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First identification of a Cathaysian continental fragment beneath the Gagua Ridge, Philippine Sea, and its tectonic implications

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ABSTRACT

The tectonic history of the Philippine Sea plate is an essential piece in understanding the tectonic evolution of Southeast Asia, but it is still unclear and controversial. We present the first geochemical data obtained from lavas from the Gagua Ridge (GR) within the Philippine Sea. The GR lavas exhibit geochemical signatures typical of subduction-related arc magmatism. Plagioclase Ar-Ar ages of ca. 124–123 Ma and subduction-related geochemical signatures support the formation of GR lavas in the vicinity of an arc during the Early Cretaceous induced by subduction of the oceanic plate along East Asia. The ages of trapped zircon xenocrysts within the GR lavas cluster at 250 Ma, 0.75 Ga, and 2.45 Ga and match well the ages of zircons recovered from the Cathaysian block, southern China. Our results imply that the GR basement is partially composed of continental material that rifted away from the Eurasian margin during opening and spreading of the Huatung Basin. The depleted mantle wedge-derived magmas evolved and picked up the continental zircons during ascent. The youngest zircon ages and the GR lava Ar-Ar ages (ca. 124–123 Ma) presented in this study newly constrain an Early Cretaceous age for the Huatung Basin. Our study provides further evidence that the Huatung Basin is a remnant of a Mesozoic-aged ocean basin that dispersed from southern China during the Cretaceous. Transport of continental slivers by growth and closure of marginal seas along the East Asia margin may have been more prevalent than previously recognized.

INTRODUCTION

The Philippine Sea plate (PSP) is composed of a mosaic of marginal basins and is almost completely bounded by subduction zones that involve the Eurasian/Sundaland plates to the west, the Pacific plate to the east, and the Indo-Australian plate to the south (e.g., Hall, 2002). Tectonic studies of the PSP have a profound influence on interpretations of the origin of marginal seas and plate-tectonic reconstructions for vast areas of southeast China, southeast Asia, and western Pacific regions since the Cretaceous (Hilde and Lee, 1984; Hall, 2002; Sibuet et al., 2002; Hsu and Deffontaines, 2009; Zahirovic et al., 2014; Lallemand, 2016; Wu et al., 2016; Huang et al., 2019). Although some portions of the PSP are better studied and show oceanic basins and ocean-island arc lithosphere of Early Cretaceous to recent ages (Deschamps and Lallemand, 2002; Taylor and Goodliffe, 2004; Hickey-Vargas et al., 2008; Tani et al., 2011), other areas are completely undrilled and remain enigmatic. One such region includes the Huatung Basin (HB) and the Gagua Ridge (GR) along the northwestern PSP (Fig. 1), and is the focus of this study.

The northwestern PSP has two ocean basins: the larger and better-studied West Philippine Basin (WPB), and the undrilled, smaller HB (Fig. 1). The GR is a bathymetric high between the HB and WPB, occupying a unique position (Fig. 1). Existing interpretations regarding the origin of the GR are diverse, including an uplifted sliver of oceanic crust (Mrozowski et al., 1982), a former intraoceanic fracture zone (Deschamps et al., 1998), the WPB-HB plate boundary (Deschamps et al., 2000; Sibuet et al., 2002), or a relict subduction zone (i.e., westward subduction of the WPB beneath the HB along the GR; Deschamps and Lallemand, 2002; Eakin et al., 2015). Each scenario has wide-ranging implications for HB-WPB interactions and southeast Asian plate tectonic evolution, and so data pertaining to these scenarios were obtained in this study.

We present new Ar-Ar geochronology and geochemistry for GR lavas, including major- and trace-element and Sr-Nd-Hf-Pb isotope data for whole rocks, and U-Pb–Hf isotopic and trace-element data for zircons from the lavas. Combined with the regional tectonic constraints, our study provides new insights into the nature, origin, and dispersal of the GR that elucidate the tectonic evolution of southeast Asia.

GEOLOGIC SETTING AND SAMPLES

The HB is a small ocean basin that has an enigmatic tectonic history. Deschamps and Lallemand (2002) proposed that the HB was near the Equator in the early Cenozoic and then docked against the WPB along the GR at ca. 35 Ma, whereas Hall (2012) considered the HB to have been near ~20°N latitude for most of its history. If the HB and Luzon were already juxtaposed by the Eocene, Luzon paleomagnetism similarly places the HB near the Equator or even at low latitudes within the Southern Hemisphere during the Eocene (Queano et al., 2007).

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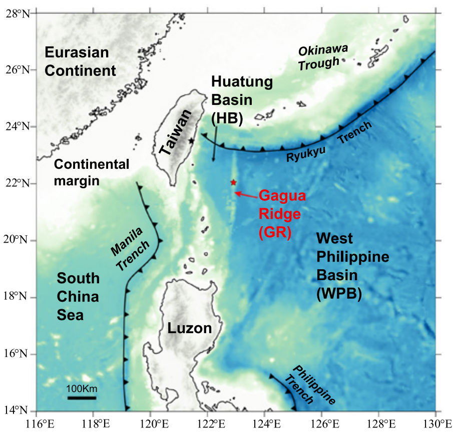

Figure 1. Geologic map of the Gagua Ridge (GR) western Philippine Sea, and adjacent regions. Red star—sampling location of GR lavas; black star—Taiwan Cathaysian continental fragment of Shao et al. (2015).

Wu et al. (2016) followed Queano et al. (2007) and reconstructed Luzon-HB to be within a now-vanished marginal "East Asian Sea."

The GR is adjacent to an unusual subduction flipping system (e.g., the PSP subducting northwestward along the Ryukyu Trench, and the South China Sea subducting eastward along the Manila Trench; Fig. 1; Angelier, 1986; Sibuet et al., 2002). The geophysical data indicate crustal thickening on the order of ~12–18 km beneath the GR (Eakin et al., 2015). In addition, the northernmost segment of this linear GR subducts beneath the Ryukyu Trench (Deschamps et al., 1998; Dominguez et al., 1998).

Lavas were collected in October 2018 from the GR by remotely operated vehicle (ROV) *Haixing 6000* (Fig. 1). Four sites around the highest peak of the ridge were investigated, but only those located at the top provided relatively fresh volcanic rocks (Figs. S1 and S2A in the Supplemental Material[1]). The lavas are massive and porphyritic, containing clinopyroxene, plagioclase, and orthopyroxene phenocrysts (Figs. S2C and S2D). Some plagioclases have resorption textures, leaving incomplete and crooked rims (Fig. S2D).

Detailed petrography of the samples, analytical methods, analytical data, and data plots are provided in the Supplemental Material.

RESULTS

The zircons from the GR lavas showed an age spectrum mainly ranging from Cretaceous to Archean, with three prominent population peaks at 250 Ma ($n = 13$), 750 Ma ($n = 24$), and 2450 Ma ($n = 14$) (Fig. 2B). The zircons displayed a wide range of $\varepsilon_{Hf}(t)$ values, from −31.0 to 23.8 (Fig. 2A), corresponding to highly variable depleted mantle (DM) crustal model ages (T_{DM}^{C}) between ca. 382 Ma and 3015 Ma (Table S4), consistent with a heterogenous source. Plagioclases in the GR lavas yielded weighted Ar-Ar mean ages of 123.99 ± 0.24 Ma and 124.06 ± 0.27 Ma (Figs. 2E and 2F).

Generally, the GR lavas were mainly basaltic andesites (Fig. 3A) that showed limited variation in major elements (e.g., SiO_2 54.38–56.21 wt%, total alkalis 4.32–5.87 wt%). They were characterized by enrichment of large ion lithophile

[1]Supplemental Material. Methods, supplemental figures, and supplemental tables. Please visit https://doi.org/10.1130/GEOL.S.14842740 to access the supplemental material, and contact editing@geosociety.org with any questions.

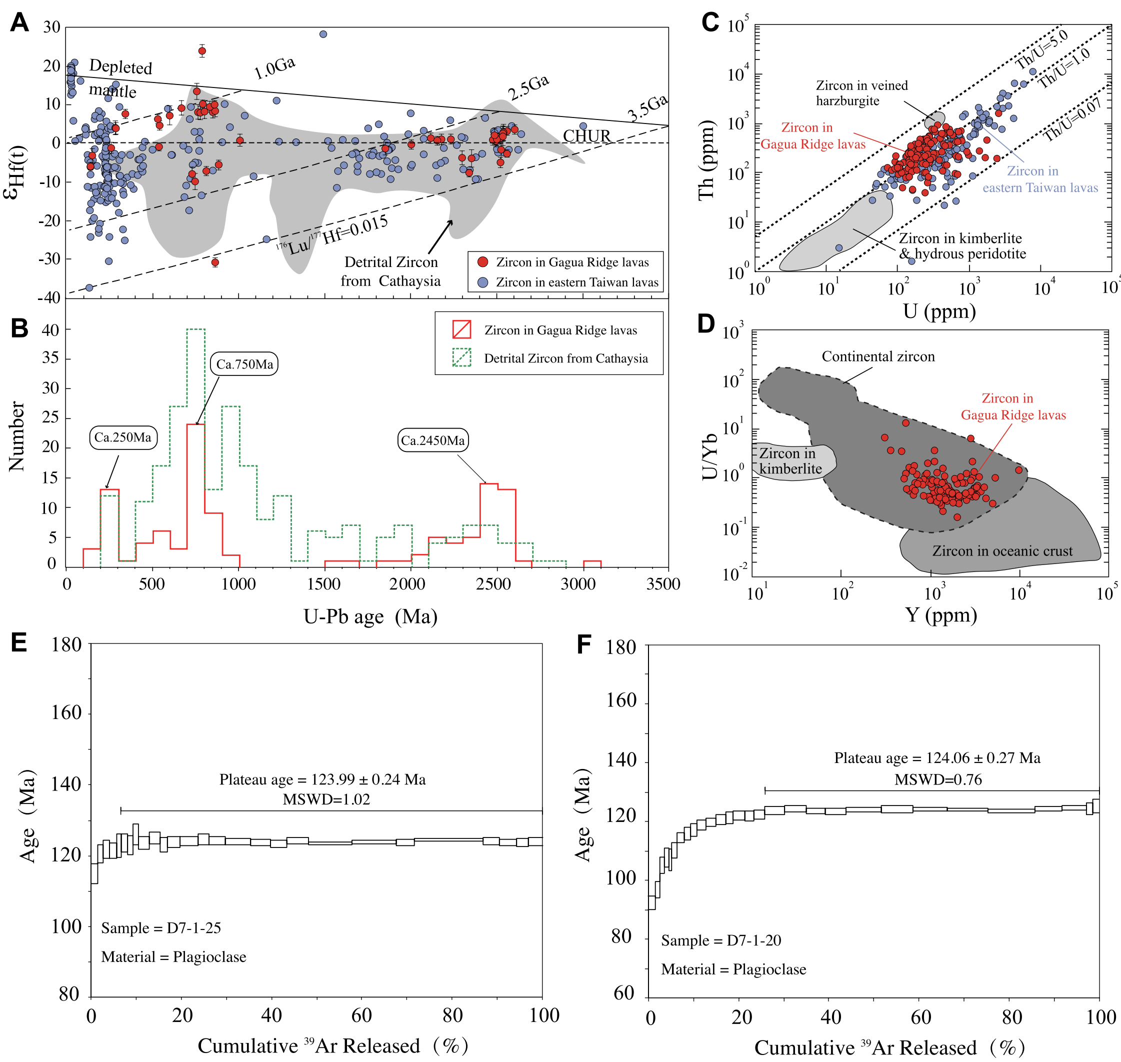

Figure 2. Zircon and plagioclase data from lava samples from the Gagua Ridge (GR), Philippine Sea. (A) $\varepsilon_{Hf}(t)$ versus U-Pb age. (B) U-Pb age histogram. (C) Th versus U. (D) U/Yb versus Y. For comparison, zircons from continental and oceanic crust, and mantle peridotite and kimberlite (Grimes et al., 2007, and references therein), eastern Taiwan lavas (Shao et al., 2015), and Cathaysia block detrital zircons (Yu et al., 2010) are plotted. CHUR—chondritic uniform reservoir. (E,F) $^{40}Ar/^{39}Ar$ age spectrum for plagioclase from GR lavas. MSWD—mean square of weighted deviates.

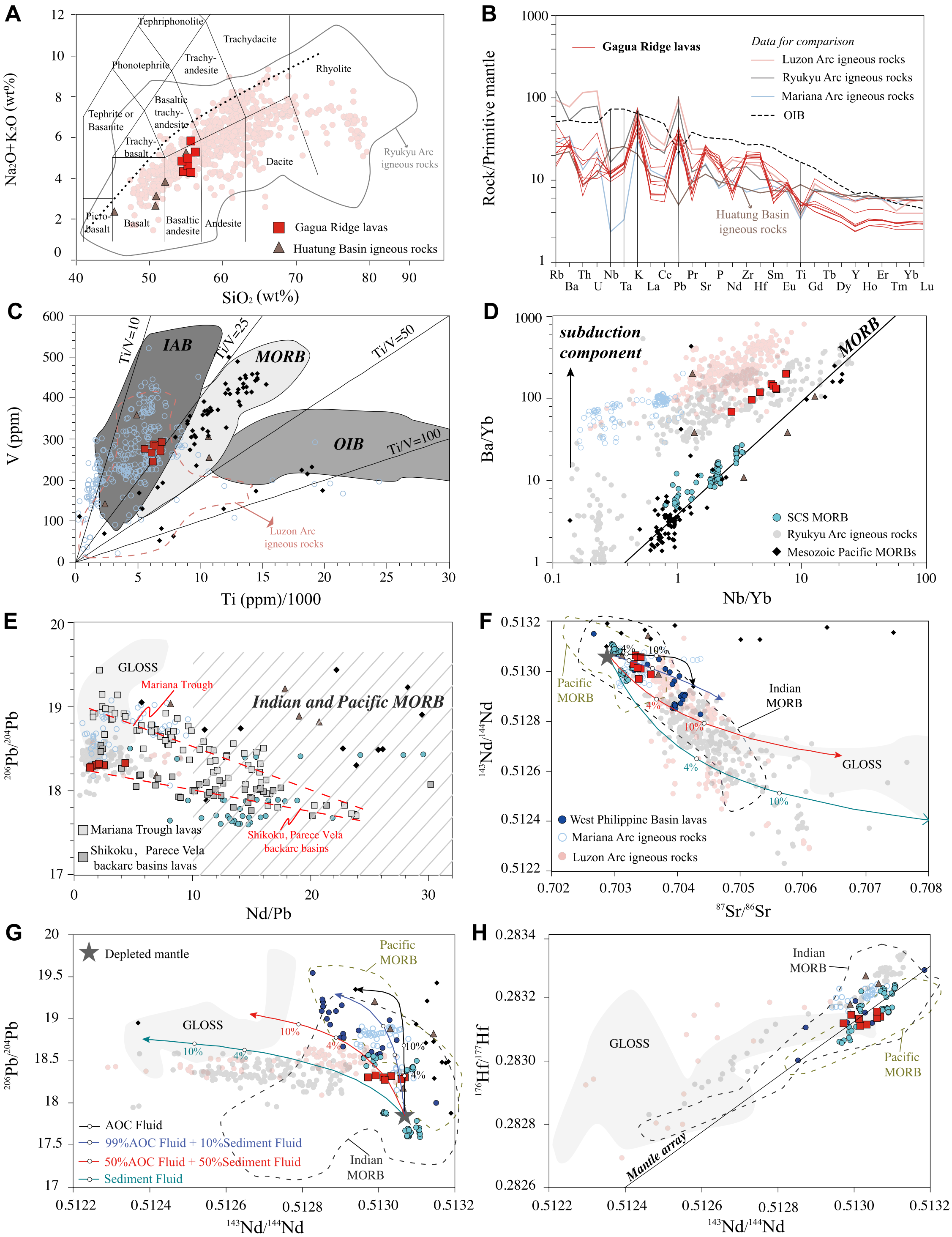

Figure 3. Gagua Ridge (GR, Philippine Sea) lava data.(A) Variation of total alkali ($Na_2O + K_2O$) versus SiO_2. (B) Primitive mantle–normalized trace-element pattern. (C) Ti-V discrimination diagram (Shervais, 1982). (D) Ba/Yb versus Nb/Yb. (E) $^{206}Pb/^{204}Pb$ versus Nd/Pb. (F–H) Isotopic compositions. Numbers adjacent to lines indicate percent of slab-derived fluid added to the source mantle (see data sources and isotope modeling details in Table S5 [see footnote 1]). OIB—ocean-island basalt; MORB—mid-oceanic ridge basalt; IAB—island-arc basalt; SCS—South China Sea; GLOSS—global subducting sediment; AOC—altered oceanic crust.

elements (LILEs, e.g., Ba, U, K, and Pb), resembling the signature of subduction-related rocks from circum-Pacific arcs (Fig. 3B). They all displayed depleted mantle–type isotopic signatures, with low $^{87}Sr/^{86}Sr$ (0.703297–0.703574) and high $^{143}Nd/^{144}Nd$ (0.512972–0.513067) and $^{176}Hf/^{177}Hf$ (0.283112–0.283157) (Figs. 3F–3H). The GR lavas showed a limited range of Pb isotope compositions ($^{206}Pb/^{204}Pb$ = 18.279–18.330, $^{207}Pb/^{204}Pb$ = 15.476–15.493, and $^{208}Pb/^{204}Pb$ = 37.961–38.038; Fig. 3E; Table S1).

CONTINENTAL FRAGMENT BENEATH THE GAGUA RIDGE

U-Pb ages of zircons in the GR lavas ranged widely from 3035 to 123 Ma (Figs. 2A and 2B), which suggests that zircon grains are likely xenocrystic. The GR zircons showed high U, Th, and Y contents and U/Yb values that markedly differ from those of recycled oceanic crust, mantle peridotite, and kimberlite, but that resemble those of continental crust (Figs. 2C and 2D). The U-Pb ages and Hf isotope systematics of the GR zircons (Figs. 2A and 2B) broadly match those of zircon records from the Cathaysian block, South China (Yu et al., 2010; Li et al., 2014). The Mesozoic age peak (250 Ma) of the GR zircons can possibly be related to widespread contemporaneous magmatic rocks in southern China, while zircon age peaks (ca. 0.75 Ga and ca. 2.45 Ga) are largely consistent with those for zircons from Cathaysia crust, southern China (Fig. 2B). Thus, the GR zircons most likely originated from Cathaysian block.

The GR zircons were likely inherited from crust-derived material within mantle sources. It is known that crust-derived materials only contain small amounts of accessory zircon. If our zircon xenocrysts had been derived from recycled continental crust in the mantle source, the erupted lavas would have continental signatures, e.g., enriched Sr-Nd isotopes, due to significantly higher trace-element contents in recycled continental crust relative to mantle. However, these features are absent in the GR lavas (e.g., the depleted mantle–like Sr-Nd isotopic compositions; Fig. 3F). Furthermore, inherited zircons with multiple episodes of recycling and/or long-distance transport are typically well rounded or ellipsoidal with pitted surfaces. In contrast, most of the inherited zircons in the GR lavas are euhedral to subhedral (Fig. S3), suggesting no long-distance transport. All these features argue against the GR zircons being from subducting sediment involving long transport distances or from crust with multiple episodes of recycling.

Alternatively, the zircons in the GR lavas could have been entrained from the Cathaysian crust during magma ascent and/or within the magma chamber. This implies the existence of continental crust beneath the GR. Compared to older continental crust, the GR lavas have remarkably depleted Sr-Nd isotope compositions (Fig. 3F), which suggests that juvenile parent magmas assimilated a small amount of older material to incorporate zircon grains but not enough to dramatically affect isotopic systematics.

PETROGENESIS

As shown in the multi-element spider diagram (Fig. 3B), enrichments in fluid-mobile elements (e.g., U, K, Pb, Sr, and Ba) in the GR lavas are typical of subduction-related magmatism. The relatively low Ti/V values, as well as high Ba/Yb values, of the GR lavas represent subduction-related signatures (Figs. 3C and 3D). Unlike mature arc systems (e.g., Luzon and Ryukyu arc), the isotopic compositions of the GR lavas plot far away from the domain of global subducting sediment (GLOSS; Figs. 3E, 3F, and 3G; Plank and Langmuir, 1998). In particular, the GR lavas are distributed along the mantle array on the plot of $^{143}Nd/^{144}Nd$ versus $^{176}Hf/^{177}Hf$ (Fig. 3H), suggesting a fairly minor contribution from subducting sediment to the mantle source (Plank and Langmuir, 1998; Hickey-Vargas et al., 2008). Additionally, the GR lavas have a typical subducted slab–derived "fluid" signature, with low Nd/Pb (<4.3, relative to ~20 in mid-oceanic ridge basalts; Fig. 3E). In the case of the GR lavas, the elevation of Sr/Th and Ba/La coupled with the narrow variations of Th/Ce and Th/Yb (Fig. S4) also underline a significant contribution of slab-derived fluids to the mantle source. Consequently, we postulate that the GR lavas were derived from depleted mantle that had been metasomatized by subducted slab–related materials. Following the approach of Ishizuka et al. (2003), a simple simulation showed that the mantle source of the GR lavas was likely to have been metasomatized by ~4% fluid derived from altered oceanic crust and subducted sediment in a mixing ratio of 50:50–90:10 (Figs. 3F and 3G).

The GR lavas show subduction-related arc geochemical signatures, suggesting a past subduction event. The GR lavas formed by 124 Ma (Figs. 2E and 2F), which is also consistent with the minimum age (123 ± 1.7 Ma) of zircon in the GR lavas within error (Table S2). Thus, it is most likely that the GR lavas were derived from a mantle source region metasomatized by slab-derived fluids along southern China during the Cretaceous, which was an active margin (e.g., Hall, 2012). In terms of geochemical compositions, the HB lavas have compositions similar to lavas formed in backarc basins and spreading centers (e.g., Nb, Ta, and Ti enrichments, relatively high Nd/Pb and Ti/V values, and low Ba/Yb values; Fig. 3), while the GR lavas were more influenced by subducted components (the arc or close to rear-arc position).

IMPLICATIONS FOR SOUTHEAST ASIA TECTONIC EVOLUTION

Published geophysical and geochemical data, sedimentation rates, and geomagnetic modeling show that the HB is likely a trapped remnant of a Cretaceous-aged oceanic basin (Deschamps et al., 2000; Hickey-Vargas et al., 2008; Eakin et al., 2015; Huang et al., 2019; Hsieh et al., 2020). However, other studies favor a younger age for the HB based on seafloor magnetics and seismology, including Eocene (Hilde and Lee, 1984), Eocene to Miocene (Sibuet et al., 2002), Oligocene–Miocene (Kuo et al., 2009), or mid–late Eocene (Doo et al., 2014). Our study affirms a Cretaceous age for the HB based on our GR lava eruption ages and the youngest zircon ages of ca. 124–123 Ma (Fig. 2; Table S2).

Our identification of a Cathaysian continental fragment in the Philippine Sea suggests that HB formation could have been related to rifting of the Cathaysian block during the Cretaceous, when southeast China transitioned from an active subducting margin to extension (Xu et al., 2014; Zahirovic et al., 2016). It is also possible that the HB formed during the Early Cretaceous from 131 to 119 Ma (Deschamps et al., 2000); both cases imply rifting of a Cathaysian continental fragment during the Cretaceous. Combining published plate models with our results, the HB could be far-traveled, or it could have remained relatively close to Eurasia during its history (Fig. 4). In the far-traveled scenario, the HB was located near southern China in the Early Cretaceous, drifted ~2000 km southward to equatorial latitudes by the Eocene, and then followed the PSP and Luzon ~2000 km northwards after 50 Ma to its present position (Fig. 4). Southward drift of the HB could have been accommodated by opening of a backarc basin or marginal sea near South China, including a large proto-South China Sea or other vanished marginal sea (Deschamps and Lallemand, 2002; Wu et al., 2016; Zahirovic et al., 2016). Alternatively, a "short-transport" scenario is possible, wherein the HB is a relict proto-South China Sea fragment that remained relatively close to southern China, moved ~500 km southward during the South China Sea opening, was captured by the PSP, and then moved ~500 km northwards (Fig. 4; Hall, 2012). This scenario requires the HB to have been tectonically transported a shorter distance and seems more favorable (Fig. 4), and it is still compatible within specific constraints used by far-traveled plate models (Deschamps and Lallemand, 2002; Wu et al., 2016).

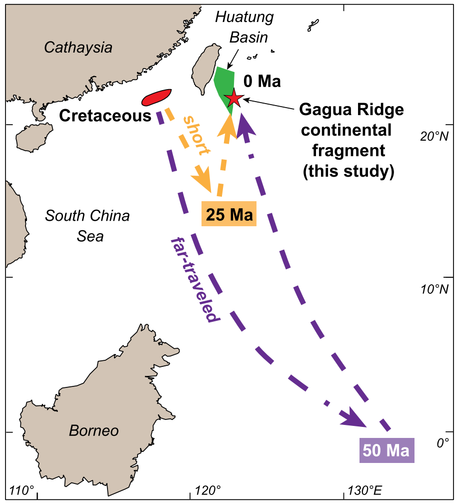

Figure 4. Present-day Southeast Asia map showing the possible tectonic journey of Cathaysian-affinity continental crustal sliver beneath the Gagua Ridge (GR) found in this study (red star). The continental sliver (red polygon) rifted from South China during the Cretaceous and possibly followed one of two paths: far travel (purple path) or short transport (orange path). Both cases reveal the transport of continental slivers by growth and closure of marginal seas along East Asia, which may be more prevalent than generally recognized. Brown areas—present-day landmasses; green area—present-day Huatung Basin (HB).

Another sliver of Cathaysian-affinity continent was found within the Luzon arc basement that apparently drifted southward during the South China Sea opening, was accreted, and then moved northward with the PSP during the mid- to late Cenozoic (Shao et al., 2015). Taken together with our results, we newly we present the undrilled HB as a narrow (up to 150 km wide) sliver of oceanic crust bounded on both sides by continental fragments of Cathaysian affinity (Fig. 4). Accretion of "ribbon continents" is a fundamental process in orogenesis and continental growth over time and space (Cawood et al., 2009). Our results now show that the transport of continental slivers by growth and closure of marginal seas along the East Asia margin (Fig. 4) may have been more prevalent than previously recognized.

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