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Research Article

Zircon U–Pb ages from tuff beds of the upper Mesozoic Tetori Group in the Shokawa district, Gifu Prefecture, central Japan†

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Abstract The upper Mesozoic Tetori Group contains numerous fossils of plants and marine and non-marine animals. The group has the potential to provide key information to improve our understanding of the Middle Jurassic to Early Cretaceous biota of East Asia. However, the depositional age of the Tetori Group remains uncertain, and without good age constraints, accurate correlation with other areas is very difficult. As a first step in obtaining reliable ages for the formations within the Tetori Group, we used laser ablation-inductively coupled plasma–mass spectrometry to measure the U–Pb ages of zircons collected from tuff beds in the Shokawa district, Takayama City, Gifu Prefecture, central Japan. The youngest reliable U–Pb ages from the tuff beds of the Ushimaru, Mitarai and Okurodani Formations are 130.2 ± 1.7, 129.8 ± 1.0 and 117.5 ± 0.7 Ma, respectively (errors represent 2 SE). These results indicate that the entire Tetori Group in the Shokawa district, which was previously believed to be correlated to the Upper Jurassic to Lower Cretaceous, is in fact correlated to the Lower Cretaceous. The maximum ages of the Ushimaru, Mitarai and Okurodani Formations are late Hauterivian to Barremian, late Hauterivian to Barremian and Barremian to Aptian, respectively.

Key words: central Japan, Cretaceous, Gifu Prefecture, laser ablation-inductively coupled plasma–mass spectrometry, Shokawa, Tetori Group, U–Pb geochronology, zircon.

INTRODUCTION

The Middle Jurassic to Lower Cretaceous Tetori Group is distributed in central Japan. The Group is composed of marine and non-marine deposits, and subdivided into three subgroups: the Kuzuryu, Itoshiro and Akaiwa Subgroups, in ascending order (Maeda 1961). Since Geyler (1877) described fossil plants from the Tetori Group, many studies have investigated the geology and paleontology of these rocks (see Kusuhashi *et al*. 2002 and references therein). Earlier studies reported fossil plants, and fossil marine and non-marine animals (e.g. Yokoyama 1889; Hayami 1960; Sato 1962; Kimura & Sekido 1975; Isaji 1993), and recent studies have documented numerous vertebrate remains, including dinosaurs, cynodonts and mammals (e.g. Azuma & Currie 2000; Matsuoka 2000; Toyama Dinosaur Research Group 2002). The Tetori Group therefore provides important information in terms of understanding the Middle Jurassic to Early Cretaceous biota of East Asia. However, the depositional age of the Tetori Group remains uncertain. Only a few formations of the Kuzuryu Subgroup have been assigned to the Middle Jurassic to Upper Jurassic on the basis of index fossils such as ammonites and inoceramids

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†Tables of concordant U-Pb isotopic data for each tuff bed will be sent to those who request to the author (N. Kusuhashi) via email.

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(e.g. Hayami 1960; Sato 1962). Index fossils are rare in the non-marine upper part of the Group, and reliable age correlations have yet to be determined. Radiometric ages have been reported for tuff beds within the Itoshiro and Akaiwa Subgroups (Gifu-ken Dinosaur Research Committee 1993; Board of Education of Toyama Prefecture 2003), but the limited amount of age data is not sufficient to discuss the age of the group as a whole.

To successfully study the fossils from the Tetori Group, it is important to determine the ages of different formations and establish stratigraphic correlations between different regions. Although vertebrate remains have been reported from several areas, it is impossible to consider their paleontological significance, including comparison with fossils from other Asian localities such as China and Mongolia, until age control and stratigraphic correlation has been established.

Stratigraphic correlation of formations within the Tetori Group is also subject to considerable uncertainty. Sediments of the Tetori Group are widely distributed over mountainous terrain, and individual formations are given local names (Maeda 1961). There are few key beds within the group, and these are of uncertain depositional age. Stratigraphic correlation between different areas is therefore very difficult.

To address the above problems, we measured U–Pb zircon ages from tuff beds of the Tetori Group in the Shokawa district, Takayama City (formerly Shokawa Village), Gifu Prefecture, as a first step toward setting age correlations within the Tetori Group on a firmer basis. In the present study we focus on the Kuzuryu and Itoshiro Subgroups of the Tetori Group, which are distributed in the Shokawa district (e.g. Maeda 1952; Kumon & Kano 1991; Matsukawa & Nakada 1999). In this district, several tuff and muddy tuff beds are intercalated in the Tetori Group, and some of them have been dated by fission-track (FT) and K–Ar methods (Gifu-ken Dinosaur Research Committee 1993). The Mitarai Formation of the Kuzuryu Subgroup has been assigned to the Callovian on the basis of ammonite fossils (Sato & Kanie 1963); however, Sato *et al.* (2003) uncovered a misidentification in Sato and Kanie's (1963) report and revised the age to Tithonian to Berriasian.

This revision demonstrates the need to reconsider the depositional ages of other formations in the district. Here, we review the available data for constraining the age of the Tetori Group. We then present U–Pb zircon ages from tuff beds within the Kuzuryu and Itoshiro Subgroups in the Shokawa district, using laser ablation-inductively coupled plasma–mass spectrometry (LA-ICP–MS), and use these data to discuss the depositional age of the Tetori Group in the Shokawa district. Many reports of previous age determinations either do not give clear error estimates or, where given, fail to mention the levels of uncertainty. We indicate these data with asterisks (*).

GEOLOGICAL SETTING

The Tetori Group in the Shokawa district, Takayama City, northern Gifu Prefecture, central Japan, represents the easternmost distribution of the Group around Mount Hakusan (Figs 1,2). The stratigraphy of the group in this district has been studied by Iwaya (1940), Maeda (1952), Kumon and Kano (1991), Gifu-ken Dinosaur Research Committee (1993), Matsukawa and Nakada (1999), and Kumon and Umezawa (2001), among others.

The basement to the Tetori Group in the Shokawa district is the Hida metagranites (Kumon & Kano 1991; Kunugiza *et al.* 2000). The Tetori Group unconformably overlies (Kamiya & Harayama 1982) or is in faulted contact with the basement (Kumon & Kano 1991). The Makido mafic complex intrudes the group in the northeast

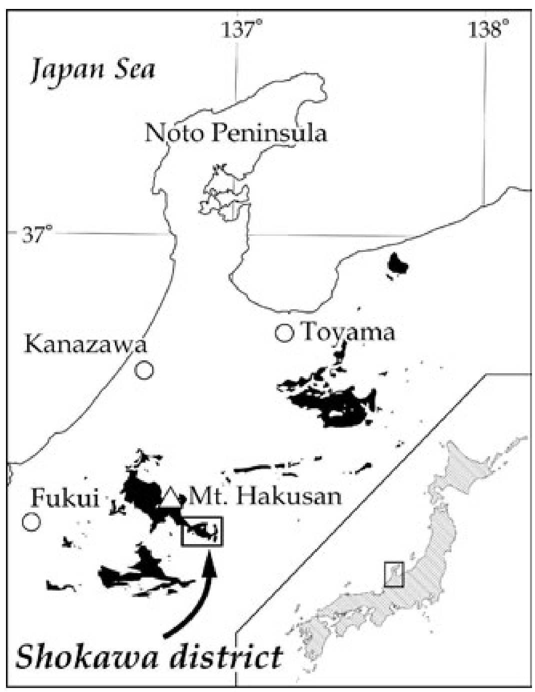


Fig. 1 Distribution of the Tetori Group (dark areas), central Japan, and location of the Shokawa district.

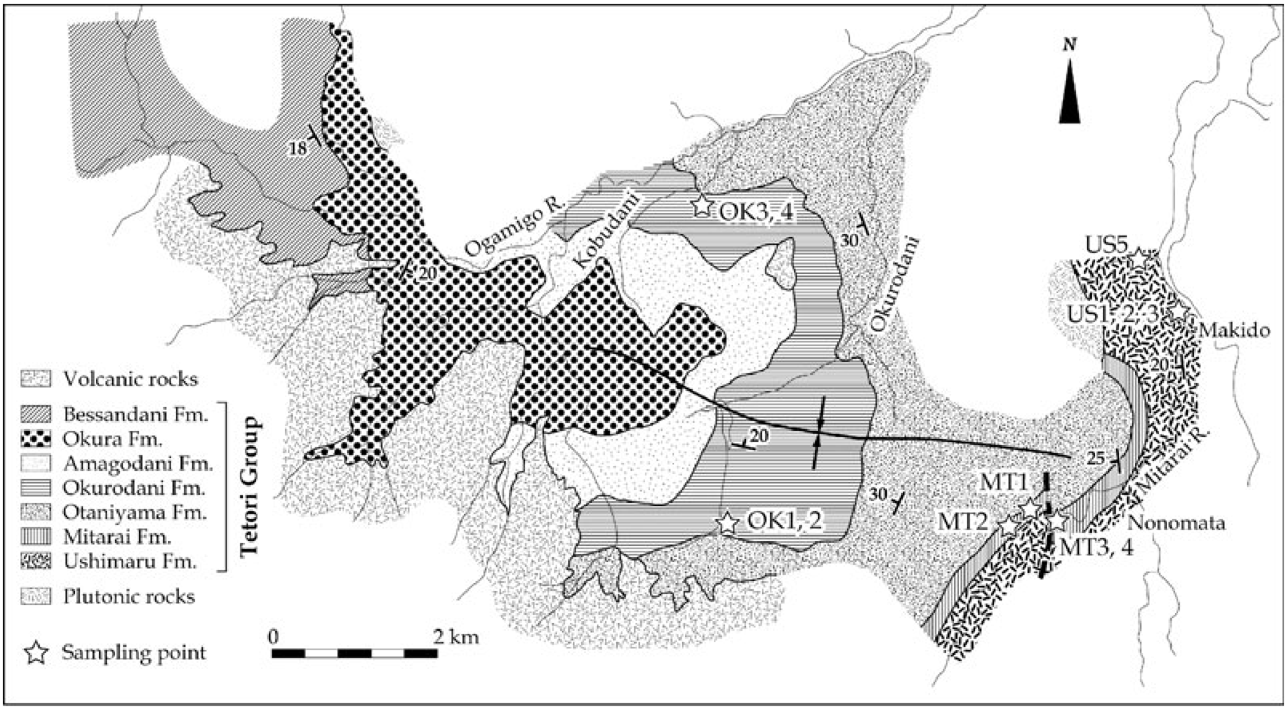


Fig. 2 Geological map of the Tetori Group in the Shokawa district, modified after Matsukawa and Nakada (1999). US1–3, 5, MT1–4 and OK1–4 are sample numbers.

of the district (Kamiya & Harayama 1982). In this district the Nohi rhyolite unconformably overlies both the Tetori Group and the Makido mafic complex (Collaborative Research Group for the Nôhi Rhyolite 1979; Kamiya & Harayama 1982; Kumon & Kano 1991).

The basement has traditionally been termed the Funatsu granitic rocks, but Kano (1990) revised this name to Hida granites, on the basis of granitic rocks of the Hida Belt. Later, Kunugiza *et al.* (2000) found that only some of the granites of the Hida Belt had undergone Hida metamorphism. The granites in the present study area record Hida metamorphism (Kunugiza *et al.* 2000), and the authors therefore refer to them as the Hida metagranites. U–Th–Pb dating of uraninite, monazite and zircon from the Hida metagranites gives ages of 200–240 Ma*, *ca* 200 Ma* to >240 Ma* and 200–350 Ma*, respectively (Kunugiza *et al.* 2000).

Shibata and Uchiumi (1995) reported K–Ar ages from the Makido mafic complex. Amphibole yielded an age of 125 ± 4 Ma*, and biotite yielded ages of 100 ± 3 Ma* and 90.7 ± 2.8 Ma*. The 125 ± 4 Ma* age is questionable as it is much older than the other two ages, and Shibata and Uchiumi (1995) explained this anomalous age as possibly resulting from excess (extraneous) ^{40}Ar within the sample. The Makido mafic complex is part of the Awara-Dani plutonic mass, which has yielded K–Ar ages from 107.4 ± 3.8 Ma* to 84.9 ± 1.8 Ma* (Gifu-ken Dinosaur Research Committee 1993). Rb–Sr, FT and chemical Th-U-total Pb isochron method (CHIME) ages of 90–70 Ma have been reported for the Nohi rhyolite that unconformably overlies both the Tetori Group and the Makido mafic complex (e.g. Seki 1978; Kawada *et al.* 1982; Yamada *et al.* 1992; Suzuki *et al.* 1998).

The Kuzuryu, Itoshiro and Akaiwa Subgroups of the Tetori Group are distributed in the Shokawa district (e.g. Maeda 1952; Kumon & Kano 1991; Matsukawa & Nakada 1999; Figs 2,3). The group is composed of mudstone, sandstone and conglomerate, and comprises the Ushimaru and Mitarai Formations of the Kuzuryu Subgroup, the Otaniyama and Okurodani Formations of the Itoshiro Subgroup, and the Amagodani, Okura and Bessandani Formations of the Akaiwa Subgroup, in ascending order (Matsukawa & Nakada 1999). The depositional age of the Tetori Group should be younger than the basement age, which is greater than 200 Ma, and older than the intrusive rocks and Nohi rhyolite, which are younger than 100 Ma, as mentioned above.

Some formations of the Tetori Group in this district are assigned geochronological stages on the basis of index fossils and radiometric ages (e.g.

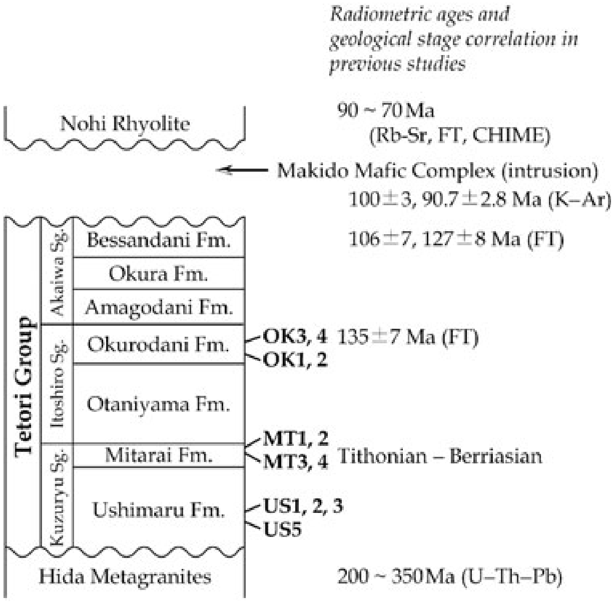


Fig. 3 Stratigraphic table of the Tetori Group in the Shokawa district. Radiometric ages and geological stage correlation are based on previous studies cited in the text.

Gifu-ken Dinosaur Research Committee 1993; Sato *et al.* 2003; Fig. 3), and the Group is thought to be Late Jurassic to Early Cretaceous in age. Sato and Kanie (1963) reported the discovery of *Lilloetia* sp. (*Lilloettia* sp., correctly) from the Mitarai Formation and assigned the formation to the Callovian. Sato *et al.* (2003), however, revised the earlier identification of *Lilloettia* sp. as *Partschiceras* sp. cf. *Partschiceras otekense*, and concluded that the Mitarai Formation is correlated to the uppermost Jurassic to lowermost Cretaceous (Tithonian to Berriasian), based on ammonite assemblages including newly described berriasellids. Hayami (1960) described *Inoceramus maedae* from this formation and suggested that this species resembles the Cretaceous form.

The Okurodani Formation yields fossil vertebrates such as fishes, turtles and dinosaurs (e.g. Cook *et al.* 1998; Hirayama *et al.* 2000), and yields K–Ar ages of 80.0 ± 1.2 Ma* to 107.9 ± 1.7 Ma* and 160.9 ± 2.4 Ma*, and a zircon FT age of 135 ± 7 Ma* from tuff beds (Gifu-ken Dinosaur Research Committee 1993). The K–Ar data are whole-rock ages, which contain great uncertainty, and it is generally believed that the depositional age of the Okurodani Formation is early Neocomian, based on the FT age mentioned above. The Gifu-ken Dinosaur Research Committee (1993) also measured the radiometric ages of tuff beds of the Bessandani Formation from the uppermost Tetori Group in this district, with results of 86.4 ± 1.3 Ma* and 149.2 ± 2.3 Ma* (K–Ar), and 106 ± 7 Ma* and 127 ± 8 Ma* (FT). The K–Ar ages are considered less reliable, as with the Okurodani Formation data.

SAMPLES AND METHODS

For U–Pb analysis, we sampled 12 tuff layers of the Tetori Group (Fig. 2) – each from the Ushimaru (US1-3, 5), Mitarai (MT1-4), and Okurodani Formations (OK1-4). Samples of US1-3 were collected from a roadside outcrop (Fig. 4a). They are gray to dun silty tuff beds, yielding plants, bivalves and gastropods, and are 30–40, 10–20 and 20–30 cm thick, respectively. US5 is a gray to greenish gray, tuffaceous siltstone bed, about 10 cm thick. MT1 is a greenish gray, poorly sorted, very fine- to medium-grained tuffaceous bed, with somewhat compressed lapilli, and is 20 cm thick. MT2 is a gray to grayish white, silty tuff bed, 20 cm thick (Fig. 4b). MT3 and MT4 were collected from outcrops exposed along the Mitarai River. MT3 is a gray, poorly sorted, tuffaceous sandy siltstone, 10 cm thick (Fig. 4c). MT4 is situated several meters above the horizon of MT3. It is a light gray, silty tuff layer, 5–10 cm thick. OK1 and OK2 were sampled from a roadside outcrop. Both are gray, very fine-grained, tuffaceous deposits, yielding plants and bivalves, and are 40–50 and 30–40 cm thick, respectively. OK3 is a 5–10-cm thick, gray to greenish gray, silty tuff layer situated approximately 1 m above the horizon that yields numerous vertebrate remains, and several meters below the horizon of sample OK4 (Fig. 4d). It changes laterally into a tuffaceous siltstone bed. OK4 is a greenish gray, tuffaceous siltstone bed, 1.4–1.5 m thick. Its upper and lower parts show parallel laminations of black silt.

We separated zircons from these samples by conventional heavy liquid and magnetic separation at Kyoto University. Zircons were also separated from nine samples (US1-3, MT1, 3 and 4, OK1-3) by Kyoto Fission-Track Co., Ltd. Some samples (US1, 3, MT1-4) were too fragile to be washed sufficiently before zircon separation, and it is possible that these samples are contaminated by young zircons. Zircon grains are abundant in samples US2, MT3, OK2 and OK3, and rare in US5, MT1 and OK4. Separated zircon crystals were mounted in PFA Teflon (R) sheets. Twenty to two hundred zircon grains were selected at random from each sample for analysis.

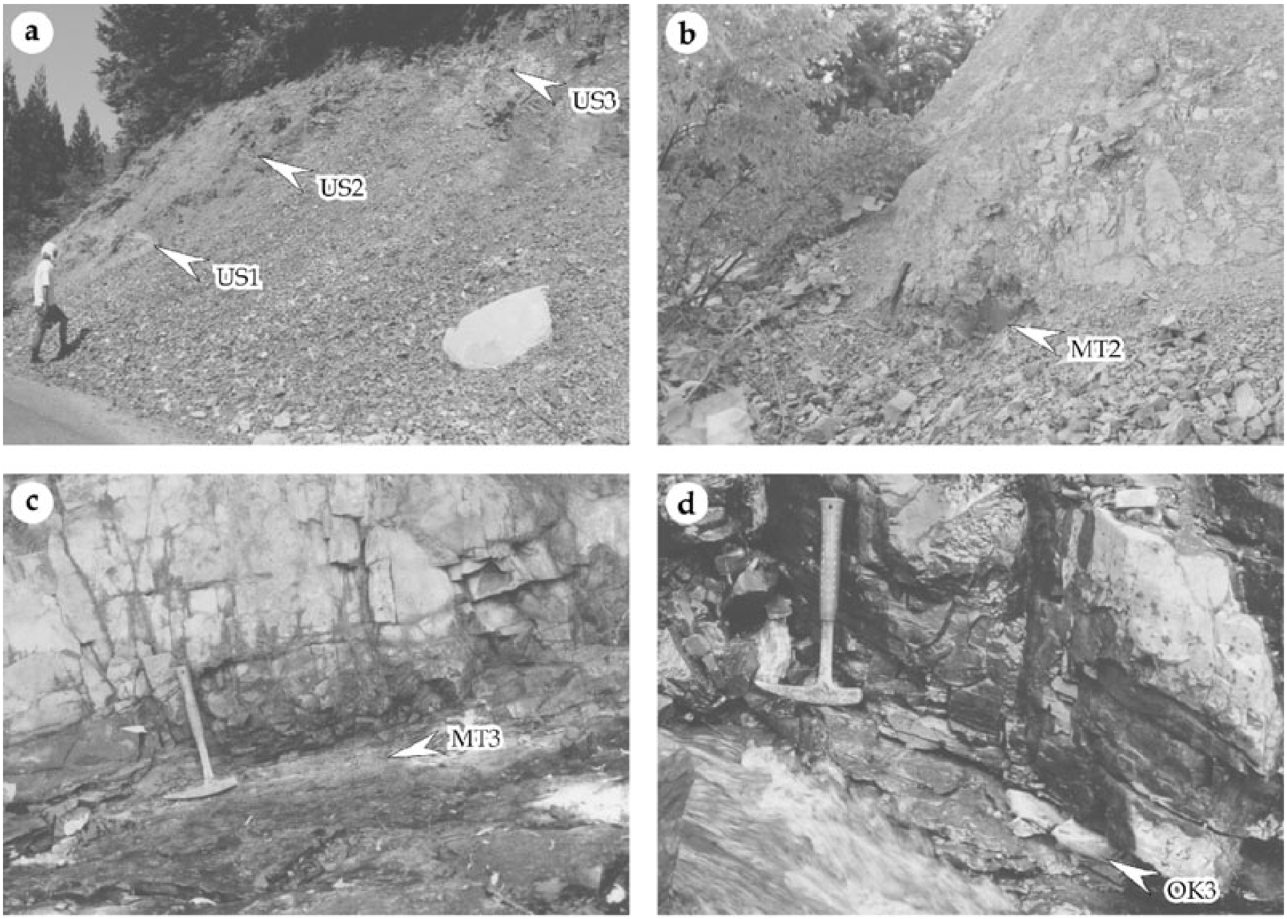


Fig. 4 Outcrops of some of the sampled tuff beds: (a) US1-3; (b) MT2; (c) MT3; (d) OK3. Arrows indicate horizons of tuff beds. In (b)–(d), a hammer (approximately 30 cm) is used for scale.

Isotopic analysis of zircons by LA-ICP–MS in the present study followed the technique described by Hirata and Nesbitt (1995) and Iizuka and Hirata (2004). The ICP–MS instrument was a VG PlasmaQuad 2 Omega quadrupole-based ICP–MS (Thermo Electron, Winchester, UK) equipped with a Chicane ion lens, housed at the Tokyo Institute of Technology, Japan. The laser ablation system was a GeoLas 200CQ (MicroLas, Göttingen, Germany). The ArF excimer laser was operated at a 193-nm deep ultraviolet (DUV) light source. For sample transport from the laser instrument to ICP, He gas was used as a carrier rather than Ar gas (Eggins *et al.* 1998). The signal stabilizer of Tunheng and Hirata (2004) was used to achieve precise isotopic data.

For U–Pb age determination, we measured the peaks in ^{202}Hg, ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{238}U of zircon samples and NIST 610 glass standard in peak jump acquisition mode. Operational settings were optimized by the signal intensity of the glass standard and were: source energy level, 140 mJ; pit size, 16 μm; pulse repetition rate, 2–5 Hz; operating period, 15 s, for each pit. Prior to measurement, surface Pb contamination on zircon samples was removed by single laser shots (Iizuka & Hirata 2004). Background signal intensities were measured before changing samples and were subtracted from signal intensities obtained by laser ablation of the zircon samples and glass standard.

Isotopic ratios of ^{207}Pb/^{206}Pb and ^{238}U/^{206}Pb were calculated from the acquired signal intensities of the glass standard and each zircon sample. ^{238}U/^{206}Pb isotopic ratios of samples were corrected by the averages of bias factors computed from the ^{206}Pb/^{238}U of the standard measured before and after each sample analysis. The ^{207}Pb/^{206}Pb and ^{238}U/^{206}Pb data for zircon samples were plotted on Tera-Wasserburg concordia diagrams (Tera & Wasserburg 1973), and concordant data (Fig. 5) were used for ^{238}U/^{206}Pb age calculations. Analytical errors were estimated from the precision of the ^{206}Pb/^{238}U ratio measurements defined as 2 SD obtained by 10 repeated analyses of the glass

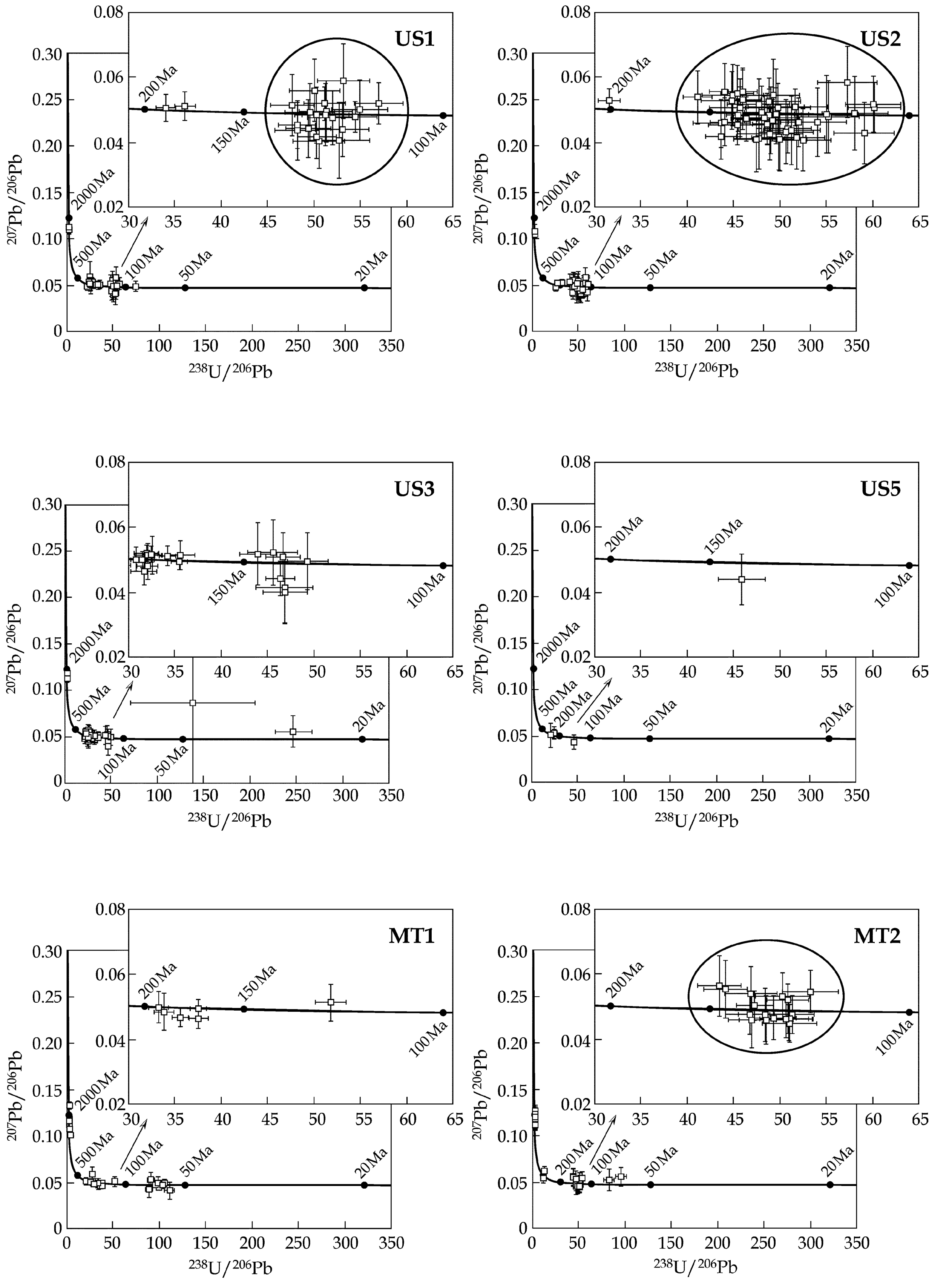


Fig. 5 Tera-Wasserburg concordia plots of whole concordant data for each sample and enlargements of data within the range 30–65 $^{238}U/^{206}Pb$. Both analytical errors represent the precision of $^{206}Pb/^{238}U$ measurements and uncertainties arising from counting statistics. The ages of tuff beds are calculated from the analyses within the ellipses (see Fig. 6). Error bars are 2 SD.

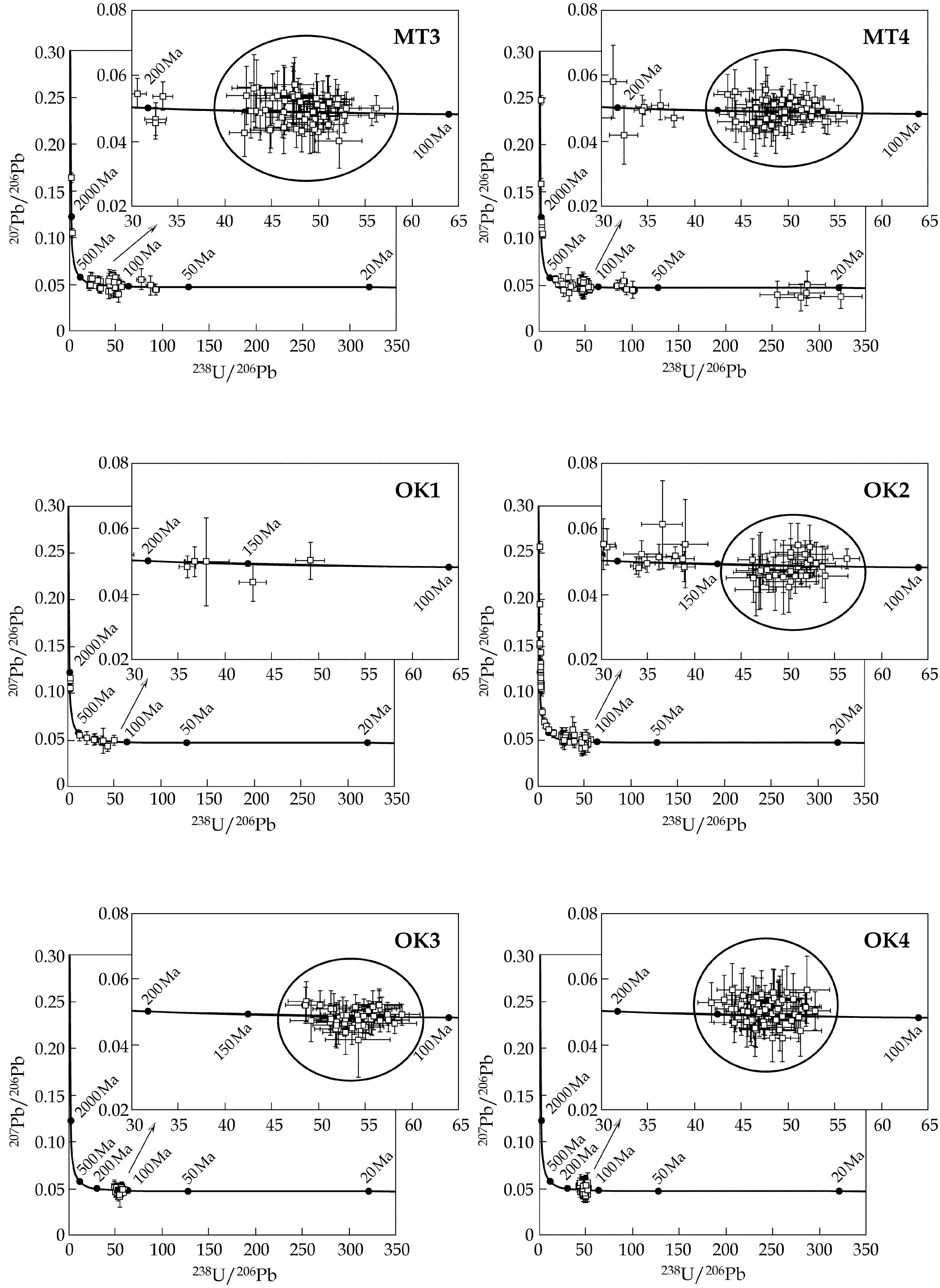


Fig. 5 *Continued*

standard. Uncertainties arising from counting statistics were also factored into the error estimates. In the case that several concordant data were obtained from a single grain, the weighted mean of the $^{238}U/^{206}Pb$ age calculated from each $^{238}U/^{206}Pb$ ratio was considered to be the age of the grain.

RESULTS AND DISCUSSION

Each sample contained zircon grains of various ages (Fig. 6). As mentioned above, the ages of the basement, intrusive rocks and overlying volcanic rocks indicate that the Tetori Group in the Shokawa district was deposited somewhere between 200 and 100 Ma. The zircon ages closest to the sedimentation age of each tuff bed are therefore the youngest age in the range 200–100 Ma. The ages are calculated from the weighted means of clusters of young ages for each sample, which are distinguished from data overlapping in the error (2 SD) ranges on concordia diagrams. Older ages are interpreted to represent recycled detrital grains. While it is also possible that the youngest ages represent detrital grains, the youngest ages still provide a constraint on the true depositional ages. As only small numbers of grains show plausible depositional ages for US3, US5, MT1 and OK1, these data are excluded from the discussion.

U–Pb ages older than 200 Ma determined in this study indicate that part of the detrital grains probably originated from the basement, the Hida metagranites. Yokoyama *et al.* (2002) reported U–Th–Pb detrital monazite ages of 180–240 Ma and approximately 1900 Ma from the Tetori Group sandstone within the Shiramine district, Hakusan City (formerly Shiramine Village), Ishikawa Prefecture. Such peaks were also reported in U–Pb detrital zircon ages from the Kitadani Formation of the Tetori Group, northeastern Fukui Prefecture (Arakawa *et al.* 2005) and in U–Th–Pb detrital monazite ages from the Itoshiro and Akaiwa Subgroups (Yamada *et al.* 2005). It is interesting in terms of the provenance of the Tetori Group that similar peaks are documented in this study. It is possible that the detrital grains originated from other tuff beds within the Tetori Group. In this case, distinction between detrital and non-detrital grains is difficult because their ages are similar.

In some samples, grains are younger than 100 Ma (Figs 5,6). These grains are interpreted to represent contamination, during sampling, by younger strata such as the Nohi rhyolite. As mentioned above, some samples (US1, 3, MT1-4) were too fragile to be washed sufficiently before zircon separation, and it is possible that young zircons remain in these samples. It is also possible that zircon grains from younger tuff beds of the Tetori Group were included in samples US1, US3, and MT1-4, resulting in anomalously young ages.

The U–Pb ages thought to be closest to the depositional age of each tuff bed are as follows (each error represents 2 SE; Figs 6,7).

Okurodani Formation: OK2, 131.4 ± 0.9; OK3, 117.5 ± 0.7; OK4, 132.9 ± 0.9 Ma.

Mitarai Formation: MT2, 130.0 ± 1.7; MT3, 129.8 ± 1.0; MT4, 125.6 ± 0.8 Ma (considered less reliable as mentioned below).

Ushimaru Formation: US1, 124.4 ± 1.4 (considered less reliable as mentioned below); US2, 130.2 ± 1.7 Ma.

The ages of US1, MT4 and OK3 are much younger than the other ages from the same formations. As mentioned above, US1 and MT4 are possibly contaminated by younger grains, and the ages of US1 and MT4 therefore are considered less reliable than the ages of other samples. The depositional ages of the Ushimaru and Mitarai Formations are therefore conservatively estimated based on US2 and MT2 and MT3, respectively, as US2 is unlikely to be contaminated by younger zircons, and ages MT2 and MT3 are similar and not significantly younger than US2.

The age of OK3 is evidently younger than the ages of OK2 and OK4. Though there are apparent detrital zircons in OK2, neither OK3 nor OK4 contains obvious detrital ages. The ages of OK3 and OK4 are therefore thought to be quite credible. It is difficult to decide which is closer to the true depositional age of the Okurodani Formation. We tentatively conclude that the age of the Okurodani Formation is within the range of the OK3 and OK4 ages, which contains the age of OK2.

The depositional age of each formation is therefore estimated to be: Ushimaru Formation, *ca* 130 Ma; Mitarai Formation, *ca* 130 Ma; Okurodani Formation, *ca* 120–130 Ma. The Ushimaru and Mitarai Formations are therefore correlated to the upper Hauterivian to Barremian or younger (Gradstein *et al.* 2004). The depositional age of the Okurodani Formation is within the range of late Hauterivian to Barremian. We consider the Okurodani Formation to be Barremian to Aptian in age (Gradstein *et al.* 2004), as the Okurodani Formation should be younger than the Ushimaru and Mitarai Formations, even though the age of OK4 raises the possibility that at least part of the Okurodani Formation is Hauterivian. The OK4 age

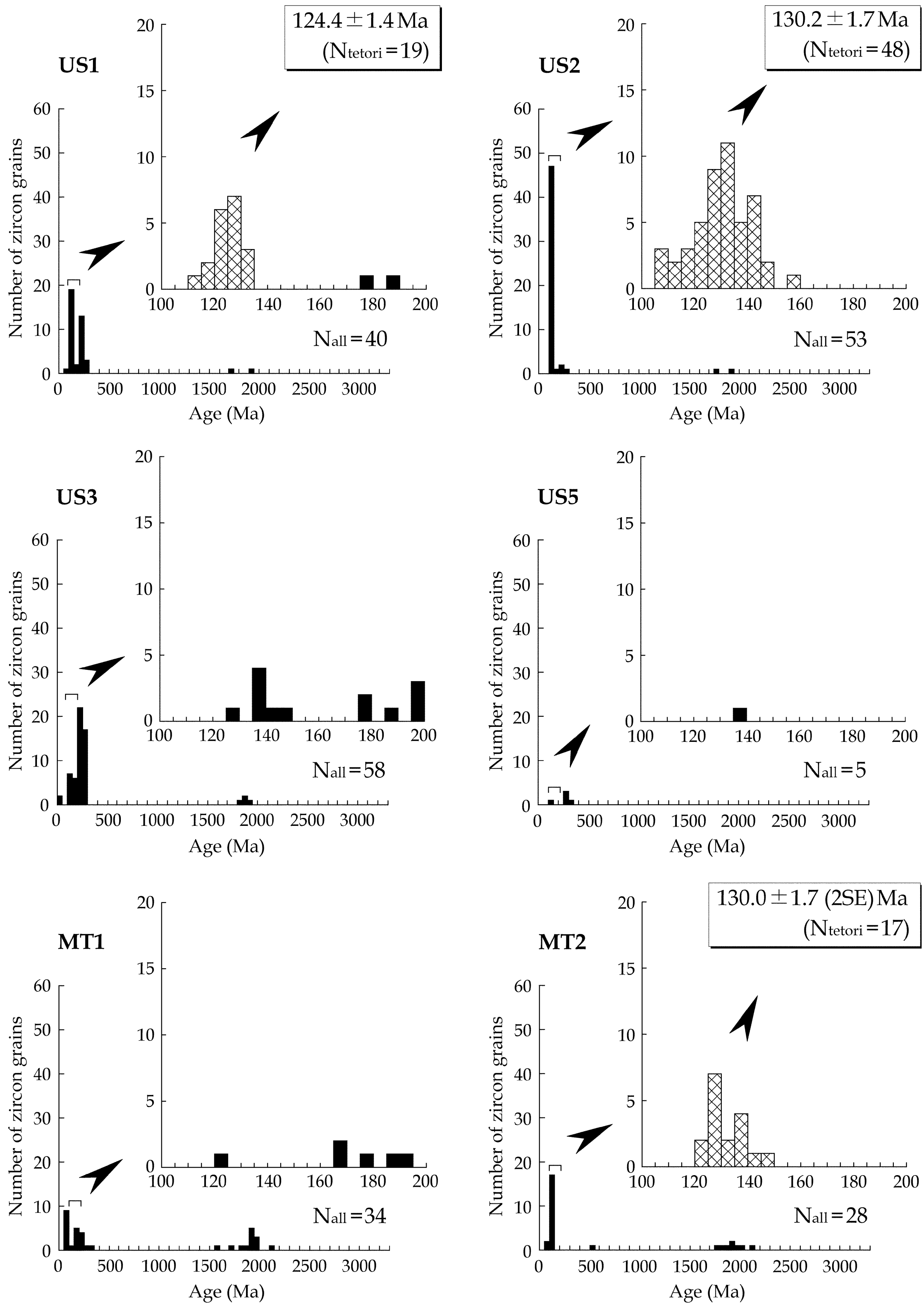
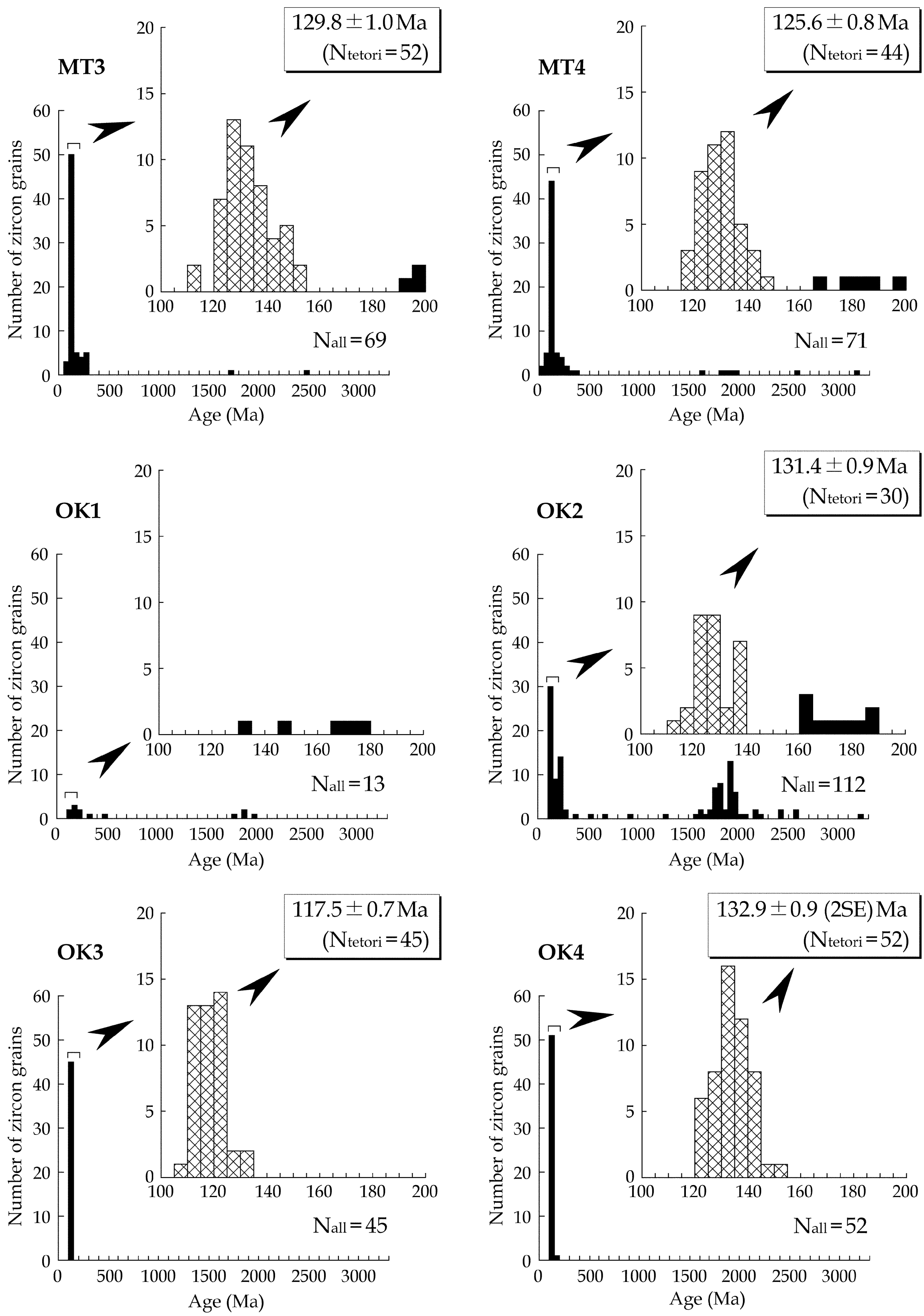


Fig. 6 Histograms of the ^{206}Pb/^{238}U ages of whole zircon grains as calculated from concordant data for each sample, and enlargements of data within the range 100–200 Ma. Cross-hatched columns represent the ages considered to be closest to the depositional age of each tuff bed (from the data enclosed by ellipses in Fig. 5). The age of each tuff bed is calculated from these data. N_{all}: number of whole zircon grains. N_{tetori}: number of zircons from which the ages of each tuff bed are calculated.



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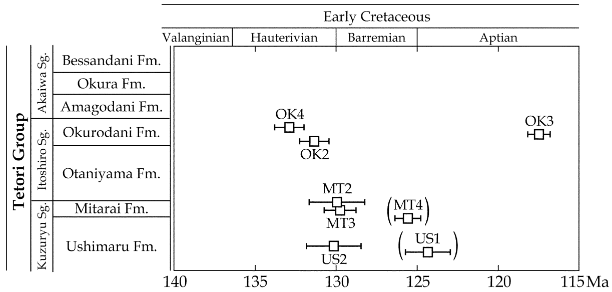

Fig. 7 U–Pb ages of tuff beds determined in this study and appropriate stage names. The data within parentheses are considered less reliable. Error bars are 2 SE.

and the FT age of 135 ± 7 Ma reported by Gifu-ken Dinosaur Research Committee (1993) are similar, and these ages are apparently supported by the age of OK2. However, the OK3 age from a sample several meters below OK4 is significantly younger than the OK2 and OK4 ages. We tentatively interpret that the ages determined for OK2 and OK4 are older than their depositional age, as the samples contain recycled detrital zircon grains. In summary, we conclude that the entire Tetori Group in the Shokawa district was deposited in the Early Cretaceous.

Matsukawa and Nakada (1999) reported *Lilloetia*? sp. (*Lilloettia*? sp., correctly) from the Ushimaru Formation, but the findings of the current study indicate that the age of the formation is not Middle Jurassic, and that identification of this specimen should be reconsidered. The Mitarai Formation is thought to be Tithonian to Berriasian in age (Sato *et al*. 2003). Our results also require a revision of the stage designation of the Mitarai Formation based on ammonite assemblages.

The results of the present study indicate the necessity of revising stratigraphic correlations between Tetori Group sediments in different regions. There is considered to be an unconformity between the Middle to Upper Jurassic Kuzuryu Subgroup and the Lower Cretaceous Itoshiro Subgroup in exposures along the Kuzuryu River, Fukui Prefecture (e.g. Maeda 1961). However, the two units have a conformable contact in the Shokawa district (e.g. Kumon & Kano 1991). Our study has demonstrated that the Kuzuryu Subgroup in the Shokawa district is correlated to the Lower Cretaceous, and this finding provides a key to solving the problematic relationship between the two subgroups. On the basis of ammonite fossils, Sato and Yamada (2005) correlated the Mitarai Formation with the Kamihambara Formation of the Itoshiro Subgroup that occurs along the Kuzuryu River. Goto (2001) reported late Hauterivian to early Barremian ammonites from the Itoshiro Subgroup along the Kuzuryu River. The present study reveals that the Mitarai Formation is Hauterivian or younger. The Mitarai Formation should therefore be compared with formations of the Itoshiro Subgroup along the Kuzuryu River.

CONCLUSIONS

The youngest reliable zircon U–Pb ages from tuff beds of the Ushimaru, Mitarai and Okurodani Formations, Tetori Group, Shokawa district, are 130.2 ± 1.7, 129.8 ± 1.0 and 117.5 ± 0.7 Ma, respectively (errors represent 2 SE). These ages indicate that the entire Tetori Group in this district is correlated to the Lower Cretaceous. The maximum ages of the Ushimaru, Mitarai and Okurodani Formations are therefore late Hauterivian to Barremian, late Hauterivian to Barremian, and Barremian to Aptian, respectively. This result requires a revision of the stratigraphic correlation between different regional outcrops of Tetori Group sediments. Radiometric dating of the group in other areas will enable precise age determination and stratigraphic correlation between different areas, and will advance our interpretations of fossils within the group.

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