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EXPRESS LETTER

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Two pulse intrusive events of the Pliocene Tanigawa-dake granites revealed from zircon U–Pb dating

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Abstract

We performed zircon U–Pb dating on the Pliocene Tanigawa-dake granites (Makihata and Tanigawa bodies) and the Cretaceous Minakami quartzdiorite, Northeast Japan Arc. Concordia ages were estimated to be 3.95 ± 0.11 Ma (± 2 sigma) for the Makihata body, 3.18 ± 0.13 Ma and 3.32 ± 0.15 Ma for the Tanigawa body, and 109.4 ± 2.2 Ma for the Minakami quartzdiorite. The Minakami quartzdiorite is possibly correlated to the bedrock in the Ashio belt because the age of the Minakami quartzdiorite is consistent with the zircon U–Pb ages of the earliest Tadamigawa granites (107–62 Ma) which are distributed to the northeast of the Tanigawa-dake region and belong to the Ashio belt. All the zircon U–Pb ages of the Tanigawa-dake granites are older than the previously reported cooling ages, i.e., K–Ar ages and zircon fission-track ages, being consistent with their difference in closure temperature. On the basis of these results, we concluded that the intrusive ages of the Tanigawa-dake granites are ~ 4–3 Ma, which are among the youngest exposed plutons on Earth. The U–Pb ages of the Makihata body and the Tanigawa body are different significantly in the 2 sigma error range. Thus, the Tanigawa body intruded later than the Makihata body by ~ 0.7 Myr.

Keywords: Pliocene granites, Tanigawa-dake granites, Minakami quartzdiorite, Zircon U–Pb dating

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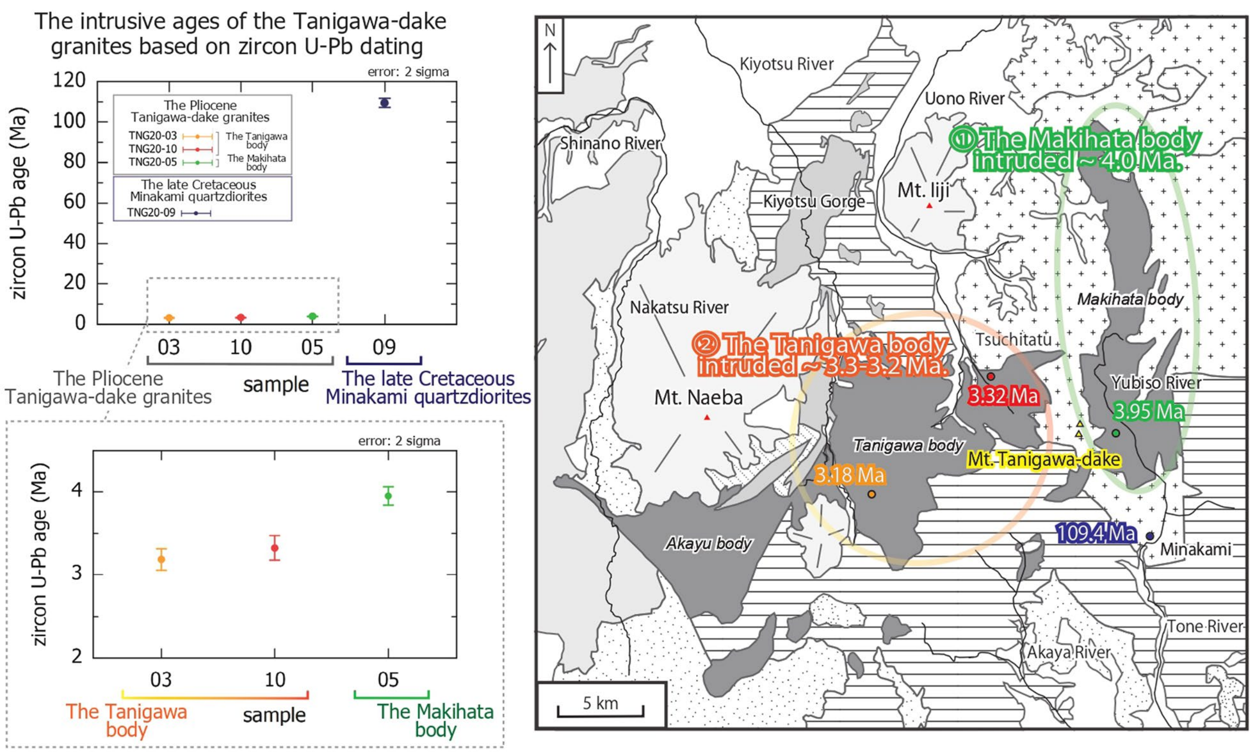
Graphical Abstract



Introduction

Granites are formed generally at a crustal depth of a few to dozen kilometers. Therefore, the regions where young granites are exposed must have been uplifted and denuded at an extraordinary high rate. Granites younger than ~ 5 Ma have been discovered basically along convergent plate boundaries (Harayama 1992). In the Japanese Islands, such young granites have been reported along arc–arc junctions in central Japan based on zircon U–Pb dating, e.g., 10–0.8 Ma in the Hida range, Northern Japan Alps (Ito et al. 2013) and ~ 4 Ma in the Tanzawa mountains, Izu collision zone (Tani et al. 2010). The Tanigawa-dake region, southern end of the Northeast Japan Arc, can also involve young granites (Sato 2016) considering the young cooling ages (Ganzawa and Kubota 1987; Kawano et al. 1992; Ohira and Honda 1999; Kubo et al. 2013; Sato 2016) although this region is located away from the arc–arc junctions. For instance, Rb–Sr age of whole rock is estimated to be 5.27 ± 1.28 Ma representing formation age of the granite (Ohira et al. 1998; Ohira and Honda 1999). Biotite K–Ar ages are 3.9–3.1 Ma (Kawano et al. 1992; Sato 2016), whose closure temperature is 350–400 °C (Harrison et al. 1985; Grove and Harrison 1996). Zircon fission-track ages are 3.3–2.9 Ma (Ohira and Honda 1999), whose closure temperature is 250–350 °C (Yamada et al. 2007; Ketcham 2019). However, the previous studies have two problems to estimate the intrusive age: (1) Rb–Sr age was obtained only from a single locality and has a large error, and (2) biotite K–Ar ages and zircon fission-track ages are cooling ages, probably younger than the intrusive ages. Thus, this study aims to estimate the reliable intrusive ages. We collected samples from the intrusive bodies and applied zircon U–Pb dating, as well as the late Cretaceous granites intruded by the young plutons.

Geology and sampling

The Tanigawa-dake area is located on the back-arc side of the Northeast Japan Arc. Mt. Tanigawa-dake (1977 m high) is a non-volcanic mountain surrounded by Quaternary volcanoes, such as, Mt. Naeba, Mt. Iiji and Mt. Hotaka (Fig. 1). Coastal areas of the Sea of Japan, including the Tanigawa-dake area, is one of the heaviest snow areas in the world (e.g., Ueda et al. 2015). In addition, glacial landforms formed at the last glacial period are distributed in the Tanigawa-dake and adjacent mountains

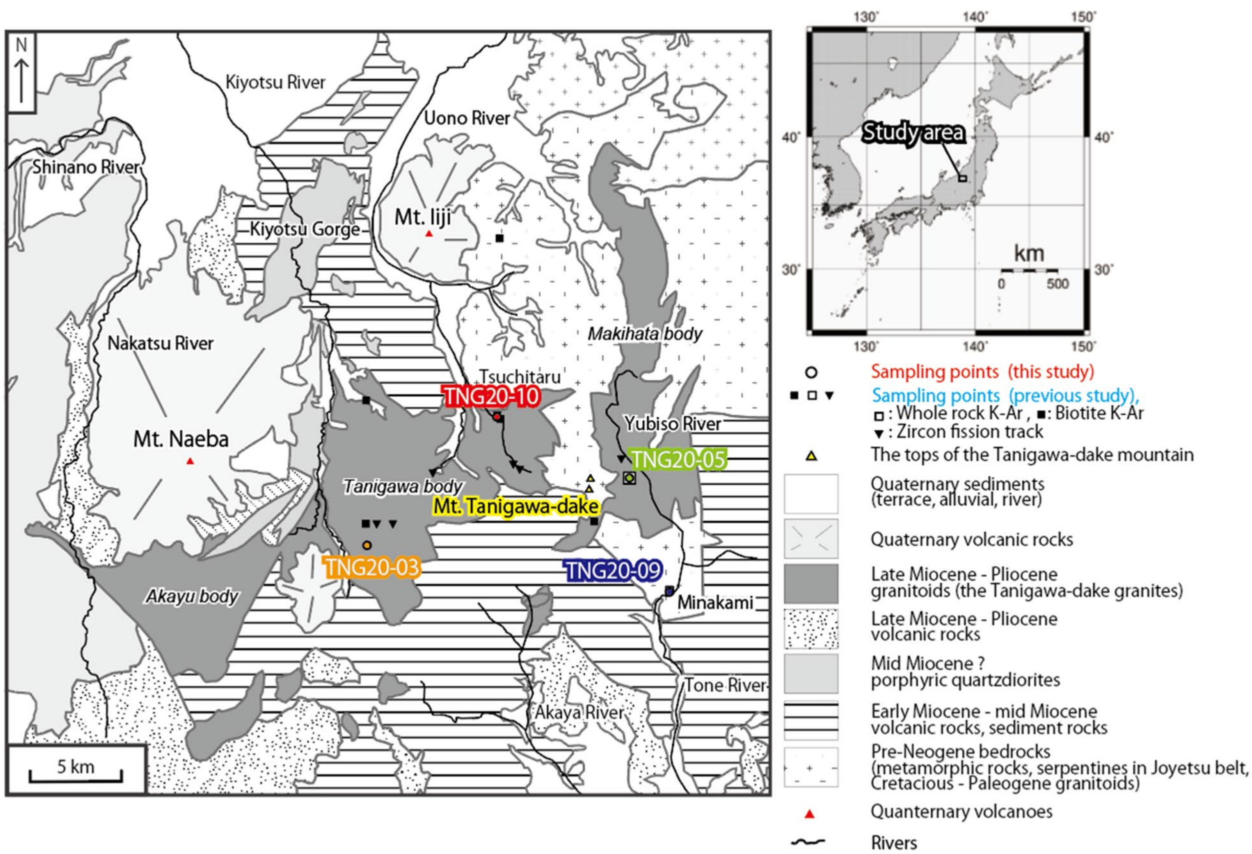


Fig. 1 Index map of the study area. The geologic map was modified from Sato (2016) and Geological Survey of Japan web page (https://gbank.gsj.jp/geonavi/geonavi.php#11,36.83525,138.87626). Circle points denote sampling localities. Colored circles denote sampling localities in this study. Sampling sites of the previous studies are shown by the following symbols. Filled square: K–Ar ages of biotite (Kawano et al. 1992; Sato 2016; Shibata et al. 1984), open squares: K–Ar ages of whole rock (Kubo et al. 2013), filled inverted triangles: fission-track ages of zircon (Ohira et al. 1998; Ohira and Honda 1999). Note that the sites of TNG20-10 indicated by a red circle overlap the localities of zircon fission-track and biotite K–Ar ages of the previous researches (Kawano et al. 1992; Ohira et al. 1998; Ohira and Honda 1999; Sato 2016). Similarly, the site of TNG20-09 shown by a navy circle overlap the locality of K–Ar age of the whole rock (Kubo et al. 2013)

(Koaze 2002). Therefore, although the uplift mechanism is not well-known, the Tanigawa-dake region is expected to be denuded rapidly enough to expose the Pliocene plutons.

Lithology of the Tanigawa-dake area consists mainly of Cretaceous to Paleogene granitoids, late Miocene to Pliocene granitoids, and Miocene to Quaternary volcanic rocks (Sato 2016: Fig. 1). The late Miocene to Pliocene granites are called the Tanigawa-dake granites, being subdivided into three bodies, i.e., the Makihata body, the Tanigawa body, and the Akayu body, from east to west (Chihara et al. 1981). The Makihata body and the Tanigawa body are exposed on the eastern and western sides of Mt. Tanigawa-dake, respectively. The Akayu body is distributed on the southern side of Mt. Naeba. The late Cretaceous plutonic rock is called the Minakami quartzdiorite (Kubo et al. 2013; Sato 2016) which is distributed to the southeast of Mt. Tanigawa-dake. In the previous studies, these rocks were dated based on fission-track dating of zircon and apatite, K–Ar dating of biotite and whole rock, and Rb–Sr dating of whole rock. The biotite K–Ar (3.9–3.1 Ma; Kawano et al 1992; Sato, 2016) and zircon fission-track ages (3.3–2.9 Ma; Ohira et al. 1998; Ohira and Honda 1999) are consistent with each other within error range of 2 sigma regardless of location. Therefore, cooling ages of the Tanigawa-dake granites were spatially uniformed at ~ 250–400 °C. However, thermal histories above the temperature range were not well-known, including the timing of the intrusion of the Tanigawa-dake granites. In this study, for obtaining clearly intrusive ages of the Tanigawa-dake granites and intruded granites, we collected 4 rock samples: TNG20-03 and TNG20-10 from the Tanigawa body, TNG20-05 from the Makihata

Table 1 Summary of dating results

Body name	Sample	Lithology	Locality		U–Pb ages (Ma)		Number of grains
			Longitude	Latitude	Concordia Age	± 2 sigma	
Tanigawa	TNG20-03	Granodiorite	138°47′39.93"E	36°48′28.31"N	3.18	0.13	29
Makihata	TNG20-05	Porphyritic granites	138°57′7.45"E	36°50′27.19"N	3.95	0.11	30
Minakami	TNG20-09	Quartzdiorite	138°58′34.44"E	36°47′6.50"N	109.4	2.2	29
Tanigawa	TNG20-10	Granodiorite	138°52′16.74"E	36°52′5.04"N	3.32	0.15	20
	OD-3-A				33.4	2.8	4
	OD-3-B				33.1	1.8	6
	OD-3-C				32.9	2.1	3
	OD-3-D				32.0	2.0	3

The reference age of OD-3 is 33.0 ± 0.1 Ma (± 2 sigma) (Iwano et al. 2013)

body, and TNG20-09 from the Minakami quartzdiorite (Fig. 1, Table 1).

U–Pb zircon dating method

Zircon grains were separated from the granitoid samples by crushing, sieving, panning, magnetic separation and heavy liquid techniques. The zircon grains were mounted in resin (SpeciFix, Struers ApS, Denmark) and then used for cathodoluminescence (CL) observation and U–Pb isotopic analysis using field-emission electron probe microanalyzer (FE-EPMA, JEOL JXA-8530F) and multiple collector inductively coupled plasma mass spectrometer (Neptune-*Plus*, Thermo Fisher Scientific, Bremen, Germany) with an excimer laser system (Analyte G2; Photon Machines, Redmond, WA, USA) (LA-MC-ICP-MS), respectively, at Tono Geoscience Center, JAEA. Elemental fractionation and instrumental mass bias on $^{206}Pb/^{238}U$, $^{207}Pb/^{206}Pb$ ratios were corrected using the measured isotope ratio of the 91,500 zircon (Wiedenbeck et al. 1995) as primary standard with a standard-sample bracketing approach. The OD-3 zircon (Iwano et al., 2013) was used as secondary standard material for age quality control. The details of analytical setting are summarized in Additional file 1: Table S1. The analytical spots of unknowns were determined based on the growth structures of zircons observed by CL images (Fig. 2); the structures show oscillatory zoning patterns (e.g., 1-TNG20-05–01, 1-TNG20-09–04) or homogeneous textures (e.g., 1-TNG20-03–13, TNG20-10–08). The zircon grains were measured for each of the 4 samples, and the results are summarized in Table 1 (for the details, see also Additional file 2: Table S2). In this paper, the data were defined as 'concordant' when overlapping the concordia curve on a concordia diagram within error range of 1sigma. Isoplot software ver. 4.15 (Ludwig 2012) was used to produce the concordia diagrams and the concordia ages (2 sigma-weighted mean age of $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ isotopes; Ludwig, 1998) using the 'concordant' data (Fig. 2).

Results and geo-/thermo-chronologic interpretation

Summaries of the dating results are shown in Table 1 and Fig. 2; uncertainties of the ages indicate 2 sigma. Zircon U–Pb ages of OD-3 (secondary standard) were computed to be 33.4 ± 2.8 Ma, 33.1 ± 1.8 Ma, 32.9 ± 2.1 Ma, 32.0 ± 2.0 Ma. These ages are consistent with the reference age (33.0 ± 0.1 Ma, 2 sigma; Iwano et al. 2013) within the 2 sigma error range.

The concordia ages were calculated from 30 zircon grains for TNG20-05, 29 zircon grains for TNG20-03 and TNG20-09, and 20 zircon grains for TNG20-10. One discordant grain was identified in TNG20-03 and TNG20-09, respectively, which was removed from the concordia age calculation. Consequently, the concordia ages were calculated to be 3.18 ± 0.13 Ma for TNG20-03, 3.95 ± 0.11 Ma for TNG20-05, 3.32 ± 0.15 Ma for TNG20-10 and 109.4 ± 2.2 Ma for TNG20-09.

The zircon U–Pb ages obtained in this study were compared with the reported cooling ages, i.e., K–Ar ages of biotite and fission-track ages of zircon. The comparison did not include the Rb–Sr age of whole rock and K–Ar age of whole rock because the sampling point of Rb–Sr age is unknown and the closure temperature of the two dating methods cannot be defined. The reported ages of the Tanigawa-dake granites are 3.9–3.1 Ma based on biotite K–Ar dating (Kawano et al. 1992; Sato 2016) and 3.3–2.9 Ma based on zircon fission-track dating (Ohira et al. 1998). The obtained zircon U–Pb ages are consistent with the reported ages given the higher closure temperature (> 900°C; Cherniak and Watson 2000). Namely, zircon U–Pb ages are coincident with or older than the reported ages close to each sampling locality within the error range of 2 sigma.

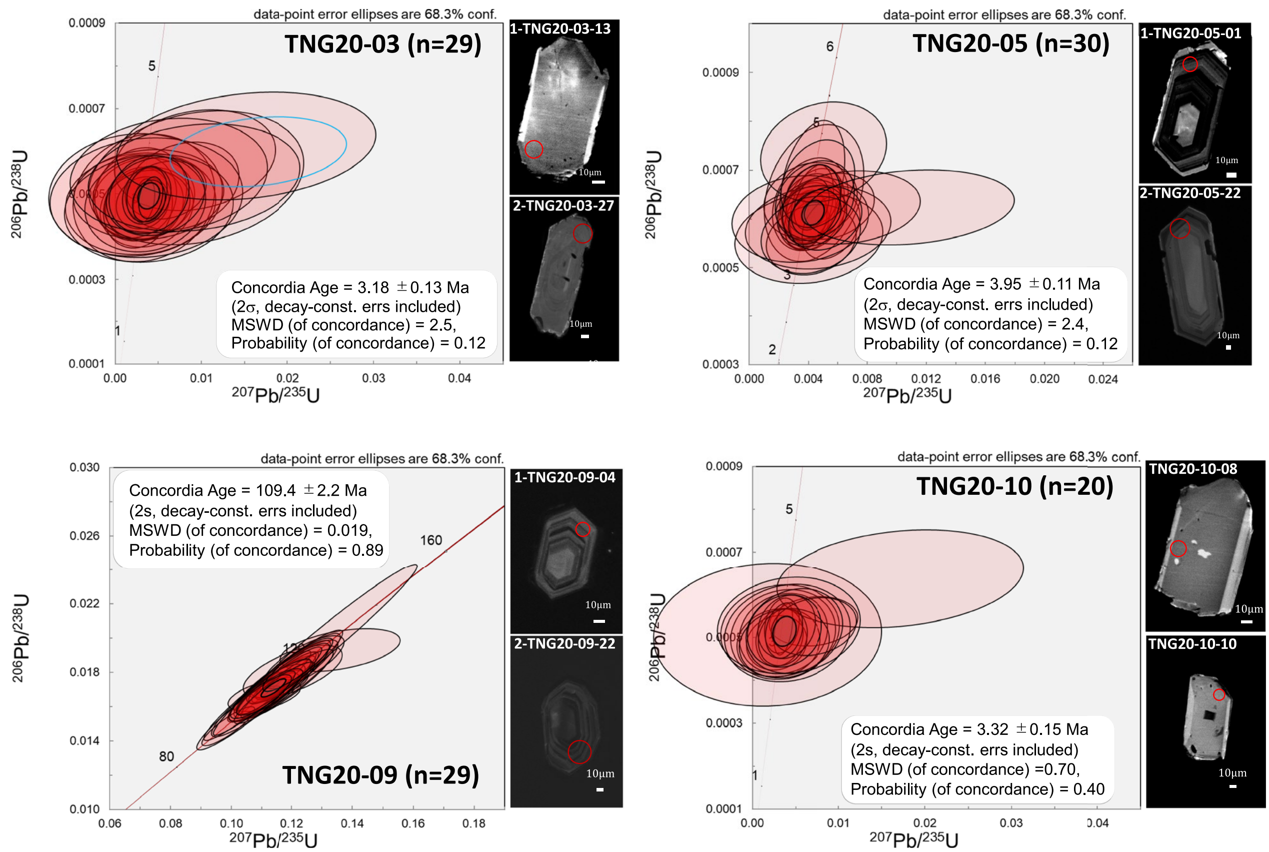


Fig. 2 The concordia diagrams and the cathodoluminescence images. The diagrams were drawn by using Isoplot 4.15 (Ludwig 2012). In the concordia diagrams, red solid circles indicate concordant dates and blue open circles mean discordant dates within the error range of 1 sigma. The heavy line circles are the concordia ages with 2 sigma errors, calculated from the concordant data. The discordant data of TNG20-09 are not displayed because it is away from the concordant curve. The red open circles in the CL images signify the analytical spots

For the Minakami quartzdiorite, the K–Ar age of whole rock was estimated at ~ 70 Ma (Kubo et al. 2013), which is the only geochronologic datum reported previously. The zircon U–Pb age is older than the K–Ar age of whole rock by 40 Myr.

Geological implication

Based on the zircon U–Pb age of TNG20-09, the Minakami quartzdiorite might be correlated with the Tadamigawa granites. The Tadamigawa granites are located to the northeast of Mt. Tanigawa-dake, belonging to the Ashio belt. The Minakami quartzdiorite age is consistent with the oldest zircon U–Pb age of the Tadamigawa granites (106.7 ± 0.6 Ma; 95% confidence interval: Wakasugi et al. 2020) within the error range of 2 sigma. As a result, the igneous activity to form the Minakami quartzdiorite is compared to the first igneous event to form the Tadamigawa granites. Namely, the Minakami quartzdiorite can be an associated body as the bedrock distributed in Ashio belt.

According to zircon U–Pb ages of TNG20-03, TNG20-05 and TNG20-10, the Tanigawa body is considered to have intruded after the Makihata body. The intrusion age for the Tanigawa body was estimated to ~ 3.3–3.2 Ma because the zircon U–Pb ages of TNG20-03 and TNG20-10 in the Tanigawa body are consistent within error range of 2 sigma. On the other hand, zircon U–Pb age of the Makihata body, TNG20-05, is significantly older than those of the Tanigawa body with error range of 2 sigma. Therefore, the Tanigawa body could have intruded 0.7 Myr later than the Makihata body. The Tanigawa-dake granites were estimated to be formed by at least two magmatism.

On the other hand, the previously reported cooling ages, i.e., biotite K–Ar ages and zircon fission-track ages, are not significantly different for Makihata and Tanigawa bodies despite the different intrusive ages. The two possible reasons follow below: (1) the biotite K–Ar and zircon fission-track ages of the Makihata body were reset by the thermal effect of the intrusion of the Tanigawa body, and (2) the Makihata body was more slowly cooled than the Tanigawa body from the intrusion to ~ 250–400ºC. In either case, the Tanigawa body and the Makihata body might have experienced different cooling histories above ~ 400 °C.

Conclusion

To determine the intrusive ages, a sequence of zircon U–Pb dating was performed for the Pliocene granites at 3 localities and late Cretaceous quartzdiorite at 1 locality in the Tanigawa-dake area. The ages of the Tanigawa body are 3.18 ± 0.13 Ma for TNG20-03 and 3.32 ± 0.15 Ma for TNG20-10, the age of the Makihata body is 3.95 ± 0.11 Ma for TNG20-05, and the age of the Minakami quartzdiorite is 109.4 ± 2.2 Ma for TNG20-09. From these results, the age of the Minakami quartzdiorite is considered to correspond to the Tadamigawa granite, bedrock of the Ashio belts. Additionally, the Makihata body intruded earlier than the Tanigawa body by 0.7 Myr. Thus, the Tanigawa-dake granites are estimated to be formed by at least two times of magmatism, being among the youngest plutons exposed on Earth.

Abbreviations

JAEA: Japan Atomic Energy Agency; FE-EPMA: Field-emission electron probe microanalyzer; LA-MC-ICP-MS: Laser ablation-multiple collector inductivity coupled plasma Mass spectrometry; CL: Cathodoluminescence.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40623-021-01556-4.

Additional file 1: Table S1. Analytical setting for zircon U–Pb dating.

Additional file 2: Table S2. Zircon U–Pb isotope data in this study.

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Authors' contributions

SM drafted the most of the manuscript, and MN drafted the section of "Dating method". SM, SS, and TT are responsible for the project, conducting research planning, sampling, and data interpretation. SF, YK and YO carried out planning and sampling. MN, SK, YO and TY performed the U–Pb isotopic analyses with SM and assisted in drafting the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The data for this paper are presented in the tables and supplementary information.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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References

Cherniak DJ, Watson EB (2000) Pb diffusion in zircon. Chem Geol 172:5–24. https://doi.org/10.1016/S0009-2541(00)00233-3

Chihara K, Komatsu M, Shimazu M, Kubota Y, Shiokawa S (1981) Geology of Echigo Yuzawa Distinct, Quadrangle Series, Scale 1:50,000, Geological Survey of Japan, 108 pp.

Ganzawa Y, Kubota Y (1987) Geological setting of Tanigawa-quartz diorite and its cooling history. Abst 94th Annu Meet Geol Soc Jpn. https://doi.org/10.14863/geosocabst.1987.0_194

Grove M, Harrison TM (1996) ^{40}Ar* diffusion in Fe-rich biotite. Am Miner 81:940–951. https://doi.org/10.2138/am-1996-7-816

Harayama S (1992) Youngest exposed granitoid pluton on earth: cooling and rapid uplift of the Pliocene-Quaternary Takidani Granodiorite in the Japan Alps, central Japan. Geology 20:657–660. https://doi.org/10.1130/0091-7613(1992)020%3c0657:YEGPOE%3e2.3.CO;2

Harrison TM, Duncan IAN, Mcdougall IAN (1985) Diffusion of ^{40}Ar in biotite: temperature, pressure and compositional effects. Geochim Cosmochim Acta 49:2461–2468. https://doi.org/10.1016/0016-7037(85)90246-7

Ito H, Yamada R, Tamura A, Arai S, Horie K, Honda T (2013) Earth's youngest expose granite and its tectonic implications; the 10–0.8 Ma Kurobegawa Granite. Sci Rep 3:1306. https://doi.org/10.1038/srep01306

Iwano H, Orihashi Y, Iwata T, Ogasawara M, Danhara T, Horie K, Hasebe N, Sueoka S, Tamura A, Hayasaka Y, Katube A, Ito H, Tani K, Kimura J, Chang Q, Kouchi Y, Haruta Y, Yamamoto K (2013) An inter-laboratory evaluation of OD-3 zircon for use as a secondary U-Pb dating standard. Island Arc 22:382–394. https://doi.org/10.1111/iar.12038

Kawano Y, Shibata K, Uchiumi S, Ohira H (1992) K-Ar age of the Tanigawadake Pliocene plutonic body, North Fossa Magna, central Japan. J Mineral Petrol Econ Geol (ganko) 87:221–225. https://doi.org/10.2465/ganko.87.221

Ketcham RA (2019) Fission-track annealing: from geologic observations to thermal history modeling. In: Malusà M, Fitzgerald P (eds) Fission-track thermochronology and its application to geology. Springer textbooks in earth sciences, geography and environment. Springer, Cham, pp 49–75 (**10.1007/978-3-319-89421-8_3**)

Koaze T (2002) Study of the Echigo mountains, central Japan. Meiji Univ Inst Human Bull 50:163–175

Kubo S, Nakazima K, Murayama A, Suzuki Y (2013) Geology of the Southeast foot of Mt. Tanigawa and K-Ar ages of Minakami granodiorite and Machigasawa granite porphyry. Bull Gunma Mus Nat Hist 17:119–130

Ludwig KR (1998) On the treatment of concordant uranium-lead ages. Geochim Cosmochim Acta 62:665–676. https://doi.org/10.1016/S0016-7037(98)00059-3

Ludwig KR (2012) Isoplot 3.75: A geochronological toolkit for Microsoft Excel, Spec. Publ., no. 5, Berkeley Geochronology Center, Berkeley, California, 75p.

Ohira H, Honda T (1999) Fission track age Th/U abundance ratio of zircon from the Tanigawadake Pluton, North Fossa Magna, Central Japan. Fission Track News Lett 12:61–63

Ohira H, Kondo K, Izumi S, Kawano Y (1998) Fission Track and Rb-Sr whole rock age of the Tanigawadake Pluton, North Fossa Magna, Central Japan. Abst 105th Annu Meet Geol Soc Jpn. https://doi.org/10.14863/geosocabst.1998.0_044

Sato K (2016) Age of the Tanigawa-dake granitoid pluton and its relevance to the Neogene felsic magmatism in the Fossa Magna region, an island-arc junction, central Japan. Bull Gunma Mus Nat His 20:85–104

Shibata K, Uchiumi S, Uto K, Nakagawa T (1984) K-Ar age results—2—new data from the Geological Survey of Japan. Bull Geol Surv Japan 35:331–340

Tani K, Dunkley JD, Kimura J, Wysoczanski JR, Yamada K, Tatsumi Y (2010) Syncollisional rapid granitic magma formation in an arc-arc collision zone: evidence from the Tanzawa plutonic complex, Japan. Geology 38:215–218. https://doi.org/10.1130/G30526.1

Ueda H, Kibe A, Saitoh M, Inoue T (2015) Snowfall variations in Japan and its linkage with tropical forcing. Int J Climatol 35:991–998. https://doi.org/10.1002/joc.4032

Wakasugi Y, Wakaki S, Tanioka Y, Ichino K, Tsuboi M, Asahara Y, Noda A (2020) A chronological and geochemical study of the Tadamigawa older-stage granites: Igneous activity in the west of the Tanakura Tectonic Line (TTL) of northeastern Japan. Geochem J 54:203–220. https://doi.org/10.2343/geochemj.2.0603

Wiedenbeck M, Alle P, Corfu FY, Griffin WL, Meier M, Oberli F, Von Quadt A, Roddick JC, Spiegel W (1995) Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. Geostandards Newslett 19(1):1–23. https://doi.org/10.1111/j.1751-908X.1995.tb00147.x

Yamada R, Murakami M, Tagami T (2007) Statistical modelling of annealing kinetics of fission tracks in zircon; Reassessment of laboratory experiments. Chem Geol 236:75–91. https://doi.org/10.1016/j.chemgeo.2006.09.002

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