

LETTER

Zircon U-Pb ages of Cretaceous intrusive rocks in Central Yamaguchi, Southwest Japan: Implications for an enriched mantle source during a magmatic flare-up

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Zircon U-Pb dating was conducted on granite, granodiorite, and gabbro from the central part of Yamaguchi Prefecture, Southwest Japan. The granodiorite and gabbro are recognized as components of the Susuma-Nagaho Plutonic Complex (SNPC). The zircon U-Pb dating yielded ages of 103 Ma for the granite and 92 Ma for the granodiorite and gabbro. These ages coincide with the magmatic flare-up event documented in Southwest Japan. A compiled dataset of Cretaceous gabbro-diorite from Southwest Japan shows that initial- ϵ Nd values (ϵ Nd I) decrease progressively to as low as -5.1 between 107 and 90 Ma. In addition, Th/La ratios exhibit a negative correlation with initial-Nd isotopic ratios. These geochemical trends, together with their temporal variation, suggest that subducted sediments increasingly interacted with the mantle wedge, producing progressively enriched mantle sources throughout the Cretaceous. This secular change may reflect variations in plate motion, such as change in the rate of subduction.

Keywords: Cretaceous flare-up event, Enriched mantle, Gabbro-diorite, Susuma-Nagaho Plutonic Complex, Southwest Japan

INTRODUCTION

Voluminous igneous activity in active continental margin typically occurs in episodic cycles characterized by intervals of anomalously high magma production followed by relatively quiescent periods. These contrasting episodes are referred to as flare-ups and lulls, respectively (Ducea et al., 2015). Such magmatic cyclicity is thought to reflect variations in angle, direction, and rate of subduction, and wedge mantle characteristics showing both enriched and depleted isotopic compositions during the flare-up events (e.g., Takagi, 2004; Imaoka et al., 2014; Chapman et al., 2021; Kawaguchi et al., 2023). Cretaceous to Paleocene granitoid intrusions and volcanic rocks are widely distrib-

uted in Southwest Japan (Nakajima et al., 2016). Recent zircon U-Pb dating has refined the chronology of magmatism, demonstrating that a major Early Cretaceous flare-up event occurred between 120 and 90 Ma (Yamaoka and Wallis, 2023). Most of igneous activity in the western part of Chugoku district is attributed to this interval. Although abundant U-Pb ages have been obtained for granitic rocks, direct zircon U-Pb constraints on mafic to intermediate lithologies such as gabbro and diorite remain limited.

The Susuma-Nagaho Plutonic Complex (SNPC), located in the central part of Yamaguchi Prefecture, western Chugoku, consists mainly of granodiorite with a minor gabbroic stock (Fig. 1; Kodama et al., 2019, 2022). Some gabbro samples exhibit relatively primitive compositions

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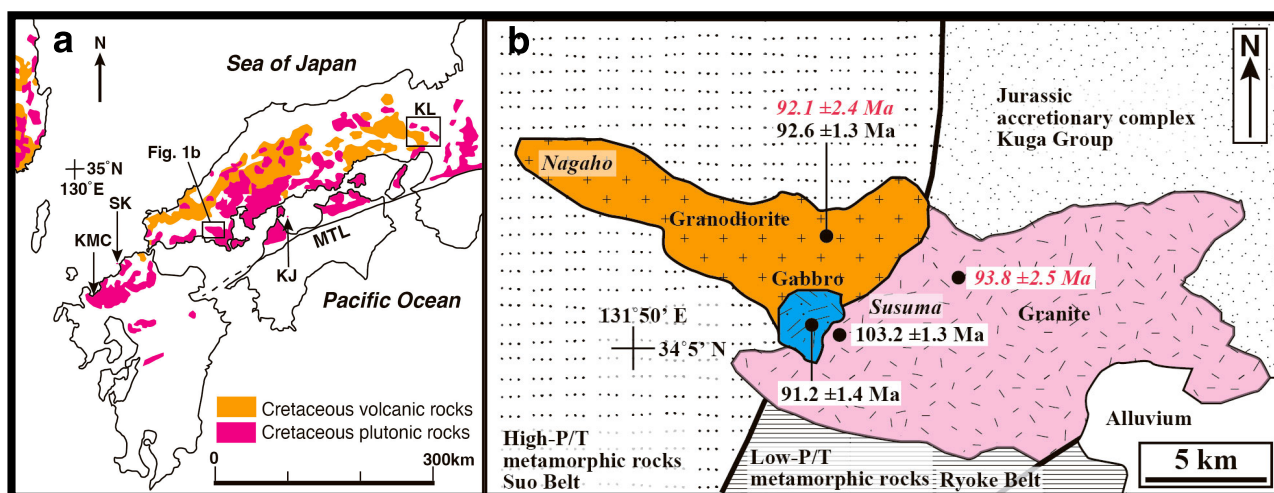


Figure 1. Simplified geological map of Southwest Japan (a) and study area (b) (Kodama et al., 2019, 2022). The sampling sites of zircon U-Pb analyses with their ages are marked on the map. The biotite K-Ar ages are also shown in red-italic numbers. The geology of surrounded basement rocks is quoted from Nishimura et al. (2012). KL, Kyoto lamprophyre; KJ, Kajishima gabbro; SK, Shikanoshima gabbro-diorite; KMC, Kita-taku mafic complex; MTL, Median Tectonic Line.

with enriched Sr-Nd isotopic signatures (Kodama et al., 2019).

The presence of Cretaceous enriched mantle beneath Southwest Japan has been inferred from Sr-Nd isotopic compositions of spessartite dikes (Imaoka et al., 2014, 2017). These dikes, recognized as part of the Kyoto lamprophyre suite together with coeval vogesite intrusions, are dated to 107–105 Ma. Kodama et al. (2019) discussed the spatial extent and temporal evolution of the enriched mantle source during the Cretaceous by comparing the SNPC with the Kyoto lamprophyre; however, the precise emplacement age of the SNPC gabbro remains unresolved. Primitive arc magmas are commonly influenced by slab-derived materials, which interact with the mantle wedge and generate isotopically enriched mantle sources (Schmidt and Jagoutz, 2017). Therefore, zircon U-Pb dating of the SNPC gabbro is essential to constrain the timing and tectonic framework of Cretaceous subduction-zone magmatism.

In this study, we present new zircon U-Pb ages of granodiorite and gabbro from the SNPC, together with adjacent granitic rock (Fig. 1). By integrating these new age data with published geochemical and isotopic datasets from the Kinki, Chugoku, Shikoku, and Kyushu districts, we refine the temporal evolution of enriched mantle generation and its implications for Cretaceous magmatism in Southwest Japan.

GEOLOGICAL OUTLINE AND PETROGRAPHY OF DATED SAMPLES

The geological outline of the SNPC and the adjacent gran-

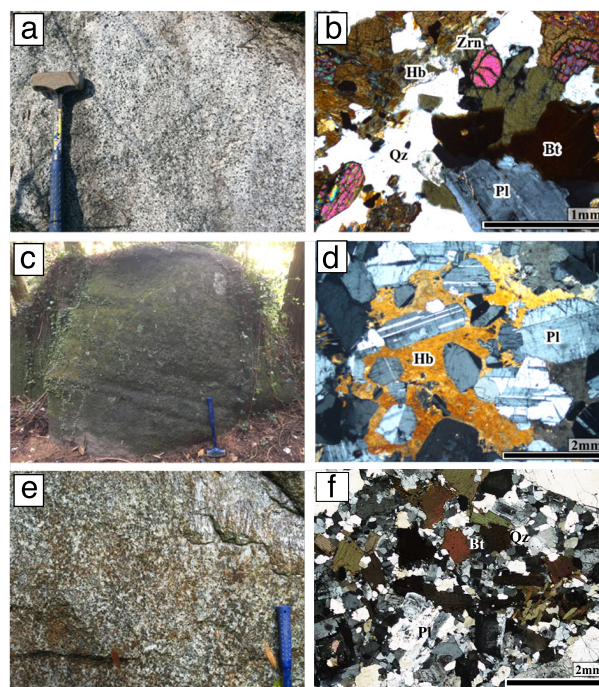


Figure 2. Field occurrence [(a), (c), and (e)] and photomicrographs [(b), (d), and (f)] of the analyzed samples. Granodiorite [(a) and (b)] and gabbro [(c) and (d)] of the SNPC. Granite [(e) and (f)] exposed on the eastern part of the SNPC. Hb, hornblende; Bt, biotite; Pl, plagioclase; Qz, quartz; Zrn, zircon.

ite, and their petrography, have been published in previous papers (Kodama et al., 2019, 2022). Therefore, these descriptions are briefly described in this chapter with some representative field occurrences and petrographical features (Fig. 2).

The western part of Honshu Island, Southwest Japan, is underlain by the high-pressure metamorphic rocks and accretionary complexes as pre-Cretaceous rocks, and the Cretaceous igneous complex accompanied by low-pressure type metamorphic rocks. The SNPC shows an elongated body that is more than 15 km in the E-W direction and 5–10 km in the N-S direction, and intrudes the pre-Cretaceous basement rocks (Fig. 1b). The SNPC consists of granodiorite and gabbro occurring as a small stock (1×1 km) (Fig. 1b). The granite located in the east of the SNPC shows leucocratic rather than those of granodiorite. The biotite K-Ar dating of the granodiorite and granite yielded the ages of 92.1 ± 2.4 and 93.8 ± 2.5 Ma, respectively (Fig. 1b; Kodama et al., 2019, 2022).

The granodiorite is medium-grained with an equigranular texture and consists mainly of plagioclase, hornblende, biotite, quartz, and alkali-feldspar (Figs. 2a and 2b). The gabbro locally shows layered structures and is composed mainly of plagioclase and hornblende with small amounts of clinopyroxene, orthopyroxene, and olivine (Figs. 2c and 2d). The granite is composed mainly of quartz, alkali-feldspar, plagioclase, and biotite (Figs. 2e and 2f). Additionally, it seems to exhibit a granoblastic texture under the microscope (Fig. 2f), suggesting it has undergone thermal effects. It is likely intrusion by the granodiorite and gabbro magma.

ZIRCON U-Pb DATING

U-Pb zircon dating was performed at Kyushu University using an Agilent 7500cx ICP-MS with an installed Photon Machines Analyte G2 193 nm ArF excimer laser. The analytical procedure for LA-ICP-MS was as described by Nakano et al. (2021). The integrated isotopic ratios were corrected using the 91500-zircon standard (Wiedenbeck et al., 1995) and Plešovice-zircon (Sláma et al., 2008), and the NIST SRM-611 glass standard was used to calculate the Th/U ratios. Standard zircons of FC1 (1099 Ma; Paces and Miller, 1993) and Temora (417 Ma; Black et al., 2003) were used as consistency standards. Concordia diagrams and weighted mean ages were obtained using Isoplot/Ex 3.7 software (Ludwig, 2008). Data with less than 10% discordancy, mostly overlapping the concordant curve, were used to calculate the mean age in this study. The uncertainties in the mean ^{238}U - ^{206}Pb ages represent 95% confidence intervals (2σ). During the analyses, the weighted mean ages for the consistency standard of FC1 and Temora were 1105 ± 11 Ma (^{238}U - ^{206}Pb age; $n = 11$) and 414 ± 5 Ma (^{238}U - ^{206}Pb age; $n = 10$), respectively. We describe the isotopic results of each rock sample, in which the term ‘age’ without any description corresponds to $^{206}\text{Pb}/^{238}\text{U}$ age. The analyzed data are listed in Supple-

mentary Table S1 (Supplementary Table S1 is available online from <https://doi.org/10.2465/jmps.251128cL>).

Granite (Sample 25070604A): This sample was collected from the western margin of granite body (Fig. 1b). Most of the zircon grains occur as interstitial or inclusion of biotite. The zircon grains were primarily euhedral with oscillatory zoning in the CL image; however, three grains have inherited cores (Figs. 3a and 3d). Twenty-five spots were identified, and the Th/U ratios were >0.13 , mostly >0.25 . Analyses yielded $^{206}\text{Pb}/^{238}\text{U}$ date of 98 ± 4 Ma– 110 ± 4 Ma (Table S1). The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age excluding three inherited cores and two rejected data yields 103.2 ± 1.3 Ma (MSWD = 1.6, $n = 18$) (Fig. 3d). Three inherited ages were 170–120 Ma (Table S1, Figs. 3a and 3d). The biotite K-Ar ages of the granodiorite and granite are also plotted in Figure 1b. The result of K-Ar dating of granite is similar to that of the granodiorite. As described above, the K-Ar age of granite is interpreted to have been reset by emplacement of the granodiorite and/or the gabbro. Tsutsumi and Tani (2025) reported two zircon U-Pb ages of 100–103 Ma from this granite.

Granodiorite (Sample 25070602): This sample was collected from the eastern part of the granodiorite (Fig. 1b). The zircon grains occur as inclusion of biotite, and are euhedral and slightly elongated (Fig. 3b). The internal structure of the zircon grains showed oscillatory zoning with minimal inherited cores (Fig. 3b, Table S1). Twenty-nine spots were analyzed, and the Th/U ratio was generally >0.45 . These data yielded $^{206}\text{Pb}/^{238}\text{U}$ date of 90 ± 4 Ma– 98 ± 5 Ma (Table S1). The weighted mean age of 92.6 ± 1.3 Ma (MSWD = 1.2, $n = 14$, 0 rejected data) was obtained (Fig. 3e). Two zircon U-Pb dating was conducted by Tsutsumi and Tani (2025) with ages of 90–93 Ma from this granodiorite.

Gabbro (Sample 23041402): The gabbroic body lies in the eastern margin of the granodiorite (Fig. 1). This sample was collected from the central part of the gabbro body (Fig. 1). The zircon grains are euhedral with mostly elongated, and occur as interstitial minerals (Fig. 3c). The internal structure of zircon grains showed oscillatory zoning with minimal inherited cores, as like as the granodiorite (Figs. 3b and 3c, Table S1). Twenty-seven spots were analyzed, and the Th/U ratio was >0.48 . Analyzed $^{206}\text{Pb}/^{238}\text{U}$ date ranged from 84 ± 4 to 96 ± 4 Ma (Table S1). The weighted mean age of 91.2 ± 1.4 Ma (MSWD = 2.0, $n = 22$, 1 rejected data) was obtained after omitting from the concordant data (Fig. 3f). This age data is consistent with that of the granodiorite (sample 25070602) within analytical error.

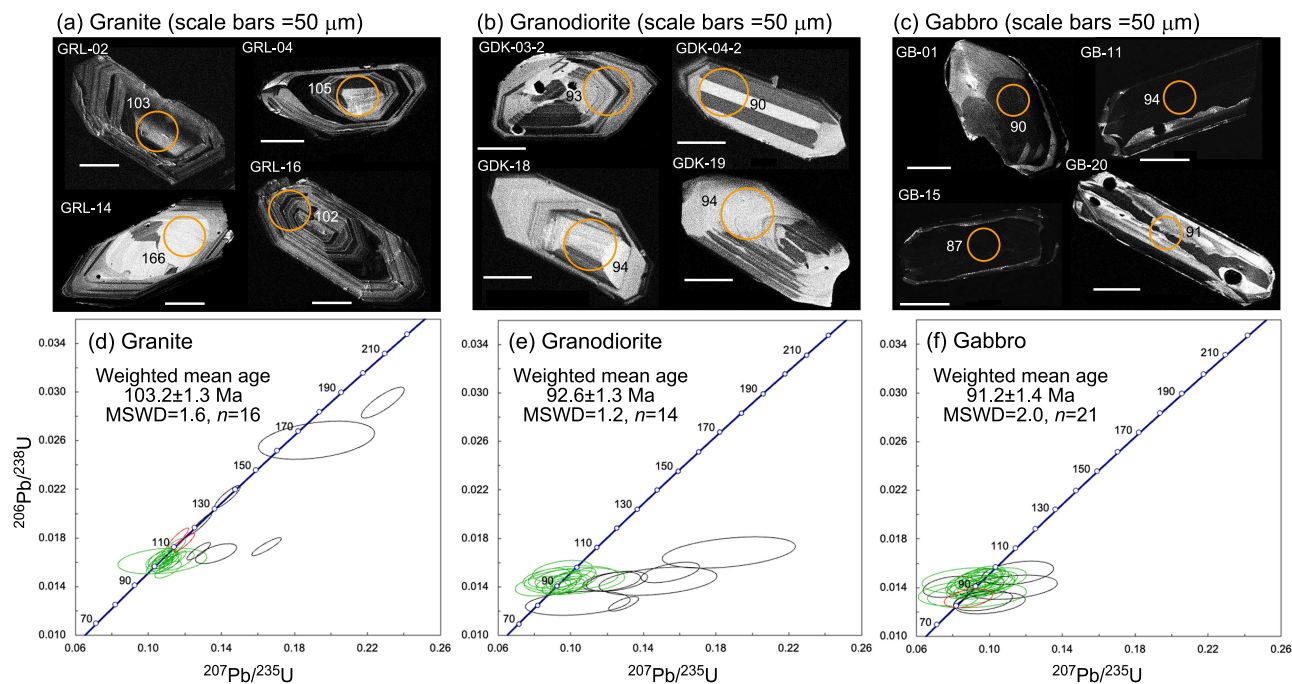


Figure 3. Results of zircon U-Pb dating. Cathodoluminescence image of zircon grains with analytical spots and their $^{206}\text{Pb}/^{286}\text{U}$ ages [(a)-(c)]. Concordia diagrams with mean values of zircon U-Pb dating are also shown [(d)-(f)]. The data of green ellipses were used for weighted mean calculation, while the red ellipses represent rejected data during the calculation. The black ellipses are inherited and discordant data.

CHARACTERISTICS OF SOURCE MANTLE DURING FLARE-UP EVENT

Zircon U-Pb dating of the examined plutonic bodies yielded ages of 103, 93, and 91 Ma (Fig. 3), all of which fall within the interval of Cretaceous magmatic activity in Southwest Japan. Yamaoka and Wallis (2023) compiled zircon U-Pb and uraninite-thorite U-Th-total Pb ages and demonstrated that magmatism in this region was interrupted between 160 and 130 Ma, followed by extensive activity between 120 and 90 Ma. They interpreted this widespread flare-up magmatism as a consequence of progressive shallowing of the subducting slab. Because flare-up events commonly involve enhanced mantle-derived mafic magmatism (Chapman et al., 2021), direct age constraints on mafic plutonism are essential. The zircon U-Pb ages obtained in this study therefore provide critical timing constraints on mafic magmatism and, when combined with geochemical analyses such as Sr-Nd isotopic compositions, can be used to infer the evolution of the mantle source during flare-up event.

Figure 4a illustrates the relationship between age and initial- ϵNd values ($\epsilon\text{Nd}/I$) for the mafic rocks. The locations of each mafic plutonic body are shown in Figure 1a. Ages of Kyoto lamprophyre are shown using hornblende and phlogopite K-Ar results (Imaoka et al., 2014, 2017), which likely approximate emplacement ages owing to the

shallow intrusion and rapid cooling of these dikes. Although the available data remain limited, $\epsilon\text{Nd}/I$ generally decreases with age. The compiled gabbro-diorite samples (Okano et al., 2000; Tiepolo et al., 2012; Imaoka et al., 2014; Yuhara et al., 2016; Imaoka et al., 2017; Kodama et al., 2019, 2022; Eshima et al., 2023; Shimooka et al., 2023) possess relatively primitive compositions, suggesting that their $\epsilon\text{Nd}/I$ largely reflect those of their mantle source. Overall, these $\epsilon\text{Nd}/I$ indicate moderately enriched, rather than strongly depleted, mantle signatures (Fig. 4a).

Arc magmas are commonly influenced by slab-derived components (Schmidt and Jagoutz, 2017). The relatively enriched $^{143}\text{Nd}/^{144}\text{Nd}$ signatures observed in the mafic rocks can be attributed to contributions from subduction-related materials, likely sediments or sediment-derived melt, which are characterized by unradiogenic $^{143}\text{Nd}/^{144}\text{Nd}$ compared with the mantle wedge (Bayon et al., 2009). Because subducted sediments typically have elevated Th concentrations and higher Th/La ratios than the mantle (Plank and Langmuir, 1998), a negative correlation between Th/La and initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (Nd/I) provides an effective proxy for assessing sediment contributions to the mantle source (Plank, 2005). Figure 4b shows Nd/I corrected to each magmatic age versus Th/La ratio. The literatures on Shikanoshima and Kajishima lacked Th and La data (Okano et al., 2000; Tiepolo et al., 2012; Yuhara et al., 2016; Shimooka et al., 2023). Al-

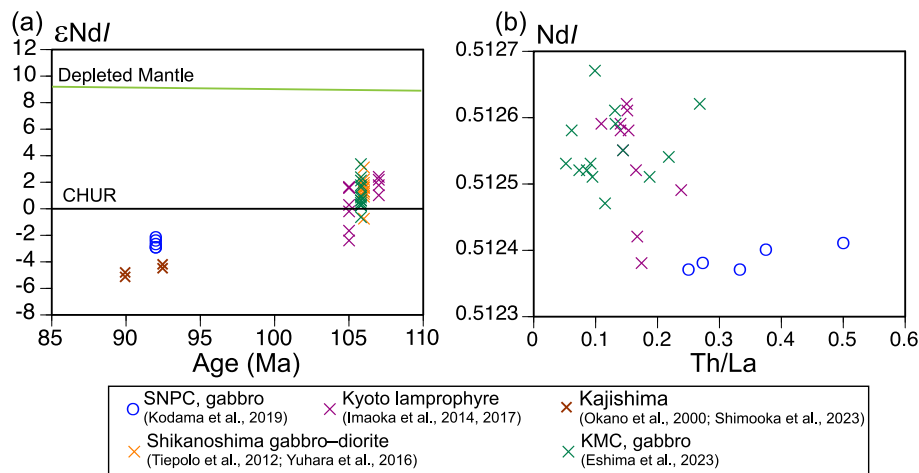


Figure 4. Age (Ma) versus ϵNdI values for the mafic rocks (a). Th/La ratios versus $^{143}\text{Nd}/^{144}\text{Nd}$ initial ratios (NdI) diagram (b). KMC, Kitatoku mafic complex. The Nd initial values were corrected to each magmatic age [(a) and (b)]. The locations of each mafic body are shown in Figure 1a. For the source of compiled data are as follows. Kyoto lamprophyre: age, Sm-Nd isotope, Th/La; Imaoka et al. (2014, 2017). Kajishima: age; Shimooka et al. (2023), Sm-Nd isotope; Okano et al. (2000). Shikanoshima: age; Tiepolo et al. (2012); Sm-Nd isotope; Yuhara et al. (2016). KMC: age, Sm-Nd isotope, Th/La; Eshima et al. (2023). The data source of depleted mantle is quoted from Workman and Hart (2005).

though gabbroic rocks from the SNPC show a slight positive correlation, such correlation probably reflects the Nd isotopic variations of contaminant materials. The negative correlation observed in gabbro-diorite samples in Figure 4b suggests that these magmas become influenced over time by slab-derived sediments or their melts.

Taken together, the regional Cretaceous flare-up magmatism in Southwest Japan appears to be enhanced thermal input to the mantle wedge (Yamaoka and Wallis, 2023). Basaltic magma derived from the mantle wedge magmatism likely required two conditions during the flare-up event: (1) raising a hot mantle from the deeper mantle due to slab roll-back forming both depleted and enriched magma at the initial stage approximately 105 Ma (Imaoka et al., 2014) and (2) over time, a flux of fertile materials such as subducted sediments into the mantle increased till ~ 92 Ma. Takagi (2004) proposed that the subduction rate peaked around 100 Ma, resulting in greater sediment delivery to the mantle wedge. The Cretaceous enriched mantle signature documented here was likely generated through this process.

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SUPPLEMENTARY MATERIAL

Supplementary Table S1 is available online from <https://doi.org/10.2465/jmps.251128cL>.

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