Yamaoka and Wallis
Progress in Earth and Planetary Science (2023) 10:62
https://doi.org/10.1186/s40645-023-00594-8

Progress in Earth and Planetary Science

RESEARCH ARTICLE

Open Access

Clockwise rotation of SW Japan and timing of Izanagi–Pacific ridge subduction revealed by arc migration

Ken Yamaoka[1,2*] and Simon R. Wallis[2]

Abstract

Igneous rocks associated with the Cretaceous to Paleogene volcanic arc in SW Japan show ages that young from west to east in a direction parallel to the Median Tectonic Line suggesting corresponding translation of a heat source traditionally interpreted in terms of oblique subduction of a spreading ridge. However, recent oceanic plate reconstructions suggest ridge subduction may be younger than the main arc activity. Age compilations of 1227 points of felsic to intermediate Cretaceous and Cenozoic igneous rocks from the Japan arc show arc magmatism that can be separated into an early active period 130–60 Ma (stage 1), a subsequent period of quiescence 60–46 Ma (stage 2), which is followed by a resumption of igneous activity from 46 Ma onward (stage 3). In southwest Japan, the orientations of the magmatic arcs of stages 1 and 3 show and angular discordance of about 20°. The lack of active arc magmatism and the occurrence patterns of adakitic and high-Mg andesitic magmas indicate that ridge subduction occurred during stage 2. The arc age distribution pattern of stage 1 is explained by the slab shallowing related to a younging of the subducting slab as the ridge approaches. Furthermore, the obliquity of the arcs formed at stages 1 and 3 is explained by a 20° clockwise rotation of the inner zone of southwest Japan during the ridge-subduction phase. Oceanic plate reconstructions show counterclockwise rotation in the subduction direction after the ridge subduction phase, and coupling of the subducting oceanic plate with the upper plate would support microplate rotation in the inner zone. The new proposed tectonic reconstructions provide a framework to related Paleogene subduction of an active spreading ridge along the east Asia margin not only to the distribution of granitic bodies but also to rift-related basin formation on the eastern margin of the Eurasian continent and to rotation of crustal blocks indicated by paleomagnetic data of Cretaceous terranes.

Keywords Izanagi plate, Pacific plate, Ridge subduction, Arc migration, Granite, Radiometric chronology, Continental block rotation, Slab shallowing, Magmatic hiatus

*Correspondence:
Ken Yamaoka
yamaoka-ken@aist.go.jp
[1] Research Institute of Geology and Geoinformation, Geological Survey of Japan (GSJ), National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8567, Japan
[2] Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan

1 Introduction

The approach and subduction of active spreading ridges is a rare but inherent part of the plate tectonic cycle. Ridge subduction is associated with anomalously warm subduction zones and has been called on to account for a broad range of events in the geological record, such as changes in magmatism in the overriding plate, changes in plate movement vectors, and the onset of phases of orogenesis including exhumation of high-pressure metamorphic rocks (e.g., Sisson et al. 2003a). On the modern Earth, ridge-trench-trench (RTT) triple junctions have been identified around Chile and the Woodlark Basin, and these are two valuable field areas of study that provide real-time data on the characteristic of igneous activity and crustal deformation in domains of active ridge subduction (Taylor and Exon 1987; Stern 2004; Ramos 2005). The reaction of the hanging wall to ridge approach, collision, and subduction over geological time scales, can be examined by studying the geologic records of such convergent margins (Bradley et al. 2003).

The Japanese Islands record evidence of active subduction throughout much of their geological history, and subduction of a spreading ridge has been highlighted as a potentially important process since the early days of plate tectonics (Uyeda and Miyashiro 1974). The large number of geological data sets and the lack of any major continental collision make the Japanese islands well-suited to studying possible interactions between spreading ridges and the eastern margin of the Eurasian continent since the Cretaceous (Fig. 1; Taira et al. 2016). Cretaceous terranes comprise a major part of the basement rocks of the Japanese Islands and consist of a set of granitoids with pairs of high-P/T and high-T/P type metamorphic rocks (Figs. 2, 3), and it has long been suggested that their formation is closely related to the approach and subduction of a spreading ridge (Uyeda and Miyashiro 1974; Takahashi 1983; Maruyama and Seno 1986; Kinoshita and Ito 1986, 1988; Brown 1998; Iwamori 2000; Uehara and Aoya 2005; Aoya et al. 2003, 2009; Isozaki et al. 2010).

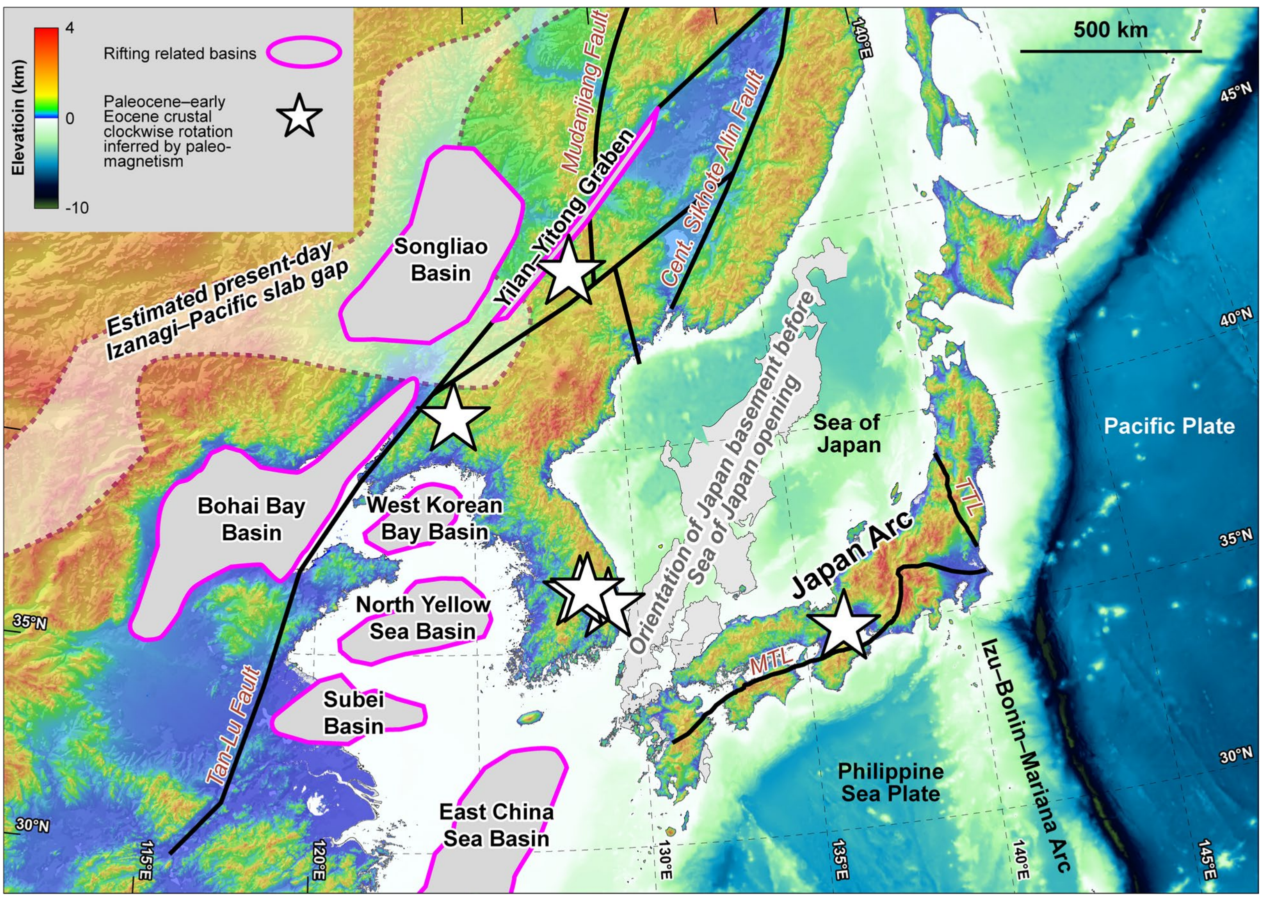

Fig. 1 The topography map of the eastern margin of Eurasia continent (data from Amante and Eakins 2009). The approximate paleo-location of the Japanese islands before the formation of the Sea of Japan in Miocene is shown in gray. The paleo-magmatic arcs (> 60 Ma) of NE and SW Japan are adjusted to be parallel when the southwest Japan is rotated 20 degrees counterclockwise. Several models have been proposed for estimating paleo-positional relationships (e.g., Otofuji et al. 1985; Jolivet et al. 1995; Yamakita and Otoh 2000). The selected basins record rifting during the early Cenozoic period of interest (Yi et al. 2003; Imaoka et al. 2011; Gu et al. 2017; Song et al. 2018; Zhu et al. 2020; Liu et al. 2022). The hatched area represents the estimated Izanagi–Pacific Slab gap based on P-wave tomographic observations and is recognized at an approximate depth of around 1000 km (Li et al. 2008; Wu et al. 2022a, b). White stars indicate the presence of a geologic record that indicates a clockwise rotation of approximately 20 degrees with respect to Eurasia continent in Late Cretaceous to Early Eocene (Otofuji et al. 1985; Uchimura et al. 1996; Fukuma et al. 2003; Lin et al. 2003; Park et al. 2005; Wang et al. 2011)

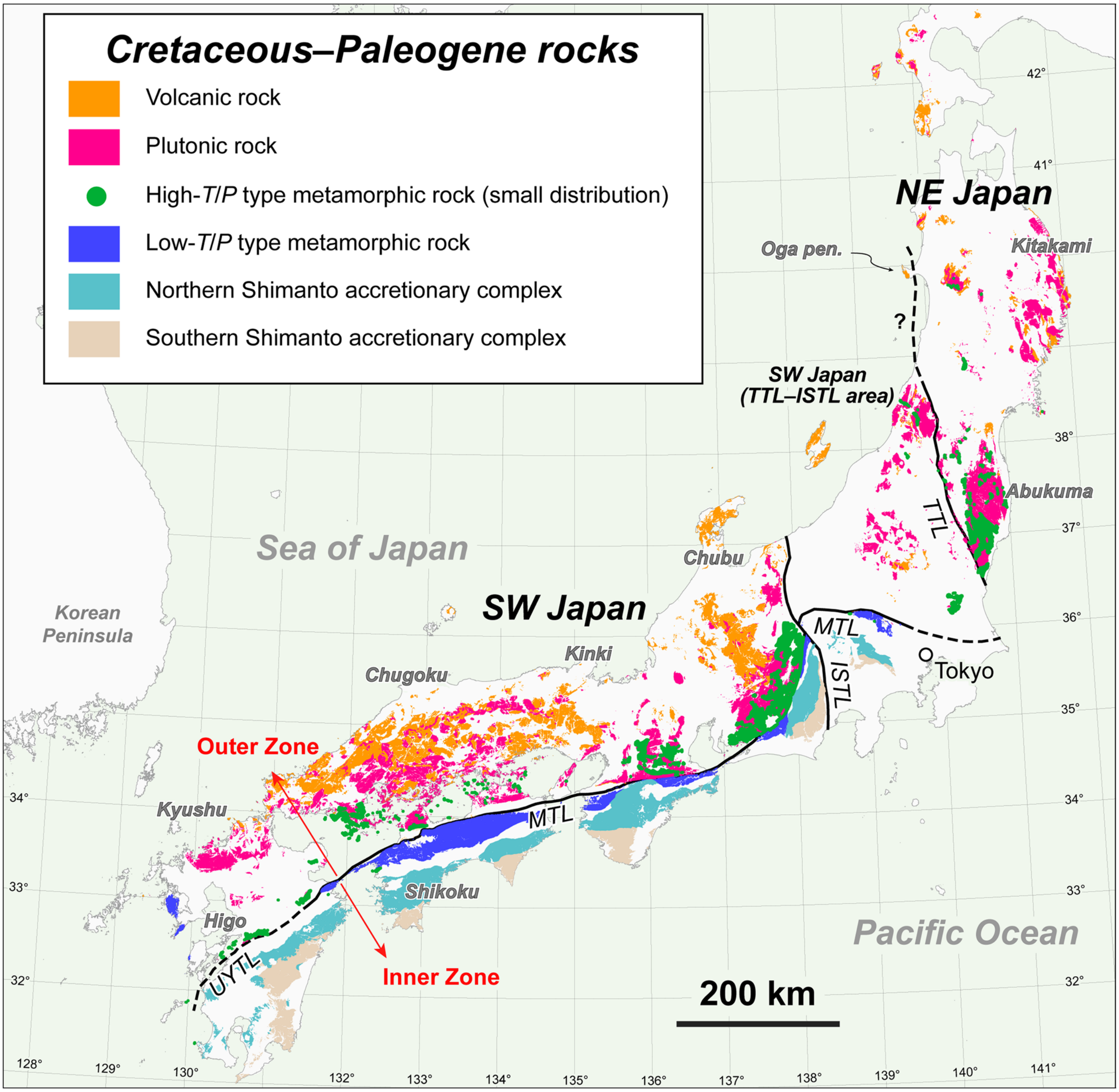

Fig. 2 Distribution of geological terranes in NE and SW Japan (data from Geological Survey of Japan, AIST 2022). NE and SW Japan are divided by the Tanakura Tectonic Line (TTL). In this study, we interpret the Median Tectonic Line (MTL) as a major fault that defines the northern limit of occurrence of geologic terranes in the outer zone (Sanbagawa, Chichibu, and Shimanto belts) and is essentially identical to the Usuki–Yatsushiro Tectonic Line (UYTL)

These ideas are in agreement with many of the earliest oceanic plate reconstructions for the Pacific realm, which proposed a spreading ridge between the Pacific and Izanagi or Kula plates was subducted at a high angle to the trench in the upper Cretaceous (e.g., Woods and Davies 1982; Engerbreston et al. 1985; Maruyama et al. 1997). However, the uncertainties in these reconstructions are large and recent oceanic plate reconstruction models that incorporate both newly analyzed ocean floor magnetic anomaly data and tomographic data constraining the amount of subducted plate—information that was not available in the 1980s—indicate that the spreading ridge (Izanagi–Pacific ridge) was oriented roughly parallel to the trench of the East Asian continental margin and subducted underneath the paleo-Japan arc in Paleogene (Fig. 1; Whittaker et al. 2007; Seton et al. 2015; Wu et al. 2022a, b). However, only a limited number of the available onshore geological data have been used to examine

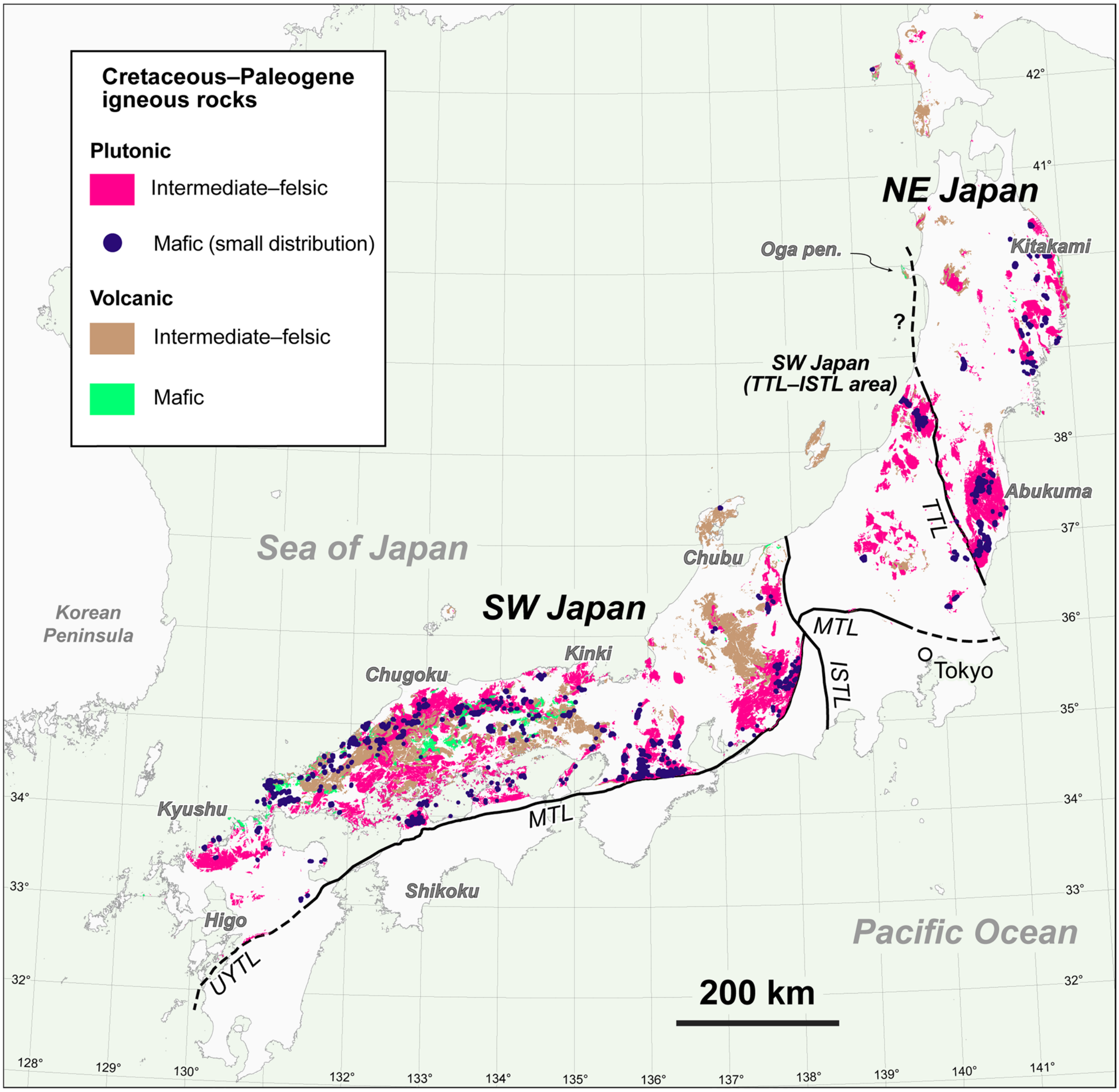

Fig. 3 Distribution of Cretaceous–Paleogene igneous rocks in NE and SW Japan (data from Geological Survey of Japan, AIST 2022)

the predictions of this model and examine its implications for the geological evolution of the Japanese Islands.

In this contribution, we first present a detailed compilation of age data and a review of available geochemical data for contemporaneous magmatic rocks to examine proposed ideas for the timing and orientation of ridge subduction in the paleo-Japan Arc. The dataset we have compiled includes information only available in papers written in Japanese (Additional files 1, 2: Table S1), and we hope this contribution will also serve as a gateway to make these valuable data more widely available.

2 Geological setting

The Cretaceous–Paleogene geological terranes of the Japan can be divided into NE Japan and SW Japan, separated by the Tanakura Tectonic Line (TTL) (Fig. 2). Throughout this area, plutons are dominantly felsic to intermediate and mafic magmatism is minor (Fig. 3).

In central part of NE Japan, Cretaceous magmatic intrusions into pre-Cretaceous basement rocks are recognized in the Kitakami and Abukuma areas. Igneous activity along the inner arc part of Japan adjacent to the Japan Sea coast is broadly similar to that in the

Kitakami–Abukuma areas, although knowledge of the basement rock distribution is limited by the presence of Neogene and later cover. On the Pacific coast side, information on the Cretaceous forearc is lacking due to progressive tectonic erosion by the Pacific plate subduction (von Huene and Scholl 1991). Cretaceous to Paleogene volcanic rocks are also present in parts of the Kitakami area (Fig. 3).

SW Japan is divided into an inner zone north of the Median Tectonic Line (MTL) (inner part of the arc) and an outer zone to the south (Fig. 2) (outer part of the arc). In Kyushu, the Usuki–Yatsushiro Tectonic Line (UYTL) is recognized as the western extension of the MTL. In the inner zone, Cretaceous-Paleogene felsic magma bodies intrude pre-Cretaceous basement rocks. Associated volcanism is recognized over a widespread area in SW Japan. The age range of high-*T*/*P* metamorphism associated with synchronous igneous activity is ~ 120–110 Ma for the southern Abukuma and Higo metamorphic rocks (Hiroi et al. 1998; Sakashima et al. 2003), and ~ 100–80 Ma for the Ryoke metamorphic rocks (e.g., Suzuki et al. 1994a, b; Takatsuka et al. 2017; Kawakami et al. 2022).

3 Post-Cretaceous spreading ridge subduction around the Japanese Islands depicted in previous studies: an overview

3.1 Highly oblique subduction of the spreading ridge at Cretaceous

The possibility of a correlation between active magmatism and high-T/P type metamorphism in the Cretaceous Japan arc and spreading ridge subduction was first addressed by Uyeda and Miyashiro (1974), and subsequently, numerical simulations of the thermal structure of subduction zones have examined possible relationships between metamorphic *P*–*T* conditions of the Ryoke metamorphic rocks in SW Japan and associated melting of the lower crust due to a large heat source related to subduction of a spreading ridge and very young oceanic lithosphere (e.g., Iwamori 2000; Okudaira and Yoshitake 2004; Aoya et al. 2009; Okudaira and Suda 2011). Thermal modelling of the high-*P/T* Cretaceous metamorphic rocks of SW Japan (Sanbagawa metamorphic rocks) showed the recorded metamorphic *P*–*T* conditions are a good match for the thermal models shortly before ridge subduction (Aoya et al. 2003; Uehara and Aoya 2005). However, it is important to note that approach and subduction of a spreading ridge subduction is a sufficient but not necessary conditions to explain the moderately warm to warm environments in the geologic record. A more recent study reveals that consideration of the effect of shear heat generated at subduction boundaries is a viable alternative explanation for the recorded *P*–*T* conditions of the Sanbagawa metamorphic rocks that does not require ridge subduction (Ishii and Wallis 2020).

Regional spatiotemporal information such as the occurrence, spatial movement with time, and cessation of igneous activities with a particular chemical composition may offer stronger constraints on tectonic reconstructions (Bradley et al. 1993, 2003) than is possible from thermal models alone. In SW Japan, it is recognized that there is a systematic E–W trend of younger-aged I-type granitoids parallel to the trend of the Median Tectonic Line (MTL) from ~ 115 Ma in the west to ~ 65 Ma in the east, and it has been argued that this trend in geologic features can be directly related to the subduction of a spreading ridge (e.g., Kinoshita and Ito 1986; Nakajima et al. 1990). This model assumes that a spreading ridge, which subducts at a high angle, i.e., highly oblique to the volcanic arc, serves as a heat source for magma generation. The granitoids of SW Japan also show a younging trend in a direction subperpendicular to the MTL with younger-aged units present in areas further north from the MTL than the older aged units. In NE Japan, where granitoids are present with slightly older ages than SW Japan (~ 130–95 Ma), a similar origin to SW Japan has been sought for the origin of the magmatism calling on subduction of a young slab and subsequent approach and subduction of an active spreading ridge. The main line of evidence is the adakitic chemical composition of magma (e.g., Osozawa et al. 2019). However, other tectonic settings have also been highlighted as compatible with the characteristics of the magmatism in NE Japan: slab rollback or slab rupture (Tsuchiya et al. 2015).

Oblique subduction ridge models for the Cretaceous-Paleogene history of Japan face two significant problems when considering the regional distribution of igneous activity and the associated ages. (i) Migration of a RTT triple junction from west to east along the length of the Japanese archipelago requires large-scale left lateral movements with a displacement that is equal to or greater than the extent of SW Japan after the magmatism to explain the presence of older granite bodies in NE Japan (Sakashima et al. 2003; Osozawa et al. 2019). Detrital zircon geochronology does not support the idea that the geologic terranes of NE Japan and the outer zone of SW Japan migrated from positions far to the south of their present locations because zircon age spectra show a strong connection to the North China Craton, implying that this was the provenance region and the two areas were not geographically isolated (e.g., Tokiwa et al. 2019; Li and Takeuchi 2021). (ii) The proposed ridge subduction models directly relate increased magmatism with the passage of a subducting spreading ridge. However, this view contradicts the observed cessation of magmatic activity around modern-day ridge subduction domains.

The most likely explanation for this reduction in magmatism despite the expected higher temperatures is the lack of water supplied by an actively subducting slab due to the formation of a slab window (Thorkelson 1996). Aoya et al. (2009) suggest that dehydration of serpentinized mantle wedges at elevated temperatures may provide the water necessary to cause widespread melting, but this would imply Cretaceous magmatism in the forearc region.

Differential exhumation has been proposed as alternative model to explain the east–west trends in granite ages seen in a direction measured parallel to the MTL in SW Japan based on the monazite chronometry of granite bodies in the southern margin of the inner zone (Suzuki and Adachi 1998). However, both volcanic and plutonic rocks show the same overall younging to the east (e.g., Nakajima et al. 1990; Sato et al. 2016). The preservation of volcanic rocks that were formed at the earth's surface shows that the effects of erosion are limited and suggests that changes in the locus of magmatic activity are more important than any differential exhumation.

Intrusion of mid-ocean ridge basalt (MORB) magma into forearc regions has commonly been highlighted as evidence for interaction between an active spreading ridge and an oceanic trench (Hibbard and Karig 1990; Kaeding et al. 1990; Sisson et al. 2003b). In SW Japan, Kiminami et al. (1994) report a set of in situ MORB intrusions in the Shimanto accretionary complex with ages that young from west to east that can be chronologically compared to trends in the inner zone igneous rocks. However, the results of subsequent field work suggest the lithological boundaries presented in this paper may be structural rather than intrusive (Onishi and Kimura 1995).

3.2 Subparallel subduction of the spreading ridge at early Paleogene

Recently proposed oceanic plate motion models make use of both an expanded data set of magnetic anomalies in modern day ocean domains and the information on the volume of subducted slabs present within the mantle from seismic tomography. The resulting revised plate reconstructions show roughly parallel subduction of a spreading ridge under the East Asia continental margin during the Paleogene (Whittaker et al. 2007; Müller et al. 2008; Facccenna et al. 2012; Seton et al. 2015; Matthews et al. 2016; Wu et al. 2022a, b). The two types of reconstruction suggest contrasting times for the ridge–trench interaction and geometrical relationships with the arc-trench system, and the Cretaceous–Paleogene onshore geological record of the Japanese Islands has great potential to contribute to testing the viability of the two contrasting types of tectonic model.

Spreading ridge subduction potentially causes extensive geomorphic changes and thermal anomalies in the forearc region associated with the approach and subduction of a warm and buoyant domain, and the corresponding geologic features recorded in accretionary complexes from Sakhalin to southwest Japan may be interpreted within the framework of this model (Wu and Wu 2019; Kimura et al. 2019). The cessation of continental arc magmatism recognized over a wide region that occurred at around 50 Ma, and the abrupt changes in Sr and Nd isotopic compositions suggesting a depleted mantle influx recognized immediately after the period of magmatic quiescence can be interpreted as signatures of the existence of the slab window associated with the spreading ridge subduction (Wu and Wu 2019; Liu et al. 2020). These proposed models are consistent with observations of modern examples of spreading ridge subduction, including the cessation of arc igneous activity. However, by itself this model does not account for the trend in the ages of igneous activity in SW Japan seen over a distance of ~ 1000 km E–W. In the following section, we present a compilation of ages of the igneous activity that sheds more light on the timing of ridge subduction since the Cretaceous and use it to propose a tectonic framework for the basement units of the Japanese Islands.

4 Method: compilation of ages of igneous activity

4.1 Radiometric ages

We collected 1227 data from the available literature that report the timing and location of Cretaceous to Paleogene igneous activity in the Japanese islands (Table 1). The age range analyzed is from 130 Ma, when Cretaceous igneous activity begins (Tsuchiya et al. 2015; Osozawa et al. 2019; Harada et al. 2023), to 30 Ma, shortly before the opening of the Sea of Japan event in the Miocene (Otofuji et al. 1985). This age range covers the time period relevant to the proposed ridge subduction models described above. For the compilation, we focused on intermediate to felsic intrusive and extrusive rocks (Tables 1, Additional files 1, 2: Table S1). Mafic rocks were not included. The ages in this study are the averaged ages of multiple analyses from a single rock sample rather than individual measurements. Reliable crystallization ages for igneous rocks are provided by zircon U–Pb ages from a number of publications. This method uses zircon, which is resistant to hydrothermal alteration and weathering, has a high closure temperature and is therefore resistant to resetting by later thermal events. In addition, two separate radiometric decay sequences can be used for the same analysis to verify the age. We also include U–Th–total Pb ages for uraninite (UO2) and thorite ($ThSiO_4$). The associated closure temperatures for both minerals may

Table 1 List of compiled chronological data counts by method

Measuring target	Number		
	SW Japan	NE Japan*	Total
Crystallization age			
U–Pb ages			
Zircon	275	76	351
U–Th–total Pb ages			
Thorite	116	38	154
Uraninite	145	47	192
Cooling age			
K–Ar ages			
Biotite	217	42	259
Hornblende	105	35	140
K-feldspar	18	6	24
Muscovite	4	0	4
Plagioclase	5	0	5
Whole rock	66	19	85
Ar–Ar ages			
Biotite	4	1	5
Hornblende	0	3	3
Plagioclase	0	1	1
Whole rock	4	0	4
Total		959	268

*Age datum from the Oga peninsula is tallied in NE Japan

be somewhat lower than zircon (Yokoyama et al. 2010, 2016), but the results are compatible with the zircon U–Pb ages and we consider they can be regarded as crystallization ages and make a useful contribution to the tectonic discussion of this study (Fig. 4A). Rb–Sr whole rock or mineral ages and monazite U–Th–total Pb ages have been given prominent treatment in former studies. However, these are commonly in marked disagreement with the age values obtained by the above methods (Shibata and Ishihara 1979; Skrzypek et al. 2018, 2020) and were excluded from the compilation to avoid complicating the discussion. We also compiled K–Ar and Ar–Ar age values (whole rock and mineral ages). These ages are interpreted as cooling ages rather than crystallization ages. It is possible that some of the results were modified by later thermal events. However, when K–Ar ages are compared to zircon U–Pb ages from the same samples or from samples taken in very close proximity, there is a good agreement in the observed trends with the K–Ar ages generally showing ages ~ 10–15 Myr younger than the zircon ages (Fig. 4B). We conclude that the K–Ar age data set is a useful addition to the geochronological record used in this study. Due to the limited number of results, it was more difficult to compare Ar–Ar ages to the U–Pb ages. However, we also included these ages because they show good consistency with neighboring K–Ar ages. In our compilation of cooling ages, we exclude data from samples where significant alteration of the measured minerals are described or where the original research considers them to have undergone secondary alteration. Filtering of data as described above leaves a data set consisting of 697 crystallization ages and 530 cooling ages (Fig. 5, Additional files 1, 2: Table S1).

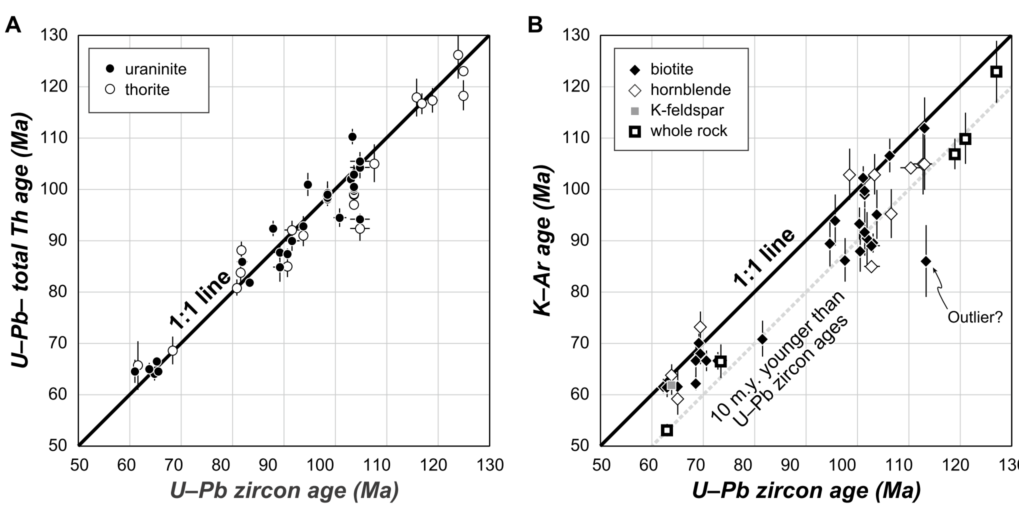

Fig. 4 Comparison of uraninite and thorite U–Th–total Pb ages (Yokoyama et al. 2016). **A** and K–Ar age values, **B** against zircon U–Pb ages based on the database of Table 1. Each point is a comparison between samples from the identical or proximal area (within a few kilometers) and expected to have the similar rock-forming age. Error bars are shown as 1*σ*

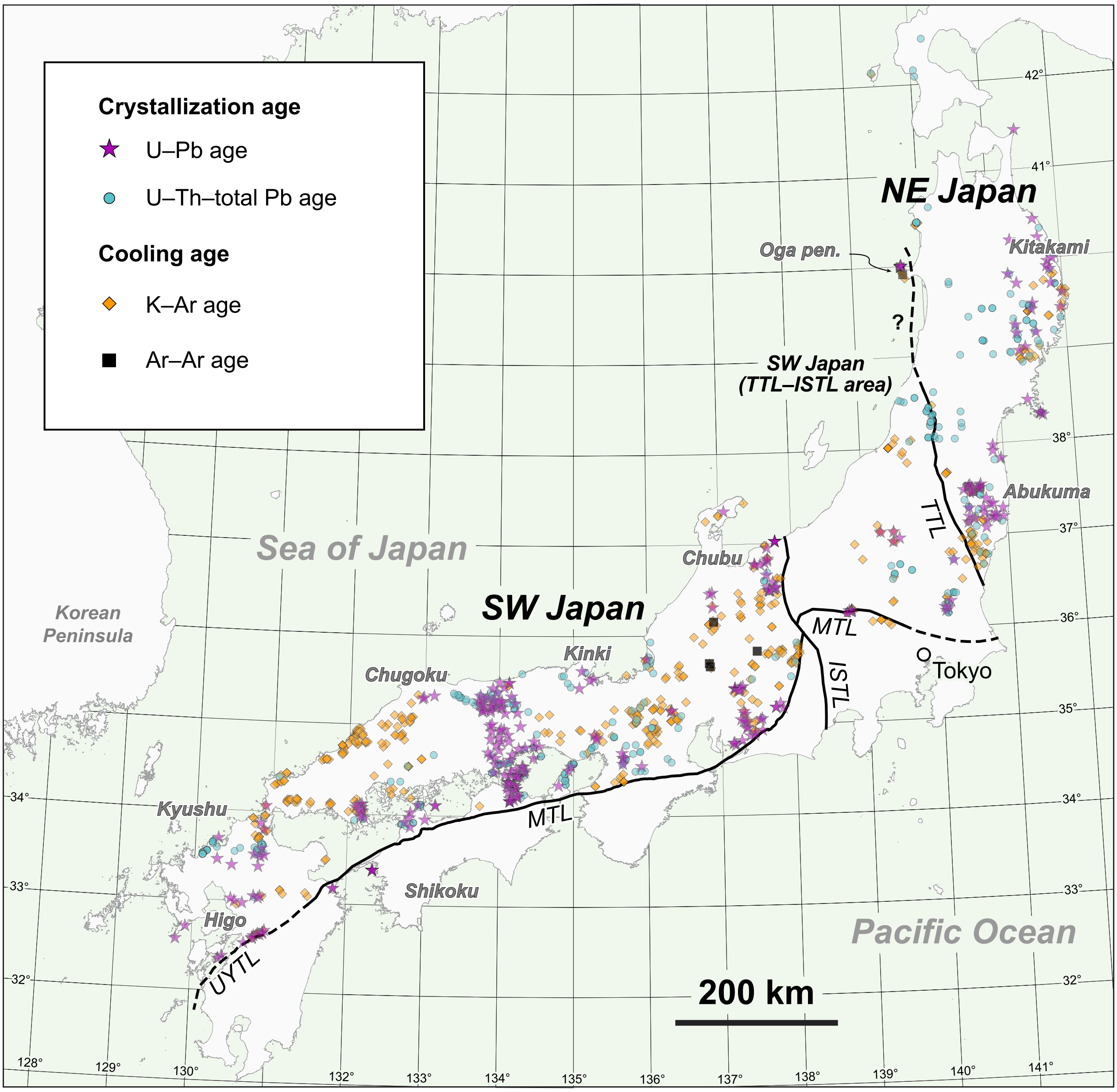

Fig. 5 Spatial distribution of chronological data and associated dating method

4.2 Adakitic magma and high-Mg andesitic magma

In our literature review, we also recorded reports of samples with geochemical data showing adakite and high-Mg andesitic magma (HMA) compositions that occur within the spatiotemporal domain covered by our compilation (Additional files 3, 4: Table S2). Such magmas can form as a result of the subduction of an oceanic plate into relatively warm mantle regions. Adakites mainly exhibit high-Sr/Y and high-La/Yb signatures which are most likely controlled by high-pressure melting in the presence of the garnet or amphibole and the absence of plagioclase (Castillo 2012). These features of adakites are generally interpreted to indicate a slab melting origin (e.g., Defant and Drummond 1990). However, the possibility of an origin controlled by intracrustal differentiation processes continues to be debated (e.g., Yada and Owada 2003; Kamei et al. 2004; Takahashi et al. 2005; Takahashi 2008; Tsuchiya 2008; Chiaradia 2015; Chapman et al. 2015). HMA magmatism is thought to be associated with partial melting of mantle under relatively low-pressure conditions with hydrated conditions (Tatsumi 1982, 1995). Occurrences of both adakitic and HMA magma compositions are rare in normal arc magmatism and are generally interpreted as features characteristic of the subduction of young slabs and magmatism during the onset of subduction.

5 Compilation results

5.1 Radiometric ages distribution

5.1.1 NE Japan

In NE Japan, there is a concentration of data on the eastern side corresponding to the Kitakami–Abukuma domain. Basement rocks of the western part of NE Japan are only locally exposed beneath extensive post-Miocene to Quaternary overlying strata on the Sea of Japan side (Fig. 6). The oldest activity is ~ 130 Ma east of the Kitakami area, with ages showing a good correlation with longitude, and an overall westward-younging trend up to ~ 100 Ma and an average migration rate for NE Japan can be calculated as ~ 130 km per 20 Myr (~ 6.5 km/Myr) (Fig. 7). Slightly younger ages down to ~ 95 Ma are also observed in the Abukuma area, but the overall trend is

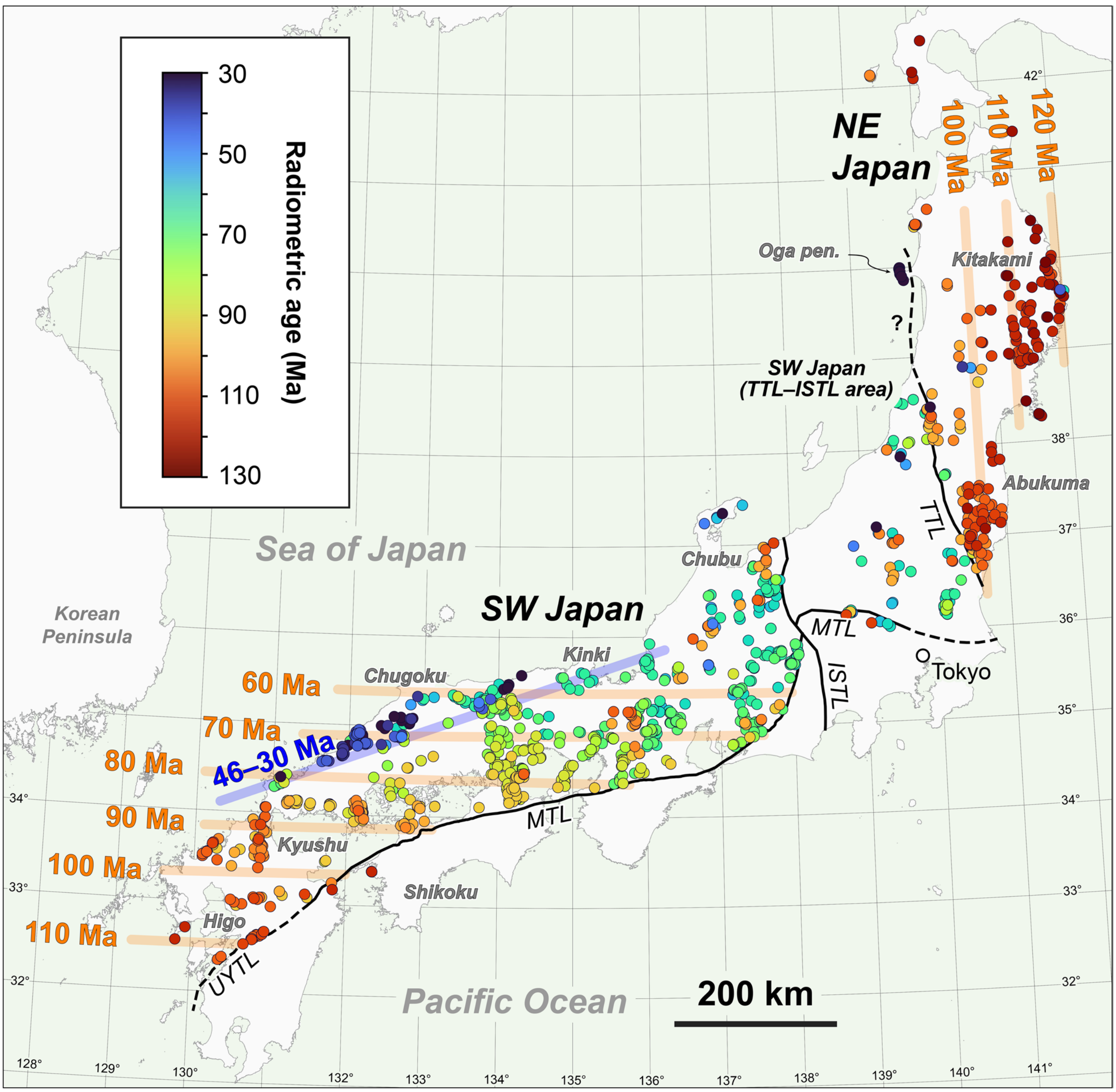

Fig. 6 Spatial distribution of compiled age values. Specific colors are assigned according to age value. Data sources are shown in Additional files 1, 2: Table S1

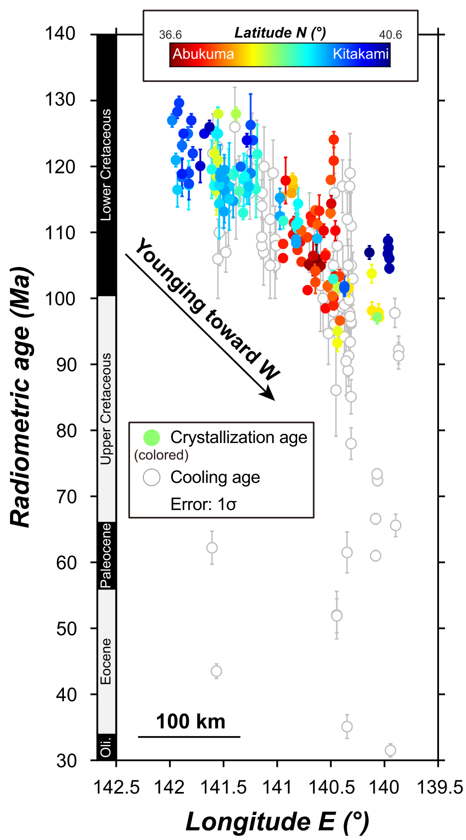

Fig. 7 Spatiotemporal variation of arc igneous activity in NE Japan, with longitude on the horizontal axis because the largest age gradient in NE Japan is in the east–west direction (e.g., Tsuchiya et al. 2015; Yokoyama et al. 2016). Colored circles indicate crystallization ages, and colors correspond to latitude. White circles indicate cooling ages. Note that the east–west direction on the horizontal axis is reversed compared to the map to facilitate a direct comparison with SW Japan in Fig. 14

consistent with the ages of the Kitakami area. Younger igneous activity is also recorded at Jodogahama, but has limited distribution (e.g., Tsuchiya et al. 2005).

5.1.2 SW Japan

West of the ISTL, there is a notable difference in the spatial configurations of igneous activity before ~ 60 Ma and after ~ 46 Ma. Major igneous activity prior to 60 Ma is 115–100 Ma in Kyushu, 100–90 Ma in the Shikoku, and 80–70 Ma in the Chubu area, and shows an overall trend of younging to the east when locations with similar distances measured perpendicular to the MTL are compared. There is also gradual younging trend to the north with increasing distance from the MTL (Figs. 6, 8A). These age distributions indicate that temporal variations in the age of igneous activity cannot be adequately expressed solely as a function of distance from the MTL (Fig. 8A). A small number of igneous rocks showing ages of 110–90 Ma are also recognized in the Chubu and Kinki areas, independent of the overall trend of younger age at greater distances from the MTL (Fig. 8A). More careful tracing of the migration of the locus of igneous activity with time shows that the isochronous lines are oriented roughly parallel to the modern lines of latitude in a direction ~ 15–20 degrees oblique to the MTL (Figs. 6, 8B, Additional files 1, 2: Table S1). When plotted in a space with horizontal axes of latitude and longitude and a vertical axis of age, the geochronological data define a clear planer surface (Figs. 8B, Additional files 1, 2: Table S1). This surface shows a horizontal migration of 300 km migration of the arc associated with a change in age from 110 to 60 Ma. The average migration rate of the arc calculated from this observation is ~ 6–7 km/Myr, which is in good agreement with the rates of migration recorded in NE Japan. On the continental side of the arc, there is vigorous igneous activity 115–90 Ma, which is followed by a quieter period 90–70 Ma and a phase of moderate activity 70–60 Ma. Thus, the region north of ~ 35°N records two peaks of igneous activity at 110–90 Ma and 70–60 Ma. The spatiotemporal trends of the > 60 Ma igneous activity of SW Japan do not extend southward beyond the MTL. In the area between the TTL and ISTL (identified as part of SW Japan in Fig. 2), a less distinct spatial change is recognized, although the area does show a similar bimodal age distribution with activity peaks at 110–90 Ma and 75–60 Ma (Figs. 6, 7C) similar to the region north of ~ 35°N in SW Japan. Most of the areas around the TTL on the NE Japan side show ages in the range 105–95 Ma, and thus, the TTL forms the border between the age distribution patterns. As shown in Fig. 6, the two major tectonic lines, the MTL and TTL, crosscut the trends of the > 60 Ma igneous activity.

Magmatic crystallization ages between 60 and 46 Ma are almost completely absent from the rock record. The only exception is the Daito granodiorite, which shows a zircon U–Pb age of 57 Ma (Ishihara and Tani 2013). Other ages from igneous bodies that fall in this age range are all cooling ages (Fig. 8). After 46 Ma, the site of igneous activity changes drastically and becomes concentrated along the Japan Sea coast. The < 46 Ma arc front, which also takes into account the distribution of igneous rocks from 30–20 Ma, is aligned parallel to the MTL and outer zone zonal structures, and no subsequent large-scale migration is recognized. This arc front is roughly consistent with the southern boundary of the San-in Belt in the traditional classification of granitic zones (e.g., Murakami 1974).

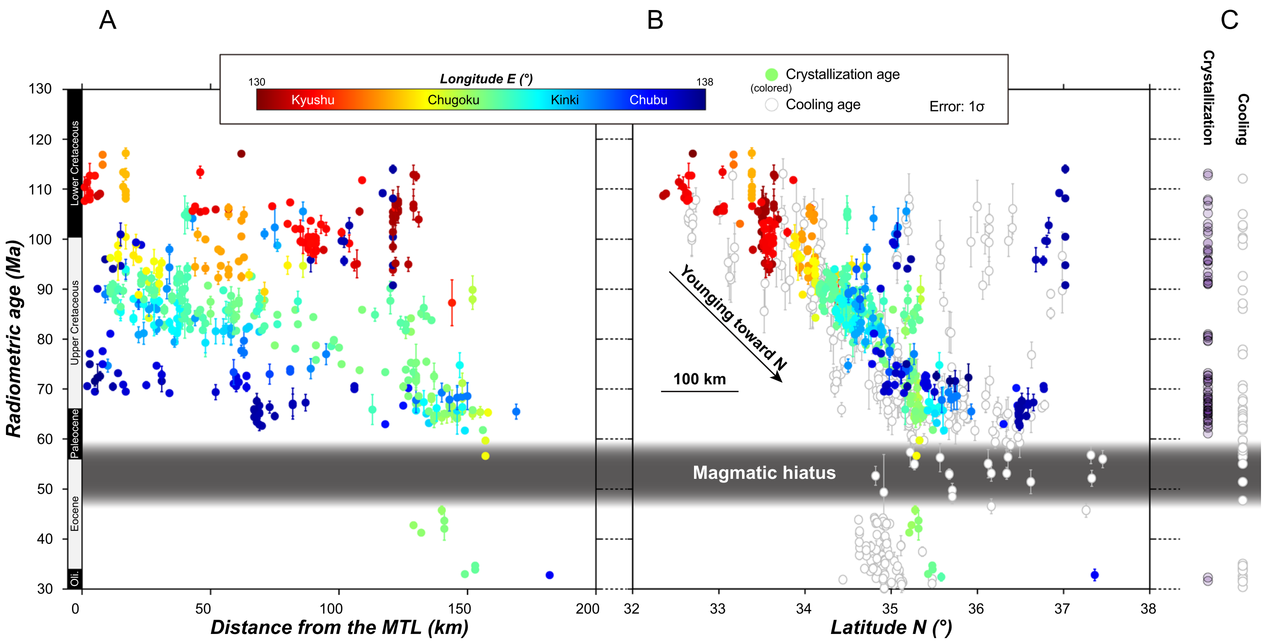

Fig. 8 Spatiotemporal variation of arc igneous activity in SW Japan west of ISTL, with distance from the MTL (**A**) and latitude (**B**) on the horizontal axis. Colored circles indicate crystallization ages. The colors correspond to longitude. White circles in (**B**) indicate cooling ages. The age distribution in the region between the ISTL and TTL is shown in (**C**)

5.2 Adakitic magma and high-Mg andesitic magma

The compiled information on adakite and HMA localities shows a variety of ages and spatial distributions (Figs. 9, 10). In many areas, adakite and HMA show a similar spatial distribution. Based on Sr and Y contents, the ages of both magma types can be separated into three distinct stages (Fig. 10). Data for La and Yb contents in the 100–30 Ma range were not available in sufficient numbers for our discussion, but there is a good correlation between high La/Yb ratios and high Sr/Y ratios for the samples with ages in the 130–100 Ma range (Additional file 3: Table S3). The first adakite- and HMA-related magmatism is observed from NE Japan to Kyushu in the period 130–100 Ma. The second is observed in the period 70–60 Ma in the Chubu region and adjacent to the TTL in SW Japan. The third is observed in the period 45–30 Ma in the Chugoku region, the Noto peninsula, the Oga peninsula, and the Jodogahama area. A comparison of these results with the overall age distribution shows the first stage corresponds to extensive igneous activity that extended over a wide part of the continental margin, whereas the second and third stages correspond to periods immediately before and after the period of magmatic quiescence.

6 Discussion: possible tectonic scenarios

In this section, we use our compilation of data related to the timing, location and type of igneous activity to propose a tectonic history for the Japan arc. We divide this history into four distinct stages: (i) subduction initiation of the Izanagi plate, (ii) subducting slab shallowing, (iii) ridge subduction and clockwise rotation of SW Japan, (iv) subduction of the Pacific plate (Fig. 11).

6.1 Onset of extensive magmatism: subduction initiation of the Izanagi plate

The earliest igneous activity of the Cretaceous is recognized in NE Japan at ~ 130 Ma, and this magmatism is accompanied by significant adakite and calc-alkaline magma production (Tsuchiya et al. 2015; Osozawa et al. 2019) (Fig. 12). Compilations of detrital zircon U–Pb ages from the Shimanto and Sanbagawa belts show a lack of igneous zircons in the 160–130 Ma range, suggesting cessation of igneous activity in the paleo-Japan realm (Fig. 13). The presence of this group of igneous bodies and the age patterns of igneous detrital zircons indicate that igneous activity in Cretaceous Japan initiated with an intense phase at 130 Ma marking a major shift from a lull during 160–130 Ma. The significance of the period in

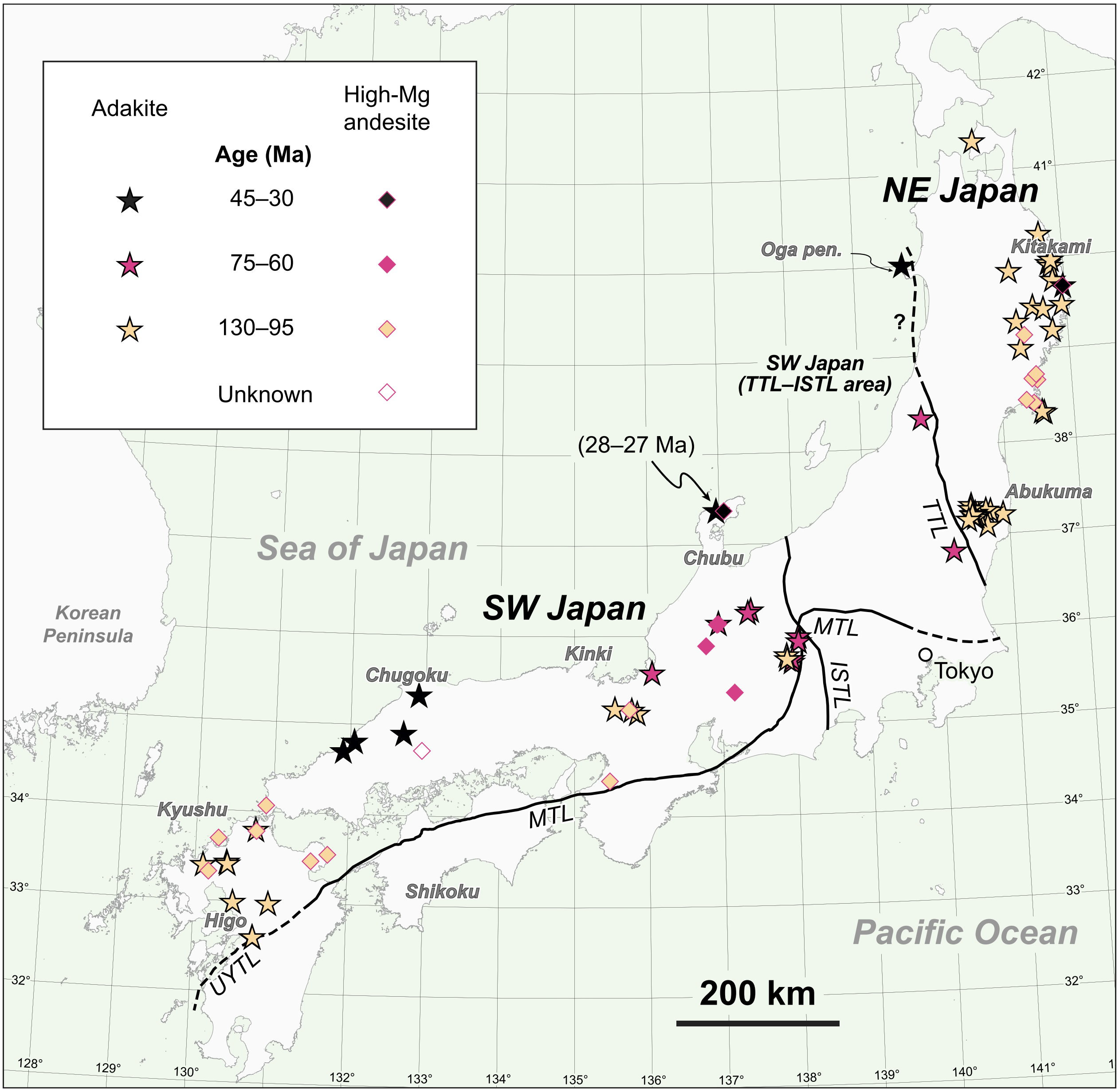

Fig. 9 Spatial distribution of adakite and high-Mg andesitic magmas. Both types of magma are represented by different symbols for each active stage. Data sources are shown in Additional files 3, 4: Table S2

the geological development of east Asia is shown by the similar magmatic histories observed in the Korean Peninsula (e.g., Sagong et al. 2005) and the Sikhote-Alin area (e.g., Wu et al. 2017).

We interpret the onset of this igneous activity as marking the onset of active subduction of a former plate generally identified as the Izanagi Plate (Woods and Davies 1982). Initiation of subduction of the Izanagi plate has been linked to both the termination of a phase of flat slab subduction of a marginal oceanic plate, and subduction at a former transform boundary due to a change in relative plate motion (Khanchuk et al. 2016; Grebennikov et al. 2016; Wu et al. 2022a, b).

The onset of subduction is expected to be associated with the formation of a hot and juvenile mantle upwelling due to the presence of a slab gap and/or the development of a return flow in the mantle as the slab is subducted (Wu et al. 2022a; b). The formation of adakites and

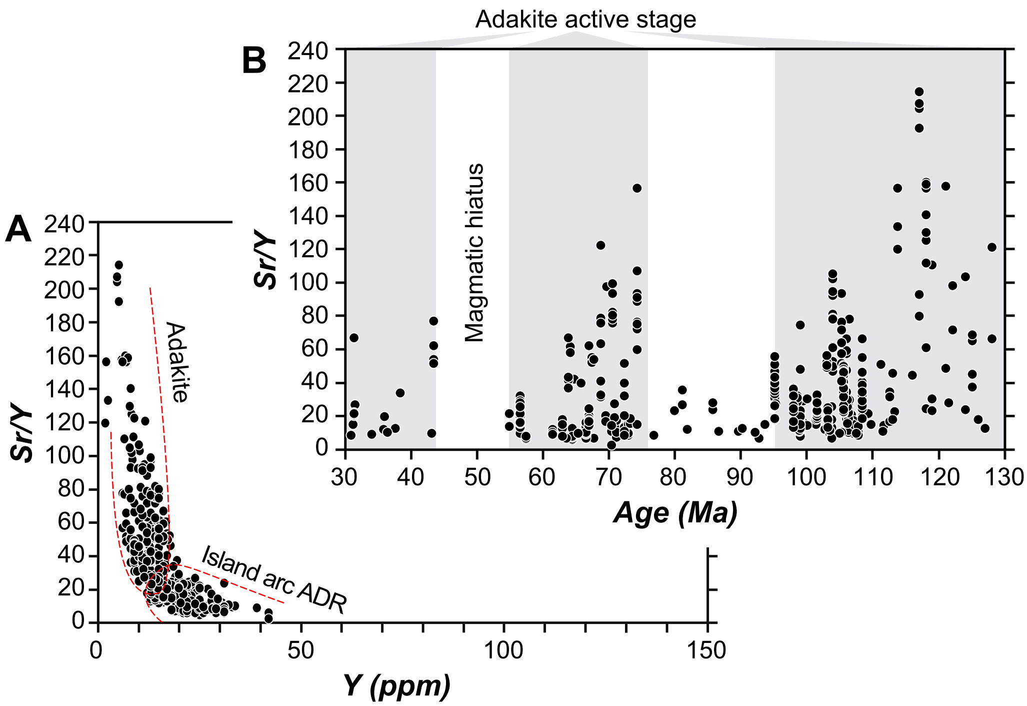

Fig. 10 **A** Adakite discrimination diagram using Sr and Y content in felsic magma during the period 130–30 Ma (Defant and Drummond 1990). Rocks showing $SiO_2 < 56$ wt%, $Al_2O_3 < 14.5$ wt% and $Na_2O < 3$ wt% are not included in the plot to find Sr and Y features in the range of major elements typical of adakite (e.g., Castillo 2012). ADR = andesite–dacite–rhyolite. **B** Re-plotted data of (**A**) with age as the horizontal axis. High-Sr/Y ratios signify adakite activity. The data sources are shown in Additional file 3: Table S3

HMAs in the period 130–95 Ma can be interpreted as magma generated as a result of the interaction of the subducting slab with this hot mantle (Fig. 11A, B). Furthermore, such high-temperature mantle influx can induce long-term and widespread mantle-tectonic thermal anomalies (Fig. 11B). Thus, it can explain the extended igneous activity on the continental side of SW Japan that continues up to 90 Ma. Evidence for widespread igneous activity from 120 to 90 Ma can be traced to the Korean Peninsula (e.g., Kim et al. 2012; Zhang et al. 2021).

Further evidence for subduction initiation at this time is also given by studies of metamorphic rocks. A counterclockwise *P*–*T* path showing isobaric cooling documented in higher-grade units of the subduction-type Sanbagawa metamorphic belt associated with a peak metamorphic age of 126–116 Ma has been interpreted by Endo (2010) and Endo et al. (2012) in terms of subduction initiation. The presence of highly depleted ultramafic rocks of mantle wedge origin in the same unit showing high degrees of influx partial melting is compatible with high-*T* conditions and active mantle flow associated with the early stages of the Sanbagawa metamorphism (Mizukami and Wallis 2005; Hattori et al. 2010).

The common occurrence of thick pelagic charts accompanying units showing accretion ages around the Albian–Aptian in the Shimanto belt (e.g., Ota et al. 2019) and the relationship between monotonous landward arc migration and younger plate ages as shown in the next section, suggest that the subducting oceanic plate subducting beneath Japan during the mid-Cretaceous was not young.

(See figure on next page.)

Fig. 11 Conceptual tectonic model for SW Japan that can explain the spatiotemporal evolution of arc magmatism. The onset of subduction of the Izanagi plate (IZA) beneath the eastern margin of Eurasia (**A**), the migration of the arc front to the continental side accompanied by slab shallowing due to the approach of the spreading ridge (**B**–**D**), cessation of the arc magmatism accompanied by ridge subduction and formation of the slab window (**E**), and the onset of subduction of the Pacific plate (PAC) after spreading ridge subduction (**F**) are shown. The remnants of the arc formed during (**A**–**D**) are oriented at an angle of about 20 degrees to the present arc orientation shown in (**F**). This rotation suggests microplate rotation associated with the IZA–PAC ridge subduction

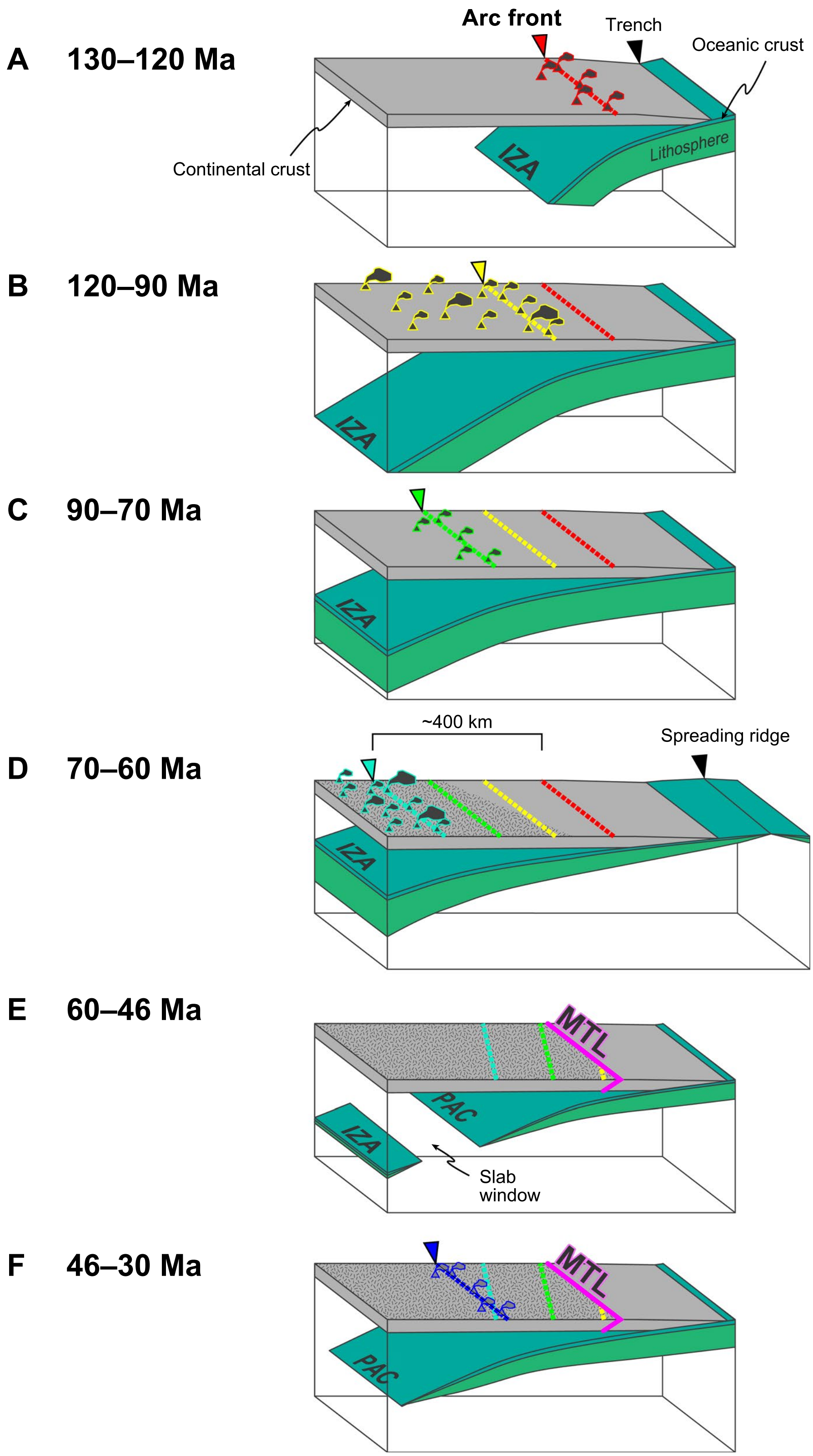

Fig. 11 (See legend on previous page.)

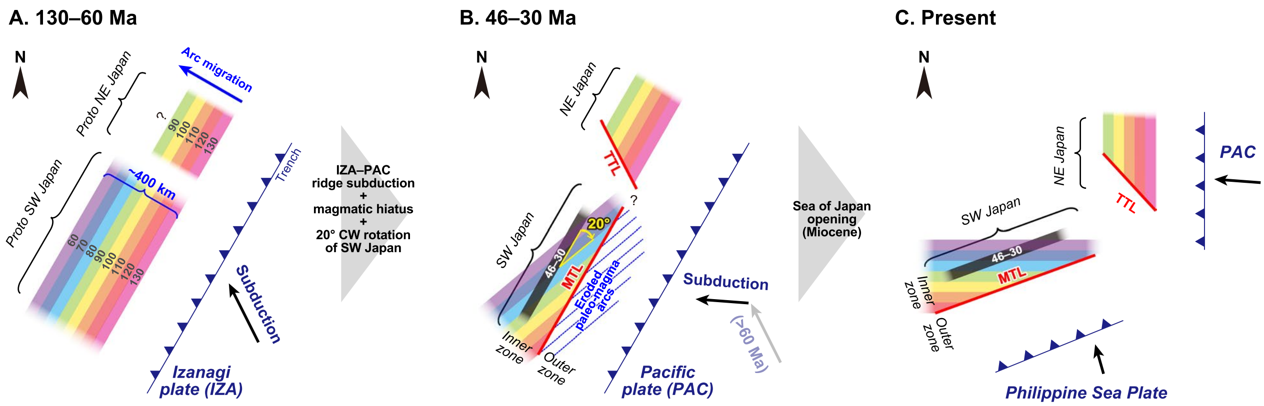

Fig. 12 Schematic illustration of magma arc configuration changes in SW and NE Japan for the periods 130–60 Ma (**A**) and 46–30 Ma (**B**) and the present (**C**) in map view. The colored bars indicate the general locations of arc fronts. Subduction of the Izanagi-Pacific Ridge between 60 and 46 Ma produced a magmatic hiatus, and the change in convergence vector associated with the change in the subducting plate induced a 20° clockwise rotation (CW) of the inner zone of SW Japan and possibly the Korean peninsula. **B** The blue dotted line indicates that the eastern part of the paleo-magmatic arc has been eroded to a greater extent in the east in association with MTL activity during the period 60–46 Ma. For simplicity, the TTL–ISTL regions where the IBM arc collided with the other Japanese arcs and the location of the magmatic arc after 30 Ma are not shown in (**C**)

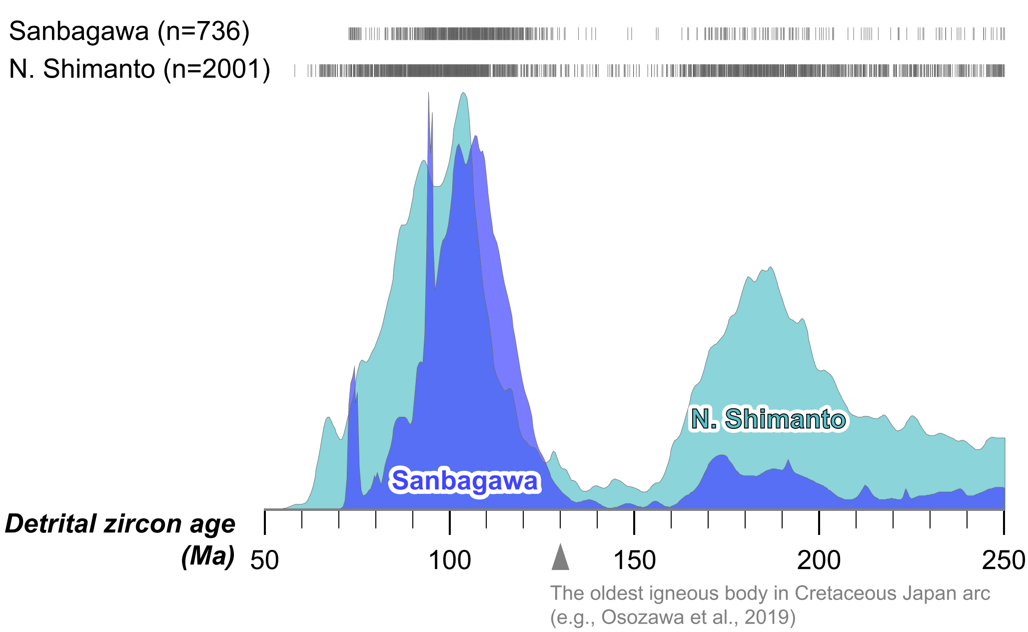

Fig. 13 Probability density plot based on a complication of U–Pb ages from detrital zircons in the Sanbagawa and Northern Shimanto belts in representative literatures. The source data do not include U–Pb ages for zircon rims grown by metamorphism, all of which can be interpreted as igneous ages. The bars show the U–Pb age for each analysis. Sanbagawa: Okamoto et al. (2004), Aoki et al. (2007, 2012, 2009), Tsutsumi et al. (2009, 2012), Knittel et al. (2014), Endo et al. (2018), Jia and Takeuchi (2020), Shimanto: Aoki et al. (2012, 2015), Tokiwa et al. (2019, 2017, 2021), Shimura et al. (2017, 2020, 2021) and Jia and Takeuchi (2020)

6.2 Arc migration: subducting slab shallowing 130–60 Ma

In NE and SW Japan, there is evidence of arc migration at similar rates of 6–7 km/Myr. The younging trends of currently observed paleo-magma arcs formed in the period > 60 Ma show a nearly orthogonal relationship between NE and SW Japan. However, reversing the NE Japan and SW Japan rotation vectors related to the Miocene Japan Sea opening, as estimated on the basis of paleomagnetic studies (e.g., Otofuji et al. 1985; Hoshi 2018), shows the younging trends in both NE Japan and SW Japan are oriented roughly parallel to the former continental margin (Fig. 12). These similarities allow

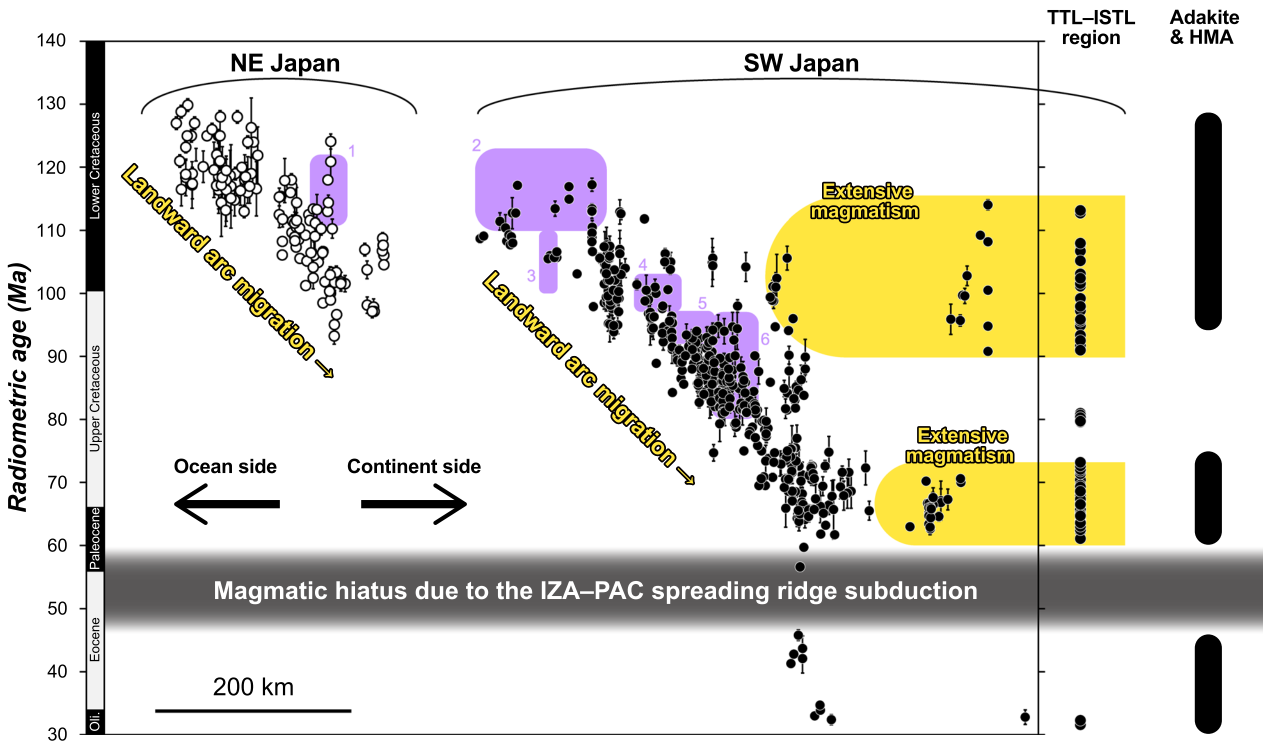

Fig. 14 Summary of arc magmatism 130–30 Ma. The white circles in the left show the crystallization ages in NE Japan as in Fig. 7. The black circles show the crystallization ages in SW Japan as in Fig. 8B, C. The age ranges of occurrences of adakite and high-Mg andesitic (HMA) magma are shown on the right side. Metamorphic ages based on zircon U–Pb chronology for the high-T/P type metamorphism are shown in purple. 1: Abukuma metamorphism (Hiroi et al. 1998). 2: Higo metamorphism (Sakashima et al. 2003; Maki et al. 2014; Tsutsumi 2020; Kawaguchi et al. 2020). 3–6: Ryoke metamorphism (Skrzypek et al. 2018; Takatsuka et al. 2018; Kawakami et al. 2019, 2022; Miyazaki et al. 2022)

us to interpret the present NE Japan and SW Japan age distributions as different parts of the same former magmatic arc (Fig. 12A). The absence of a rock record of the 130–120 Ma arc in the western part of SW Japan can be explained by excision due to movements on the MTL and erosion. These ideas are compatible with proposals for the former existence of a 'paleo-Ryoke' domain, which is originally located to the south of the present Ryoke belt prior to MTL activity (Fig. 12B, Ichikawa 1990; Ono 2002; Takagi and Shibata 2000; Takagi and Arai 2003). In this study, we estimate that the magmatic arc migrated away from the trench over a distance of ~ 400 km (Fig. 14). Such large-scale continentward migration of the arc is best explained by shallowing of the dip of the subducting slab (Fig. 11B, C; Gianni and Pérez Luján 2021). As we show in the following section, such shallowing is consistent with increased buoyancy of the subducting slab as its age decreases until the ridge reaches the subduction zone between 60 and 46 Ma.

The approach or subduction of an active spreading ridge has commonly been called on to explain the *P*–*T* conditions of the Ryoke metamorphic rocks (e.g., Brown 1998; Iwamori 2000). However, the spatiotemporal configuration of high-*T* metamorphism including that in the Abukuma, and Higo regions is in good agreement with the major younging trends we found in the distribution of paleo-magma arcs, indicating that high-*T* metamorphism occurred in association with major arc magmatism for at least 120–80 Ma (Fig. 14). The temporal and spatial proximity of the high-*T* metamorphism to arc magmatism indicates that the high-*T* metamorphism has moved continentward with time together with the main magma arc trend and that these *P*–*T* conditions are best explained by the subduction of young oceanic lithosphere at some distance from the spreading ridge. Since the age and subduction angle of the subducting slab may have changed with time, the slightly older Abukuma–Higo metamorphism (~ 120–110 Ma) is likely associated with older slab ages and deeper subduction angles, and more recent Ryoke metamorphism (~ 110–80 Ma) with younger and shallower subduction.

6.3 Magmatic hiatus: ridge subduction at 60–46 Ma

The 60–46 Ma magmatic hiatus in southwest Japan recognized in this study can be correlated with that of Wu and Wu (2019). However, since igneous activity several million years younger than 60 Ma is reported not only from the Daito granodiorite but also the Korean Peninsula and detrital zircon chronology (e.g., Tokiwa et al. 2016; Cheong and Jo 2017; Nakano et al. 2021), it is possible that more data on igneous ages in SW Japan will show the start of this magmatic hiatus is somewhat younger.

As discussed by Wu and Wu (2019), the 60–46 Ma hiatus in igneous activity is best explained by the arrival of the Izanagi–Pacific spreading ridge at a low angle to the trench. This hypothesis implies that the periods just before and after the magmatic hiatus should be associated with young slab subduction. Adakite and HMA igneous activity is commonly interpreted as associated with subduction of young oceanic lithosphere and the presence of these types of magmatism immediately before and after the igneous hiatus supports the idea of ridge subduction during the 60–46 Ma igneous hiatus (Figs. 9, 12).

In more general terms, the 70–60 Ma period represents an igneous flare up stage with widespread and voluminous igneous activity accompanied by very large ignimbrite forming events typified by the Nohi-rhyolite deposits (Koido 1991; Yamada and Koido 2005; Sonehara and Harayama 2007). Likewise, igneous activity after 46 Ma is also characterized by high activity with numerous caldera formations (e.g., Imaoka et al. 2011). These stages associated with common caldera-formation both before and after ridge subduction may be related to high crustal temperatures due to subduction of younger slabs and the presence of tensile stress fields.

6.4 Clockwise rotation of SW Japan during the ridge subduction time

The > 1000-point igneous age compilation allows the recognition of two linear non-parallel arrays of former arcs in the SW Japan basement (Fig. 6). The linear nature of the arrays shows there has been minimal deformation within the separate basement domains and the main effect of crustal movements has been to cause rotations about vertical axes. The ages of the arc arrays and their obliquity allow us to estimate the timing and of this rotation of the different basement domains or blocks. The locations of the arc arrays can also be used as marker horizons to estimate displacement of the blocks.

We interpret the observed ~ 20° obliquity between the 46–30 Ma arc and the 130–60 Ma arc as representing a clockwise rotation of the inner zone of SW Japan between 60 and 46 Ma (Fig. 11). Since the overall age trend of igneous activity before 60 Ma in the Chubu region and ISTL–TTL regions is very similar, we consider the ISTL–TTL region acted as a continuous microplate to the west of ISTL region during the period 130–60 Ma. However, the TTL and MTL cross-cut the continuous 130–60 Ma arc sequence seen in SW Japan, indicating that both these tectonic lines are major boundaries between two distinct microplates and their cross-cutting relationships developed after 60 Ma. The age gap along the TTL is recognized between the ~ 105 Ma arc in NE Japan and magmatic activity on continent side of the 65–60 Ma arc in SW Japan. This gap indicates that there is at least a 200 km arc-normal component of sinistral displacement along the TTL relative to NE Japan. Hence, the trend noted in previous studies that the igneous age of the Cretaceous arc front near the MTL is younger to the east can be explained by clockwise rotation of the inner zone of SW Japan relative to the outer zone and NE Japan, and the loss of the eastern part of the arc due to movement along the MTL (Figs. 11, 12). This crustal loss is discussed in Sect. 6.5.

Paleomagnetism is an ideal method to test for the rotation about a vertical axis proposed in this study. Two such studies by Fukuma et al. (2003) and Uno et al. (2021) report a ~ 20 degrees clockwise rotation of the SW Japan basement area between 70 and 20 Ma that occurred prior to rotation associated with the Miocene Japan Sea opening event (Otofuji et al. 1985). The good continuity and parallel nature within each of the 70–60 Ma and 46–20 Ma arcs revealed in our data set imply rotation did not occur during these periods. This is in agreement with the results of Fukuma et al. (2003) and Uno et al. (2021) but potentially narrows the timing of rotation to the period 60–46 Ma.

A similar rotational history has been confirmed at multiple locations around the Korean Peninsula (Fig. 1; Lin et al. 2003; Huang et al. 2007), suggesting that clockwise rotation relative to Eurasia continent may have occurred within a 1000 km-scale microplate that includes SW Japan (Fig. 1; Uno et al. 2021).

A change in the direction of oceanic plate subduction may help explain the trigger for the rotational motion. Recent oceanic plate reconstructions and analysis of deformational structures as kinematic indicator in the Shimanto accretionary complexes suggest there was a significant rapid shift from pre-ridge subduction of the Izanagi plate with a sinistral lateral convergence to a dextral lateral convergence of the Pacific plate after ridge subduction (Whittaker et al. 2007; Byrne and DiTullio 1992; Onishi and Kimura 1995; Raimbourg et al. 2014; Müller et al. 2022). This counterclockwise change in convergence vector changes the overlying plate at the eastern margin of the Asian continent into a dextral transpression zone, which in turn allows clockwise rotation of the inner zone of southwest Japan (Fig. 12).

Ridge subduction and the resulting plate rearrangement have the potential to have a major influence on regional geology. A series of fault basins around the

Japan Sea and the East China Sea have been recognized that developed or reactivated during the period we propose corresponds to the phase of the Izanagi–Pacific ridge subduction (Fig. 1). The development of these basin-forming faults may have been influenced by mantle flow driven by subduction of the Izanagi plate or Izanagi–Pacific ridge and the changes in subduction vectors described above (Cao et al. 2018). A multistage faulting system in the Bohai Bay Basin including movements before and after the proposed time of ridge subduction records a clockwise shift of the main extensional trend of basin-forming lifting compatible with our proposed rotation history (Zhu et al. 2020; Yuan et al. 2022) and suggests that the switching of subducting oceanic plates with different convergent vectors can result in widespread deformation of the continental margin.

6.5 Crustal erosion: relationship with the Median Tectonic Line

Reconstructions of Cretaceous–Paleogene arc migration in SW Japan suggest the presence of a stage of large-scale crustal removal along the MTL. The recognition of an arc deficit and the ~ 20 degrees obliquity of the SW Japan arc front to the MTL indicates that shallower crustal erosion occurred associated with block rotation of SW Japan during 60–46 Ma (Fig. 12).

The locations of the paleo-arcs can be used to estimate the amount of material lost perpendicular to the arc. If the parallelism of the paleo-arcs is preserved, the crustal loss can be estimated as the distance to the envisaged 130 Ma arc front. For example, since arc fronts of the 110–100 Ma and 70–60 Ma periods can be observed in the Kyushu and Chubu regions, respectively; the horizontal distances perpendicular to the 130 Ma arc estimated based on arc migration rates (6–7 km/Myr) are 100–200 km and 400–500 km. Note that these estimated amounts of crustal shortening are assumed to be all accounted for by the CW block rotation, but they are minimum estimates because they do not consider the possibility of erosion of the forearc region between the 130 Ma arc and the younger accretionary complexes.

The age of igneous activity constrains the timing of crustal removal associated with block rotation to have occurred 60–46 Ma. The crustal removal during this stage is inferred to have been surface erosion, since the MTL during the relevant period shows large-scale normal fault movement with the foot wall on the outer zone side uplifting (Kobayashi 1995; Fukunari and Wallis 2007; Kubota and Takeshita 2008; Kubota et al. 2020). Large-scale normal fault movement at this time is also supported by the exposure of the Sanbagawa metamorphic belt (Narita et al. 1999; Kusuhashi et al. 2022).

7 Conclusions

A reassessment of the spatiotemporal evolution of felsic to intermediate arc magmatism in NE and SW Japan in the period 130–30 Ma based on a compilation of a 1227-entry database, combined with geochemical considerations and contemporaneous the geological events in Japan and surrounding regions leads to the following conclusions.

1. Arc magmatism occurred throughout the period 130–60 Ma in both northeastern and southwestern Japan and during this period underwent a ~ 400 km migration toward the continental side. This migration is best accounted for by a shallowing of the slab subducting angle associated with a slab progressively younging following the onset of subduction of old lithosphere of the Izanagi plate at around 130–120 Ma.
2. Cessation of arc magmatism is recognized in the period 60–46 Ma throughout the Japanese arc and is explained by the subduction of the Izanagi–Pacific spreading ridge subparallel to the trench.
3. A new volcanic arc formed in the period 46–30 Ma in SW Japan and remained in a similar location throughout this time with no significant arc migration.
4. The ~ 20° obliquity between the 46–30 Ma arc and the 130–60 Ma arc suggests a clockwise rotation of the inner zone of SW Japan during the ridge subduction stage. Such a rotation is supported by paleomagnetic data. The proposed rotation is accompanied by dextral transpression tectonics immediately after the Izanagi–Pacific ridge subduction.
5. Magmatic arcs developed during the period 130–30 Ma in Japan provide a robust reference frame for analyzing microplate rotational motion and recognizing localized crustal excision within this convergent plate margin domain.

Abbreviations

MTL	Median Tectonic Line
TTL	Tanakura Tectonic Line
ISTL	Itoigawa–Shizuoka Tectonic Line
UYTL	Usuki–Yatsushiro Tectonic Line

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40645-023-00594-8.

Additional file 1: Table S1. References.

Additional file 2: Table S1. List of compiled ages on igneous rock from southwest Japan (SWJ) and northeast Japan (NEJ).

Additional file 3: Table S2 and S3. References.

Additional file 4: Table S2. Summary of descriptions of 130–30 Ma adakite and High-Mg andesite.

Additional file 5: Table S3. List of Sr & Y features for Cretaceous–Paleogene igneous rock with chronological data.

Acknowledgements
We are grateful to two anonymous reviewers and the editor Tim Byrne for constructive comments on the manuscript.

Author contributions
Conceptualization, methodology, writing, review and editing were contributed by KY and SW. Data were analyzed by KY. All authors read and approved the final manuscript.

Funding
This work was supported by JSPS Grants-in-Aid, 20J20834 and 23K19076 awarded to KY, and 21H01188 and 21H05202 awarded to SW.

Availability of data and materials
The datasets supporting the conclusions of this article are included within the article and its Additional files 1, 2, 3, 4, 5.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 17 July 2023 Accepted: 6 October 2023
Published online: 20 October 2023

References

Amante C, Eakins BW (2009) ETOPO1 1 arc-minute global relief model: procedures, data sources and analysis, NOAA technical memorandum NESDIS NGDC-24. Natl Geophys Data Center NOAA. https://doi.org/10.7289/V5C8276M.Accessed23Oct2022

Aoki K, Iizuka T, Hirata T, Maruyama S, Terabayashi M (2007) Tectonic boundary between the Sanbagawa belt and the Shimanto belt in central Shikoku, Japan. J Geol Soc Jpn 113:171–183. https://doi.org/10.5575/geosoc.113.171

Aoki K, Kitajima K, Masago H, Nishizawa M, Terabayashi M, Omori S, Yokoyama T, Takahata N, Sano Y, Maruyama S (2009) Metamorphic P-T–time history of the Sanbagawa belt in central Shikoku, Japan and implications for retrograde metamorphism during exhumation. Lithos 113:393–407. https://doi.org/10.1016/j.lithos.2009.04.033

Aoki K, Isozaki Y, Yamamoto S, Maki K, Yokoyama T, Hirata T (2012) Tectonic erosion in a Pacific-type orogen: detrital zircon response to Cretaceous tectonics in Japan. Geology 40:1087–1090. https://doi.org/10.1130/G33414.1

Aoki K, Isozaki Y, Sakata S, Sato T, Yamamoto S, Hirata T (2015) Detrital zircon geochronology of sandstones from Jurassic and Cretaceous accretionary complexes in the Kanto Mountains, Japan: implications for arc provenance. Eng Geol Jpn 5:11–27

Aoya M, Uehara S, Matsumoto M, Wallis SR, Enami M (2003) Subduction-stage pressure-temperature path of eclogite from the Sambagawa belt: Prophetic record for oceanic-ridge subduction. Geology 31:1045–1048. https://doi.org/10.1130/G19927.1

Aoya M, Mizukami T, Uehara S, Wallis SR (2009) High-*P* metamorphism, pattern of induced flow in the mantle wedge, and the link with plutonism in paired metamorphic belts. Terra Nova 21:67–73. https://doi.org/10.1111/j.1365-3121.2008.00860.x

Bradley DC, Haeussler PJ, Kusky TM (1993) Timing of early tertiary ridge subduction in southern Alaska. In: Dusel-Bacon C, Till AB (eds) Geologic studies in Alaska by the U.S. Geological Survey, U.S. Geological Survey Bulletin 2068, pp 163–177. https://doi.org/10.3133/b2068

Bradley DC, Kusky TM, Haeussler PJ, Goldfarb RJ, Miller ML, Dumoulin JA, Nelson SW, Karl SM (2003) Geologic signature of early Tertiary ridge subduction in Alaska. In: Sisson VB, Roeske SM, Pavlis TL (eds) Geology of a transpressional orogen developed during ridge-trench interaction along the North Pacific margin. GSA Special Papers 371, pp 19–49. https://doi.org/10.1130/0-8137-2371-X.19

Brown M (1998) Unpairing metamorphic belts: *P-T* path and a tectonic model for the Ryoke Belt, southwest Japan. J Metamorph Geol 16:3–22. https://doi.org/10.1111/j.1525-1314.1998.00061.x

Byrne T, DiTullio L (1992) Evidence for changing plate motions in southwest Japan and reconstructions of the Philippine Sea plate. Island Arc 1:148–165. https://doi.org/10.1111/j.1440-1738.1992.tb00066.x

Castillo PR (2012) Adakite petrogenesis. Lithos 134–135:304–316. https://doi.org/10.1016/j.lithos.2011.09.013

Cao X, Flament N, Müller D, Li S (2018) The dynamic topography of eastern China since the latest Jurassic period. Tectonics 37:1274–1291. https://doi.org/10.1029/2017TC004830

Chapman JB, Ducea MN, DeCelles PG, Profeta L (2015) Tracking changes in crustal thickness during orogenic evolution with Sr/Y: an example from the North American Cordillera. Geology 43:919–922. https://doi.org/10.1130/G36996.1

Cheong AC-S, Jo HJ (2017) Crustal evolution in the Gyeongsang Arc, southeastern Korea: geochronological, geochemical and Sr–Nd–Hf isotopic constraints from granitoid rocks. Am J Sci 317:369–410. https://doi.org/10.2475/03.2017.03

Chiaraida M (2015) Crustal thickness control on Sr/Y signatures of recent arc magmas: an Earth scale perspective. Sci Rep 5:8115. https://doi.org/10.1038/srep08115

Defant MJ, Drummond MS (1990) Derivation of some modern arc magmas by melting of young subducted lithosphere. Nature 347:662–665. https://doi.org/10.1038/347662a0

Endo S (2010) Pressure-temperature history of titanite-bearing eclogite from the Western Iratsu body, Sanbagawa Metamorphic Belt, Japan. Island Arc 19:313–335. https://doi.org/10.1111/j.1440-1738.2010.00708.x

Endo S, Wallis SR, Tsuboi M, Aoya M, Uehara S (2012) Slow subduction and buoyant exhumation of the Sanbagawa eclogite. Lithos 146–147:183–201. https://doi.org/10.1016/j.lithos.2012.05.010

Endo S, Miyazaki K, Danhara T, Iwano H, Hirata T (2018) Progressive changes in lithological association of the Sanbagawa metamorphic complex, Southwest Japan: relict clinopyroxene and detrital zircon perspectives. Island Arc 27:e12261. https://doi.org/10.1111/iar.12261

Engebretson DC, Cox A, Gordon RG (1985) Relative Motions between oceanic and continental plates in the Pacific Basin. GSA Special Papers 206. https://doi.org/10.1130/SPE206-p1

Faccenna C, Becker TW, Lallemand S, Steinberger B (2012) On the role of slab pull in the Cenozoic motion of the Pacific plate. Geophys Res Lett 39:L03305. https://doi.org/10.1029/2011GL050155

Fukuma K, Tsurudome H, Torii M (2003) A late Cretaceous paleomagnetic pole from Koto rhyolite, southwest Japan: Implications for eastern margin deformation of Asia. J Geophys Res Solid Earth 108:2544. https://doi.org/10.1029/2001JB000425

Fukunari T, Wallis SR (2007) Structural evidence for large-scale top-to-the-north normal displacement along the Median Tectonic Line in southwest Japan. Island Arc 16:243–261. https://doi.org/10.1111/j.1440-1738.2007.00570.x

Geological Survey of Japan, AIST (2022) Seamless digital geological map of Japan V2 1: 200,000. https://gbank.gsj.jp/seamless. Accessed 17 June 2022

Gianni GM, Pérez Luján S (2021) Geodynamic controls on magmatic arc migration and quiescence. Earth Sci Rev 218:103676. https://doi.org/10.1016/j.earscirev.2021.103676

Grebennikov AV, Khanchuk AI, Gonevchuk VG, Kovalenko SV (2016) Cretaceous and Paleogene granitoid suites of the Sikhote-Alin area (Far East Russia): Geochemistry and tectonic implications. Lithos 261:250–261. https://doi.org/10.1016/j.lithos.2015.12.020

Gu C, Zhu G, Zhang S, Liu C, Li Y, Lin S, Wang W (2017) Cenozoic evolution of the Yilan-Yitong Graben in NE China: an example of graben formation controlled by pre-existing structures. J Asian Earth Sci 146:168–184. https://doi.org/10.1016/j.jseaes.2017.05.024

Harada T, Nagata M, Ogita Y, Kagami S, Yokoyama T (2023) Zircon U–Pb–Hf isotopes and whole-rock geochemistry of rhyolite and tuff from the Harachiyama formation, North Kitakami Mountains, NE Japan. Geogr (chigaku Zasshi) 132:57–65. https://doi.org/10.5026/jgeography.132.57

Hattori K, Wallis S, Enami M, Mizukami T (2010) Subduction of mantle wedge peridotites: evidence from the Higashi-akaishi ultramafic body in the Sanbagawa metamorphic belt. Island Arc 19:192–207. https://doi.org/10.1111/j.1440-1738.2009.00696.x

Hibbard JP, Karig DE (1990) Structural and magmatic responses to spreading ridge subduction: an example from southwest Japan. Tectonics 9:207–230. https://doi.org/10.1029/TC009i002p00207

Hiroi Y, Kishi S, Nohara T, Sato K, Goto J (1998) Cretaceous high-temperature rapid loading and unloading in the Abukuma metamorphic terrane, Japan. J Metamorph Geol 16:67–81. https://doi.org/10.1111/j.1525-1314.1998.00065.x

Huang B, Piper JDA, Zhang C, Li Z, Zhu R (2007) Paleomagnetism of Cretaceous rocks in the Jiaodong Peninsula, eastern China: insight into block rotations and neotectonic deformation in eastern Asia. J Geophys Res Solid Earth 112:B03106. https://doi.org/10.1029/2006JB004462

Ichikawa K (1990) Pre-Cretaceous terranes of Japan. In Ichikawa K, Mizutani S, Hara I, Hada S, Yao A (eds) Pre-Cretaceous terranes of Japan. Publication of IGCP Project No. 224, pp 1–12

Imaoka T, Kiminami K, Nishida K, Takemoto M, Ikawa T, Itaya T, Kagami H, Iizumi S (2011) K-Ar age and geochemistry of the SW Japan Paleogene cauldron cluster: Implications for Eocene–Oligocene thermo-tectonic reactivation. J Asian Earth Sci 40:509–533. https://doi.org/10.1016/j.jseaes.2010.10.002

Hoshi H (2018) Miocene clockwise rotation of Southwest Japan. J Geol Soc Japan 124:675–691. https://doi.org/10.5575/geosoc.2017.0056. (**in Japanese with English abstract**)

Ishihara S, Tani K (2013) Zircon age of granitoids hosting molybdenite-quartz vein deposits in the central Sanin Belt. Shigen-Chishitsu 63:11–14. https://doi.org/10.11456/shigenchishitsu.63.11. (**in Japanese with English abstract**)

Ishii K, Wallis SR (2020) High- and low-stress subduction zones recognized in the rock record. Earth Planet Sci Lett 531:115935. https://doi.org/10.1016/j.epsl.2019.115935

Isozaki Y, Aoki K, Nakama T, Yanai S (2010) New insight into a subduction-related orogen: a reappraisal of the geotectonic framework and evolution of the Japanese Islands. Gondowana Res 18:82–105. https://doi.org/10.1016/j.gr.2010.02.015

Iwamori H (2000) Thermal effects of ridge subduction and its implications for the origin of granitic batholith and paired metamorphic belts. Earth Planet Sci Lett 181:131–144. https://doi.org/10.1016/S0012-821X(00)00182-5

Jia S, Takeuchi M (2020) Sedimentary history and provenance analysis of the Sanbagawa Belt in eastern Kii Peninsula, Southwest Japan, based on detrital zircon U–Pb ages. J Asian Earth Sci 196:104342. https://doi.org/10.1016/j.jseaes.2020.104342

Jolivet L, Shibuya H, Fournier M (1995) Paleomagnetic rotations and the Japan sea opening. In Taylor B, Natland J (eds) Active margins and marginal basins of the Western Pacific. Geophysical Monograph Series, vol 88. AGU, Washington D.C., pp 355–369. https://doi.org/10.1029/GM088p0355

Kaeding M, Forsythe RD, Nelson EP (1990) Geochemistry of the Taitao ophiolite and near-trench intrusions from the Chile margin triple junction. J S Am Earth Sci 3:161–177. https://doi.org/10.1016/0895-9811(90)90001-H

Kamei A (2004) An adakitic pluton on Kyushu Island, southwest Japan arc. J Asian Earth Sci 24:43–58. https://doi.org/10.1016/j.jseaes.2003.07.001

Kawaguchi K, Hayasaka Y, Das K, Shibata T, Kimura K (2020) Zircon U–Pb geochronology of "*Sashu mylonite*", eastern extension of Higo plutono-metamorphic complex, Southwest Japan: Implication for regional tectonic evolution. Island Arc 29:e12350. https://doi.org/10.1111/iar.12350

Kawakami T, Horie K, Hokada T, Hattori K, Hirata T (2019) Disequilibrium REE compositions of garnet and zircon in migmatites reflecting different growth timings during single metamorphism (Aoyama area, Ryoke belt, Japan). Lithos 338–339:189–203. https://doi.org/10.1016/j.lithos.2019.04.021

Kawakami T, Ichino T, Kazuratachi K, Sakata S, Takatsuka K (2022) Multistage zircon growth recording polyphase metamorphic evolution caused by pulsed granitoid intrusions into a low-*P/T* type metamorphic belt: *P-T-D-t* evolution of migmatites in the Ryoke belt, southwest Japan. Island Arc 31:e12454. https://doi.org/10.1111/iar.12454

Khanchuk AI, Kemkin IV, Kruk NN (2016) The Sikhote-Alin orogenic belt, Russian South East: terranes and the formation of continental lithosphere based on geological and isotopic data. J Asian Earth Sci 120:117–138. https://doi.org/10.1016/j.jseaes.2015.10.023

Kim SW, Kwon S, Ryu I-C, Jeong Y-T, Choi S-J, Kee W-S, Yi K, Lee YS, Kim BC, Park DW (2012) Characteristics of the Early Cretaceous igneous activity in the Korean Peninsula and tectonic implications. J Geol 120:625–646. https://doi.org/10.1086/667811

Kiminami K, Miyashita S, Kawabata K (1994) Ridge collision and in situ greenstones in accretionary complexes: an example from the Late Cretacesou Ryukyu Islands and southwest Japan. Island Arc 3:103–111. https://doi.org/10.1111/j.1440-1738.1994.tb00098.x

Kimura G, Kitamura Y, Yamaguchi A, Kameda J, Hashimoto Y, Hamahashi M (2019) Origin of the early Cenozoic belt boundary thrust and Izanagi-Pacific ridge subduction in the western Pacific margin. Island Arc 28:e12320. https://doi.org/10.1111/iar.12320

Kinoshita O, Ito H (1986) Migration of Cretaceous igneous activity in Southwest Japan related to ridge subduction. J Geol 92:723–735. https://doi.org/10.5575/geosoc.92.723

Kinoshita O, Ito H (1988) Cretaceous magmatism in Southwest and Northeast Japan related to two ridge subduction and Mesozoic magmatism along East Asia continental margin. J Geol Soc Jpn 94:925–944. https://doi.org/10.5575/geosoc.94.925

Knittel U, Suzuki S, Nishizawa N, Kimura K, Tsai W-L, Lu H-Y, Ishikawa Y, Ohno Y, Yanagida M, Lee Y-H (2014) U–Pb ages of detrital zircons from the Sanbagawa Belt in western Shikoku: additional evidence for the prevalence of Late Cretaceous protoliths of the Sanbagawa metamorphics. J Asian Earth Sci 96:148–161. https://doi.org/10.1016/j.jseaes.2014.09.001

Kobayashi K (1995) Median Tectonic Line in the northern marginal area of the Kanto Mountains, central Japan. J Geol Soc Jpn 101:729–738. https://doi.org/10.5575/geosoc.101.729

Koido Y (1991) A late Cretaceous-Paleogene cauldron cluster: the Nôhi Rhyolite, central Japa. Bull Volcanol 53:132–146. https://doi.org/10.1007/BF00265418

Kubota Y, Takeshita T, Yagi K, Itaya T (2020) Kinematic Analyses and radiometric dating of the large-scale Paleogene two-phase faulting along the Median Tectonic Line, Southwest Japan. Tectonics 39:e2018TC005372. https://doi.org/10.1029/2018TC005372

Kubota Y, Takeshita T (2008) Paleocene large-scale normal faulting along the Median Tectonic Line, western Shikoku, Japan. Island Arc 17:129–151. https://doi.org/10.1111/j.1440-1738.2007.00607.x

Kusuhashi N, Ando Y, Tani K, Matsubara T, Kurita H, Nara M, Yamaji A (2022) The Eocene Hiwadatoge Formation, SW Japan: constraints on the timing of the denudation of the Sambagawa metamorphic rocks. J Geol Soc Jpn 128:411–426. https://doi.org/10.5575/geosoc.2022.0038

Li C, van der Hilst RD, Engdahl ER, Burdick S (2008) A new global model for P wave speed variations in Earth's mantle. Geochem Geophys Geosyst 9:Q05018. https://doi.org/10.1029/2007GC001806

Li Y, Takeuchi M (2021) U–Pb dating of detrital zircon from Permian successions of the South Kitakami Belt, Northeast Japan: clues to the paleogeography of the belt. Island Arc 31:e12435. https://doi.org/10.1111/iar.12435

Lin W, Chen Y, Faure M, Wang Q (2003) Tectonic implications of new Late Cretaceous paleomagnetic constraints from Eastern Liaoning Peninsula, NE China. J Geophys Res Solid Earth 108:B62313. https://doi.org/10.1029/2002JB002169

Liu K, Zhang J, Xiao W, Wilde SA, Alexandrov I (2020) A review of magmatism and deformation history along the NE Asian margin from ca. 95 to 30 Ma: transition from the Izanagi to Pacific plate subduction in the early Cenozoic. Earth-Sci Rev 209:103317. https://doi.org/10.1016/j.earscirev.2020.103317

Liu Y, Liu L, Li Y, Peng D, Wu Z, Cao Z, Li S, Du Q (2022) Global back-arc extension due to trench-parallel mid-ocean ridge subduction. Earth Planet Sci Lett 600:117889. https://doi.org/10.1016/j.epsl.2022.117889

Maki K, Yui T-F, Miyazaki K, Fukuyama M, Wang K-L, Martens U, Grove M, Liou JG (2014) Petrogenesis of metatexite and diatexite migmatites determined using zircon U–Pb age, trace element and Hf isotope data, Higo metamorphic terrane, central Kyushu, Japan. J Metamorph Geol 32:301–323. https://doi.org/10.1111/jmg.12073

Maruyama S, Seno T (1986) Orogeny and relative plate motions: examples of the Japanese Islands. Tectonophysics 127:305–329. https://doi.org/10.1016/0040-1951(86)90067-3
Maruyama S, Isozaki Y, Kimura G, Terabayashi M (1997) Paleogeographic maps of the Japanese Islands: plate tectonic synthesis from 750 Ma to the present. Island Arc 6:121–142. https://doi.org/10.1111/j.1440-1738.1997.tb00043.x
Matthews KJ, Maloney KT, Zahirovic S, Williams SE, Seton M, Müller RD (2016) Global plate boundary evolution and kinematics since the late Paleozoic. Global Planet Change 146:226–250. https://doi.org/10.1016/j.gloplacha.2016.10.002
Miyazaki K, Ikeda T, Iwano T, Hirata T, Danhara T (2022) Kinetics and pulses of zircon growth in migmatites beneath a volcanic arc: an example from the high-T Ryoke Complex, southwest Japan. J Metamorph Geol 41:639–664. https://doi.org/10.1111/jmg.12711
Mizukami T, Wallis SR (2005) Structural and petrological constraints on the tectonic evolution of the garnet-lherzolite facies Higashi-akaishi peridotite body, Sanbagawa belt, SW Japan. Tectonics 24:TC6012. https://doi.org/10.1029/2004TC001733
Müller RD, Sdrolias M, Gaina C, Steinberger B, Heine C (2008) Long-term sea-level fluctuations driven by ocean basin dynamics. Science 319:1357–1362. https://doi.org/10.1126/science.1151540
Müller RD, Flament N, Cannon J, Tetley MG, Williams SE, Cao X, Bodur ÖF, Zahirovic S, Merdith A (2022) A tectonic-rules-based mantle reference frame since 1 billion years ago—implications for supercontinent cycles and plate–mantle system evolution. Solid Earth 13:1127–1159. https://doi.org/10.5194/se-13-1127-202
Murakami N (1974) Some problems concerning late Mesozoic to early Tertiary igneous activity on the inner side of Southwest Japan. Pac Geol 8:139–151
Nakajima T, Shirahase T, Shibata K (1990) Along-arc lateral variation of Rb–Sr and K–Ar ages of Cretaceous granitic rocks in Southwest Japan. Contrib Miner Petrol 104:381–389. https://doi.org/10.1007/BF01575616
Nakano T, Isozaki Y, Tsutsumi Y (2021) New constraints on the distributary pattern of clastics in fore-arc and tectonics in paleogene SW Japan: U–Pb ages of detrital zircons of the Domeki formation in the Shimanto Belt, Western Shikoku. J Geogr (chigaku Zasshi) 130:707–718. https://doi.org/10.5026/jgeography.130.707
Narita K, Yamaji A, Tagami T, Kurita H, Obuse A, Matsuoka K (1999) Depositional age of the Tertiary Kuma Group, Shikoku, and its significance. J Geol Soc Jpn 105:305–308. https://doi.org/10.5575/geosoc.105.305. (**in Japanese with English abstract**)
Okamoto K, Shinjoe H, Katayama I, Terada K, Sano Y, Johnson S (2004) SHRIMP U–Pb zircon dating of quartz-bearing eclogite from the Sanbagawa Belt, south-west Japan: implications for metamorphic evolution of subducted protolith. Terra Nova 16:81–89. https://doi.org/10.1111/j.1365-3121.2004.00531.x
Okudaira T, Suda Y (2011) Cretaceous events at the Eastern Margin of East Asia recorded in rocks of the Ryoke Belt, SW Japan. J Geogr (chigaku Zasshi) 120:452–465. https://doi.org/10.5026/jgeography.120.452. (**in Japanese with English abstract**)
Okudaira T, Yoshitake Y (2004) Thermal consequences of the formation of a slab window beneath the Mid-Cretaceous southwest Japan arc: a 2-D numerical analysis. Island Arc 13:520–532. https://doi.org/10.1111/j.1440-1738.2004.00444.x
Onishi CT, Kimura G (1995) Change in fabric of melange in the Shimanto Belt, Japan: Change in relative convergence? Tectonics 14:1273–1289. https://doi.org/10.1029/95TC01929
Ono A (2002) Comments on researchers of Paleo-Ryoke belts. Struct Geol 46:1–7 (**in Japanese with English abstract**)
Osozawa S, Usuki T, Usuki M, Wakabayashi J, Jahn B-M (2019) Trace elemental and Sr–Nd–Hf isotopic compositions, and U–Pb ages for the Kitakami adakitic plutons: Insights into interactions with the early Cretaceous TRT triple junction offshore Japan. J Asian Earth Sci 184:103968. https://doi.org/10.1016/j.jseaes.2019.103968
Ota A, Takeuchi M, Bayart N, Yamamoto K (2019) Detrital zircon U–Pb ages from the Cretaceous accretionary complexes in the Takaharagawa area, central Kii Peninsula. J Geol Soc Jpn 125:329–347. https://doi.org/10.5575/geosoc.2019.0002. (**in Japanese with English abstract**)
Otofuji Y, Matsuda T, Nohda S (1985) Opening mode of the Japan Sea inferred from the paleomagnetism of the Japan arc. Nature 317:603–604. https://doi.org/10.1038/317603a0
Park YH, Doh S-J, Ryu I-C, Suk D (2005) A synthesis of Cretaceous paleomagnetic data from South Korea: tectonic implications in east Asia. Geophys J Int 162:709–724. https://doi.org/10.1111/j.1365-246X.2005.02584.x
Raimbourg H, Augier R, Famin V, Gadenne L, Palazzin G, Yamaguchi A, Kimura G (2014) Long-term evolution of an accretionary prism: the case study of the Shimanto Belt, Kyushu, Japan. Tectonics 33:936–959. https://doi.org/10.1002/2013TC003412
Ramos VA (2005) Seismic ridge subduction and topography: foreland deformation in the Patagonian Andes. Tectonophysics 399:73–86. https://doi.org/10.1016/j.tecto.2004.12.016
Sagong H, Kwon S-T, Ree J-H (2005) Mesozoic episodic magmatism in South Korea and its tectonic implication. Tectonics 24:TC5002. https://doi.org/10.1029/2004TC001720
Sakashima T, Terada K, Takeshita T, Sano Y (2003) Large-scale displacement along the Median Tectonic Line, Japan: evidence from SHRIMP zircon U–Pb dating of granites and gneisses from the South Kitakami and paleo-Ryoke belts. J Asian Earth Sci 21:1019–1039. https://doi.org/10.1016/S1367-9120(02)00108-6
Sato D, Matsuura H, Yamamoto T (2016) Timing of the Late Cretaceous ignimbrite flare-up at the eastern margin of the Eurasian Plate: new zircon U–Pb ages from the Aioi-Arima-Koto region of SW Japan. J Volcanol Geoth Res 310:89–97. https://doi.org/10.1016/j.jvolgeores.2015.11.014
Seton M, Flament N, Whittaker J, Müller RD, Gurnis M, Bower DJ (2015) Ridge subduction sparked reorganization of the Pacific plate-mantle system 60–50 million years ago. Geophys Res Lett 42:1732–1740. https://doi.org/10.1002/2015GL063057
Shibata K, Ishihara S (1979) Rb–Sr whole-rock and K–Ar mineral ages of granitic rocks in Japan. Geochem J 13:113–119. https://doi.org/10.2343/geochemj.13.113
Shimura Y, Tokiwa T, Takeuchi M, Yamamoto K (2017) Geology and detrital zircon U–Pb age of the Cretaceous Mugitani formation in the Shimanto Belt, central Kii Peninsula, Southwest Japan. J Geol Soc Jpn 123:925–937. https://doi.org/10.5575/geosoc.2017.0032
Shimura Y, Takeuchi M, Tokiwa T (2020) Chert–clastic sequence in the Cretaceous Shimanto Accretionary Complex on the central Kii Peninsula, SW Japan. Island Arc 29:e12345. https://doi.org/10.1111/iar.12345
Shimura Y, Nakamura Y, Tokiwa T, Sugimoto T, Mito S (2021) The latest Early Cretaceous detrital zircons from clastic rocks in the Koshibu-gawa area of the central Akaishi Mountains. J Geol Soc Jpn 127:51–58. https://doi.org/10.5575/geosoc.2020.0048. (**in Japanese with English abstract**)
Sisson VB, Pavlis TL, Roeske SM, Thorkelson DJ (2003a) Introduction: an overview of ridge-trench interactions in modern and ancient settings. In: Sisson VB, Roeske SM, Pavlis TL (eds) Geology of a transpressional orogen developed during ridge-trench interaction along the North Pacific margin. GSA Special Papers 371, pp 1–18. https://doi.org/10.1130/0-8137-2371-X.1
Sisson VB, Poole AR, Harris NR, Burner HC, Pavlis TL, Copeland P, Donelick RA, McLelland WC (2003b) Geochemical and geochronologic constraints for genesis of a tonalite-trondhjemite suite and associated mafic intrusive rocks in the eastern Chugach Mountains, Alaska: a record of ridge-transform subduction. In: Sisson VB, Roeske SM, Pavlis TL (eds) Geology of a transpressional orogen developed during ridge-trench interaction along the North Pacific margin. GSA Special Papers 371, pp 293–326. https://doi.org/10.1130/0-8137-2371-X.293
Skrzypek E, Kato T, Kawakami T, Sakata S, Hattori K, Hirata T, Ikeda T (2018) Monazite behaviour and time-scale of metamorphic processes along a low-pressure/high-temperature field gradient (Ryoke belt, SW Japan). J Petrol 59:1109–1144. https://doi.org/10.1093/petrology/egy056
Skrzypek E, Sakata S, Sorger D (2020) Alteration of magmatic monazite in granitoids from the Ryoke belt (SW Japan): processes and consequences. Am Miner 105:538–554. https://doi.org/10.2138/am-2020-7025
Sonehara T, Harayama S (2007) Petrology of the Nohi Rhyolite and its related granitoids: a late Cretaceous large silicic igneous field in central Japan. J Volcanol Geoth Res 167:57–80. https://doi.org/10.1016/j.jvolgeores.2007.05.012
Song Y, Stepashko A, Liu K, He Q, Shen C, Shi B, Ren J (2018) Post-rift tectonic history of the Songliao Basin, NE China: cooling events and post-rift unconformities driven by orogenic pulses from plate boundaries. J

Geophys Res Solid Earth 123:2363–2395. https://doi.org/10.1002/2017JB014741

Stern C (2004) Active Andean volcanism: its geologic and tectonic setting. Revista Geológica De Chile 31:161–206. https://doi.org/10.4067/S0716-02082004000200001

Suzuki K, Adachi M (1998) Denudation history of the high T/P Ryoke metamorphic belt, southwest Japan: constraints from CHIME monazite ages of gneisses and granitoids. J Metamorph Geol 16:23–37. https://doi.org/10.1111/j.1525-1314.1998.00057.x

Suzuki K, Adachi M, Kajizuka I (1994a) Electron microprobe observations of Pb diffusion in metamorphosed detrital monazites. Earth Planet Sci Lett 128:391–405. https://doi.org/10.1016/0012-821X(94)90158-9

Suzuki K, Morishita T, Kajizuka I, Nakai Y, Adachi M, Shibata K (1994b) CHIME ages of monazites from the Ryoke metamorphic rocks and some granitoids in the Mikawa-Tono area, central Japan. Bull Nagoya Univ Furukawa Museum 10:7–38 (**in Japanese with English abstract**)

Taira A, Ohara Y, Wallis SR, Ishiwatari A, Iryu Y (2016) Geological evolution of Japan: an overview. In: Moreno T, Wallis S, Kojima T, Gibbons W (eds) The geology of Japan. The Geological Society of London, pp 1–24. https://doi.org/10.1144/GOJ.1

Takagi H, Arai H (2003) Restoration of exotic terranes along the Median Tectonic Line, Japanese Islands: overview. Gondowana Res 6:657–668. https://doi.org/10.1016/S1342-937X(05)71015-7

Takagi H, Shibata K (2000) Constituents of the Paleo-Ryoke Belt and restoration of the Paleo-Ryoke and Kurosegawa Terranes. Mem Geol Soc Jpn 56:1–12 (**in Japanese with English abstract**)

Takahashi M (1983) Space-time distribution of late Mesozoic to early Cenozoic magmatism in east Asia and its tectonic implications. In: Hashimoto M, Uyeda (eds) Accretion tectonics in the Circum-Pacific regions, TERRA PUB, Tokyo, pp 69–88

Takahashi Y (2008) Early Cretaceous adakitic magmatism in the Inner Zone of Southwest Japan and its implications for tectonics. Earth Sci (chikyu Kagaku) 62:211–220. https://doi.org/10.15080/agcjchikyukagaku.62.3_211. (**in Japanese with English abstract**)

Takahashi Y, Kagashima S, Mikoshiba MU (2005) Geochemistry of adakitic quartz diorite in the Yamizo Mountains, central Japan: implications for Early Cretaceous adakitic magmatism in the inner zone of southwest Japan. Island Arc 14:150–164. https://doi.org/10.1111/j.1440-1738.2005.00465.x

Takatsuka K, Kawakami T, Skrypek E, Sakata S, Obayashi H, Hirata T (2017) Age gap between the intrusion of gneissose granitoids and regional high-temperature metamorphism in the Ryoke belt (Mikawa area), central Japan. Island Arc 27:e12224. https://doi.org/10.1111/iar.12224

Takatsuka K, Kawakami T, Skrzypek E, Sakata S, Obayashi H, Hirata T (2018) Spatiotemporal evolution of magmatic pulses and regional metamorphism during a Cretaceous flare-up event: constraints from the Ryoke belt (Mikawa area, central Japan). Lithos 308–309:428–445. https://doi.org/10.1016/j.lithos.2018.03.018

Tatsumi Y (1982) Origin of high-magnesian andesites in the Setouchi volcanic belt, southwest Japan, II. Melting phase relations at high pressures. Earth Planet Sci Lett 60:305–317. https://doi.org/10.1016/0012-821X(82)90009-7

Tatsumi Y (1995) Subduction zone magmatism-A contribution to whole mantle dynamics. The University of Tokyo Press (in Japanese), p 186

Taylor B, Exon NF (1987) An investigation of ridge subduction in the Woodlark-Solomons region: introduction and overview. In Taylor B, Exon NF (eds) Marine geology, geophysics, and geochemistry of the Woodlark basin-Solomon Islands, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, no. 7 Circum-Pacific Council for Energy and Mineral Resources, Huston, TX, pp 1–24

Thorkelson DJ (1996) Subduction of diverging plates and the principles of slab window formation. Tectonophysics 255:47–63. https://doi.org/10.1016/0040-1951(95)00106-9

Tokiwa T, Shimura Y, Takeuchi M, Shimosato S, Yamamoto K, Mori H (2019) Provenance of trench-fill deposits of the Jurassic Chichibu accretionary complex, Southwest Japan. J Asian Earth Sci 184:103970. https://doi.org/10.1016/j.jseaes.2019.103970

Tokiwa T, Shimura Y, Takeuchi M, Mori H (2021) Use of detrital zircon U–Pb ages to assess the timing of deposition of Cretaceous trench-fill deposits in the active continental arc along the East Asian margin. J Asian Earth Sci 207:104657. https://doi.org/10.1016/j.jseaes.2020.104657

Tokiwa T, Takeuchi M, Shimura Y, Ota A, Yamamoto K (2016) U–Pb ages of detrital zircon from the tuffaceous sandstone of the Shimanto Belt in the Kii Peninsula. J Geol Soc Jpn 122:625–635. https://doi.org/10.5575/geosoc.2016.0045. (**in Japanese with English abstract**)

Tokiwa T, Takeuchi M, Shimura Y, Shobu K, Ota A, Yamamoto K, Mori H (2017) Effectiveness for determination of depositional age by detrital zircon U–Pb age in the cretaceous shimanto accretionary complex of Japan. In Itoh Y (ed) Evolutionary models of convergent margins—origin of their diversity. InTech, Rijeka, pp 197–228

Tsuchiya N (2008) Petrogenesis of adakites and their geological significance. Earth Science (chikyu Kagaku) 62:161–182. https://doi.org/10.15080/agcjchikyukagaku.62.3_161. (**in Japanese with English abstract**)

Tsuchiya N, Suzuki S, Kimura J, Kagami H (2005) Evidence for slab melt/mantle reaction: petrogenesis of Early Cretaceous and Eocene high-Mg andesites from the Kitakami Mountains, Japan. Lithos 79:179–206. https://doi.org/10.1016/j.lithos.2004.04.053

Tsuchiya N, Takeda T, Adachi T, Nakano N, Osanai Y, Adachi Y (2015) Early Cretaceous adakitic magmatism and tectonics in the Kitakami Mountains, Japan. Jpn Mag Mineral Petrol Sci 44:69–90. https://doi.org/10.2465/gkk.131228. (**in Japanese with English abstract**)

Tsutsumi Y (2020) Depositional and metamorphic age estimations of low-*P/T* type Higo gneiss in the Amakusa-Kamishima Island, Kumamoto, southwest Japan. Bull Natl Museum Nat Sci Ser C 46:15–22

Tsutsumi Y, Miyashita A, Terada K, Hidaka H (2009) SHRIMP U–Pb dating of detrital zircons from the Sanbagawa Belt, Kanto Mountains, Japan: need to revise the framework of the belt. J Mineral Petrol Sci 104:12–24. https://doi.org/10.2465/jmps.080416

Tsutsumi Y, Miyashita A, Horie K, Shiraishi K (2012) Existence of multiple units with different accretionary and metamorphic ages in the Sanbagawa Belt, Sakuma-Tenryu area, central Japan. Island Arc 21:317–326. https://doi.org/10.1111/iar.12001

Uchimura H, Kono M, Tsunawaka H, Kimura G, Wei Q, Hao T, Liu H (1996) Palaeomagnetism of late Mesozoic rocks from northeastern Chin: the role of the Tan-Lu fault in the North China Block. Tectonophysics 262:301–319. https://doi.org/10.1016/0040-1951(96)00016-9

Uehara S, Aoya M (2005) Thermal model for approach of a spreading ridge to subduction zones and its implications for high-P/high-T metamorphism: importance of subduction versus ridge approach ratio. Tectonics 24:TC4007. https://doi.org/10.1029/2004TC001715

Uno K, Idehara Y, Morita D, Furukawa K (2021) An improved apparent polar wander path for southwest Japan: post-Cretaceous multiphase rotations with respect to the Asian continent. Earth Planets Space 73:132. https://doi.org/10.1186/s40623-021-01457-6

Uyeda S, Miyashiro A (1974) Plate tectonics and the Japanese Islands: a synthesis. GSA Bull 85:1159–1170. https://doi.org/10.1130/0016-7606(1974)85%3c1159:PTATJI%3e2.0.CO;2

von Huene R, Scholl DW (1991) Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust. Rev Geophys 29:279–316. https://doi.org/10.1029/91RG00969

Wang HL, Huang BC, Qiao QQ, Chen JS (2011) Paleomagnetic study on Cretaceous and Paleogene rocks from eastern Heilongjiang, NE China and its tectonic implications. Chin J Geophys 54:793–806. https://doi.org/10.3969/j.issn.0001-5733.2011.03.020

Whittaker JM, Müller RD, Leitchenkov G, Stagg H, Sdrolias M, Gaina C, Goncharov A (2007) Major Australian-Antarctic plate reorganization at Hawaiian-Emperor bend time. Science 318:83–86. https://doi.org/10.1126/science.1143769

Woods MT, Davies GF (1982) Late Cretaceous genesis of the Kura plate. Earth Planet Sci Lett 58:161–166. https://doi.org/10.1016/0012-821X(82)90191-1

Wu T-J, Wu J (2019) Izanagi-Pacific ridge subduction revealed by a 56 to 46 Ma magmatic gap along the northeast Asian margin. Geology 47:953–957. https://doi.org/10.1130/G46778.1

Wu JT-J, Jahn B-M, Nechaev V, Chashchin A, Popov V, Yokoyama K, Tsutsumi Y (2017) Geochemical characteristics and petrogenesis of adakites in the Sikhote-Alin area, Russian Far East. J Asian Earth Sci 145:512–529. https://doi.org/10.1016/j.jseaes.2017.06.024

Wu J, Lin Y-A, Flament N, Wu JT-J, Liu Y (2022a) Northwest Pacific-Izanagi plate tectonics since Cretaceous times from western Pacific mantle structure.

Earth Planet Sci Lett 583:117445. https://doi.org/10.1016/j.epsl.2022.117445

Wu JT-J, Wu J, Okamoto K (2022b) Intra-oceanic arc accretion along Northeast Asia during Early Cretaceous provides a plate tectonic context for North China craton destruction. Earth Sci Rev 226:103952. https://doi.org/10.1016/j.earscirev.2022.103952

Yada J, Owada M (2003) Genetic relationship between the Cretaceous high-Sr tonalite (Itoshima mass) and trondhjemite (Fukae mass) in the central part of Saga Prefecture, northwest Kyushu: Implications for magmatic differentiation. J Geol Soc Jpn 109:518–532. https://doi.org/10.5575/geosoc.109.518. (**in Japanese with English abstract**)

Yamada N, Koido Y (2005) Nohi rhyolite: distributioin, basement rocks, ages and lithologic features. Monograph 53:15–28 (**in Japanese with English abstract**)

Yamakita S, Otoh S (2000) Cretaceous rearrangement processes of pre-cretaceous geologic units of the Japanese Islands by MTL-Kurosegawa left-lateral strike-slip fault system. Mem Geol Soc Jpn 56:23–38 (**in Japanese**)

Yi S, Yi S, Batten DJ, Yun H, Park S-J (2003) Cretaceous and Cenozoic non-marine deposits of the Northern South Yellow Sea Basin, offshore western Korea: palynostratigraphy and palaeoenvironments. Palaeogeogr Palaeoclimatol Palaeoecol 191:15–44. https://doi.org/10.1016/S0031-0182(02)00637-5

Yokoyama K, Shigeoka M, Goto A, Terada K, Hidaka H, Tsutsumi Y (2010) U-Th-total Pb ages of uraninite and thorite from granitic rocks in the Japanese Islands. Bull Natl Museum Nat Sci Ser C 36:7–18

Yokoyama K, Shigeoka M, Otomo Y, Tokuno K, Tsutsumi Y (2016) Uraninite and thorite ages of around 400 granitoids in the Japanese Islands. Mem Natl Museum Nat Sci 51:1–24

Yuan H, Chen S, Dai K, Jia G, Wang P, Li J, Gou Q (2022) Cenozoic tectonic evolution of the Bohai Bay Basin: constraints from strike-slip activities of the Wangjiagang fault zone, NE China. J Asian Earth Sci 233:105262. https://doi.org/10.1016/j.jseaes.2022.105262

Zhang Y-B, Zhai M-G, Wu F-Y, Zhang X-H, Li Q-L, Peng P, Zhao L, Zhou L-G (2021) Reviews on the Paleozoic–Mesozoic granitoids and sedimentary rocks in North Korea. J Geol Soc Korea 57:523–544. https://doi.org/10.14770/jgsk.2021.57.4.523

Zhu Y, Liu S, Zhang B, Gurnis M, Ma P (2020) Reconstruction of the Cenozoic deformation of the Bohai Bay Basin, North China. Basin Res 33:364–381. https://doi.org/10.1111/bre.12470

Publisher's Note