [24] (Kashiwagi Unit) in the Kanto Mountains, and [72] (Oboke Unit), [16,17] (Besshi Unit), and [19] (Kashiwagi Unit) in Shikoku.

6.2. Tectonic Evolution of the Sanbagawa–Chichibu Belts

6.2.1. Subduction of the Ancient Mikabu Seamount

In the Sanbagawa Belt to the north-east of the study area, the K–Ar ages of white mica monotonously increase toward the upper structural unit; the K–Ar ages of white mica in pelitic, psammitic, and basic schists in the chlorite, garnet, and biotite zones of the Sanbagawa schists in the Kanto Mountains range from 84–72 Ma, 82–58 Ma, and 67–53 Ma, respectively [20,28] (Figure 11). The illite K–Ar age of the Mikabu Greenstones (115 Ma) determined in the present work was definitely older than the muscovite ages cited above. As the peak metamorphic temperatures in the high-grade zones exceed the closure temperature of muscovite, the younger ages in the biotite and garnet zones might be partly attributed to the difference in cooling ages. However, the metamorphic temperature achieved in the chlorite zone would not significantly differ from that in the Mikabu Greenstones (up to 325 °C, according to T_{CI}). Hence, a chronological gap between the Mikabu Greenstones and the Sanbagawa Belt can be inferred. The K–Ar age of the 'Mikabu unit' (82 Ma), previously reported from the Kanto Mountains by Miyashita and Itaya [20] (Figure 2), likely represents the metamorphic age of the Sanbagawa Belt. The peak metamorphic age of 115 Ma determined at the type locality of the Mikabu Greenstones indicated that the timing of the underplating of the Mikabu seamount was contemporaneous with the peak metamorphism of the Kashiwagi Unit (117–110 Ma) in the Early Cretaceous. This supports the idea that the Mikabu Greenstones and the oceanic and terrigenous sediments of the Kashiwagi Unit constitute the same oceanic plate stratigraphy [36,73].

The peak metamorphic ages estimated from the K–Ar ages of illite in the Manba Unit have bimodal concentrations around 115 Ma and 130 Ma. Notably, the younger ages ca. 115 Ma overlap with the peak metamorphic age of the Kashiwagi Unit, although there is a large gap in the accretion ages determined from radiolarian fossils and detrital zircon (134–127 Ma) [50] between the Kashiwagi Unit (the Early Cretaceous) and the Manba Unit (the Middle Jurassic). These include data from samples taken from the boundary region of the Kashiwagi and Manba Units. A possible scenario is that the basal part of the Middle Jurassic strata that formerly constituted the accretionary wedge was scratched out, accreted to the downgoing plate and subducted with the Kashiwagi Unit, and metamorphosed together at the deeper part of the subduction zone. The tectonic erosion of the basal part of the accretionary wedge due to the subduction of the Mikabu seamount may possibly account for the distribution of the Manba Unit.

6.2.2. Comparison with Chronological Data in Central Shikoku

The tectono-thermal history of the Sanbagawa Belt in Shikoku has been extensively studied using K–Ar and Ar–Ar dating methods (Figure 11). One of the conspicuous features addressed in the NS cross-section of the Sanbagawa Belt in Shikoku is the positive correlation between metamorphic grades and muscovite mineral ages [11]. Takasu and Dallmeyer [9] have explained chronological gaps by nappe structures, and considered that the main suite (Besshi Unit) of the Sanbagawa Belt thrusted over a younger unit (Oboke Unit). Aoki et al. [15] have divided the Besshi Unit into two sub-units based on the protolith ages. The older sub-unit (renamed as the 'Besshi unit') was assumed to be metamorphosed in the Early Cretaceous (120–110 Ma), whereas the younger one (named the 'Asemi-gawa unit') was considered as the Late Cretaceous metamorphic belt. However, recent U–Pb zircon dating evidence obtained by Knittel et al. [16,17] suggests that the deposition ages are no older than 100 Ma everywhere in central Shikoku. This means that the Early Cretaceous metamorphic event was absent in the Sanbagawa Belt. In the following discussion, we use the unit names in the original sense of Takasu and Dallmeyer [9].

Aoki and coworkers [56,74] have correlated the Sanbagawa schists in the Kanto Mountains with the Oboke Unit in a broader sense (i.e., the 'Shimanto metamorphic belt', in their definition). However, unlike the Oboke Unit, coarse-grained turbiditic deposits are not observed in the Kanto Mountains, and the K–Ar and Ar–Ar ages of the Oboke Unit (70–63 Ma) [8,9,72] are significantly younger than the K–Ar ages reported from the same metamorphic grade zone in the Kanto Mountains (i.e., 84–76 Ma in the chlorite zone). Herein, we define the Sanbagawa schists in the Kanto Mountains as the 'Ayukawa Unit' of the Sanbagawa Belt, and distinguish it from the Besshi and Oboke Units in Shikoku.

The main constituents of the Ayukawa Unit are pelitic and basic schists, which are intercalated with siliceous and psamitic schists. These lithological features are similar to those of the Bessi Unit, except for eclogite bodies in the highest grade zone. Furthermore, the range of the muscovite K–Ar ages (83–53 Ma) in the Ayukawa Unit overlaps with those reported in the Bessi Unit (88–72 Ma); however, the inverted thermal structure is absent and the correlation between the metamorphic grades and K–Ar and Ar–Ar ages has an opposite sense in the Kanto Mountains. The Ar–Ar ages in 'the southern marginal belt' to the south of the Kiyomizu Tectonic Line in Shikoku [10,75] range from 87 to 97 Ma [10], and the K–Ar ages have also been found to be concentrated around 90 Ma [11]. Previously reported phyllite ages of the 'Mikabu greenstone belt' (98–96 Ma) [10] may represent the metamorphic age of the southern marginal belt.

In the Northern Chichibu Belt in Shikoku, the western extensions of the Kashiwagi and Kamiyoshida Units have been identified based on lithology and radiolarian fossil ages [19,41]. The illite K–Ar ages reported from mudstone in the Kamiyoshida Unit in central Shikoku range from 159 Ma to 128 Ma, concentrated around 140 Ma, whereas those reported from mudstone and basic tuff in the Kashiwagi Units in central Shikoku range from 124 Ma to 104 Ma and are concentrated around 115 Ma [12,76]. These chronological data are consistent with the present results in the Kanto Mountains at the type localities of the Kamiyoshida and Kashiwagi Units. Dallmeyer et al. [10] have applied the Ar–Ar dating method to mudstone (phyllite) in the Northern Chichibu Belt. They have reported whole-rock ages of ca. 110 Ma in the northern part, 120–140 Ma in the middle part, and ca. 215 Ma in the southern part; however, no clear relationships could be recognized between the chronological data and the stratigraphic units [75]. Isozaki and coworkers [11,13] have considered that the northern part of the Northern Chichibu complex, comprising the Late Jurassic to Early Cretaceous radiolaria, is a relatively in situ unit that underwent the Sanbagawa metamorphism at ca. 115 Ma; meanwhile, the southern part is a nappe of the Middle Jurassic accretionary complex, which originated in the Mino–Tanba Belt in the Inner Zone of SW Japan. The geological unit equivalent with the Manba Unit is missing (or overlooked) in Shikoku. The present results obtained from mudstone and tuff in the Kashiwagi and Kamiyoshida Units in the Kanto Mountains were consistent with the K–Ar ages obtained in Shikoku; however, there were no large gaps in the metamorphic ages between the Late Jurassic complex (Kashiwagi Unit) and the Middle Jurassic complex (Manba and Kamiyoshida Unit). The presented results indicated that the chronological discontinuity defined by K–Ar and Ar–Ar dating did not strictly correlate with a difference in accretion age. It is possible that the Manba Unit underplated at a deep part of the the accretionary wedge, whereas the Kamiyoshida Unit accreted in a shallow part and later juxtaposed with the Manba Unit with an out-of-sequence thrust.

Regarding the protolith ages of the Sanbagawa schists, Aoki et al. [72] have reported Late Cretaceous detrital zircon ages (82 $\pm$ 11 Ma and 92 $\pm$ 4 Ma) from psammitic schists in the Oboke Unit, indicating that its deposition age is no older than 93 Ma. Detrital zircon of a similar age (90–80 Ma) has also recently been reported in the Besshi Unit [16,17]. In the Ayukawa Unit, Tsutsumi et al. [71] have reported detrital zircon ages of 91.4 $\pm$ 1.4 Ma and 95.3 $\pm$ 1.5 Ma from psammitic schists in the chlorite zone, and 78.8 $\pm$ 1.3 Ma from those in the biotite zone. Hence, the subduction of the host rock of the chlorite zone occurred no earlier than 97 Ma, whereas that of the biotite zone was no earlier than 80 Ma. Compared with the K–Ar ages of white mica reported in the Ayukawa Unit [20,28], which represents the timing of the peak metamorphism (for the chlorite zone) or cooling ages (for the biotite zones), the duration from deposition to the peak metamorphism in each zone was estimated to be 20–21 My at most. The deposition of the protolith of the biotite zone occurred during or after the peak metamorphism of the chlorite zone (84–72 Ma). In the Northern Chichibu Unit in the Kanto Mountains, Tominaga et al. [50] have reported the youngest detrital zircon age of 128.2 $\pm$ 1.4 Ma and 126.7 $\pm$ 2.0 Ma from sandstone, and 134.2 $\pm$ 1.5 Ma from acidic tuff in the Kashiwagi Unit. Accordingly, the duration between deposition and the peak metamorphic age (117–109 Ma) was estimated to be 20 My at most.

In the Kanto Mountains, K–Ar age data between 107 Ma and 84 Ma are missing, and the deposition of the protolith sandstone of the chlorite zone (<93 Ma) post-dated the peak metamorphism of the Kashiwagi Unit (ca. 117–109 Ma). Hence, there exists a chronological gap between the Northern Chichibu Belt (including the Mikabu Greenstones) and the Sanbagawa Belt. However, regarding the Sanbagawa marginal belt as the upper part of the Ayukawa Unit, the chronological gap between the Chichibu–Sanbagawa Belt, in the classical sense, can be reduced to less than 15 My. Thus, the major discontinuity between the Kashiwagi and Ayukawa Units, as proposed by Isozaki et al. [56], is questionable—in their terminology, the Kashiwagi Unit belongs to the 'Sanbagawa metamorphic belt sensu stricto' and the Ayukawa Unit belongs to the 'Shimanto metamorphic belt'. Rather, the evolution of the Cretaceous metamorphic zone can be understood as the progressive growth of accretionary complexes with multiple cycles of subduction and metamorphism events; the 'Sanbagawa metamorphic belt' can be re-defined in this sense. The Kamiyoshida Unit likely experienced older metamorphism (before 130 Ma), and may be excluded from the Sanbagawa metamorphic belt.

7. Conclusions

K–Ar dating was conducted using low-grade meta-sedimentary rocks from the Northern Chichibu Belt and the Mikabu Greenstones in the Kanto Mountains. The measurement results revealed the following:

1. The whole-rock and illite mineral ages of chert and red shale showed large variations. Overall, the K–Ar ages of chert and red shale were significantly older than those of mudstone, acidic tuff, and basic tuff in the same stratigraphic units, although pelagic materials of chert and red shales were almost free of detrital mica. Thus, it is possible that the K–Ar ages of chert and red shale reflect hydrothermal activities on the sea floor before subduction.
2. The fractionated illite samples of chert, red shale, mudstone, acidic tuff, and basic tuff displayed older ages for larger grain sizes. The observed changes in CI can be explained by the formation of illite–smectite mixed-layer clays during retrograde stages, rather than contamination with detrital mica. The illite K–Ar ages of the largest grain size class (3–4 μm) obtained from mudstone and tuff likely represent the peak metamorphic ages.
3. Based on the K–Ar dating of mudstone, acidic tuff, and basic tuff, the peak metamorphic age of the Kashiwagi Unit was estimated as 117–110 Ma (Early Cretaceous), and a similar age (113 Ma) was obtained for an acidic tuff sample taken from the type locality of the Mikabu Greenstones. Hence, the Mikabu Greenstones can be considered as constituents of the Kashiwagi Unit in the Northern Chichibu Belt.
4. Among the Middle Jurassic accretionary complexes, the lower structural unit (Manba Unit) yielded a peak metamorphic age in the Early Cretaceous (132–107 Ma); whereas the upper structural unit (Kamiyoshida Unit) showed apparently older ages in the Late Jurassic (163–144 Ma). As such, the lower part of the Manba Unit can be interpreted as a re-worked part of the Middle Jurassic accretionary complex, which acted as a shadow zone of the subducting Mikabu seamount. The discontinuity in the peak metamorphic age between the Manba and Kamiyoshida Units supports the post-metamorphic nappe model proposed by Shimizu [36].

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Appendix A. List of Samples

Table A1. List of samples for K–Ar dating. See Figure A1 for locality names. * Samples taken from the boundary zone between the Kashiwagi and Manba Units.

Sample	Geologic Unit	Rock type	Locality
26-01A *	Manba Unit	acidic tuff	Kashiwagi
26-01B *	Manba Unit	mudstone	Kashiwagi
26-03	Kashiwagi Unit	acidic tuff	Kashiwagi
26-04	Manba Unit	mudstone	Syouri
26-05	Manba Unit	chert	Syouri
27-01	Manba Unit	mudstone	Kuroda
27-02	Kamiyoshida Unit	chert	Kuroda
27-03	Kamiyoshida Unit	chert	Kuroda
27-04	Manba Unit	basic tuff	Kodaira
27-05	Kashiwagi Unit	acidic tuff	Kodaira
27-06	Kashiwagi Unit	mudstone	Kodaira
27-07	Kashiwagi Unit	red shale	Aonashi
27-08	Kashiwagi Unit	red chert	Aonashi
27-10	Manba Unit	chert	Kodaira
27-11	Manba Unit	mudstone	Kodaira
27-12A	Manba Unit	sandstone	Kodaira
27-12B	Manba Unit	chert	Kodaira
28-01	Mikabu Greenstones	red shale	Mt. Nishi-Mikaboyama (NM)
28-02	Unknown	chert	Akiba-touge pass
28-03A	Manba Unit	chert	Asou
28-03B	Manba Unit	chert	Asou
28-04	Manba Unit	mudstone	Asou
L-7	Kashiwagi Unit	acidic tuff	Aonashi
L-11	Kamiyoshida Unit	mudstone	Tsuchisaka-touge pass
L-13	Kamiyoshida Unit	mudstone	Tsuchisaka-touge pass
Mi-10	Mikabu Greenstones	acidic tuff	Mt. Odokeyama (OD)

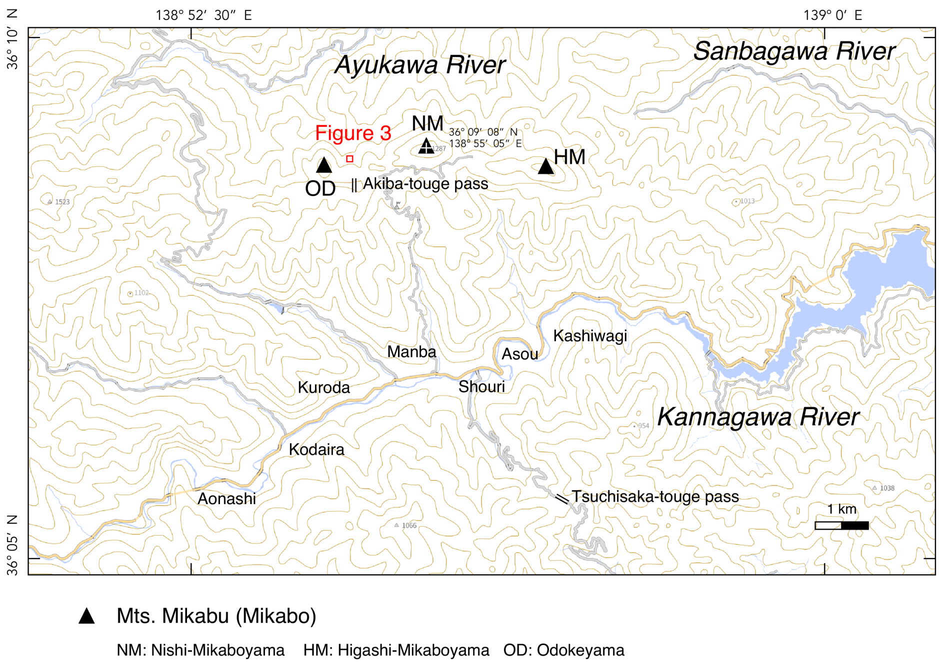

Figure A1. The topographic map [53] of the study area showing the locality names in Table A1. The red rectangle area corresponds to the route map in Figure 3.

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