

Izanagi-Pacific ridge subduction revealed by a 56 to 46 Ma magmatic gap along the northeast Asian margin

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ABSTRACT

Recent studies have debated the timing and spatial configuration of a possible intersection between the Pacific-Izanagi spreading ridge and the northeast Asian continental margin during Cretaceous or early Cenozoic times. Here we examine a newly compiled magmatic catalog of ~900 published Cretaceous to Miocene igneous rock radioisotopic values and ages from the northeast Asian margin for ridge subduction evidence. Our synthesis reveals that a near-synchronous 56–46 Ma magmatic gap occurred across ~1500 km of the Eurasian continental margin between Japan and Sikhote-Alin, Russian Far East. The magmatic gap separated two distinct phases of igneous activity: (1) an older, Cretaceous to Paleocene pre-56 Ma episode that had relatively lower $\epsilon_{\text{Nd}(t)}$ (–15 to +2), elevated $(^{87}\text{Sr}/^{86}\text{Sr})_0$ (initial ratio, 0.704–0.714), and relatively higher magmatic fluxes (~1090 km²/m.y.); and (2) a younger, late Eocene to Miocene post-46 Ma phase that had relatively elevated $\epsilon_{\text{Nd}(t)}$ (–2 to +10), lower $(^{87}\text{Sr}/^{86}\text{Sr})_0$ (0.702–0.707), and a lower 390 km²/m.y. magmatic flux. The 56–46 Ma magmatic gap links other geological evidence across northeast Asia to constrain an early Cenozoic, low-angle ridge-trench intersection that had profound consequences for the Eurasian continental margin, and possibly led to the ca. 53–47 Ma Pacific plate reorganization.

INTRODUCTION

The Eurasian margin along East Asia has been a long-lived convergent margin since early Mesozoic times (e.g., Müller et al., 2016). Several plate tectonic reconstructions have suggested that at least one paleo-Pacific plate, probably the Izanagi plate, subducted beneath the margin during the Mesozoic (Maruyama et al., 1997; Müller et al., 2016). Consequently, a mid-ocean ridge between the modern Pacific plate and the Izanagi plate could have intersected the East Asia Eurasian continental margin and subducted. Three competing classes of plate tectonic reconstructions have been proposed for Pacific-Izanagi ridge-trench intersections along East Asia (Fig. 1) that imply alternative geological histories for the East Asian margin, for northwest Pacific Ocean plate reconstructions, and possibly for a 50 Ma Pacific hemisphere plate-mantle reorganization. The *high-angle ridge-trench intersection model* proposed that a north-west-southeast-trending mid-ocean ridge that separated the Izanagi plate to the north and the Pacific plate to the south intersected the northeast Asian margin at a high angle; the resultant

trench-trench-ridge triple junction swept from south to north in the late Cretaceous (Fig. 1B; Maruyama et al., 1997). In the *low-angle ridge-trench intersection model*, a NNE-SSW-trending Izanagi-Pacific spreading ridge intersected subparallel to a large swath of the northeast Asian margin and was subducted beneath the margin in the early Cenozoic at 60–50 Ma (Fig. 1C; Whittaker et al., 2007; Seton et al., 2015). Finally, the *marginal sea closure model* involved the closure of now-vanished East Asian marginal seas in the early Cenozoic (Fig. 1D) (Domeier et al., 2017; Itoh et al., 2017).

Each plate model class predicts distinct igneous activities along the East Asian margin, and we tested each using magmatic ages, radioisotopic values, and magmatic flux. We compiled ages and Sr-Nd isotopic values of intermediate to felsic igneous rocks within the continental arc of northeast Asia (Fig. 1), aged between 110 and 20 Ma, to search for spatiotemporal constraints on possible ridge subduction. We digitally rebuilt published end-member Japan Sea opening plate reconstructions to palinspastically restore the magmatism to prior to Japan Sea opening.

GEOLOGICAL SETTING

The southern Russian Far East and the Japanese Islands along northeast Asia have widely distributed Cretaceous to Cenozoic igneous rocks (Fig. 1) that provide a magmatic record of subduction history. In Sikhote-Alin, Russian Far East, the continental margin grew from subduction of oceanic plates, and is formed by Mesozoic geological units such as accreted terranes and accretionary prisms (Zharov, 2005; Khanchuk et al., 2016). Likewise, the Japanese Islands are a segmented, subduction-related orogen that has grown along the East Asian margin since at least the Jurassic (Wakita, 2013; Taira et al., 2016). During the Japan Sea opening in the early Miocene, northeast and southwest Japan separated from the continental margin (Otofujii et al., 1985). The pre-rift positions of the Japanese Islands remain debated, but there is general consensus that Japan was a southern extension of Sikhote-Alin prior to rifting (Van Horne et al., 2017).

METHODS

A 110–20 Ma magmatic record for Japan, Sikhote-Alin, and Sakhalin (Russia) was compiled from published literature (Shibata and Ishihara, 1979; Tanaka, 1987; Terakado and Nohda, 1993; Yuhara, 1998; Morioka et al., 2000; Imaoka et al., 2011; Jahn et al., 2015; Okamura et al., 2016; Zhao et al., 2017; Liao et al., 2018; see other references in Table DR1 in the GSA Data Repository¹). Intermediate to felsic compositions are typically produced within continental arcs (Ducea et al., 2015), and Cretaceous to early Cenozoic subduction in the study area primarily manifested in silicic magmatism (Jahn et al., 2015). Therefore, we compiled ages and whole-rock Sr-Nd isotopic values for igneous rocks with intermediate to felsic compositions into a database of 1291 values (Table DR1). Initial Sr and Nd isotope

¹GSA Data Repository item 2019337, Figure DR1 (comparison between alternative Japan Sea reconstructions) and Table DR1 (database of magmatic rocks in northeast Asia), is available online at <http://www.geosociety.org/datarepository/2019/>, or on request from editing@geosociety.org.

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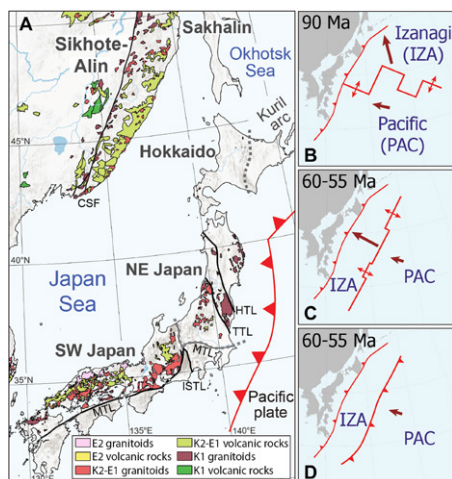


Figure 1. (A) Tectonic framework and distribution of Cretaceous to Eocene igneous rocks at the northeast Asian margin. K1—Early Cretaceous, K2—Late Cretaceous, E1—Paleocene, E2—Eocene. Two gray dashed lines show boundaries between southwest and northeast Japan, and between the Kuril arc system and western Hokkaido. CSF—Central Sikhote-Alin fault; HTL—Hatagawa tectonic line; TTL—Tanakura tectonic line; MTL—Median tectonic line; ISTL—Itoigawa-Shizuoka tectonic line. (B–D) Proposed plate tectonic reconstructions of the Izanagi and Pacific plates and the Izanagi-Pacific spreading ridge. Lengths of plate-motion arrows in red denote relative velocities. (B) High-angle ridge-trench intersection model (Maruyama et al., 1997). (C) Low-angle ridge-trench intersection model (Whittaker et al., 2007; Seton et al., 2015). Modeled Izanagi-Pacific spreading ridge extends further south into southeast Asia, but only the northern portion is shown here for comparative purposes. (D) Marginal sea closure model (Domeier et al., 2017).

values were recalibrated using the same decay constants (Table DR1). Ages from zircon U-Pb analyses were used where possible (173 samples); the remainder were relatively good-quality Rb-Sr and K-Ar dates and a small minority (<40) of estimated ages (Table DR1). To roughly estimate magmatic influx across time, we digitized the areal extents of Cretaceous to early Cenozoic igneous rocks from southwest Japan to southern Sikhote-Alin (30°N to 46°N) following the 1:5,000,000-scale *International Geological Map of Asia* (Ren et al., 2013) in QGIS software (<https://www.qgis.org>). The digitized igneous rock polygons were later input into our plate reconstruction within the software Gplates (<https://www.gplates.org>; Boyden et al., 2011). We palinspastically restored the igneous rocks to prior to the Japan Sea opening by digitally recreating published end-member Japan Sea opening plate models using GPlates. Here we present our preferred model, following Yamakita and Otoh (2000; for southwestern Japan and most of northeastern Japan); the Kuril arc, including eastern Hokkaido, was restored closer to the Sakhalin island, and the Kuril ba-

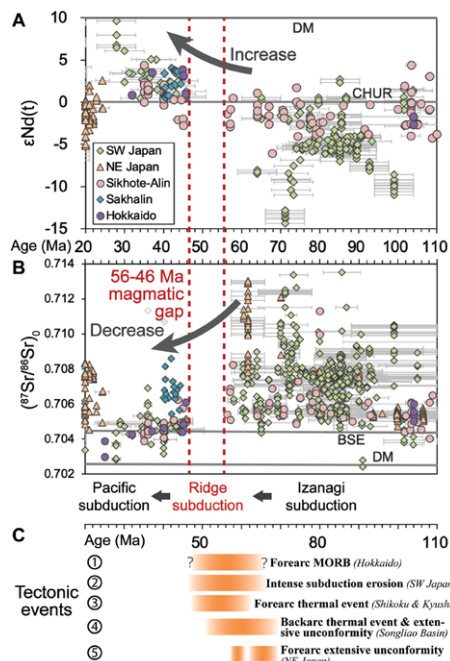


Figure 2. (A,B) Nd and Sr isotopic composition across time for felsic to intermediate igneous rocks of 110–20 Ma ages along the northeast Asian margin between 30°N and 46°N. Increase in $\epsilon_{Nd(t)}$ and decrease in $(^{87}Sr/^{86}Sr)_0$ (initial ratio) after the 56–46 Ma magmatic gap (red area) indicates a more depleted mantle component after 46 Ma. DM—depleted mantle; CHUR—chondritic unfractionated reservoir; BSE—bulk silica earth. (C) Early Cenozoic tectonic events 1–5 (circled numbers) possibly related to ridge subduction along the northeast Asian margin. Location of events 1–5 is shown in Figure 3A. MORB—mid-oceanic ridge basalt. References: event 1—Maeda and Kagami (1996), Nanayama et al. (2019); event 2—Raimbourg et al. (2014); event 3—Agar et al. (1989), MacKenzie et al. (1990), Hara and Kimura (2008), Mukoyoshi et al. (2009); event 4—Song et al. (2014); Song et al. (2018), Wang et al. (2013); event 5—Ando (2003).

sin was closed, following Ueda (2016). We also show that our results are valid within other end-member reconstructions (Fig. DR1 in the Data Repository).

RESULTS

Plots of igneous rock ages against whole-rock $\epsilon_{Nd(t)}$ and $(^{87}Sr/^{86}Sr)_0$ (initial ratio) values show that felsic to intermediate rocks of 56–46 Ma ages are absent (i.e., there is a magmatic gap) along the entire study area (Fig. 2). Age errors proximal to the magmatic gap were carefully checked to confirm feature integrity. Isotopically, Cretaceous to Paleocene rocks formed prior to the gap show relatively lower $\epsilon_{Nd(t)}$ = -15 to +2 and higher $(^{87}Sr/^{86}Sr)_0$ = 0.704–0.714 compared to post-gap rocks. In contrast, the Eocene to Oligocene rocks have relatively higher $\epsilon_{Nd(t)}$ = -2 to +6 and lower $(^{87}Sr/^{86}Sr)_0$ = 0.702–0.707. Our palinspastic restoration shown in Figure 3A reveals that the 56–46 Ma magmatic gap occurred near-synchro-

nously across the northeast Asian margin between 38°N to 48°N paleolatitudes, including Sikhote-Alin and Sakhalin (42°–48° N), Hokkaido and northeast Japan (38°–46° N), and southwest Japan (31°–38° N) (Fig. 3B). Comparison to other published Japan Sea reconstructions shifted northeast and southwest Japan paleolatitudes by 1°–3° northward relative to our reference model (Fig. DR1) but preserved the spatiotemporal trends shown in Figure 3. Cretaceous to Paleocene arc magmatic fluxes were ~1090 km²/m.y. prior to the 56–46 Ma magmatic gap and decreased to ~390 km²/m.y. from the mid- to end Eocene (Fig. 3C).

DISCUSSION

Implications for East Asia Ridge-Trench Interactions during the Early Cenozoic

Ridge subduction events profoundly affect the upper plate, but specific processes are non-unique and time transgressive; therefore, multiple geological constraints must be considered in unison to properly diagnose past ridge subduction (Sisson et al., 2003). Accordingly, we synthesize other geological evidence with our 56–46 Ma magmatic gap to discuss proposed Eurasia–northwest Pacific ridge-trench intersections (Fig. 1). We then discuss our isotopic values and magmatic addition rates relative to our preferred plate model.

Basalts with mid-oceanic ridge basalt (MORB) chemical characteristics extruded in the forearc region are considered the most distinctive indicator of ridge-trench intersections (Lagabriele et al., 1994). Syn-sedimentary pillow basalts with MORB chemical characteristics have been found in the early Cenozoic Hidaka belt in Hokkaido (event 1 in Fig. 2C; Maeda and Kagami, 1996; Nanayama et al., 2019). Therefore, evidence exists for ridge-trench intersection at Hokkaido during our observed 56–46 Ma near-simultaneous shutdown of subduction magmatism between Japan and southern Sikhote-Alin (Figs. 2 and 3). Ridge subduction has also been linked to termination of arc magmatism by Dickinson and Snyder (1979), Thorkelson (1996), and Sisson et al. (2003). These studies proposed that ridge subduction would have created a slab-free region (i.e., slab window) within the downgoing slab beneath the overriding plate, resulting in a temporarily inactive volcanic arc (Fig. 4B; Thorkelson, 1996), which is consistent with the 56–46 Ma magmatic gap revealed here (Figs. 2 and 3). Indeed, a magmatic gap and forearc basaltic magmatism have also been observed within the Chile Rise ridge-trench intersection (Nur, 1981; Lagabriele et al., 1994; Gutiérrez et al., 2005).

Ridge-trench intersections commonly produce elevated heat flows and topographic uplift (Sisson et al., 2003). These have been interpreted within the northeast Asian margin for the early Cenozoic, near the magmatic gap time interval (events 2–5 in Figs. 2C and 3). At the southern

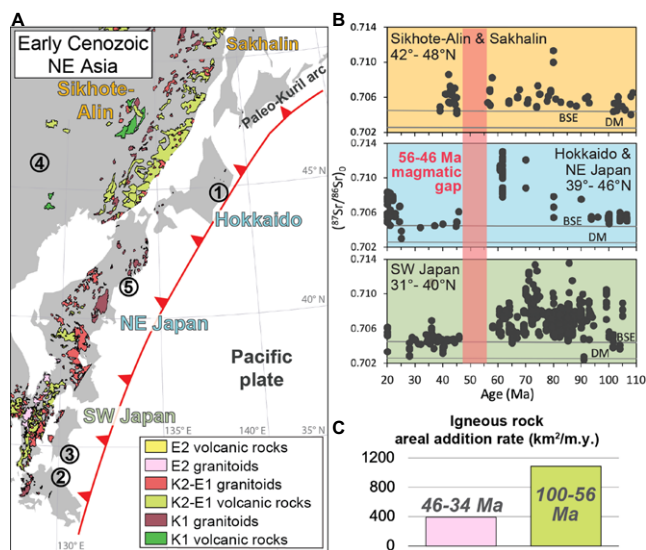


Figure 3. (A) Reconstructed configuration of the northeast Asian margin based on our preferred Japan Sea plate reconstruction, modified from Yamakita and Otoh (2000). Reconstructions following other published models are shown in Figure DR1 (see footnote 1). Locations of early Cenozoic tectonic events from Figure 2 are shown by circled numbers 1–5. K1—Early Cretaceous, K2—Late Cretaceous, E1—Paleocene, E2—Eocene. (B) Spatio-temporal distribution of igneous rocks across three regions. All regions show a near-simultaneous 56–46 Ma magmatic gap. DM—depleted mantle; BSE—bulk silica earth. (C) Comparison of areal addition rate of igneous rocks with ages before and after the 56–46 Ma magmatic gap in southwest Japan to the southern Sikhote-Alin area (30°N to 46°N). Relatively higher magmatic addition rates before 56 Ma and lower rates after 46 Ma are consistent with a change from fast Izanagi-Eurasia plate convergence (~20 cm/yr) to slow Pacific-Eurasia convergence (~7 cm/yr) predicted by the low-angle ridge-trench intersection plate model in Figure 1C.

BSE—bulk silica earth. (C) Comparison of areal addition rate of igneous rocks with ages before and after the 56–46 Ma magmatic gap in southwest Japan to the southern Sikhote-Alin area (30°N to 46°N). Relatively higher magmatic addition rates before 56 Ma and lower rates after 46 Ma are consistent with a change from fast Izanagi-Eurasia plate convergence (~20 cm/yr) to slow Pacific-Eurasia convergence (~7 cm/yr) predicted by the low-angle ridge-trench intersection plate model in Figure 1C.

end of the magmatic gap, thermochronology has revealed an early Eocene thermal event within the Shimanto belt in southwest Japan during 58–46 Ma (event 3 in Figs. 2C and 3; Agar et al., 1989; MacKenzie et al., 1990; Hara and Kimura, 2008; Mukoyoshi et al., 2009; Raimbourg et al., 2014). Extensive early Cenozoic unconformities have also been recorded in northeast Japan (event 5 in Figs. 2C and 3; Ando, 2003). Kimura et al. (2019) showed that the Japan islands experienced a general Paleocene to early Eocene interruption in volcanism and trench wedge accretion; unconformities formed in the forearc basins, followed by shallowing of sedimentary facies that was consistent with a ridge subduction. At the northern end of our identified magmatic gap, a strong Paleocene to early Eocene unconformity has been identified within the Songliao Basin (northeast China; Wang et al., 2013; Song et al., 2014). Apatite fission-track dating has suggested intense uplift in the area at ca. 65–50 Ma (Song et al., 2018). Together, these possible ridge-subduction signals corroborate the spatial extent and timing of our magmatic gap, thus strengthening the case that our 56–46 Ma magmatic gap is evidence of ridge subduction.

Implications for Izanagi-Pacific Plate Tectonic Reconstructions

Here we consider our results against proposed plate model classes (Figs. 1B–1D), but other valid solutions exist because the Izanagi plate is conceptual (i.e., fully subducted). The low-angle Izanagi-Pacific ridge-trench intersection model of Whittaker et al. (2007) and Seton et al. (2015) (Fig. 1C) is generally most consistent with the 56–46 Ma magmatic gap (Fig. 3),

but their modeled ridge-trench intersection extended >5000 km into southeast China and southeast Asia, albeit with a time dependence to when it interacted with the Eurasian margin. Magmatism in southeast China (Li, 2000; Zhou et al., 2006) and west Borneo (e.g., Hennig et al., 2017) ceased at ca. 80 Ma and is highly contrasted to that of our study area, which showed continuous igneous activity until 56 Ma followed by the magmatic gap (Fig. 2). This suggests that Izanagi-Pacific ridge-trench intersections did not extend south of southernmost Japan, in contrast to the model of Seton et al. (2015).

An alternative plate model proposed that marginal seas closed along East Asia in the early Cenozoic (Fig. 1D) and that the Izanagi-Pacific spreading ridge never reached Japan (Domeier et al., 2017). Our study shows that the Izanagi-Pacific ridge did subduct along East Asia in the early Cenozoic (Fig. 2), and likely at a low angle to the margin (Figs. 3B and 4). Nonetheless, the presence of now-subducted marginal seas north of the paleo-Kurile trench, from Domeier et al. (2017), may explain the early Cenozoic tectonic setting north of 48°N present latitude. The high-angle ridge-trench intersection model (Fig. 1B) implies that a spatially restricted, amagmatic area migrated along the East Asian margin during the Cretaceous (Maruyama et al., 1997), which is incompatible with our observed synchronous and areally extensive 56–46 Ma magmatic gap (Fig. 3B). Finally, given uncertainties, it is possible that a Kula-Pacific ridge-trench intersection with Eurasia in the early Cenozoic could have produced the magmatism shown here; however, a viable plate model has yet to be proposed.

Implications for ca. 50 Ma Pacific Plate Reorganization

Seton et al. (2015) suggested that subparallel arrival of the Pacific-Izanagi ridge along the East Asian margin led to a margin-wide slab detachment that significantly decreased the slab pull force acting on the Pacific plate at 60–50 Ma, possibly leading to the Pacific plate-mantle reorganization at ca. 53–47 Ma (Whittaker et al., 2007; O'Connor et al., 2013). The simultaneous 56–46 Ma magmatic gap along the northeast Asia margin shown here (Figs. 2 and 3B) supports formation of an ~1500-km-long margin-parallel slab window beneath the East Asian margin during this time frame. However, the apparent lack of magmatic evidence for early Cenozoic Izanagi-Pacific ridge subduction south of Japan (i.e., in South China and southeast Asia) suggests that the modeled >5000 km slab detachment of Seton et al. (2015) may be overestimated by more than a factor of two. Furthermore, studies to the north of our area suggest that Izanagi-Pacific ridge subduction was limited to the south of southern Sakhalin (Vaes et al., 2019), which would further shorten a slab detachment. The geodynamic viability of a much shorter (i.e., ~1500 km length from this study) Izanagi-Pacific ridge-trench intersection for producing a ca. 50 Ma Pacific plate reorganization should be reexamined.

Implications for Northeast Asian Margin Magmatic Evolution

Contrasted areal addition rates (Fig. 3C) and isotopic compositions (Fig. 2) of igneous rocks astride the 56–46 Ma magmatic gap between Japan and Sikhote-Alin are generally consistent with a subduction zone reorganization during low-angle Izanagi-Pacific ridge-trench intersection (Fig. 4). Studies have shown positive correlations between magma generation and subduction rates (Cagnioncle et al., 2007; Hughes and Mahood, 2008; Zellmer, 2008). Our preferred low-angle ridge-trench intersection model (Figs. 1C and 4) indicates that the northeast Asian continental margin was dominated by fast, ~20 cm/yr, Izanagi subduction before 55 Ma and slower (65% reduced) Pacific subduction after 50 Ma, at ~7 cm/yr (Fig. 4) (Whittaker et al., 2007; Seton et al., 2015). Interestingly, our estimated magma addition rates over time show a similar reduction (~65%) in magmatism after the Paleocene, from ~1090 km²/m.y. to ~390 km²/m.y. (Fig. 3C). Isotopically, late Eocene igneous rocks show more-depleted mantle compositions [i.e., higher $\epsilon_{\text{Nd}(t)}$ and lower $(^{87}\text{Sr}/^{86}\text{Sr})_0$] than Cretaceous to Paleocene igneous rocks (Fig. 2). This could be consistent with input of depleted mantle to the mantle wedge through a slab window during the ridge subduction (Fig. 4) and/or input of relatively enriched crustal material into the subduction zone during earlier Izanagi subduction.

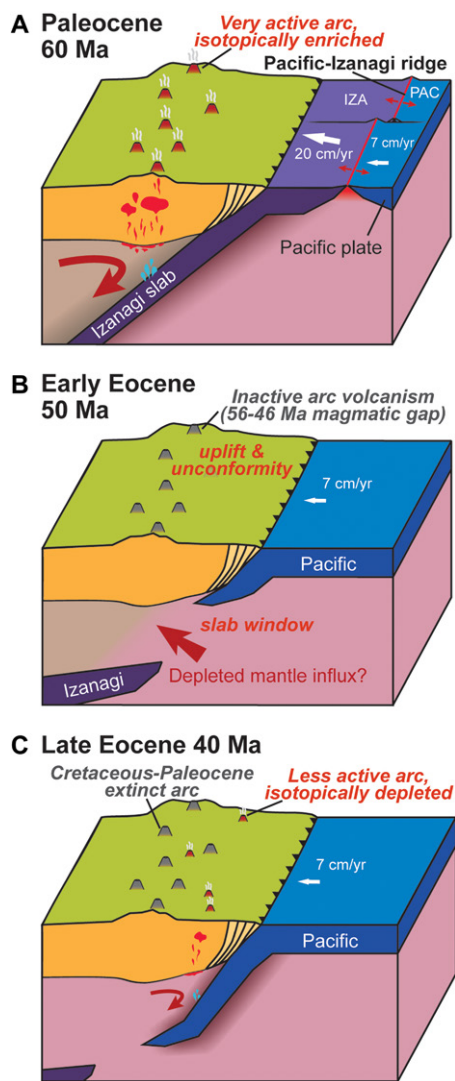


Figure 4. Tectonic evolution of Sikhote-Alin (Russian Far East) to Japan during the Izanagi-Pacific ridge-trench intersection in the early Cenozoic based on this study. PAC—Pacific plate; IZA—Izanagi plate. (A) Mid-Cretaceous to Paleocene arc magmatism was characterized by more-enriched isotopic signatures and relatively high ($1090 \text{ km}^2/\text{m.y.}$) magmatic areal addition rates during the fast 20 cm/yr Izanagi-Eurasia subduction compared to the period after 46 Ma. (B) Izanagi-Pacific ridge-trench intersection produced a 56–46 Ma magmatic gap and a slab window. Influx of asthenosphere into the mantle wedge through the slab window arguably led to relatively depleted isotopic signatures in arc magmatism after 46 Ma. (C) After 46 Ma, a less-developed igneous arc formed that was characterized by more-depleted isotopic signatures and relatively lower ($390 \text{ km}^2/\text{m.y.}$) magmatic area addition rates during the slower $\sim 7 \text{ cm/yr}$ Pacific subduction compared to the mid-Cretaceous to Paleocene period.

CONCLUSION

Past plate kinematics can be reliably reconstructed from spreading ridge geometries, but Eurasia–northwest Pacific plate reconstructions remain controversial because the ridges have

subducted. Our compiled and palinspastically restored magmatic record between Sikhote-Alin and southwest Japan in the early Cenozoic links fragmentary geological evidence to present new, definitive spatiotemporal constraints on low-angle ridge-trench intersection along $\sim 1500 \text{ km}$ of the northeast Eurasian margin, clarifying an ongoing, first-order plate tectonic controversy. The 56–46 Ma magmatic gap shown here coincides with the major Pacific plate reorganization at ca. 53–47 Ma. Although this may support a Pacific Ocean basin plate-mantle reorganization sparked by widespread Izanagi-Pacific ridge subduction, we limit the ridge subduction to north of southwest Japan, over a significantly shorter length ($\sim 1500 \text{ km}$ versus 5000 km) than previously thought. This may require reevaluation of circum-Pacific geodynamic models.

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