Document 1 Procedures from zircon separation to U–Pb dating.

Zircon separation from the tuff sample (IS2) was performed at the University of Toyama. The sample was crushed into granule- to silt-sized fragments and sieved through a disposable 350 μm mesh cloth. We then separated zircon grains from the 500 g of rock powder using panning, magnetic separation, and heavy liquid (methylene iodide) techniques. We randomly selected 32 zircon grains on a glass slide under a microscope, embedded them in acrylic resin, and polished them until the surfaces of the zircon grains were exposed. We then captured transmission and reflection images of the polished zircon grains to confirm the locations of cracks and inclusions in each grain. Most of the extracted zircon grains were euhedral, colorless, and transparent. Euhedral zircon grains had an aspect ratio of 2.

We captured cathodoluminescence (CL) images of the polished zircon grains using the scanning electron microscope (JSM-IT500HR; JEOL) connected to a CL detector (ChromaCL2; Gatan) installed at the Fukui Prefectural Dinosaur Museum. Most of the zircon grains observed in the CL images exhibited oscillatory zoning (Fig. A4b). Using these images, we selected areas of oscillatory zoning with no inclusions or cracks for measurement.

Isotopic analysis of zircon grains was performed using an inductively coupled plasma mass spectrometer (ICPMS; Agilent 7700x, Agilent Technologies) with an Nd-YAG laser system (LA; NWR-213; ESI) at the Graduate School of Environmental Studies, Nagoya University. The analytical conditions of LA-ICPMS and calculation methods for U–Pb dates were based on Orihashi et al. (2008) and Kouchi et al. (2015). The analytical settings and conditions are summarized in Table A1. The primary standard material was SRM 610 glass (recommended $^{206}Pb/^{238}U$ ratio = 0.2236; Horn and von Blanckenburg, 2007) normalized to 91500 zircon (Wiedenbeck et al., 1995) in the $^{206}Pb/^{238}U$ ratio. 91500 ($^{206}Pb/^{238}U$ recommended date = 1062.4 ± 0.8 Ma; Wiedenbeck et al., 1995) and OD-3 ($^{206}Pb/^{238}U$ recommended date = 33.0 ± 0.1 Ma; Iwano et al., 2013) zircons were used to confirm the isotopic correction. We acquired the data in sequences of 28 analyses, consisting of analyses of 5 spots for the gas blank, 4 spots for NIST SRM 610, 1 spot for 91500, 1 spot for OD-3, 8 spots for IS2, 4 spots for NIST SRM 610, and 5 spots for the gas blank. The standard deviation (2SD) of each measurement was calculated by multiplying the date value by the 2SD of the repeated measurements of NIST SRM 610 and the error propagation of each isotopic ratio of NIST SRM 610 (e.g., Nagata et al., 2020). The weighted mean $^{206}Pb/^{238}U$ dates of the 91500 and OD-3 zircons during the measurement of zircons from sample IS2 were 1051 ± 17 Ma (2σ; MSWD: 0.45; Probability: 0.72) and 32.7 ± 1.1 Ma (2σ; MSWD: 1.7; Probability: 0.16), respectively (Tables A1, A2). The error (uncertainty) range of these dates included the recommended dates from previous studies (Wiedenbeck et al., 1995; Iwano et al., 2013). Data was plotted on the Wetherill Concordia diagram (Wetherill, 1956) as an error ellipse using $^{207}Pb/^{206}Pb$, $^{207}Pb/^{235}U$, and $^{206}Pb/^{238}U$ ratios and their uncertainties (2SD). We defined the data with the error ellipse overlapping the Concordia curve as concordant (e.g., Matsui et al., 2018). The zircon dates obtained in this study correspond to the Phanerozoic (< ca. 538 Ma; Cohen et al., 2023). Hence, we used the $^{206}Pb/^{238}U$ date of each zircon grain, which is more precise than the $^{207}Pb/^{206}Pb$ and $^{207}Pb/^{235}U$ dates for a Phanerozoic zircon sample.

Igneous and pyroclastic rocks often include zircon grains that are older than their formational or depositional ages (e.g., Tsutsumi et al., 2017; Nagata et al., 2018; Miyata et al., 2020; Nagata and Otoh, 2021). Thus, various methods have been used to determine the dates of igneous or pyroclastic rocks using zircon U–Pb dates. A typical example is using the Isoplot unmix ages routine to calculate the age of the youngest peak in the probability density plot or the youngest cluster age (Ludwig et al., 2012). However, the former has no clear discrimination criteria for excluding antecrysts and exotic crystals. Meanwhile, the latter has reproducibility problems (e.g., Takeuchi et al., 2017; Nagata et al., 2019; Miyata et al., 2020).

In this study, we defined the date of sample IS2 as the weighted average of $^{206}Pb/^{238}U$ dates from the youngest date cluster, consisting of the youngest $^{206}Pb/^{238}U$ date and other $^{206}Pb/^{238}U$ dates with an error (2SD) range overlapping with that of the youngest $^{206}Pb/^{238}U$ date (Nagata et al., 2018). Zircon grains older than those forming the youngest date cluster were interpreted as exotic, following Nagata and Otoh (2021).