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ARTICLE

NEW DETRITAL ZIRCON AGE DATA FROM THE TETORI GROUP IN THE MANA AND ITOSHIRO AREAS OF FUKUI PREFECTURE, CENTRAL JAPAN

Yuta KAWAGOE[1], Shin-ichi SANO[2], Yuji ORIHASHI[3], Hokuto OBARA[1], Yoshikazu KOUCHI[1] and Shigeru OTOH[1]

[1]Graduate School of Science and Engineering, University of Toyama, 3190 Gofuku, Toyama 930-8555, Japan
[2]Fukui Prefectural Dinosaur Museum, 51-11 Terao, Muroko, Katsuyama, Fukui 911-8601, Japan
[3]Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan

ABSTRACT

The age of non-marine formations of the Tetori Group was reexamined in the Mana and Itoshiro areas in Fukui Prefecture, central Japan. The Tetori Group in the Itoshiro area has been divided into the Kuzuryu, Itoshiro, and Akaiwa subgroups, whereas that in the Mana area is divided into the Middle and Upper formations of the “Kuzuryu Subgroup”. Among them, the age of the following marine formations has been determined from ammonoid fossils: the Kaizara (latest Bathonian–Callovian) and Yambarazaka (Oxfordian) formations of the Kuzuryu Subgroup in the Itoshiro area and the uppermost part of the Itoshiro Subgroup (Late Hauterivian–Early Barremian) in the Uchinamigawa area, 5 km to northwest of the Itoshiro area. Moreover, the Middle Formation of the “Kuzuryu Subgroup” in the Mana area likely yields Tithonian ammonoids. We obtained LA-ICPMS U-Pb ages of detrital zircons in (1) sandstone of the Itsuki Formation in the uppermost part of the Itoshiro Subgroup in the Itoshiro area and (2) lapilli tuff of the Upper Formation of the “Kuzuryu Subgroup” in the Mana area. As a result, the youngest zircon from the sandstone of the Itsuki Formation has the concordant age of 127.2 ± 2.5 Ma (2σ; Barremian), whereas the lapilli tuff of the Upper Formation of the “Kuzuryu Subgroup” in the Mana area has the intercept age of 124.6 ± 2.3 Ma (2σ; late Barremian–early Aptian). Hence the Itsuki Formation of the Itoshiro Subgroup in the Itoshiro area is presumably correlated with the ammonoid-bearing bed in the Uchinamigawa area and is correlated with the Lower Barremian. On the other hand, the Middle and Upper formations of the “Kuzuryu Subgroup” in the Mana area are likely correlated with the Itoshiro and Akaiwa subgroups in the Itoshiro area.

Key words: U-Pb age, detrital zircon, LA-ICPMS, Tetori Group, Fukui Prefecture

川越雄太・佐野晋一・折橋裕二・小原北士・高地吉一・大藤　茂（2012）福井県大野市真名地域および石徹白地域の手取層群から得られた新たな砕屑性ジルコン年代．福井県立恐竜博物館紀要 11：1－18.

福井県大野市の石徹白及び真名地域に分布する手取層群非海成層の年代を再検討した．石徹白地域の手取層群は下位より九頭竜，石徹白，および赤岩亜層群に，真名地域の手取層群は下位より“九頭竜亜層群”中部層および上部層にそれぞれ区分される．これらの内，以下の海成層は産出するアンモナイトにより堆積時代が推定されている：石徹白地域の九頭竜亜層群貝皿層（Bathonian最後期～Callovian）及び山原坂層（Oxfordian）と，石徹白地域の北西５キロ，打波川地域の石徹白亜層群最上部（Hauterivian後期～Barremian前期）．さらに，真名地域の“九頭竜亜層群”中部層はTithonianに対比される可能性がある．筆者らは，(1) 石徹白地域の石徹白亜層群最上部を占める伊月層の砂岩と (2) 真名地域の“九頭竜亜層群”上部層の火山礫凝灰岩に含まれる砕屑性ジルコンのウラン－鉛年代を LA-ICPMS で測定した．その結果，伊月層砂岩中の最も若いジルコンのコンコーディア年代は 127.2 ± 2.5 Ma（2σ；Barremian），真名地域の火山礫凝灰岩のインターセプト年代は 124.6 ± 2.3 Ma（2σ；Barremian後期～Aptian前期）となった．従って，石徹白地域の石徹白亜層群伊月層は恐らく打波川地域のアンモナイト産出層とともに，下部Barremianに対比される可能性が大きい．一方，真名地域の“九頭竜亜層群”中部層から上部層は，石徹白地域の石徹白～赤岩亜層群に対比可能である．

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Corresponding author—Shigeru OTOH
E-mail: shige*sci.u-toyama.ac.jp
（*を半角@に変えてご入力ください）

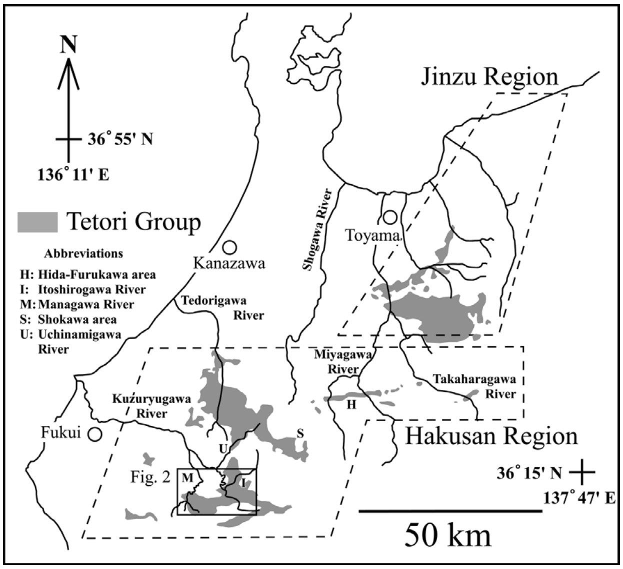

FIGURE 1. Index map showing the distribution of the Tetori Group and the locations of regions and areas mentioned in the text.

INTRODUCTION

The Tetori Group exposes in the Hida and Hida Gaien belts of Southwest Japan and is composed mostly of Middle Jurassic to Early Cretaceous shallow marine to terrestrial clastic rocks. The exposure of the Tetori Group is subdivided into the Hakusan and Jinzu regions, northern central Japan; the former includes the upper reaches of the Kuzuryugawa, Tedorigawa, Shogawa, Miyagawa, and Takaharagawa rivers (Maeda, 1961b; Fig. 1). This study focuses on the detrital zircon chronology of the Tetori Group in the Mana and Itoshiro areas along the upper reaches of the Kuzuryugawa River in the southwestern part of the Hakusan Region (Figs. 1 and 2).

The Tetori Group consists of three subgroups: the Kuzuryu, Itoshiro, and Akaiwa subgroups, in ascending order (Maeda, 1957, 1961a, b). Among them, the timing of sedimentation of marine beds in the Kuzuryu and Itoshiro subgroups has been well constrained using ammonoids and other index fossils (e.g., Sato and Westermann, 1991; Sato and Yamada, 2005; Goto, 2007; Sato, 2008). The age of non-marine formations, however, is mostly unknown because of the following reasons: (1) the non-marine formations yield virtually no index fossils; (2) lateral continuity of lithofacies of the Tetori Group is not very well; and (3) key beds that help to correlate the strata in different areas are very few. Accordingly, although various ideas of correlation among formations in different areas were presented (e.g., Maeda, 1961b; Yamada et al., 1989; Fujita, 2003; Matsukawa et al., 2003; Matsukawa et al., 2006; Sano et al., 2008; Matsukawa and Asahara, 2010), they have not been widely accepted.

Recent progress in analytical technique has enabled rapid and exact in situ U-Pb age determination of zircons using sensitive high-resolution ion-microprobe (SHRIMP) or inductively coupled plasma-mass spectrometry with laser ablation sampling (LA-ICPMS) (e.g., Compston, 1996; Williams, 1998; Kosler and Sylvester, 2003; Jackson et al., 2004). It has thereby become easy to measure the age distribution of hundreds of detrital zircons in a single clastic-rock sample and to reconstruct the age structure of the hinterland (e.g., Rino et al., 2004; Iizuka et al., 2005; Rino et al., 2008). Moreover, the analytical technique has helped many geologists to constrain the upper age limit of sedimentation of a clastic-rock bed, including a pyroclastic-rock bed, using the youngest age of detrital zircons (e.g., Tsutsumi et al., 2000; Kusuhashi et al., 2006; Aoki et al., 2007; Shimojo et al., 2010; Otoh et al., 2010; Lee et al., 2010).

Following the studies mentioned above, this paper aims to constrain the sedimentary age of some non-marine clastic rocks of the Tetori Group in the Mana and Itoshiro areas in the southern part of Ono City, Fukui Prefecture, through LA-ICPMS, U-Pb dating of detrital zircons. Moreover, the paper presents an idea of correlation of the Tetori Group in the Mana, Itoshiro, and Kamihambara areas, combining the new age data and previous studies of biostratigraphy.

OUTLINE OF GEOLOGY

The outline of geology of the Tetori Group in the Mana and Itoshiro areas, and of the Kamihambara area on the east of the former two areas (Fig. 2) is described below.

Mana area

The geology of the Tetori Group in the Mana area was studied by Maeda (1952, 1957, 1961a), Kawai et al. (1957), and Yamada et al. (1989). Here we mainly follow the descriptions of Yamada et al. (1989), who clarified the geologic structure of the area using sedimentological way-up criteria.

The Tetori Group in the Mana area is divided into the "Kuzuryu" and "Itoshiro" subgroups. The "Kuzuryu Subgroup" in this area consists of the Middle and Upper formations; the Lowest and Lower formations, which occur in other areas (Fig. 2), are lacking. The Middle and Upper formations are correlated with the Kaizara and Yambarazaka formations in the Itoshiro area, respectively (Yamada et al., 1989). The "Kuzuryu Subgroup" in the Mana area generally strikes east and dips moderately to north, forming a northward-facing sequence, although the subgroup strikes north and dips and faces to east on the west of the Managawa River. The "Itoshiro Subgroup" of the Mana area, on the other hand, is in fault contact with the apparently overlying "Kuzuryu Subgroup" (Fig. 2) and does not form a continuous succession with the "Kuzuryu Subgroup". Thus the "Itoshiro Subgroup" of Yamada et al. (1989) in the Mana area is excluded from the object of this study. As will be discussed later, the "Kuzuryu Subgroup" of Yamada et al. (1989)

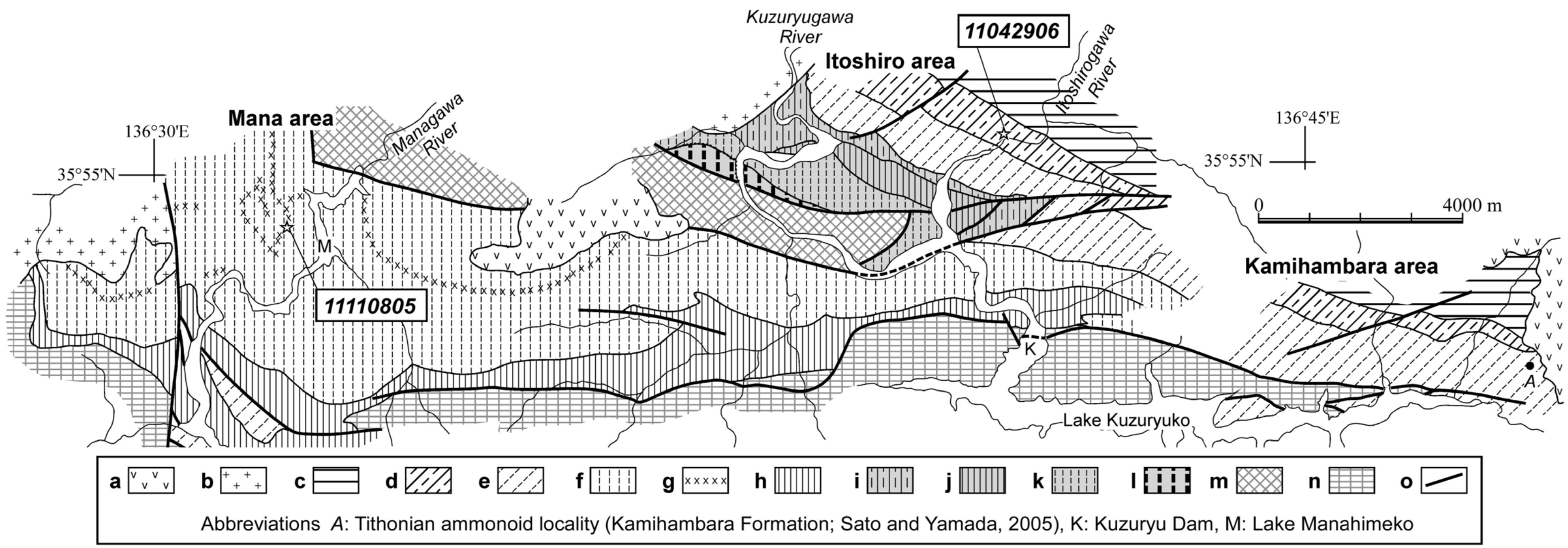

FIGURE 2. Geologic map of the Mana, Itoshiro, and Kamihambara areas in Ono City, Fukui Prefecture, central Japan, compiled from the geologic maps of Yamada et al. (1989) and Fujita (2002). **a,** Post-Tetori volcanic rocks; **b,** Post-Tetori plutonic rocks; **c,** Nochino Formation (Akaiwa Subgroup); **d–e,** Itoshiro Subgroup (**d,** Itsuki Formation; **e,** Obuchi, Kamihambara, Ashidani, and Yambara formations); **f–h,** Kuzuryu Subgroup in the Mana area (**f,** Upper Formation; **g,** pyroclastic rocks; **h,** Middle Formation), **i–l,** Kuzuryu Subgroup in the Itoshiro and Kamihambara areas (**i,** Yambarazaka Formation; **j,** Kaizara Formation; **k,** Tochimochiyama Formation; **l,** Lowest Formation); **m,** Constituent rocks of the Hida Belt; **n,** Constituent rocks of the Hida Gaien Belt; **o,** Fault. Italicized numbers denote dated samples.

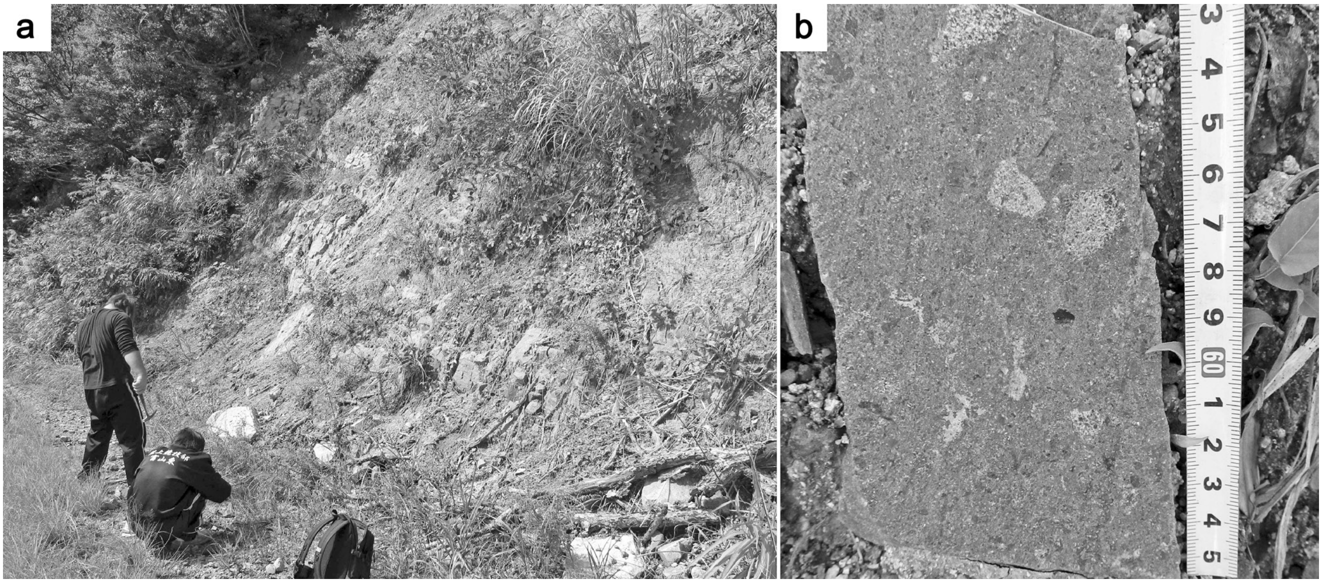

FIGURE 3. An exposure of the lapilli tuff of the Upper Formation of the "Kuzuryu Subgroup" in the Mana area (sample 11110805). **a,** Whole outcrop view; **b,** A close-up view showing the texture of the lapilli tuff.

in the Mana area is mostly correlated with the Itoshiro Subgroup in the Itoshiro area; the distribution of the coeval strata with the Kuzuryu Subgroup in the Itoshiro area is, if any, very narrow in the Mana area.

The Middle Formation of the "Kuzuryu Subgroup" in the Mana area, about 600 m thick, overlies the Carboniferous Fujikuradani Formation of the Hida Gaien Belt and is composed mainly of black shale covering basal calcareous coarse sandstone with the thickness of 3 m or less. The black shale is partly interbedded with fine to medium sandstone and intercalates a couple of thin layers of coarse sandstone and conglomerate. The interbedded sandstone and shale are dominant in the middle part of the Formation. The conglomerate is well-round and contains pebbles of granite, black shale, and sandy limestone (Yamada et al.,1989). Yamada et al. (1989) correlated the Middle Formation of the "Kuzuryu Subgroup" in the Mana area with the uppermost Bathonian–Callovian Kaizara Formation (or Kaizara Shale), because the two formations are both ammonoid-bearing, shale-rich formations, although the ammonoids reported by Yamada et al. (1989) have not been identified (Sato, 2008). On the other hand, a Tithonian ammonoid, *Parapallasiceras* sp. cf. *P. pseudocontiguum*, was reported from the Mana area, suggesting that the ammonoid-bearing beds of the Middle Formation of the "Kuzuryu Subgroup" can be correlated with the Tithonian (Yamada and Uemura, 2008).

The Upper Formation of the "Kuzuryu Subgroup" consists mainly of sandstone, with intercalations of conglomerate, shale, and interbedded sandstone and shale. A layer of pyroclastic rock (tuff breccia or lapilli tuff), about 10 m thick, is intercalated in the upper part of the formation (Fig. 3). The sandstone is massive or bedded feldspathic arenite with feldspar fragments of more than 50%, whereas the conglomerate bears granule- to cobble-sized clasts of granite and gneisses. The thickness of the Upper Formation of the "Kuzuryu Subgroup" is about 1,500 m, and the thickness between the base of the formation and the pyroclastic rock layer is 1,000 m or more (Yamada et al., 1989).

Itoshiro and Kamihambara areas

Geology of the Tetori Group in the Kamihambara and Itoshiro areas was studied by Oishi (1933), Maeda (1952, 1957, 1961b), Kawai et al. (1957), Yamada et al. (1989), Fujita (2002), and Matsukawa et al. (2003, 2006, 2008). Most of them have regarded that the Tetori Group along the Itoshirogawa River in the Itoshiro area as a type section. Here we mainly follow the descriptions of Fujita (2002).

The Tetori Group in the Kamihambara and Itoshiro areas forms a northward-dipping and northward-facing succession, comprising the Kuzuryu, Itoshiro, and Akaiwa subgroups in ascending order. The Kuzuryu Subgroup consists of the Tochimochiyama, Kaizara, and Yambarazaka formations, whereas the Itoshiro Subgroup consists of Yambara, Ashidani, Kamihambara, Obuchi, and Itsuki formations, in ascending order (Fujita, 2002). The Akaiwa Subgroup in the two areas consists only of the Nochino Formation (Oishi, 1933; Fujita, 2002). The Itoshiro Subgroup covers the Kuzuryu Subgroup unconformably (Umagatani Unconformity; Maeda, 1952), and the Akaiwa Subgroup covers the Itoshiro Subgroup conformably (Maeda, 1961b). The distribution width of the Kuzuryu Subgroup gradually thins out from the Itoshiro area to the Kamihambara area (Kawai et al., 1957; Yamada et al., 1989; Fujita, 2002), whereas the Kamihambara Formation of the Itoshiro Subgroup is absent along the Itoshirogawa River of the Itoshiro area (Fujita, 2002). The southern boundary of the Tetori Group in the Kamihambara area is in fault contact with the constituent rocks of the Hida Gaien Belt such as Ise Metamorphic Rocks and the Shibasudani, Konogidani, Otani, and Motodo formations, whereas that in the Itoshiro area is in fault contact with Tandoguchi Gneiss of the Hida Belt (e.g., Kawai et al., 1957).

The Tochimochiyama Formation of the Kuzuryu Subgroup, about 500 m thick, consists mainly of interbedded granular sandstone and fine sandstone with intercalations of shale. The Kaizara Formation, about 250 m thick, consists mainly of mica-rich dark gray shale with intercalations of sandstone. The following three ammonoid assemblage zones have been discriminated in the Kaizara Formation (Sato and Westermann, 1991): *Pseudoneuqueniceras yokoyamai* assemblage zone (uppermost Bathonian), *Kepplerites japonicus* assemblage zone (lowermost Callovian), and *Oxycerites* assemblage zone (upper Lower Callovian?). The Yambarazaka Formation is the uppermost formation of the Kuzuryu Subgroup and is composed of interbedded sandstone and siltstone. The thickness of the Yambarazaka Formation is about 150 m in average, but significantly changes because of the erosion during the formation of the Umagatani Unconformity. An ammonite assemblage zone, *Kranaosphinctes matsushimai* assemblage zone (Middle Oxfordian) has been discriminated in the Yambarazaka Formation (Sato and Westermann, 1991).

The Yambara Formation of the Itoshiro Subgroup, 150 m thick, consists of conglomerate, granular sandstone, and coarse sandstone. The conglomerate contains pebble- to boulder-sized clasts of gneisses, schists (Tsujimori, 1995), granite, quartz porphyry, limestone, sandstone, and shale, of which the latter two were likely originated from the Kuzuryu Subgroup. The largest clast reaches up to 1 m in diameter. The granular sandstone of the Yambara Formation yields *Vaugonia yambarensis* (Kobayashi, 1956). The Ashidani Formation, 200–600 m thick, consists mainly of interbedded sandstone and shale and intercalates conglomerate and coal seams. The formation yields plant and brackish molluscan fossils. The Kamihambara Formation, about 200 m thick, consists chiefly of shale interbedded with thin sandstone on top of thin basal conglomerate. The Kamihambara Formation is a Tithonian formation yielding marine molluscan fossils such as *Inoceramus* sp. cf. *I. maedae* (Fujita et al., 1998) and *Parapallasiceras* sp. cf. *P. pseudocontiguum* (Sato and Yamada, 2005; point *A* in Fig. 2). The Obuchi Formation, about 250 m thick, consists of conglomerate and massive sandstone. The conglomerate contains pebbles of chert, siliceous mudstone, shale, and granite. The Itsuki Formation, about 300 m thick, consists of interbedded sandstone and shale with some coal seams. The formation yields common brackish water bivalves with the Monobegawa Group in the Northern Chichibu Belt, Southwest Japan, such as the Tatsukawa-type fauna (Hauterivian; Kozai et al., 2002, 2005) and *Myopholas* sp. cf. *M. semicostata* (Hauterivian–Barremian; Fujita, 2002). Moreover, Goto (2007) reported Late Hauterivian–Early Barremian ammonoid *Pseudothurmannia* sp. from the uppermost part of the Itoshiro Subgroup in the Uchinamigawa area, 5 km to northwest of the Itoshiro area.

In spite of these interpretations of correlation, Yamada et al. (1989) had colored the Ashidani, Kamihambara, Obuchi, and Itsuki formations in the Kamihambara area of Fujita (2002) as the Upper Formation of the Itoshiro Subgroup, i.e., the Itsuki Formation. We cannot deny the interpretation of Yamada et al. (1989), because the Itoshiro Subgroup in the Itoshiro and Kamihambara areas has not yet been correlated with marine index fossils.

The Nochino Formation of the Akaiwa Subgroup consists mainly of sandstone and siltstone with some intercalations of conglomerate. The sandstone is feldspathic arenite and partly contains some pebbles (Maeda, 1961b; Fujita, 2002). The conglomerate characteristically contains pebbles of orthoquartzite and granite (Fujita, 2002).

SAMPLE DESCRIPTIONS

We studied the following two samples and constrained their age of deposition: (1) sandstone of the Itsuki Formation in the Itoshiro area, and (2) lapilli tuff of the Upper Formation of the "Kuzuryu Subgroup" in the Mana area (Fig. 2). Here follows the description of studied samples.

Sandstone (11042906) of the Itsuki Formation, Itoshiro area (N35°55'28.9", E136°40'56.5")

Sample 11042906 of the Itsuki Formation was collected from the exposure above the rock shed at the type locality of the formation along the Itoshirogawa River (N35°55'28.9", E136°40'56.5"). The sample was collected from interbedded sandstone and thin shale about 100 m above the base of the Itsuki Formation. The sandstone is light brown, well-sorted, and sub-angular feldspathic arenite (Fig. 4a, b) composed of monocrystalline quartz (52.3%), polycrystalline quartz (3.5%), feldspar (37.6%), lithic fragments (3.2%), and matrix (2.8%). The polycrystalline quartz fragments show wavy extinction and subgrain boundary, and were likely derived from metamorphic rock or protomylonite. The lithic fragments are mostly of volcanic rocks and mudstone.

Lapilli tuff (11110805) of the Upper Formation of the "Kuzuryu Subgroup", Mana area (N35°54'28.9", E136°31'28.5")

Sample 11110805 of the Upper Formation of the "Kuzuryu Subgroup" was collected from an outcrop along a logging road to the west of Lake Manahimeko (N35°54'28.9",E136°31'28.5"), about 1,000 m above the base of the formation. The lapilli

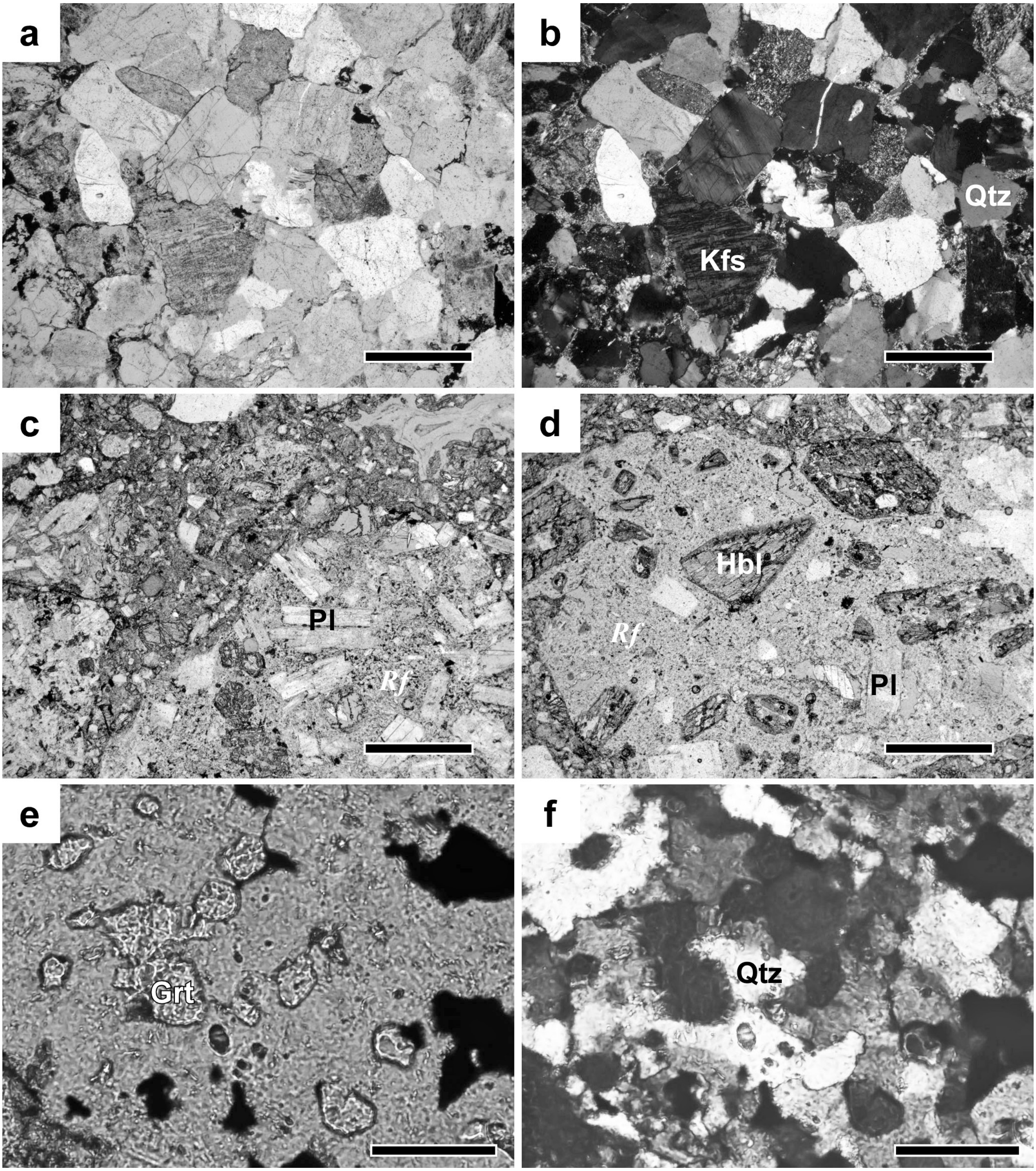

FIGURE 4. Photomicrographs of analyzed samples. **a–b,** Sandstone of the Itsuki Formation (sample 11042906). Scale bars denote 0.5 mm. a, Open nicol; b, Crossed nicols. **c–d,** Volcanic rock fragments in a lapilli tuff of the Upper Formation of the "Kuzuryu Subgroup" (sample 11110805). Scale bars denote 0.5 mm. **e–f,** Garnet-bearing metamorphic rock fragment in sample 11110805. Scale bars denote 0.1 mm. **e,** Open nicol; **f,** Crossed nicols. Abbreviations Grt: garnet, Hbl: hornblende, Kfs: K-feldspar, Pl: plagioclase, Qtz: quartz, *Rf*: rock fragment.

tuff consists of lapilli (25%), other lithic fragments (5%), and matrix (70%). The matrix is crystal tuff composed of euhedral to subhedral plagioclase, hornblende, and augite of 0.3–1.3 mm in diameter.

The lapilli are composed mostly of andesite lava with some felsic lava and tuff: (1) aphanitic andesite lava with microcrystalline plagioclase, (2) andesite lava with glomeroporphyritic plagioclase (Fig. 4c), (3) porphyritic andesite lava with phenocrysts (ca. 15%) of plagioclase and hornblende (Fig. 4d), (4) porphyritic andesite lava with phenocrysts(ca. 10%)of plagioclase and augite, (5) aphyric andesite lava or hypabyssal rock consisting of plagioclase and hornblende, (6) porphyritic dacite or rhyolite lava with phenocrysts of quartz and biotite, (7) welded pumice, and (8) felsic crystal tuff consisting of fragments of plagioclase, quartz, and opaque minerals. Besides the lapilli listed above, fragments of sandstone, mudstone, and metamorphic rock are included. Among them, the metamorphic rock fragments consist of recrystallized quartz and small amounts of garnet (Fig. 4e, f), and are most likely of felsic gneiss.

ANALYTICAL METHOD

The U-Pb dating method makes use of the growth of lead isotopes caused by the decay of uranium isotopes. The method relies on two parallel decay chains: the uranium series from ^{238}U to ^{206}Pb and the actinium series from ^{235}U to ^{207}Pb (e.g., Kaneoka, 1998; Hirata and Nesbitt, 1994). The U-Pb dating is commonly performed on zircon ($ZrSiO_4$), a non-magnetic silicate mineral with the density of 4.6–4.7. Zircon is one of the best minerals to determine the timing of crystallization from magma or metamorphic fluids, because of the following reasons. (1) Zircon contains certain amount of uranium but virtually no common lead; (2) it has high closure temperature (ca. 900°C; Cherniak and Watson, 2001); and (3) it is highly resistant to weathering, alteration, and metamorphism. Hence the youngest age of detrital zircons in a clastic rock sample is interpreted to show the youngest age of igneous activity in a provenance before the deposition of the sample, and in turn constrains the oldest age limit of the deposition.

The zircon samples for analyses were prepared in the following procedures. Zircon grains were separated from each sample using standard crushing, sieving (< 250 μm), panning and heavy-liquid (diiodomethane; density up to 3.3 kg/m^3) techniques. We picked up 400 zircon grains from the sample of the Itsuki Formation (sample 11042906), and 52 zircon grains from the sample of lapilli tuff in the Mana area (sample 11110805). The grains were mounted in acrylic resin and polished. The internal textures, inclusions, and microcracks of the zircons were observed using transmitted and reflected optical microscopy and cathodoluminescence (CL) imaging. CL images were captured on a scanning electron microscope (JEOL JSM-5910LV) equipped with a JEOL MP-Z01118T CL detector in the Fukui Prefectural Dinosaur Museum. Grains showing clear oscillatory zoning in CL images (Fig. 5), a common feature of igneous zircons (Corfu et al., 2003), and having few inclusions or microcracks were chosen for analyses to avoid a possible effect of common lead on the age dating.

The measurement was carried out on a laser ablation inductively coupled plasma mass spectrometer (LA-ICPMS) equipped in the Earthquake Research Institute of the University of Tokyo. The ICPMS instrument used was a Thermo Elemental Plasma Quad 3 quadropole-based ICPMS connected with a New Wave UP-213 LA system, which used the frequency quintupled Nd-YAG 213-nm wavelength (Orihashi et al., 2008). Orihashi et al. (2008) measured 7 standard zircons on this system with a NIST SRM610 glass reference material, and found out the best conditions for precise measurement and determined the correction factor, ^{206}Pb/^{238}U = 0.2302; the conditions and correction factor have enabled the system to measure the age of the 7 standard zircons within ±2% of their published ages obtained with both isotope dilution-thermal ionization mass spectrometry (ID-TIMS) and SHRIMP. The measurement conditions were as follows: the ablation pit size of 30 μm, energy density of 11–13 J/cm^2, pulse width of 4 ns nominal and pulse repetition rate of 10 Hz. All analyses were carried out in a peak-jumping mode and the peaks of ^{202}Hg, ^{204}(Hg+Pb), ^{206}Pb, ^{207}Pb, ^{232}Th, and ^{238}U were monitored. Data were acquired in sequences of 28 analyses, consisting of 5 analyses of gas blank, 4 SRM610 NIST (National Institute of Standards and Technology, U.S.A.) glass standard, 1 standard zircon (91500 zircon with the ^{206}Pb/^{238}U age of 1062.4 ± 0.4 Ma; Wiedenbeck et al., 2004), 9 unknown, 4 SRM610 standard, and 5 gas blank.

After the analyses, transmitted and reflected optical photomicrographs of zircons were reexamined. If an ablation spot contains inclusions or microcracks, which may contain common lead, the analytical data from the spot were rejected. The obtained data were plotted on concordia diagrams and the relative probability diagram using the Isoplot 3.70 software (Ludwig, 2008).

RESULTS

Sandstone (11042906) of the Itsuki Formation, Itoshiro area

The detrital zircons from sample 11042906 are commonly abraded and have anhedral to subhedral shapes. They have columnar shape with the aspect ratio ranging from 1.1 to 2.9 (1.5–2.0 in average). More than half of the zircons are colored brown or purple and tend to be Precambrian in age, and the others are colorless. Most of the zircons show oscillatory zoning in CL images, a common feature of igneous zircons (Corfu et al., 2003; Fig. 5).

From the 400 zircon grains we picked up, we chose 148 grains with remarkable oscillatory zoning in CL images, sampled an outer part (rim or mantle) of each grain and an inner part (core)

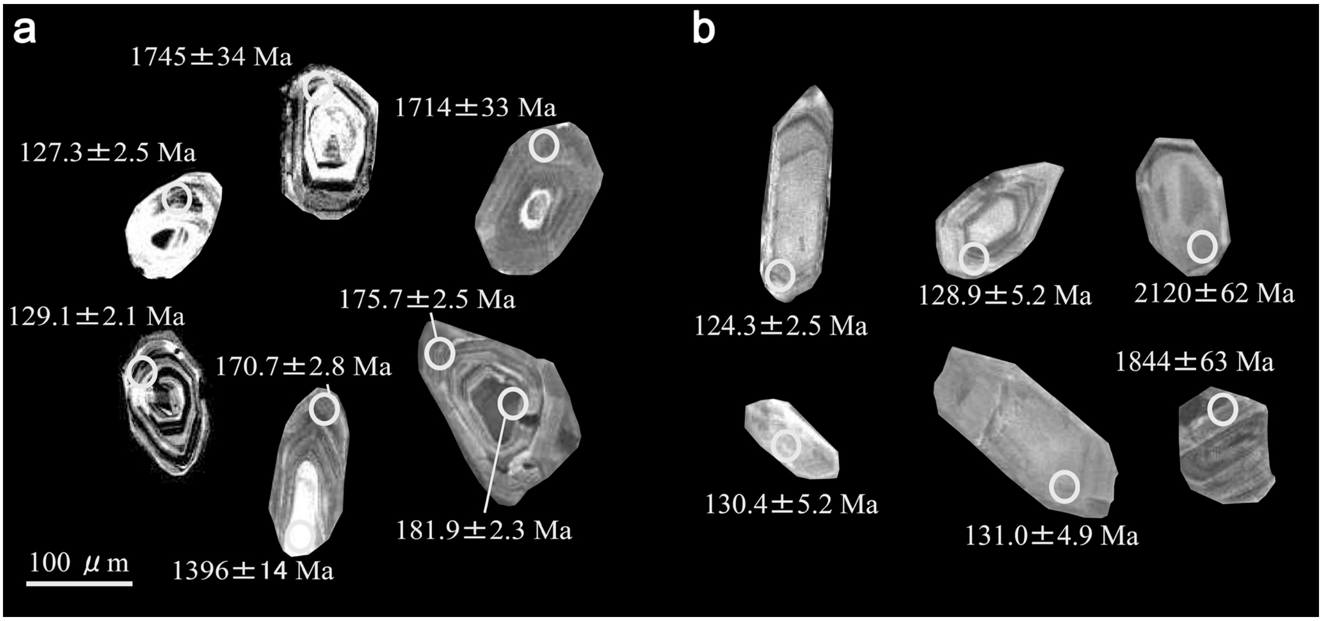

FIGURE 5. Cathodoluminescence images of some zircons analyzed in this study. **a**, Zircons from sandstone of the Itsuki Formation in the Itoshiro area (sample 11042906); **b**, Zircons from lapilli tuff of the Upper Formation of the "Kuzuryu Subgroup" in the Mana area (sample 11110805).

of 5 grains with the laser ablation technique, and analyzed the sample with the ICPMS. After the analyses, we rejected the analytical data of 27 spots from the criteria described in the previous section.

The analytical data from 126 spots in 121 detrital zircon grains were thus adopted (Table 1). The Th/U ratio of each spot was 0.11–2.8 and falls in the range of igneous zircons, Th/U > 0.1 (Rubatto and Hermann, 2003). Table 1 and the concordia diagram drawn with Isoplot 3.70 (Fig. 6a, b) show that the concordance of $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages is quite well; 104 spots out of 126 have the % conc value (100·($^{207}Pb/^{235}U$ age)/($^{206}Pb/^{238}U$ age)) between 90 and 110. Fig. 6c is the probability distribution of $^{206}Pb/^{238}U$ ages of 102 concordant outer spots on 102 zircons from sample 11042906. Fig. 6a and 6c show some age clusters: 3500–3300 Ma (2 grains, 2%), 2500–1500 Ma (86 grains, 84%), 260–210 Ma (6 grains, 6%), 180–165 Ma (5 grains, 5%), and around 130 Ma (2 grains, 2%). The concordant age of the youngest zircon was 127.2 ± 2.5 Ma (Fig. 6b).

Lapilli tuff (11110805) of the upper part of the "Kuzuryu Subgroup", Mana area

Most detrital zircons in sample 11110805 exhibit euhedral shapes with some abraded subhedral crystal faces. They have columnar shape with the aspect ratio ranging from 1.0 to 3.3 (about 1.5 in average). More than half of the zircons are colorless and euhedral, and the others are brown or purple. Most of the zircons show oscillatory zoning in CL images, a common feature of igneous zircons (Corfu et al., 2003; Fig. 5).

From the 52 zircon grains we picked up, we chose 33 grains, sampled an outer part (rim or mantle) of each grain with the laser ablation technique, and analyzed the sample with the ICPMS. After the analyses, we rejected the analytical data of 11 spots from the criteria described in the previous section.

The analytical data from 22 spots in 22 detrital zircon grains were thus adopted (Table 2). The Th/U ratio of each spot was 0.12–1.03 and falls in the range of igneous zircons, Th/U > 0.1 (Rubatto and Hermann, 2003). The concordia diagram drawn from all the analytical data, including some discordant ones, with Isoplot 3.70 (Fig. 7a, b) shows two distinct age clusters: 2500–1450 Ma (13 grains, 60%) and 130–120 Ma (6 grains, 27%). The zircons forming the younger age cluster are all colorless and euhedral. The intercept age of the younger age cluster, which shows some influence of common lead, was 124.6 ± 2.3 Ma (Fig. 7b).

DISCUSSION

Age of deposition of the investigated samples

Sandstone of the Itsuki Formation.—The youngest $^{206}Pb/^{238}U$-age cluster of detrital zircons from the sandstone (sample 11042906) of the lower part of the Itsuki Formation in the Itoshiro area consists only of two concordant grains (IT-1.2 and IT-1.40; Table 1) and one discordant grain (IT-1.65; Table 1). We interpret that the small number of Early Cretaceous zircon is due to the magmatic hiatus (Sagong et al., 2005) in the provenance as discussed in a later section. The concordant

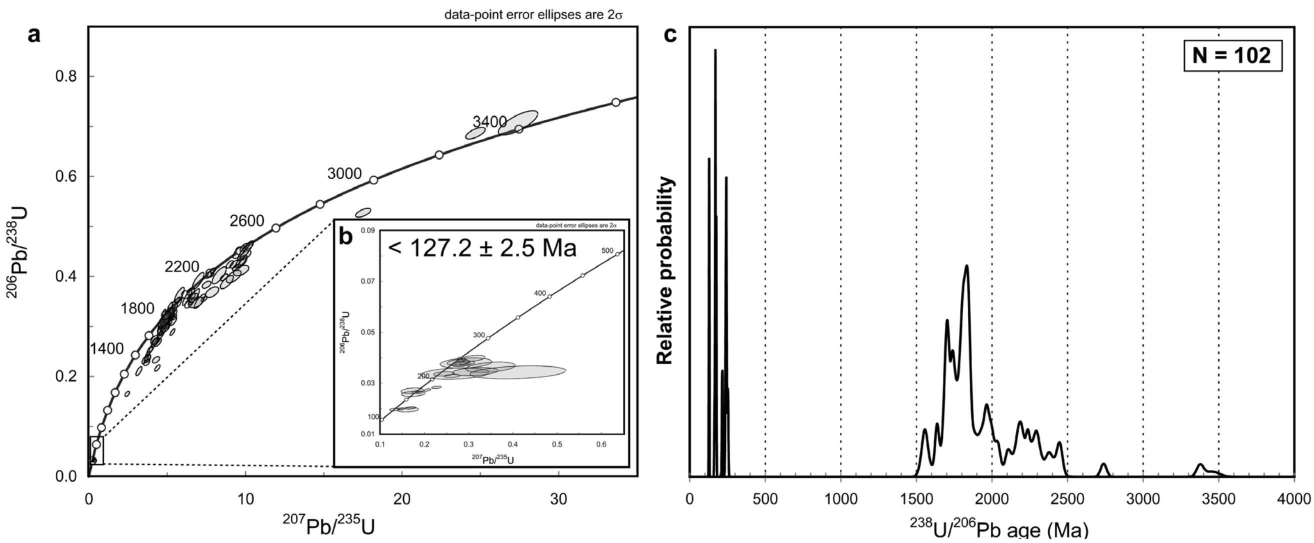

FIGURE 6. Analytical data of detrital zircons from sandstone of the Itsuki Formation in the Itoshiro area (sample 11042906). **a,** Concordia diagram for all data; **b,** Concordia diagram for 500–100 Ma data set; **c,** Relative probability diagram.

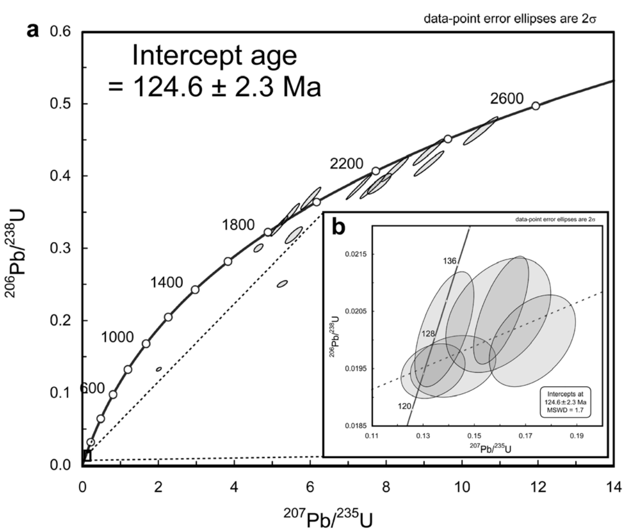

FIGURE 7. Analytical data of detrital zircons from lapilli tuff of the Upper Formation of the "Kuzuryu Subgroup" in the Mana area (sample 11110805). **a,** Concordia diagram for all data; **b,** Concordia diagram for 140–120 Ma data set.

age of the youngest detrital zircon (grain IT-1.40; Table 1) in sample 11042906 was 127.2 ± 2.5 Ma, which corresponds to the Barremian age of Early Cretaceous (International Commissions on Stratigraphy (ICS), 2010). Hence the Itsuki Formation was presumably deposited in Barremian or later, except for its lowermost part.

Lapilli tuff of the Upper Formation of the "Kuzuryu Subgroup".—The lapilli tuff (sample 11110805) of the Upper Formation of the "Kuzuryu Subgroup" in the Mana area contains zircons of various ages, but the intercept age of the younger age cluster was 124.6 ± 2.3 Ma (Fig. 7b). A youngest age cluster of zircons extracted from a pyroclastic-rock sample most likely show the age of formation of essential volcanic-rock fragment, and hence show the age of sedimentation of the pyroclastic rock. Accordingly we regard that the age of sedimentation of the lapilli tuff of the Upper Formation of the "Kuzuryu Subgroup" is 124.6 ± 2.3 Ma, corresponding to late Barremian–early Aptian of Early Cretaceous (ICS, 2010).

Age of deposition of the Tetori Group in the Itoshiro and Mana areas

Here we discuss the age of the Tetori Group in the Itoshiro and Mana areas from previous stratigraphical and paleontological studies and the U-Pb ages presented in this study.

Itoshiro area.—The Tetori Group along the Itoshirogawa River in the Itoshiro area is a type section of the group (e.g., Maeda, 1961b). The Tetori Group in the Itoshiro area consists of Kuzuryu, Itoshiro, and Akaiwa subgroups in ascending order. The Kuzuryu Subgroup, in turn, is composed of the Tochimochiyama, Kaizara, and Yambarazaka formations in ascending order. Latest Bathonian–Early Callovian and Oxfordian ammonoid fossil assemblages have been reported from the Kaizara and Yambarazaka formations, respectively (Sato and Westermann, 1991), although the age of the Tochimochiyama Formation is still unknown. According to Fujita (2002), the continuous succession of the Itoshiro and Akaiwa subgroups in the Kamihambara area (Fig. 2), except for the Kamihambara Formation, extends to the Itoshiro area. The

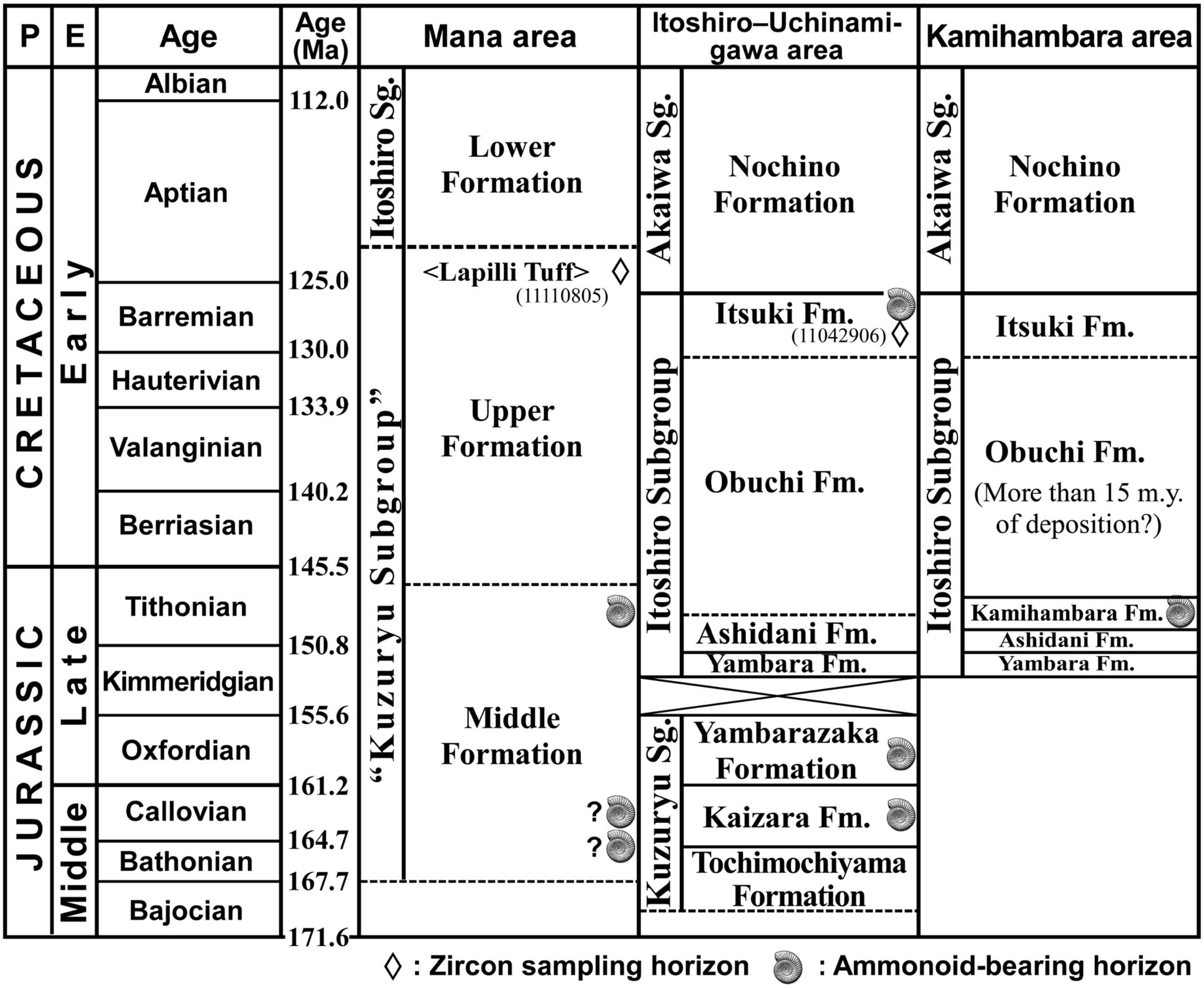

FIGURE 8. Age and correlation of the Tetori Group in the Mana, Itoshiro, and Kamihambara areas. Numerical ages on geologic-age boundaries are from ICS (2010). Parenthesized numbers denote dated samples. Abbreviations E: Epoch, Fm.: Formation, P: Period, Sg.: Subgroup.

Itsuki Formation of the Itoshiro Subgroup in the Itoshiro area was correlated with the Hauterivian from the occurrence of the Tatsukawa-type fauna (Kozai et al., 2002, 2005). On the other hand, Goto (2007) reported a Late Hauterivian–Early Barremian ammonoid, *Pseudothurmannia* sp., from the uppermost part of the Itoshiro Subgroup in the Uchinamigawa area, 5 km to northwest of the Itoshiro area. The ammonoid-bearing horizon is most likely correlated with the uppermost part of the Itsuki Formation in the Itoshiro area. In this study, we reported that the youngest age of the detrital zircons from a sandstone sample (11042906) of the lower part of the Itsuki Formation was 127.2 ± 2.5 Ma (Barremian; ICS, 2010). Our new data, combined with the previous paleontological data, strongly suggest that the age of the Itsuki Formation, except for the lowermost part, is Early Barremian (Fig. 8).

Mana area.—The Tetori Group in the Mana area, reexamined in this study, was assigned to the Middle and Upper formations of the "Kuzuryu Subgroup"; the two formations were correlated with the Kaizara and Yambarazaka formations in the Itoshiro area, respectively (Yamada et al., 1989). However, the ammonoid fossils reported from the Middle Formation of the "Kuzuryu Subgroup" by Yamada et al. (1989) have not been identified (Sato, 2008). On the other hand, the occurrence of another ammonoid species, *Parapallasiceras* sp. cf. *P. pseudocontiguum*, from a float of the Middle Formation of the "Kuzuryu Subgroup" has been informally reported, suggesting that the Middle Formation of the "Kuzuryu Subgroup" in the Mana area can be correlated, at least partly,

TABLE 1. U-Pb isotopic data for zircons from sandstone of the Itsuki Formation in the Itoshiro area (sample 11042906). % conc = 100· (^{207}Pb/^{235}U age)/(^{206}Pb/^{238}U age) is a measure of concordance between ^{206}Pb/^{238}U and ^{207}Pb/^{235}U ages. Analyses shown in italics are discordant and are not included in the probability plot.

Grain	Spot	^{206}Pb /^{238}U (2σ)	^{207}Pb /^{235}U (2σ)	^{206}Pb /^{238}U age (2σ) in Ma	^{207}Pb /^{235}U age (2σ) in Ma	% conc	Th/U
IT-1.1	Outer	0.2901 ± 0.0039	4.62 ± 0.10	1642 ± 22	1752 ± 39	106.7	0.28
IT-1.2	Outer	0.02022 ± 0.00033	0.1450 ± 0.0076	129.1 ± 2.1	137.5 ± 7.2	106.6	0.71
IT-1.3	Outer	0.3091 ± 0.0042	5.05 ± 0.11	1736 ± 23	1828 ± 39	105.3	0.31
IT-1.4	Outer	0.3575 ± 0.0049	7.39 ± 0.16	1970 ± 27	2159 ± 46	109.6	0.19
IT-1.5	Outer	0.03827 ± 0.00055	0.290 ± 0.010	242.1 ± 3.5	258.6 ± 8.5	106.8	0.88
	Inner	0.03935 ± 0.00045	0.2826 ± 0.0087	248.8 ± 2.8	252.7 ± 7.8	101.6	1.58
IT-1.6	Outer	0.4632 ± 0.0062	10.25 ± 0.21	2453 ± 33	2458 ± 50	100.2	0.61
IT-1.7	Outer	0.3313 ± 0.0044	5.26 ± 0.11	1845 ± 24	1863 ± 38	101.0	0.70
IT-1.8	Outer	0.3013 ± 0.0041	4.846 ± 0.081	1698 ± 23	1793 ± 30	105.6	0.54
IT-1.9	Outer	0.3007 ± 0.0040	4.747 ± 0.098	1695 ± 23	1776 ± 37	104.8	0.27
IT-1.10	Outer	0.02665 ± 0.00040	0.188 ± 0.007	169.5 ± 2.5	174.7 ± 6.7	103.0	0.25
IT-1.11	Outer	0.3242 ± 0.0045	5.30 ± 0.12	1810 ± 25	1868 ± 42	103.2	0.30
IT-1.12	Outer	0.02763 ± 0.00039	0.2054 ± 0.0064	175.7 ± 2.5	189.7 ± 5.9	108.0	1.0
	Inner	*0.02861 ± 0.00036*	*0.2260 ± 0.0090*	*181.9 ± 2.3*	*206.9 ± 8.2*	*113.8*	*0.84*
IT-1.13	Outer	0.4007 ± 0.0056	8.65 ± 0.20	2172 ± 30	2302 ± 52	106.0	1.3
IT-1.14	Outer	0.3280 ± 0.0044	5.20 ± 0.11	1829 ± 25	1852 ± 41	101.3	0.33
IT-1.15	Outer	0.3030 ± 0.0042	4.75 ± 0.11	1706 ± 24	1776 ± 42	104.1	0.72
IT-1.16	Outer	0.5292 ± 0.0075	17.54 ± 0.40	2738 ± 39	2965 ± 67	108.3	0.95
IT-1.17	Outer	0.6883 ± 0.0093	24.69 ± 0.51	3376 ± 46	3296 ± 68	97.6	0.67
IT-1.18	Outer	0.3294 ± 0.0046	5.52 ± 0.12	1836 ± 26	1904 ± 40	103.7	0.18
IT-1.19	Outer	0.4263 ± 0.0060	9.02 ± 0.19	2289 ± 32	2340 ± 50	102.2	1.6
IT-1.20	Outer	0.3307 ± 0.0047	4.83 ± 0.11	1842 ± 26	1790 ± 39	97.2	0.17
IT-1.21	Outer	0.3271 ± 0.0046	5.18 ± 0.11	1824 ± 25	1849 ± 39	101.3	0.56
IT-1.22	Outer	0.3552 ± 0.0050	5.69 ± 0.12	1959 ± 28	1930 ± 42	98.5	0.22
IT-1.23	Outer	0.3209 ± 0.0045	5.47 ± 0.12	1794 ± 25	1897 ± 42	105.7	0.19
IT-1.24	Outer	0.3095 ± 0.0044	5.20 ± 0.12	1738 ± 25	1852 ± 41	106.5	1.1
IT-1.25	Outer	0.4605 ± 0.0066	9.95 ± 0.23	2442 ± 35	2430 ± 55	99.5	1.1
IT-1.26	Outer	0.3303 ± 0.0046	5.28 ± 0.11	1840 ± 26	1865 ± 39	101.4	0.31
IT-1.27	Outer	0.3423 ± 0.0066	5.22 ± 0.13	1898 ± 37	1855 ± 47	97.8	0.26
IT-1.28	*Outer*	*0.2913 ± 0.0056*	*5.36 ± 0.13*	*1648 ± 32*	*1879 ± 46*	*114.0*	*0.13*
IT-1.29	Outer	0.4089 ± 0.0078	7.80 ± 0.18	2210 ± 42	2208 ± 52	99.9	0.12
IT-1.30	Outer	0.3108 ± 0.0060	4.96 ± 0.12	1744 ± 34	1813 ± 46	103.9	0.27
IT-1.31	Outer	0.3221 ± 0.0062	5.19 ± 0.13	1800 ± 34	1851 ± 45	102.8	0.36
IT-1.32	Outer	0.4310 ± 0.0083	9.85 ± 0.24	2310 ± 44	2421 ± 59	104.8	2.5
IT-1.33	Outer	0.3046 ± 0.0058	4.76 ± 0.11	1714 ± 33	1778 ± 42	103.7	0.37
IT-1.34	*Outer*	*0.2460 ± 0.0047*	*3.747 ± 0.093*	*1418 ± 27*	*1581 ± 39*	*111.5*	*0.14*
IT-1.35	Outer	0.4269 ± 0.0068	9.33 ± 0.24	2292 ± 36	2371 ± 61	103.4	0.45
IT-1.36	Outer	0.03394 ± 0.00070	0.243 ± 0.019	215.1 ± 4.5	221 ± 17	102.5	0.25
	Inner	*0.03306 ± 0.00050*	*0.262 ± 0.015*	*209.7 ± 3.2*	*236 ± 14*	*112.6*	*0.85*
IT-1.37	Outer	0.3253 ± 0.0052	5.17 ± 0.14	1816 ± 29	1847 ± 50	101.7	1.1
IT-1.38	Outer	0.4448 ± 0.0073	10.02 ± 0.28	2372 ± 39	2436 ± 68	102.7	0.39
IT-1.39	Outer	0.02683 ± 0.00044	0.1782 ± 0.0061	170.7 ± 2.8	166.5 ± 5.7	97.6	0.60
	Inner	*0.2418 ± 0.0025*	*3.7547 ± 0.0663*	*1396 ± 14*	*1583 ± 28*	*113.4*	*0.94*
IT-1.40	Outer	0.01994 ± 0.00039	0.1308 ± 0.0090	127.3 ± 2.5	124.8 ± 8.6	98.0	0.32
IT-1.41	Outer	0.3387 ± 0.0054	5.39 ± 0.14	1880 ± 30	1883 ± 50	100.1	0.25
IT-1.42	*Outer*	*0.2572 ± 0.0043*	*4.00 ± 0.12*	*1476 ± 25*	*1634 ± 48*	*110.7*	*1.4*
IT-1.43	Outer	0.3234 ± 0.0044	5.23 ± 0.13	1806 ± 24	1857 ± 46	102.8	0.77
IT-1.44	Outer	0.4051 ± 0.0054	7.63 ± 0.17	2193 ± 29	2189 ± 50	99.8	0.58
IT-1.45	Outer	0.03761 ± 0.00068	0.282 ± 0.019	238.0 ± 4.3	252 ± 17	106.0	0.55
	Inner	0.03808 ± 0.00069	0.290 ± 0.019	240.9 ± 4.4	258.5 ± 17.1	107.3	0.56

(continued on next page)

TABLE 1. (*Continued*)

Grain	Spot	$^{206}Pb/^{238}U$ (2σ)	$^{207}Pb/^{235}U$ (2σ)	$^{206}Pb/^{238}U$ age (2σ) in Ma	$^{207}Pb/^{235}U$ age (2σ) in Ma	% conc	Th/U
IT-1.46	Outer	0.3630 ± 0.0048	6.61 ± 0.15	1996 ± 26	2060 ± 47	103.2	0.39
IT-1.47	Outer	0.2879 ± 0.0038	4.63 ± 0.11	1631 ± 22	1754 ± 42	107.5	0.17
IT-1.48	Outer	0.4201 ± 0.0055	9.44 ± 0.21	2261 ± 30	2381 ± 54	105.3	0.30
IT-1.49	Outer	0.3035 ± 0.0032	5.037 ± 0.090	1709 ± 18	1825 ± 33	106.8	0.85
IT-1.50	Outer	0.4148 ± 0.0043	7.95 ± 0.13	2237 ± 23	2226 ± 37	99.5	0.82
IT-1.51	Outer	0.2733 ± 0.0063	4.31 ± 0.16	1558 ± 36	1695 ± 65	108.8	0.32
IT-1.52	Outer	0.3150 ± 0.0076	4.95 ± 0.22	1765 ± 43	1810 ± 80	102.5	0.36
IT-1.53	*Outer*	*0.2706 ± 0.0063*	*4.40 ± 0.18*	*1544 ± 36*	*1712 ± 69*	*110.9*	*0.11*
IT-1.54	Outer	0.4023 ± 0.0096	9.27 ± 0.37	2180 ± 52	2365 ± 94	108.5	0.42
IT-1.55	Outer	0.3250 ± 0.0074	5.22 ± 0.19	1814 ± 41	1855 ± 69	102.3	0.13
IT-1.56	Outer	0.3132 ± 0.0078	5.02 ± 0.20	1757 ± 44	1822 ± 74	103.7	0.24
IT-1.57	Outer	0.02727 ± 0.00091	0.171 ± 0.021	173.4 ± 5.8	160 ± 20	92.4	0.72
IT-1.58	Outer	0.3081 ± 0.0083	4.77 ± 0.26	1731 ± 47	1779 ± 97	102.8	0.76
IT-1.59	Outer	0.0382 ± 0.0016	0.293 ± 0.048	241 ± 10	261 ± 43	108.1	0.53
IT-1.60	*Outer*	*0.2194 ± 0.0050*	*4.38 ± 0.14*	*1278 ± 29*	*1709 ± 55*	*133.6*	*0.30*
IT-1.61	Outer	0.3492 ± 0.0082	6.43 ± 0.23	1931 ± 45	2036 ± 74	105.5	0.42
IT-1.62	*Outer*	*0.1677 ± 0.0041*	*2.48 ± 0.11*	*1000 ± 25*	*1267 ± 57*	*126.7*	*0.13*
IT-1.63	*Outer*	*0.2381 ± 0.0059*	*3.76 ± 0.17*	*1377 ± 34*	*1584 ± 70*	*115.1*	*0.50*
IT-1.64	Outer	0.3131 ± 0.0073	5.38 ± 0.19	1756 ± 41	1882 ± 67	107.2	0.27
IT-1.65	*Outer*	*0.01980 ± 0.00069*	*0.162 ± 0.019*	*126.4 ± 4.4*	*152 ± 18*	*120.6*	*0.31*
IT-1.66	Outer	0.2985 ± 0.0072	4.62 ± 0.18	1684 ± 41	1753 ± 69	104.1	0.23
IT-1.67	*Outer*	*0.0340 ± 0.0018*	*0.269 ± 0.063*	*215 ± 11*	*242 ± 57*	*112.2*	*0.31*
IT-1.68	Outer	0.3271 ± 0.0079	5.15 ± 0.20	1824 ± 44	1844 ± 73	101.1	0.25
IT-1.69	Outer	0.451 ± 0.011	9.63 ± 0.33	2399 ± 57	2400 ± 82	100.0	0.98
IT-1.70	Outer	0.4328 ± 0.0100	9.77 ± 0.30	2318 ± 53	2413 ± 73	104.1	0.43
IT-1.71	Outer	0.2761 ± 0.0070	4.22 ± 0.20	1572 ± 40	1678 ± 80	106.7	1.0
IT-1.72	Outer	0.3207 ± 0.0077	5.21 ± 0.20	1793 ± 43	1854 ± 71	103.4	0.33
IT-1.73	Outer	0.3223 ± 0.0075	5.06 ± 0.18	1801 ± 42	1830 ± 63	101.6	0.55
IT-1.74	Outer	0.3711 ± 0.0086	7.88 ± 0.34	2034 ± 47	2218 ± 97	109.0	0.50
IT-1.75	Outer	0.02610 ± 0.00087	0.174 ± 0.022	166.1 ± 5.5	163 ± 21	98.0	0.68
IT-1.76	Outer	0.3303 ± 0.0075	5.22 ± 0.23	1840 ± 42	1855 ± 81	100.8	0.12
IT-1.77	Outer	0.3043 ± 0.0066	4.97 ± 0.19	1713 ± 37	1815 ± 69	106.0	0.20
IT-1.78	Outer	0.3168 ± 0.0070	4.98 ± 0.20	1774 ± 39	1815 ± 73	102.3	0.45
IT-1.79	Outer	0.3487 ± 0.0078	5.64 ± 0.24	1928 ± 43	1922 ± 82	99.7	0.27
IT-1.80	*Outer*	*0.0365 ± 0.0017*	*0.349 ± 0.046*	*231 ± 11*	*304 ± 40*	*131.4*	*0.91*
IT-1.81	*Outer*	*0.2135 ± 0.0074*	*3.22 ± 0.16*	*1247 ± 43*	*1462 ± 71*	*117.2*	*0.41*
IT-1.82	Outer	0.352 ± 0.012	7.07 ± 0.29	1946 ± 65	2120 ± 87	108.9	0.21
IT-1.83	Outer	0.404 ± 0.014	8.34 ± 0.38	2188 ± 75	2268 ± 103	103.7	2.8
IT-1.84	Outer	0.325 ± 0.011	5.12 ± 0.25	1815 ± 63	1840 ± 91	101.4	0.24
IT-1.85	Outer	0.393 ± 0.013	7.01 ± 0.30	2138 ± 73	2113 ± 91	98.8	0.31
IT-1.86	Outer	0.365 ± 0.012	5.78 ± 0.26	2008 ± 68	1944 ± 86	96.8	0.14
IT-1.87	Outer	0.3297 ± 0.0092	5.22 ± 0.21	1837 ± 51	1856 ± 74	101.1	0.25
IT-1.88	Outer	0.3297 ± 0.0093	5.12 ± 0.21	1837 ± 52	1839 ± 77	100.1	0.34
IT-1.89	Outer	0.3152 ± 0.0090	4.87 ± 0.21	1766 ± 50	1796 ± 79	101.7	0.24
IT-1.90	*Outer*	*0.2357 ± 0.0067*	*3.62 ± 0.16*	*1364 ± 39*	*1553 ± 70*	*113.8*	*0.28*
IT-1.91	Outer	0.391 ± 0.011	8.83 ± 0.34	2128 ± 60	2321 ± 90	109.1	0.21
IT-1.92	Outer	0.3075 ± 0.0086	4.89 ± 0.20	1728 ± 48	1800 ± 73	104.1	0.72
IT-1.93	*Outer*	*0.2550 ± 0.0071*	*3.92 ± 0.15*	*1464 ± 41*	*1617 ± 64*	*110.4*	*0.16*
IT-1.94	Outer	0.709 ± 0.020	27.4 ± 1.0	3454 ± 97	3399 ± 128	98.4	0.36
IT-1.95	*Outer*	*0.02059 ± 0.00039*	*0.168 ± 0.010*	*131.4 ± 2.5*	*157.3 ± 9.5*	*119.8*	*0.78*

(continued on next page)

TABLE 1. (*Continued*)

Grain	Spot	^{206}Pb /^{238}U (2σ)	^{207}Pb /^{235}U (2σ)	^{206}Pb /^{238}U age (2σ) in Ma	^{207}Pb /^{235}U age (2σ) in Ma	% conc	Th/U
IT-1.96	Outer	0.2694 ± 0.0075	4.20 ± 0.17	1538 ± 43	1674 ± 68	108.8	0.51
IT-1.97	Outer	0.2992 ± 0.0046	4.75 ± 0.14	1688 ± 26	1776 ± 52	105.2	0.24
IT-1.98	Outer	0.3327 ± 0.0048	5.23 ± 0.13	1851 ± 27	1858 ± 45	100.4	0.52
IT-1.99	Outer	0.3318 ± 0.0048	5.25 ± 0.13	1847 ± 27	1861 ± 46	100.7	0.12
IT-1.100	Outer	0.3857 ± 0.0060	7.53 ± 0.22	2103 ± 33	2177 ± 64	103.5	0.32
IT-1.101	Outer	0.3719 ± 0.0059	6.52 ± 0.20	2038 ± 32	2048 ± 64	100.5	0.43
IT-1.102	Outer	0.335 ± 0.012	5.38 ± 0.24	1861 ± 67	1882 ± 84	101.1	0.45
IT-1.103	Outer	0.298 ± 0.011	4.66 ± 0.21	1679 ± 61	1760 ± 81	104.8	0.23
IT-1.104	Outer	0.314 ± 0.012	4.83 ± 0.30	1760 ± 67	1790 ± 110	101.7	0.44
IT-1.105	Outer	0.362 ± 0.013	6.73 ± 0.28	1990 ± 71	2077 ± 88	104.4	0.57
IT-1.106	Outer	0.454 ± 0.016	10.02 ± 0.41	2412 ± 86	2437 ± 99	101.0	0.43
IT-1.107	Outer	0.287 ± 0.010	4.61 ± 0.21	1628 ± 59	1752 ± 78	107.6	0.37
IT-1.108	Outer	0.360 ± 0.013	6.29 ± 0.26	1981 ± 70	2017 ± 83	101.8	0.57
IT-1.109	*Outer*	*0.0348 ± 0.0013*	*0.315 ± 0.042*	*220.5 ± 8.1*	*278 ± 37*	*126.0*	*0.73*
IT-1.110	Outer	0.3241 ± 0.0068	4.98 ± 0.20	1810 ± 38	1816 ± 73	100.3	0.71
IT-1.111	Outer	0.2998 ± 0.0066	4.90 ± 0.23	1690 ± 37	1801 ± 83	106.6	0.25
IT-1.112	*Outer*	*0.2361 ± 0.0050*	*4.30 ± 0.18*	*1366 ± 29*	*1694 ± 70*	*124.0*	*0.43*
IT-1.113	Outer	0.3508 ± 0.0087	6.86 ± 0.38	1938 ± 48	2094 ± 117	108.0	0.48
IT-1.114	*Outer*	*0.2306 ± 0.0050*	*3.70 ± 0.16*	*1338 ± 29*	*1571 ± 70*	*117.4*	*0.28*
IT-1.115	Outer	0.2724 ± 0.0058	4.26 ± 0.18	1553 ± 33	1685 ± 69	108.5	0.16
IT-1.116	Outer	0.04001 ± 0.00095	0.311 ± 0.022	252.9 ± 6.0	275 ± 19	108.6	0.46
IT-1.117	Outer	0.4139 ± 0.0085	9.73 ± 0.40	2233 ± 46	2409 ± 99	107.9	0.38
IT-1.118	Outer	0.3597 ± 0.0075	6.66 ± 0.29	1981 ± 41	2068 ± 90	104.4	0.19
IT-1.119	*Outer*	*0.2407 ± 0.0049*	*3.78 ± 0.16*	*1390 ± 28*	*1588 ± 66*	*114.2*	*0.18*
IT-1.120	*Outer*	*0.0345 ± 0.0020*	*0.412 ± 0.089*	*218 ± 13*	*350 ± 76*	*160.3*	*0.53*
IT-1.121	Outer	0.03841 ± 0.00093	0.276 ± 0.021	242.9 ± 5.9	247 ± 18	101.7	0.28

with the Tithonian (Yamada and Uemura, 2008). In this study, we reported that the lapilli tuff layer in the Upper Formation of the "Kuzuryu Subgroup" in the Mana area was presumably deposited at 124.6 ± 2.3 Ma (late Barremian–early Aptian; Fig. 8).

Revision of previous ideas of chronology and correlation

Correlation of the Tetori Group in the Mana and Itoshiro areas.—From the foregoing discussion, previous ideas of chronology and correlation of the Tetori Group in the Mana area (e.g., Yamada et al., 1989) need to be revised. The Middle Formation of the "Kuzuryu Subgroup" in the Mana area yields Tithonian ammonoid (Yamada and Uemura, 2008), though from a float, and the lapilli tuff layer in the Upper Formation of the "Kuzuryu Subgroup" has been dated to 124.6 ± 2.3 Ma (late Barremian–early Aptian). On the other hand, the Itoshiro Subgroup of the Itoshiro area covers the Oxfordian Yambarazaka Formation by the Umagatani Unconformity, and the Itsuki Formation, the youngest formation of the Itoshiro Subgroup, is most likely an Early Barremian formation as discussed above. Although the age of the Itoshiro Subgroup in the Itoshiro area has not precisely been constrained except for the Itsuki Formation, the "Kuzuryu Subgroup" in the Mana area is mostly correlated with the Itoshiro Subgroup in the Itoshiro area, and its uppermost part may be correlated with the Akaiwa Subgroup. There are other ideas that assume (1) that the Itsuki Formation is a Tithonian–Berriasian marine formation, (2) that there is a large time interval between the Itsuki and Nochino formations (e.g., Matsukawa et al., 2003, 2006), and (3) that the ammonoid-bearing Late Hauterivian–Early Barremian bed in the Uchinamigawa area (Goto, 2007) is correlated with the Amagodani Formation (equivalent to the Nochino Formation) in the Shokawa area but is never correlated with the Itsuki Formation (Matsukawa and Asahara, 2010). However, none of these ideas are consistent with our data and interpretation. The Itsuki Formation in the Itoshiro area and the ammonoid-bearing bed in the Uchinamigawa area can both be correlated with the Lower Barremian. Although the age of the Nochino Formation has not nicely been constrained, the conformable relationship between the Itsuki and Nochino formations (Maeda, 1961b), together with the new age data presented in this study, indicates that the time interval between the Itsuki and Nochino formations must be much shorter than Matsukawa et al. (2003, 2006) assumed.

TABLE 2. U-Pb isotopic data for zircons from lapilli tuff of the Upper Formation of the "Kuzuryu Subgroup" in the Mana area (sample 11110805).

Grain	$^{206}Pb/^{238}U$ (2σ)	$^{207}Pb/^{235}U$ (2σ)	$^{206}Pb/^{238}U$ age (2σ) in Ma	$^{207}Pb/^{235}U$ age (2σ) in Ma	Th/U
ML-1.1	0.01955 ± 0.00044	0.142 ± 0.014	124.8 ± 2.8	134 ± 13	1.03
ML-1.2	0.2511 ± 0.0038	5.30 ± 0.11	1444 ± 22	1868 ± 40	0.12
ML-1.3	0.3017 ± 0.0046	4.66 ± 0.10	1700 ± 26	1760 ± 40	0.58
ML-1.4	0.1341 ± 0.0021	2.036 ± 0.053	811 ± 13	1127 ± 29	0.48
ML-1.5	0.01946 ± 0.00039	0.134 ± 0.010	124.3 ± 2.5	127.4 ± 9.7	0.38
ML-1.6	0.02019 ± 0.00082	0.1381 ± 0.0094	128.9 ± 5.2	131.3 ± 8.9	0.75
ML-1.7	0.02044 ± 0.00082	0.159 ± 0.017	130.4 ± 5.2	150 ± 16	0.48
ML-1.8	0.02052 ± 0.00077	0.1603 ± 0.0088	131.0 ± 4.9	151.0 ± 8.3	0.30
ML-1.9	0.385 ± 0.014	7.30 ± 0.27	2100 ± 77	2149 ± 80	0.30
ML-1.10	0.410 ± 0.014	8.25 ± 0.29	2213 ± 76	2259 ± 80	0.40
ML-1.11	0.370 ± 0.013	6.03 ± 0.22	2031 ± 70	1980 ± 71	0.25
ML-1.12	0.417 ± 0.014	9.14 ± 0.32	2249 ± 77	2352 ± 83	0.31
ML-1.13	0.385 ± 0.013	7.66 ± 0.27	2100 ± 72	2192 ± 77	0.39
ML-1.14	0.433 ± 0.015	9.13 ± 0.32	2320 ± 79	2351 ± 83	0.28
ML-1.15	0.463 ± 0.016	10.51 ± 0.37	2451 ± 84	2481 ± 88	0.76
ML-1.16	0.331 ± 0.011	5.21 ± 0.18	1844 ± 63	1855 ± 66	0.15
ML-1.17	0.348 ± 0.012	5.51 ± 0.20	1923 ± 66	1902 ± 67	0.18
ML-1.18	0.3186 ± 0.0093	5.59 ± 0.19	1783 ± 52	1915 ± 64	0.58
ML-1.19	0.02833 ± 0.00083	0.2085 ± 0.0075	180.1 ± 5.3	192.3 ± 6.9	0.77
ML-1.20	0.0339 ± 0.0010	0.262 ± 0.010	214.9 ± 6.4	235.9 ± 9.2	0.75
ML-1.21	0.01999 ± 0.00065	0.173 ± 0.014	127.6 ± 4.2	162 ± 13	0.73
ML-1.22	0.389 ± 0.011	7.85 ± 0.26	2120 ± 62	2214 ± 74	0.69

Correlation of the Tetori Group in the Mana and Kamihambara areas.—The Kamihambara Formation in the Kamihambara area yields Tithonian ammonoid *Parapallasiceras* sp. cf. *P. pseudocontiguum*, the same ammonoid with that reported from a float of the Middle Formation of the "Kuzuryu Subgroup" in the Mana area (Sato and Yamada, 2005; Yamada and Uemura, 2008). If the Itsuki and Nochino formations of the Itoshiro area are correlated with the Itsuki and Nochino formations in the Kamihambara area, respectively, as Fujita (2002) proposed, the continuous succession of the "Kuzuryu Subgroup" in the Mana area can directly be correlated with the continuous succession from the Kamihambara Formation to the Itsuki (or Nochino) Formation in the Kamihambara area. However, the correlation of the Itoshiro Subgroup between the Itoshiro and Kamihambara areas needs further examination from the following reasons: (1) a marine bed correlative with the Kamihambara Formation has not been found in the Itoshiro area; (2) the sandstone and fossil samples that Fujita (2002) used as the basis for the correlation were mostly collected in the western part(Itoshiro side)of the Kamihambara area; and (3) a different interpretation of correlation was addressed by Yamada et al. (1989) who had colored the Ashidani, Kamihambara, Obuchi, and Itsuki formations in the Kamihambara area of Fujita (2002) as the Upper Formation of the Itoshiro Subgroup, i.e., the Itsuki Formation.

Geologic structure of the Tetori Group in the three areas studied.—From the discussion in the previous paragraphs, it is presumable that the Tetori Group in the Mana, Itoshiro, and Kamihambara areas all exhibit a northward-facing, Tithonian–Barremian (or earliest Aptian) succession. Although the Tetori Group in the Mana area is apparently overlain by the Tetori Group in the Itoshiro area, they contain coeval successions and must have been juxtaposed by faulting. Moreover, although the Tetori Group in the Kamihambara area has been assumed to extend to the Tetori Group in the Itoshiro area (e.g., Maeda, 1957; Fujita, 2002), there arises another possibility that the Tetori Group in the Kamihambara area laterally extends to the Tetori Group in the Mana area. In any case, further geological study of the blank area in the eastern part of Fig. 2 is necessary to clarify the geologic structure of the three areas.

Transgressive phases recorded in the Tetori Group and the Umagatani Unconformity.—Matsukawa et al. (2007) discriminated three phases of marine transgression from their study of the Tetori Group in the Shokawa and Hida-Furukawa areas (Fig. 1): (1) Bathonian–Oxfordian, (2) Tithonian–Berriasian, and (3) Hauterivian–Barremian. They further discuss that the Kamihambara and Itsuki formations are correlative formations deposited during the second (Tithonian–Berriasian) transgressive phase. The three transgressive phases can also be discriminated in four neighboring areas in Ono City, i.e., the Mana, Kamihambara, Itoshiro, and Uchinamigawa areas. Namely, the first transgressive phase corresponds to the age of sedimentation of the Kaizara and Yambarazaka formations of the Kuzuryu Subgroup in the Itoshiro area (Bathonian–Oxfordian), the second phase corresponds to the timing of sedimentation of the Kamihambara Formation in the Kamihambara area and the Middle Formation of the "Kuzuryu Subgroup" in the Mana area (Tithonian), and the third phase corresponds to the age of sedimentation of the uppermost part of the Itoshiro Subgroup (Itsuki Formation) in the Uchinamigawa and Itoshiro areas (Early Barremian). The Umagatani Unconformity at the base of the Itoshiro Subgroup in the Itoshiro area has been interpreted as a product of regression between the first and second transgressive phases as shown in Fig. 8 (e.g., Fujita, 2002). So far, however, the age of formation of the Umagatani Unconformity has not well been constrained. Considering the facts that the marine bed correlative with the Kamihambara Formation has not been found in the Itoshiro area, and that there is a significant time interval (> 15 m.y.) between the Kamihambara and Itsuki formations (Fig. 8), there arises another possibility that the Umagatani Unconformity was formed between the second and third transgressive phases and the Kamihambara Formation was eroded out in the Itoshiro area. With further geochronological studies, more precise age constraints (particularly Yambara Formation) and correlation of transgressive phases have potential to yield a greater understanding of the Tetori Group.

Provenance of clastic rocks of the Tetori Group in the study area

The analyzed samples in this study, the sandstone (sample 11042906) of the Itsuki Formation in the Itoshiro area and the lapilli tuff (sample 11110805) of the Upper Formation of the "Kuzuryu Subgroup", were both deposited in Barremian and/or earliest Aptian and contained many Archean to Paleoproterozoic zircons (84% in sample 11042906 and 60% in sample 11110805). The fact indicates that Archean to Paleoproterozoic rocks were widely exposed in the provenance of the Tetori Group in Barremian–earliest Aptian time. The exposure of Archean to Paleoproterozoic rocks around present-day Japanese Islands has been reported from northeast China and North Korea, in the northeastern part of the Eastern Block of the North China Craton, and from the Jiao–Liao–Ji Belt, the failed rift along the eastern margin of the Eastern Block (e.g., Zhao et al., 2005). The Archean to Paleoproterozoic rocks in these areas were most likely exposed in the provenance of the two samples. These areas were included in the 'Tetori-Type' floristic province in Late Jurassic to Early Cretaceous times (e.g., Kimura, 1987).

Another distinctive feature of the two investigated samples is that they include 240–170 Ma zircons. If we consider geological relationships between the Archean to Paleoproterozoic rocks mentioned above and the Tetori Group, we can find the 240–170 Ma granitoids in the Hida and Hida Gaien belts in Japan (Kunugiza and Kaneko, 2001) and 180–170 Ma granitoids in the Yeongnam Massif of South Korea (Sagong et al., 2005). These areas must also have constituted the provenance of the Tetori Group. This idea is consistent with that of Kim et al. (2007) who addressed that the quartz arenite clasts in the Yambara and Nochino formations were supplied from the Cambro–Ordovician formations in the east–central part of the present-day Korean Peninsula.

In the Korean Peninsula, 158–110 Ma magmatic hiatus (Sagong et al., 2005) has been known as a distinctive geotectonic event. Although we could not find 165–135 Ma zircons from the two samples, the 130–125 Ma zircons in the sandstone sample of the Itsuki Formation and the 125 Ma lapilli tuff of the Mana area suggest an igneous activity in the nearby provenance of the Tetori Group. Minor igneous activities have already been reported in East Asia: e.g., in the metamorphic core complexes on the north of Beijing and in Inner Mongolia, China (e.g., Davis et al., 1996, 2001), volcano-plutonic complex in Northeast Japan (e.g., Kanisawa, 1974), and the Early Cretaceous detrital zircons in the Early Cretaceous Shindong Group, South Korea (Lee et al., 2010). Early Cretaceous zircons and pyroclastic rocks in the Tetori Group may have been related to local contemporaneous igneous activities in East Asia.

CONCLUSIONS

We obtained LA-ICPMS U-Pb ages of detrital zircons from (1) a lapilli tuff sample of the Upper Formation of the "Kuzuryu Subgroup" of the Mana area and (2) a sandstone sample of the Itsuki Formation of the Itoshiro Subgroup in the Itoshiro area, Ono City, Fukui Prefecture, central Japan. The results of the study and their implications can be summarized as follows.

1. The youngest zircon from the sandstone of the Itsuki Formation was 127.2 ± 2.5 Ma (Barremian). Combining the results of previous paleontological studies, the Itsuki Formation must be correlated with the Lower Barremian. The lapilli tuff of the Upper Formation of the "Kuzuryu Subgroup" in the Mana area, on the other hand, was dated to 124.6 ± 2.3 Ma (late Barremian–early Aptian).
2. A Tithonian ammonoid reported from the Middle Formation of the "Kuzuryu Subgroup" in the Mana area (Sato and Yamada, 2005) indicates that the formation is correlated with the Kamihambara Formation of the Kamihambara area. The Barremian–earliest Aptian lapilli tuff of the Upper Formation of the "Kuzuryu Subgroup" dated in this study can be correlated with the Itsuki or Nochino Formation in

the Itoshiro area. The continuous succession of the Itoshiro Subgroup and Nochino Formation in the Itoshiro area was assumed to be correlated with the Itoshiro Subgroup and Nochino Formation in the Kamihambara area, although the Kamihambara Formation of the Itoshiro Subgroup is missing in the former area (Fujita, 2002). Further study is however needed to better constrain the age of the Itoshiro Subgroup and Nochino Formation.

3. Three phases of marine transgression can be discriminated from the Tetori Group in nearby four areas in Ono City, the Mana, Kamihambara, Itoshiro, and Uchinamigawa areas. They are (1) age of sedimentation of the Kaizara and Yambarazaka formations of the Kuzuryu Subgroup in the Itoshiro area (Bathonian–Oxfordian), (2) the age of sedimentation of the Kamihambara Formation in the Kamihambara area and the Middle Formation of the "Kuzuryu Subgroup" in the Mana area (Tithonian), and (3) the age of sedimentation of the uppermost part of the Itoshiro Subgroup (Itsuki Formation) in the Uchinamigawa and Itoshiro areas (Early Barremian).
4. Judging from the age distribution of detrital zircons in the two samples, the provenance of the Tetori Group in Barremian–Early Aptian time was likely (1) the northeastern part of the Eastern Block of the North China Craton where Archean–Paleoproterozoic rocks were widely exposed, and (2) Early Mesozoic volcano-plutonic province of the Hida and Hida Gaien Belt in Japan and the Yeongnam massif in South Korea.

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* : in Japanese with English abstract

**: in Japanese

＜　地名・地層名　＞

Akaiwa Subgroup ……… 赤岩亜層群
Amagodani Formation ……… アマゴ谷層
Ashidani Formation ……… 葦谷層
Fujikuradani Formation ……… 藤倉谷層
Fukui Prefecture ……… 福井県
Hakusan Region ……… 白山区
Hida Belt ……… 飛騨帯
Hida Gaien Belt ……… 飛騨外縁帯
Ise Metamorphic Rocks ……… 伊勢変成岩類
Itoshiro ……… 石徹白
Itoshiro Subgroup ……… 石徹白亜層群
Itoshirogawa River ……… 石徹白川
Itsuki Formation ……… 伊月層
Jinzu Region ……… 神通区
Kaizara Formation ……… 貝皿層
Kaizara Shale ……… 貝皿頁岩層
Kamihambara ……… 上半原
Kamihambara Formation ……… 上半原層
Konogidani Formation ……… 此木谷層
Kuzuryu Subgroup ……… 九頭竜亜層群
Kuzuryugawa River ……… 九頭竜川
Lake Manahimeko ……… 麻那姫湖
Mana ……… 真名
Managawa River ……… 真名川
Miyagawa River ……… 宮川
Monobegawa Group ……… 物部川層群
Motodo Formation ……… 本戸層
Nochino Formation ……… 後野層
Northern Chichibu Belt ……… 北部秩父帯
Obuchi Formation ……… 大淵層
Ono City ……… 大野市
Otani Formation ……… 大谷層
Ryoseki Formation ……… 領石層
Shibasudani Formation ……… 子馬巣谷層
Shikoku Island ……… 四国
Shogawa River ……… 庄川
Shokawa ……… 荘川
Takaharagawa River ……… 高原川
Tandoguchi Gneiss ……… 谷戸口片麻岩
Tatsukawa ……… 立川
Tedorigawa River ……… 手取川
Tetori Group ……… 手取層群
Tochimochiyama Formation ……… 栃餅山層
Uchinamigawa ……… 打波川
Umagatani ……… 馬ヶ谷
Yambara Formation ……… 山原層
Yambarazaka Formation ……… 山原坂層