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$^{40}Ar/^{39}Ar$ geochronology of Middle Miocene calcareous nannofossil biohorizons in Central Japan

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Abstract

The Middle Miocene marine sequence in the Karasuyama area, Central Japan, is interbedded with numerous volcaniclastic layers and contains calcareous nannofossils and planktonic foraminifera. This succession is thus of great interest for both age calibration of biostratigraphic events and for refinements to the geologic time scale. The volcaniclastic layers contain various minerals suitable for isotopic dating and six purified mineral separates of biotite, hornblende, sanidine, and plagioclase were analysed by the conventional step heating $^{40}Ar/^{39}Ar$ technique. Geochronological results for the calcareous nannofossil zonal boundaries CN4/CN5a (last occurrence [LO] of *Sphenolithus heteromorphus*) and CN5a/CN5b (LO of *Cyclicargolithus floridanus*) have been determined at 13.7 (13.74 ± 0.16, 2σ) and 12.0 Ma (11.99 ± 0.18, 2σ), respectively, which are valid for Central Japan. The age estimate for the LO of *S. heteromorphus* of 13.7 Ma is analytically indistinguishable to results determined for the same biohorizon in Italy, thus, indicating a potentially significant biological time horizon occurring on a global scale.

Keywords: $^{40}Ar/^{39}Ar$ dating; Miocene; Stratigraphy; Volcaniclastic rock; Time scale; Japan

1. Introduction

In Japan, Neogene sediments (Miocene to Recent) deposited in an open marine environment contain calcareous nannofossils, planktonic foraminifera, diatoms and radiolaria. Complete Middle Miocene to Pliocene sedimentary sections record the evolutionary history of these fossil groups and biostratigraphic correlations can be made with other sedimentary basins. Because sedimentation was synchronous with nearly continuous volcanic activity (Takahashi and Oda, 1997a), the sedimentary succession is interbedded with volcaniclastic material suitable for $^{40}Ar/^{39}Ar$ isotopic dating thus making this area a

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prime target for both stratigraphic correlations and for refinements to the geological time scale.

The Middle Miocene sequence in Central Japan is particularly suited for the study of two independent stratigraphic tools: biostratigraphy and geochronology (Ikebe, 1973; Okada et al., 1991; Odin et al., 1995b; Saito et al., 1997; Takahashi and Danhara, 1997; Takahashi and Oda, 1997b; Takahashi and Saito, 1997; Takahashi et al., 1997). In this investigation, the Karasuyama sequence of Central Japan (Fig. 1) has been targeted for study because of its nearly complete sedimentary record and its abundance of fossils and volcanic layers. The sequence is 770 m thick and appears to represent a continuous period of sedimentation during the interval 14 to 9 Ma. While both calcareous nannofossil and foraminiferal biostratigraphic data are available for the section, only the former are presently known with enough detail to be used with full confidence. Three volcaniclastic levels (two tuffs and one bentonite) were selected for isotopic dating from this section; they are located near two calcareous nannofossil biohorizons of great potential for global correlation. Each level is rich in either biotite, sanidine,

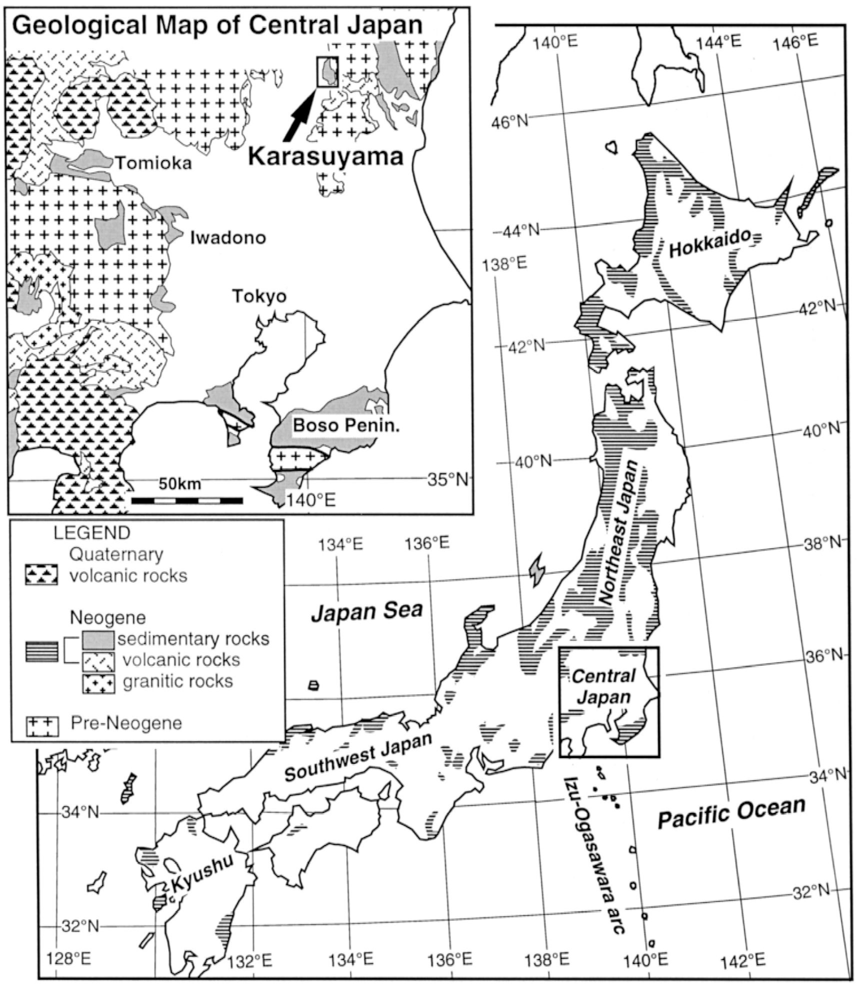


Fig. 1. Geographical location of the Neogene sedimentary serie of Central Japan.

hornblende or plagioclase, thus providing a means to date the time of deposition using $^{40}Ar/^{39}Ar$ geochronology.

The aim of this paper is to determine the precise absolute age of two calcareous nannofossil events in Central Japan using $^{40}Ar/^{39}Ar$ geochronology: the last occurrence (LO) of *Sphenolithus heteromorphus* and the LO of *Cyclicargolithus floridanus*. This study also supplements information obtained from similar volcaniclastic material in Italy (Odin et al.,

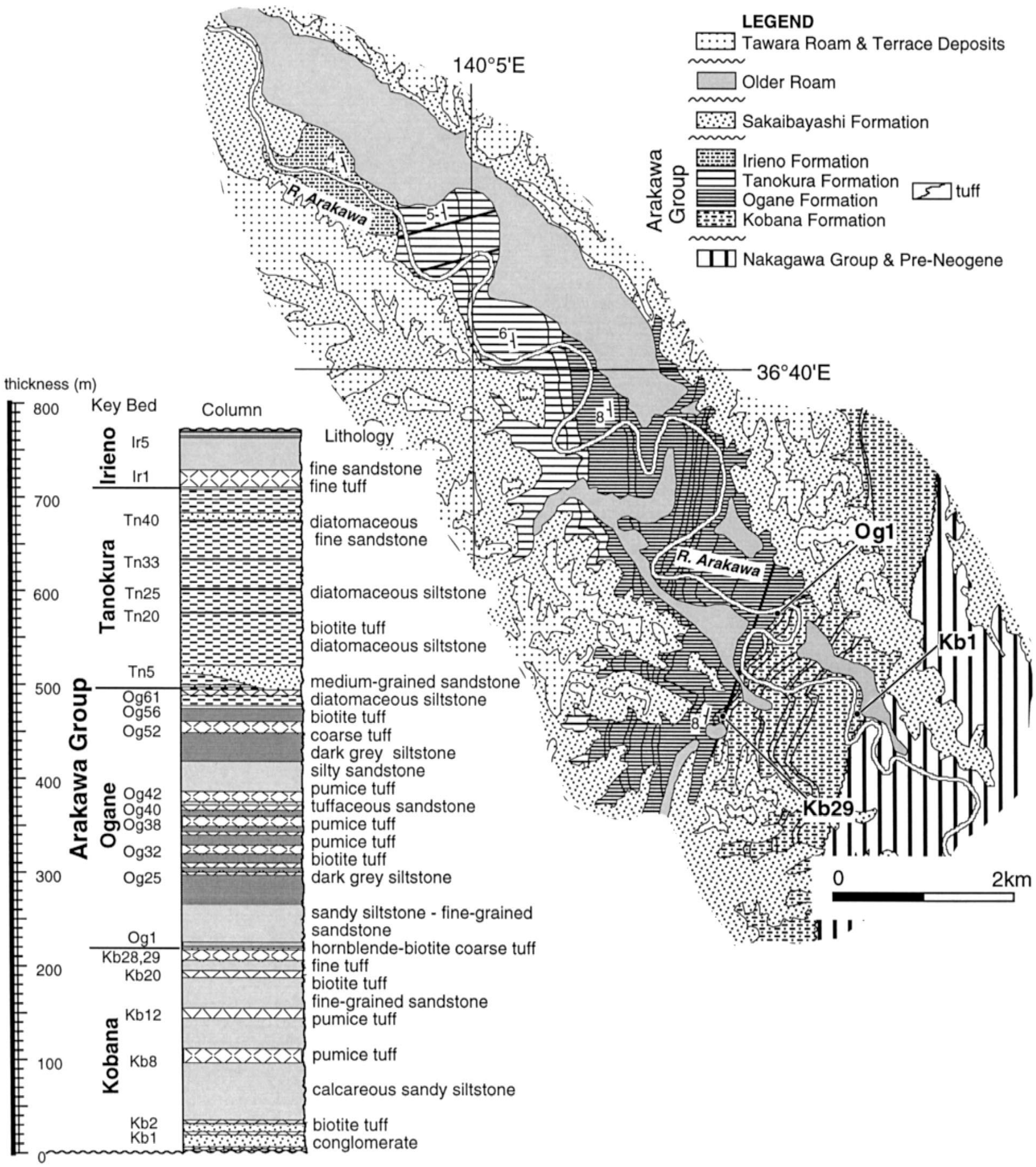


Fig. 2. Geological sketch map of the Miocene Arakawa Group in the Karasuyama area.

1995b), where the events are well-correlated to chronostratigraphic units (stages) and together, these data provide a test of whether the biohorizons can be considered synchronous on a global scale and used as key horizons for correlating stage boundaries.

2. Lithostratigraphy

2.1. Geographical location of the Karasuyama sequence

The active volcanic arc of the Japanese islands is located at the eastern margin of the Asian continent, northwestern Pacific region. Well-preserved upper Cenozoic marine sequences occur mainly in Central and Northeast Japan. The marine environment of the Japanese islands has been affected by both warm and cold currents at different latitudes. Calcareous microfossils, which prefer warm environment, occur mainly in the southern part of Japan. In contrast, siliceous microfossils, such as diatoms and radiolaria, occur mainly in Northeast Japan. In Central Japan, the presence of both warm and cold currents resulted in the deposition of both calcareous and siliceous microfossils, which is a great advantage for correlating both biostratigraphies.

The Karasuyama area is in the northern part of Central Japan (Fig. 1), where the Middle to Upper Miocene marine sequence (Arakawa Group), is well exposed along the Arakawa river (Fig. 2). The Arakawa Group unconformably overlies the Lower Miocene volcanic rocks of the Nakagawa Group in the eastern part of the study area; it is covered by the Pleistocene non-marine conglomerate of the Sakaibayashi Formation in the western part (Takahashi and Hoshi, 1996). The Arakawa Group is subdivided into four units in ascending order: Kobana, Ogane, Tanokura and Irieno Formations (Fig. 2). The lower two formations are mainly composed of medium to fine-grained sandstone and siltstone containing calcareous microfossils. In contrast, diatomaceous siltstone is dominant in the Tanokura Formation, which yields siliceous microfossils (diatoms and radiolaria). The Irieno Formation is a 50-m thick medium-grained sandstone, from which no calcareous microfossils are reported. Volcaniclastic layers consist of fine tuff (grain size smaller than 0.1 mm), coarse tuff and pumice tuff, some of which contain biotite and/or hornblende phenocrysts.

Tectonic deformation of the Miocene Arakawa Group is negligible. The strata tilt gently westward and only five megascopic faults have been observed within the study area. Outcrops are restricted along the river cut cliffs, and 11 detailed stratigraphic columns were made and combined in Fig. 5. The surface weathering of each outcrop can be neglected except for the stratigraphic intervals between meter levels 115–120 and 140–180 (see Fig. 5), where attempts to obtain calcareous microfossils from fresh samples failed.

2.2. The Karasuyama sequence

The Karasuyama sequence comprises the following four units from bottom to top (Fig. 2): the top of the Motegi Formation (several meters below level 0), the Kobana Formation (0 to 233 m), the Ogane Formation (233 to 496 m), and the Tanokura Formation (496 to 648 m). The present study concerns levels in the two middle formations. The Kobana Formation contains 30 volcaniclastic levels numbered Kb1 to Kb30 from bottom to top; the Ogane Formation includes 61 volcaniclastic levels numbered Og1 to Og61. Fifteen volcaniclastic levels were selected in the field for preliminary study of their content in datable material and three levels were finally chosen for $^{40}Ar/^{39}Ar$ analyses.

3. Biostratigraphy

Calcareous nannofossil biostratigraphy was first reported by Honda (1981) on the basis of 15 samples. Sugie (1993) was only able to establish the radiolaria biostratigraphy of the upper half of the sequence because fossils from the lower sequence are dissolved. Preliminary results on planktonic foraminifera were reported by Usami et al. (1995, 1996) from the lowest 50-m portion of the sequence. According to these studies, the first evolutionary occurrence (FO) of the genus *Orbulina* (represented by the species *O. suturalis*) or “Orbulina datum”, was thought to be located at meter level 23. Therefore, the two volcaniclastic levels (Kb1 and Kb2) would have bracketed this event and the correspond-

Table 1
Location of the three volcaniclastic levels analysed in this study and location of related biosignals including the two calcareous nannofossil biohorizons to be dated. Zircon is present in all levels

Sample	Level (m)	Tuff	Datable minerals and biostratigraphic events
	295	*Og25*	
	?250–270?	–	FO of the foraminifera *Globigerina nepenthes*
T228	236.5	Og1	Hornblende (+biotite)+feldspars
	235.5 ± 0.5	–	LO of the nannofossil *C. floridanus*
T227	229–230	Kb29	Biotite (+hornblende)+feldspars
	46.5 ± 0.5	–	LO of the nannofossil *S. heteromorphus*
T225	18–22	Kb1	Biotite (+hornblende)+feldspars
	≪ 18	–	FO of foraminiferal genus *Orbulina* (*Orbulina* datum)

ing boundary between N8 and N9 foraminiferal biozones (FO of *O. suturalis*) could be dated using the mineral separate T225. However, more recent investigation suggests that the biozonal boundary could be older than the two levels and the separates T225 would only suggest a minimum age for the *Orbulina* datum event as documented in Japan (Table 1).

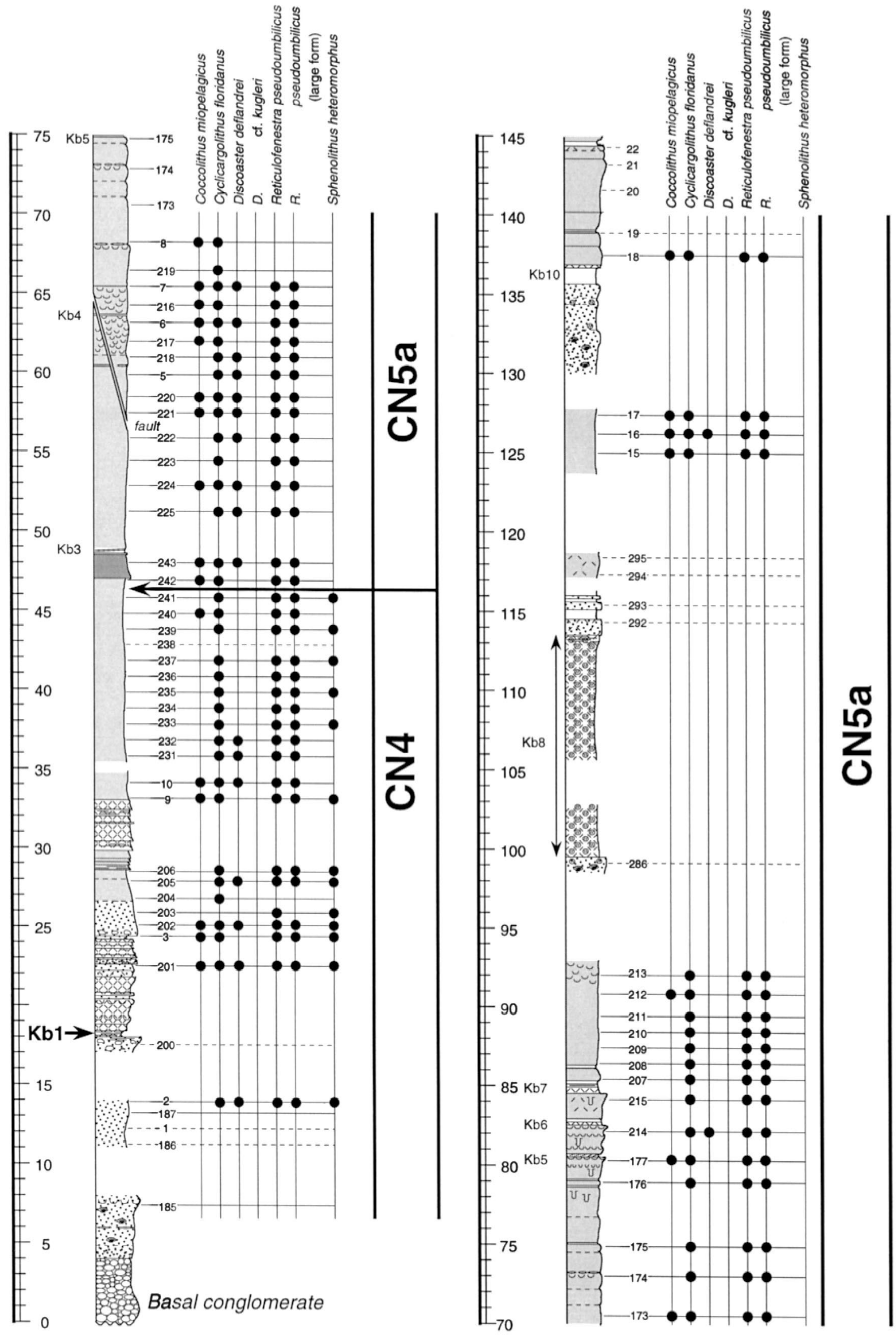
Tanaka and Takahashi (1998) established calcareous nannofossil biostratigraphy of the lower part of the Karasuyama sequence (Kobana and lowest Ogane Formations, Fig. 3). They recognised calcareous nannofossils from more than 90 samples among 138. They documented two calcareous nannofossil biozonal boundaries: the CN4/CN5a and the CN5a/CN5b of Okada and Bukry's (1980) zonation which are equivalent to the NN5/NN6 and NN6/NN7 boundaries of Martini (1971). The last appearance datum (LAD) of the key species *S. heteromorphus*, defines the CN4/CN5a boundary. The species was yielded almost continuously from sample 2 (meter level 14) up to sample 13 (meter level 47) in the lower part of the Kobana Formation. Preservation relative to the other nannofossil material implies that the observed specimens of *S. heteromorphus* are not reworked, and therefore, the CN4/CN5a boundary was determined between meter level 46 (sample horizon 241) and meter level 47 (sample horizon 242).

Another important biostratigraphic event, the CN5a/CN5b boundary, was recognised at meter level 236 in the lowest Ogane Formation. That boundary was originally defined by the FO of *Discoaster kugleri*, but this biostratigraphic event could not be recognised due to the sporadic occurrence of this species. Tanaka and Takahashi (1998) considered the LO of *C. floridanus* for location of the CN5a/CN5b boundary, because this biohorizon is often well recognised and commonly used as a second marker for the CN5a/CN5b boundary. *C. floridanus* occurs continuously from the lowest Kobana Formation up to the lowermost part of the Ogane Formation (sample 59: meter level 235). Despite good preservation of calcareous nannofossils from samples above (sample 406 to 416 in Fig. 3), the key species *C. floridanus* did not occur. Therefore, Tanaka and Takahashi (1998) concluded that *C. floridanus* disappeared between sample horizons 59 (meter level 235) and 60 (meter level 236) and that the CN5a/CN5b boundary was well determined between these two levels.

4. Geochronology

4.1. Preparation and characterisation of samples

Purified mineral separates (Table 2) were obtained by disaggregation, heavy liquid separation, magnetic separation, acetic acid cleaning and hand picking. Tuff Kb1 (sample T225) was disaggregated by a paraffin/water treatment. The sediment swells in water and is perhaps better termed a bentonite rather than a tuff in contrast to the two other samples in which pumice is unaltered. Idiomorphic biotite, sanidine, and plagioclase are present together with volcanic quartz, a small proportion of hornblende, and zircon. The biotite separates indicate minor clay mineral content as seen from a small, broad peak at 18 Å on the XRD pattern. This possibly represents a slightly altered portion of the mica separate. Pure


Coccolithus miopelagicus
Cyclicargolithus floridanus
Discoaster deflandrei
D. cf. kugleri
Reticulofenestra pseudoumbilicus
R. pseudoumbilicus (large form)
Sphenolithus heteromorphus
CN5a
CN4
Kb1
Kb3
Kb4
Kb5
Kb6
Kb7
Kb8
Kb10
fault
Basal conglomerate

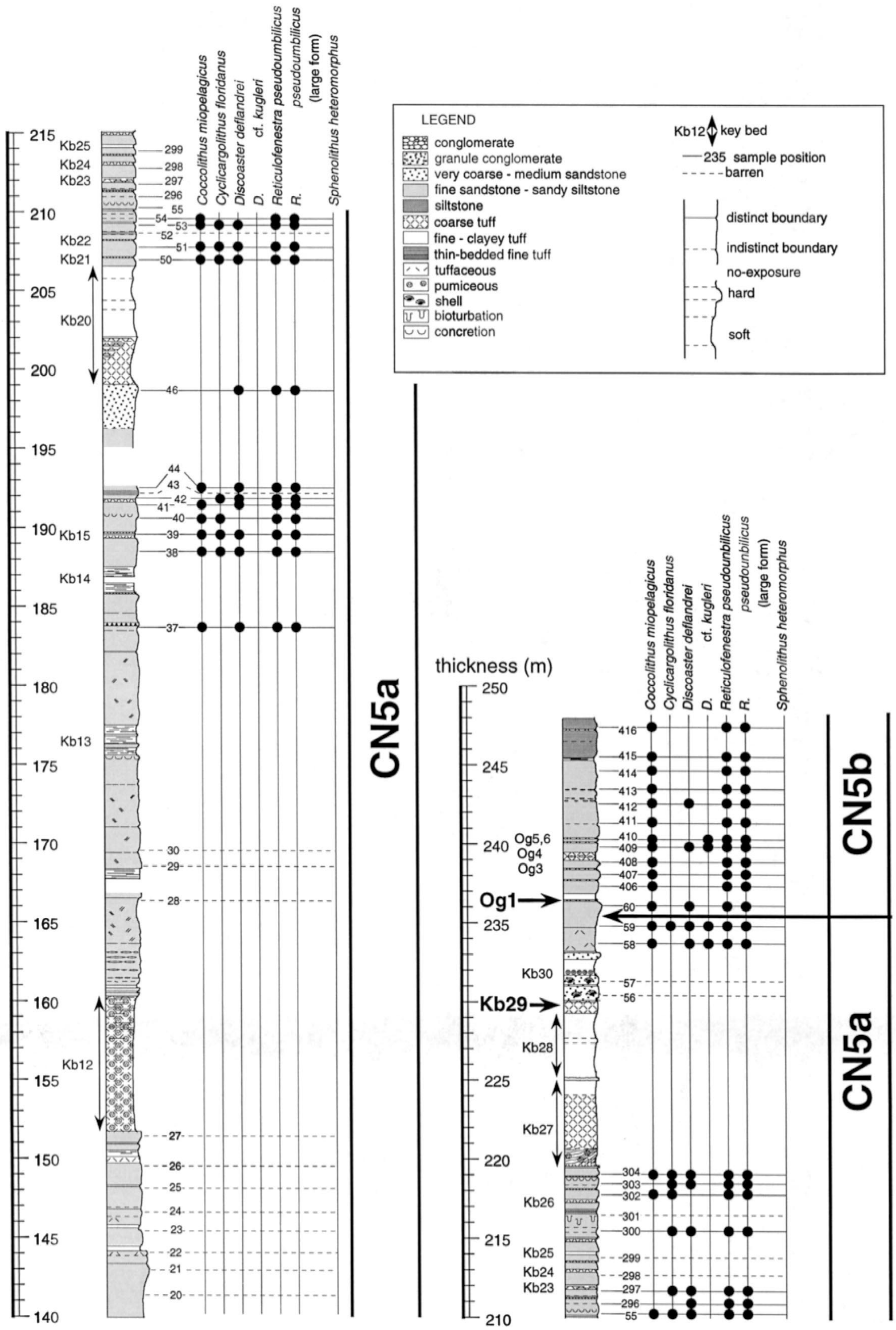

LEGEND
conglomerate
granule conglomerate
very coarse - medium sandstone
fine sandstone - sandy siltstone
siltstone
coarse tuff
fine - clayey tuff
thin-bedded fine tuff
tuffaceous
pumiceous
shell
bioturbation
concretion
Kb12 key bed
235 sample position
barren
distinct boundary
indistinct boundary
no-exposure
hard
soft
Coccolithus miopelagicus
Cyclicargolithus floridanus
Discoaster deflandrei
D. cf. kugleri
Reticulofenestra pseudoumbilicus
R. pseudoumbilicus (large form)
Sphenolithus heteromorphus
thickness (m)
CN5a
CN5b
Og1
Og3
Og4
Og5,6
Kb29
Kb30
Kb28
Kb27
Kb26
Kb25
Kb24
Kb23
Kb22
Kb21
Kb20
Kb15
Kb14
Kb13
Kb12

Table 2
Pyroclastic minerals of the dated levels (in stratigraphic order). Plagioclase can be characterised by the distance (D) between reflections ($13\bar{1}$) and (131) as measured from X-ray diffraction (XRD) patterns obtained using Kα Cu radiation

Level	Separate	Geochronometer	Optical + XRD analysis of the separate
Og1	228	Hornblende	XRD: hornblende; very small peaks of biotite
		Plagioclase	XRD: $D = 1.9°$ to $2.0°$; density 2.710–2.653
Kb29	227	Biotite	XRD: biotite; (trace of hornblende); very small 18 Å (admixed clay)
		Sanidine	XRD: sanidine; (very small amounts of quartz + pumice)
Kb1	225	Biotite	XRD: biotite; (hornblende); small dome at 18 Å (altered mica)
		Sanidine	XRD: pure sanidine; density 2.557 to 2.520, pumice
		Plagioclase	Density ≥ 2.637; milky

sanidine was hand picked from crystals, many of which were still coated with a small amount of pumice following a long ultrasonic treatment.

Tuff Kb29 (sample T227) contains biotite (> 1%), hornblende, plagioclase, sanidine, zircon and a large amount of quartz (> 5%). Brilliant pyrite is also present suggesting little aerial alteration of the sample. XRD patterns of the biotite show a small peak at 18 Å (not vermiculite) probably indicating adhering clay minerals and not alteration products of the biotite. Plagioclase (density between 2.637 and 2.601) was difficult to separate from quartz and mixed grains and was not analysed. Purified sanidine crystals still retained a small amount of adhering pumice following hand picking; XRD patterns indicated that quartz was admixed.

Tuff Og1 (sample T228) contains a large proportion of hornblende (> 7% WR), a small amount of biotite (well-preserved), plagioclase (> 2%), quartz and zircon. Hornblende separates include a small amount of apatite and pumice after hand picking. XRD patterns also show the presence of a small amount of biotite. Optically pure plagioclase (density between 2.710 and 2.653) was obtained from the non-magnetic fraction and hand picked.

In conclusion, the three sedimentologically investigated levels contain pyroclastic minerals which characterise purely volcaniclastic beds. Each one seems to result from an eruptive episode with aerial transport before direct ocean deposition. Level Kb1 corresponds to a bentonite originating from acid magma; the other two beds are less modified (quickly buried) tuffs.

4.2. $^{40}Ar/^{39}Ar$ analysis

The $^{40}Ar/^{39}Ar$ analyses were made at the Université de Lausanne. Samples together with the standards were irradiated for 18 MWH in the CLICIT position of the Oregon State Triga reactor. All analyses were made using a low blank, double vacuum resistance furnace and metal extraction line connected to a MAP 215-50 mass spectrometer using an electron multiplier. The samples were incrementally heated in the furnace and the gas was expanded and purified using activated Zr/Ti/Al getters and a metal cold finger maintained at liquid nitrogen temperature. Time zero regressions were fitted to data collected from eight scans over the mass range 40 to 36. Peak heights above backgrounds were corrected for mass discrimination, isotopic decay and interfering nucleogenic Ca-, K-, and Cl-derived isotopes of Ar. Blanks were measured at temperature and subtracted from the sample signal. For mass 40, blank values ranged from 4×10^{-15} mol below 1350°C to 9×10^{-15} mol at 1650°C. Blank values for masses 36–39 were below 2×10^{-17} mol for all temperatures. Isotopic production ratios for the Triga reactor were determined from analyses of irradiated CaF_2 and K_2SO_4 and the following values have been used in the calculations: $^{36}Ar/^{37}Ar$ (Ca) = 0.0002640 ± 0.0000017; $^{39}Ar/^{37}Ar$ (Ca) = 0.0006730 ±

Fig. 3. Lithostratigraphical sequence of the Kobana Formation and base of the Ogane Formation. Detail of the tuff levels and results of the nannofossil study are shown.

0.0000037; and $^{40}Ar/^{39}Ar$ (K) = 0.00086 ± 0.00023. A mass discrimination correction of 1.008 amu was determined by online measurement of air and was applied to the data. Correction for the neutron flux was determined using the biotite standard HD-BI (Fuhrmann et al., 1987) assuming an age of 24.21 Ma (Hess and Lippolt, 1994). The latter interlaboratory comparison (based on conventional-isotope dilution-technique results) leads to an observed interlaboratory SD of 0.32 Ma, or a (2σ) uncertainty of 2.5% on the age. For this investigation, an uncertainty on the neutron flux (J) was determined with a precision of 0.5%, and this uncertainty is propagated throughout the uncertainties on the reported ages. All ages and regressions in this paper are reported at the 95% confidence level.

4.3. Results

The results of the $^{40}Ar/^{39}Ar$ experiments are given in Table 3 and as age spectrum diagrams in Fig. 4.

4.3.1. Sample T225 (Kb1)

Biotite and sanidine from this sample yielded flat $^{40}Ar/^{39}Ar$ spectra. The sanidine yielded an age plateau at 14.05 ± 0.10 Ma and a $^{39}Ar/^{40}Ar$ vs. $^{36}Ar/^{40}Ar$ isotope correlation (isochron) age of 14.00 ± 0.16 Ma (MSWD = 1.0). The biotite did not yield a plateau, and progressive heating produced small, but measurable age differences that became younger with increasing experiment temperature. The integrated age for the biotite is 14.77 Ma, however the heating steps between 975°C and 1050°C yielded an age of 14.14 ± 0.16 Ma. The slight variations in age observed in this age spectrum may be related to small amounts of mixed-layer illite/smectite in the biotite. Alternatively, a small amount of excess argon may be present, and possibly indicated by the isotope correlation diagram, which yielded an age of 14.14 ± 0.16 Ma, with an initial $^{40}Ar/^{36}Ar$ ratio of 478. The sanidine isochron age of 14.00 ± 0.16 Ma is preferred as the best estimate of the age for this tuff layer, based on the flat $^{40}Ar/^{39}Ar$ age spectrum and the precision of the isochron (MSWD = 1.0).

4.3.2. Sample T227 (Kb29)

Biotite and sanidine from this tuff yielded flat $^{40}Ar/^{39}Ar$ age spectra with analytically indistinguishable $^{40}Ar/^{39}Ar$ plateau and isotope correlation ages. Sanidine yielded an $^{40}Ar/^{39}Ar$ age plateau of 12.08 ± 0.06 Ma and an isotope correlation age of 12.13 ± 0.14 Ma, vs. $^{40}Ar/^{39}Ar$ plateau and isochron ages of 12.23 ± 0.08 and 12.13 ± 0.14 Ma, respectively for biotite. The identical isochron ages of 12.13 ± 0.14 Ma are considered the best estimate for the age of this tuff layer.

4.3.3. Sample T228 (Og1)

Hornblende failed to yield an $^{40}Ar/^{39}Ar$ age plateau and the saddle-shaped form of the age spectrum is consistent with the presence of excess argon. The single step forming the minimum of the saddle and representing 75% of the ^{39}Ar released gives an age of 11.96 ± 0.18 Ma, which is considered a maximum age for this sample. This sample failed to yield a statistically viable isochron age. The plagioclase yielded a $^{40}Ar/^{39}Ar$ plateau over 90% of the ^{39}Ar released giving an age of 13.19 ± 0.34 Ma and an

Table 3
Summary of $^{40}Ar/^{39}Ar$ age plateau and $^{39}Ar/^{40}Ar$ vs. $^{36}Ar/^{40}$ isochron results in Ma (all uncertainties 2σ and include a 0.5% uncertainty on the value of J)

Tuff	Sample	Mineral	Plateau age	Isochron age	MSWD	$^{40}Ar/^{36}Ar$	N° and t°	Plateau and isochron ages
Og1	T228	Hornblende	11.96 ± 0.18[a]					
		Plagioclase	13.19 ± 0.34	13.11 ± 0.28	3.1	298 ± 6	7	(800–1650°C)
Kb29	T227	Sanidine	12.08 ± 0.06	12.13 ± 0.14	0.5	273 ± 31	5	(1100–1235°C)
		Biotite	12.23 ± 0.08	12.13 ± 0.14	0.7	342 ± 24	10	(850–1150°C)
Kb1	T225	Sanidine	14.05 ± 0.10	14.00 ± 0.16	1.0	316 ± 18	7	(1000–1250°C)
		Biotite	14.38 ± 0.12[b]	14.14 ± 0.16	4.4	478 ± 27	9	(800–1100°C)

[a] Single step age (75% of ^{39}Ar released) for the minimum in the saddle-shaped spectrum.
[b] Forced plateau age (four steps 975–1050°C).

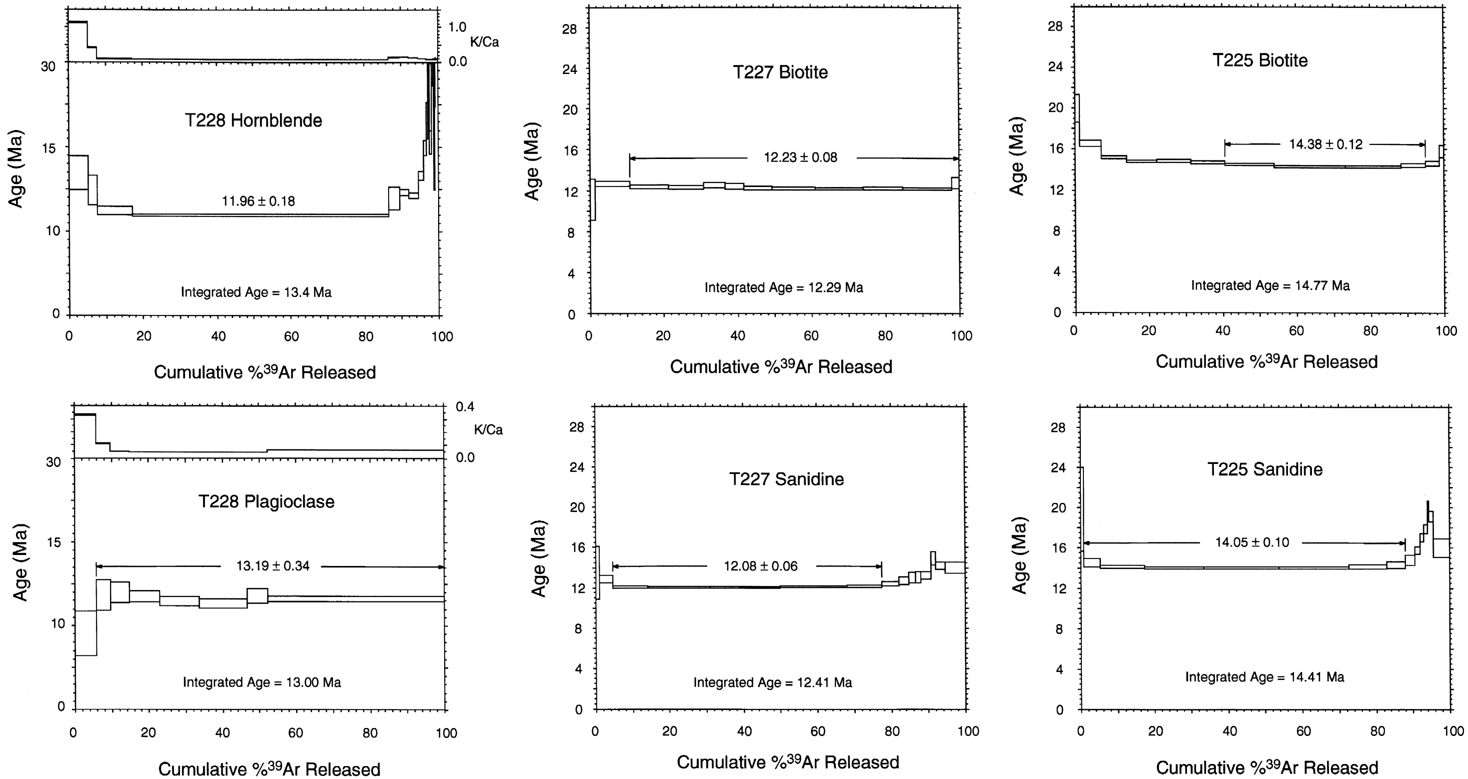


Fig. 4. Age spectrum diagrams for the minerals dated from the Karasuyama sequence (Central Japan).

isochron age of 13.11 ± 0.28 Ma. The apparently old age of the plagioclase, considering its stratigraphic position, perhaps indicates the presence of excess argon, although the isotope correlation diagram failed to detect this. The plagioclase age is thus not considered reliable for reason of inconsistency with other results. Our prior attempts to use this mineral in volcaniclastic levels (Odin et al., 1997a,b) gave mixed results, and the hornblende age of 11.96 ± 0.18, while clearly needing confirmation, is presently considered a reasonable estimate for the age of this tuff.

5. Discussion

5.1. Previous estimates of the numerical age of the two events

The LO of *S. heteromorphus* is younger than the *Orbulina* datum (FO of *O. suturalis*) which is a key event in the evolutionary trend of planktonic foraminifera. In the Mediterranean area, the *Orbulina* datum occurs in the first (Langhian) of the two regional substages of the Middle Miocene chronostratigraphic unit. The numerical age of this event has been repeatedly determined, and is estimated at 15.0 Ma in Japan (Ikebe, 1973) and Europe (Odin et al., 1997c, p. 611, Fig. 4).

The LO of the *S. heteromorphus* has been dated in Italy, where the Conero Riviera section contains pyroclastic minerals that bracket the event and its age has been determined at 13.6 Ma (Montanari et al., 1997, p. 447) or 13.7 Ma (Odin et al., 1997c, p. 612) with an uncertainty estimated at ±0.5 Ma. Levels Kb1 and Kb2 from the base of the Karasuyama sequence are bracketed between the above quoted foraminiferal (older) and calcareous nannofossil (younger) events (see Table 1).

In Japan the LO of *C. floridanus* is located immediately near the Am-4 tuff horizon (< 5 m) in the Boso Peninsula that yielded a K–Ar hornblende age of 11.7 ± 0.4 Ma (Takahashi et al., 1999). Takahashi and Hayashi (1991) suggested that tuff level Og1 of the Karasuyama area could be correlated with tuff level Am-4 of the Amatsu Formation in the Boso Peninsula (see Fig. 1) as well as with the Kitamura tuff in the Tomioka area (see Fig. 1) based on zircon morphology and fission track ages; however, these criteria are not sufficiently precise for definitive support. Fission track ages of 11.8 ± 1.6 Ma for Og1 (Kasuya, 1987) of the Karasuyama area, and of 11.5 ± 1.6 Ma for Am-4 (Kasuya, 1991) of the Boso Peninsula were reported. Takahashi et al. (1999) have shown the LO of *C. floridanus* is located within foraminiferal biozone N13, the top of which is drawn at the FO of the key marker *G. nepenthes*. This latter event was once concluded as 13.1 ± 0.9 Ma old (K–Ar biotite dating of the Kitamura tuff of the Tomioka sequence, Takahashi and Saito, 1997). However, independent analytical research on the same tuff and on a contemporaneous volcaniclastic level in the Apennines (Ancona level) led Odin et al. (1995a,b) to estimate the FO of *G. nepenthes* as 11.76 ± 0.10 Ma in Japan (the underlying Kitamura tuff was dated at 11.79 Ma) and 11.53 ± 0.13 Ma old in Italy (Ancona level, see also Montanari et al., 1997, p. 444). According to our present opinion and in agreement with Takayanagi et al. (1978), the age of the event in Japan was overestimated because the FO of *G. nepenthes* is now considered significantly younger than the Kitamura tuff and not subcontemporaneous as was believed in 1995.

5.2. Present results

In the Karasuyama area, the LO of *S. heteromorphus* is located about 28.5 m above bentonite Kb1 (Fig. 3). The LO of *S. heteromorphus* can be estimated from the two sanidine and biotite pairs from bentonite Kb1 and tuff Kb29, which record a time interval of 1.87 Ma for the accumulation of 212 m of sediment (including 58 m of pyroclastic deposits). The mean clastic sedimentation rate is thus 82 m/Ma, calculated from the total sediment thickness minus the thickness of the pyroclastic units and divided by time. Using this rate and noting that the LO of *S. heteromorphus* is located at 21.5 m above tuff Kb1 (total distance minus pyroclastic deposits) leads to an age difference of 0.26 Ma or an estimated age for the LO of *S. heteromorphus* at 13.74 ± 0.16 Ma. This age estimate for the biohorizon and related CN4/CN5a biozonal boundary is in perfect agreement with the Italian age estimate at 13.7 Ma.

In the Karasuyama area, the LO of *C. floridanus* is located between 5 and 6 m above tuff Kb29 (12.13 Ma) and about 1 m below tuff Og1 (11.96 Ma). The

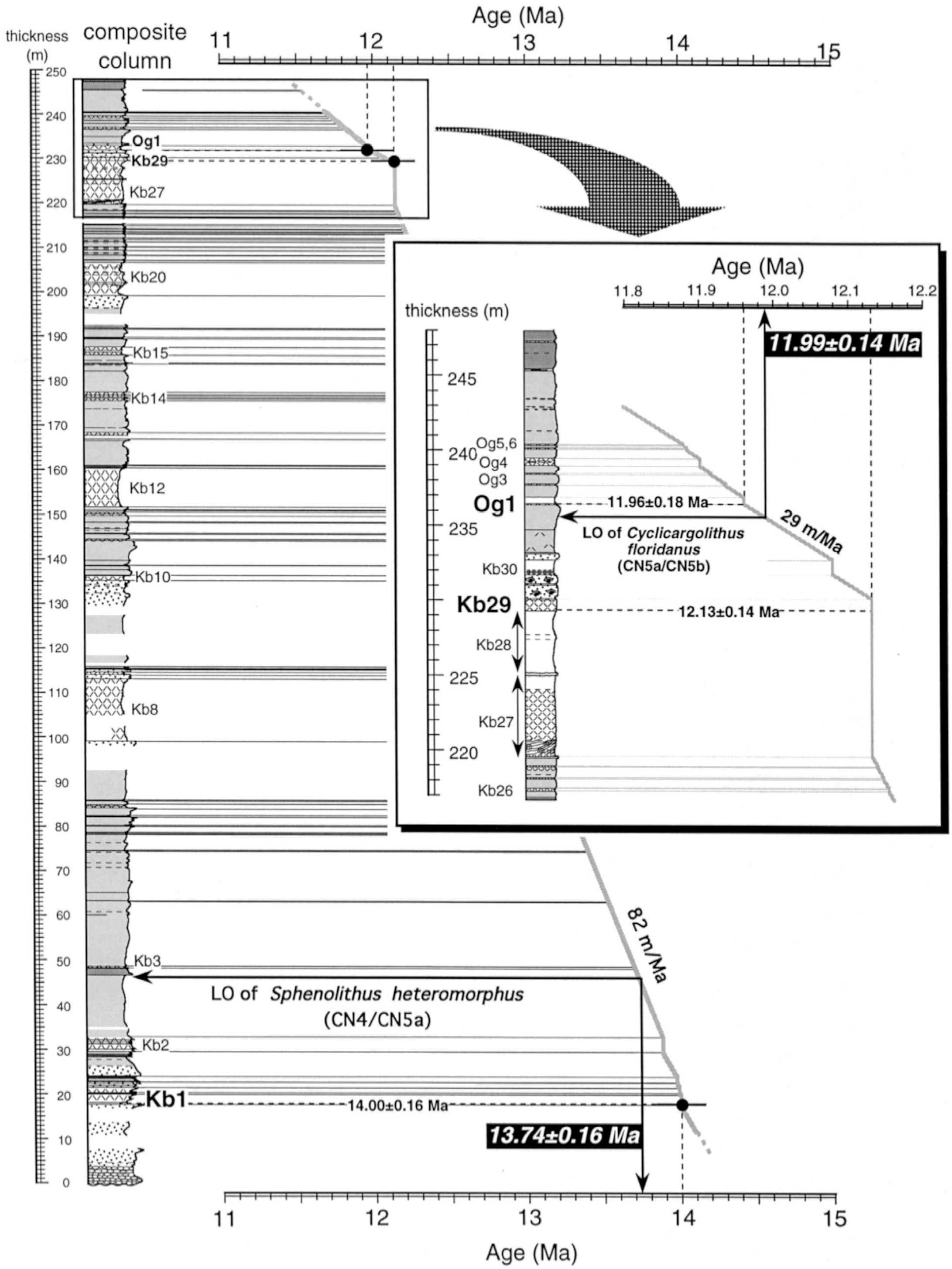


Fig. 5. Summarised succession of the Kobane Formation. The age results are shown together with a mean curve for interpolating ages between the two portions geochronologically documented in this work.

mean sedimentation rate varies from a formation to another so that the best way to derive an age for the biohorizon is an independent short distance interpolation between the two dated levels; this suggests an age of 11.99 ± 0.18 Ma (Fig. 5) interpreted as a maximum age given the imperfect result obtained from hornblende Og1.

The age of 11.79 ± 0.08 Ma for the Kitamura tuff of the Tomioka area (Odin et al., 1995b) is within uncertainty of the hornblende of tuff Og1 (11.96 ± 0.18 Ma) of the Karasuyama area providing evidence that the two tuffs could be contemporaneous; geochronological confirmation is needed.

The estimated age for the LO of *C. floridanus* in Japan at 11.99 ± 0.18 Ma cannot be compared directly to Italy where the event has not been observed. However, the FO of *G. nepenthes* dated in Italy at 11.5 ± 0.1 Ma by Montanari et al. (1997) and at 11.53 ± 0.13 Ma by Odin et al. (1995a) is suspected to occur in Japan between the tuff levels Og1 and Og25 (60 m above Og1). The latter is given by Takahashi et al. (1999) with a K–Ar age at 11.5 ± 0.4 Ma which would thus be a minimum age for the Japanese FO of *G. nepenthes*. The isotopic data do not indicate significant age inconsistencies between the biohorizons observed about 7500 km apart.

6. Conclusions

Three volcaniclastic layers within the Middle Miocene Karasuyama sequence in Central Japan yield $^{40}Ar/^{39}Ar$ ages that can be correlated with important biostratigraphic events. The LO of the calcareous nannofossil *S. heteromorphus* is estimated at 13.74 ± 0.16 Ma from the sanidine and biotite age data and a mean sedimentation rate of 82 m/Ma. This age estimate is identical to the same event dated in the Apennines (Italy) at 13.6 to 13.7 Ma. The corresponding CN4/CN5a biozonal boundary can be considered contemporaneous within the precision of existing geochronological data in these two distant areas supporting the global chronological significance of this biohorizon.

The LO of the calcareous nannofossil *C. floridanus* is calculated at 11.99 ± 0.18 Ma using a short distance interpolation and represents a maximum age. These results are consistent with the previously suggested stratigraphic similarity between volcaniclastic tuff Og1 of the Karasuyama area dated in this study and the Kitamura tuff of the Tomioka area dated in a previous study at 11.79 ± 0.08 Ma.

The CN5a/CN5b biozonal boundary in Japan appears older (by 0.50 ± 0.20 Ma) than the FO of *G. nepenthes* dated in Italy. Direct dating of the latter biohorizon in Japan is desirable.

The LOs of *S. heteromorphus* and *C. floridanus* are usually observed near the base and in the late portion of the Serravallian chronostratigraphic unit, respectively. This unit is the youngest of the two regional Italian substages (Langhian and Serravallian) composing the (still unnamed) single stage of the Middle Miocene series of the geological time scale (Odin et al., 1997c). The limits of the Serravallian were located at 14.3 (±0.5) and 11.0 (±0.3) Ma for the base and top, respectively (Odin, 1994). The present results generally confirm these estimates.

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