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Challenger Deep basalts reveal Indian-type Early Cretaceous oceanic crust subducting in the southernmost Mariana Trench

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ABSTRACT

Why the Challenger Deep, the deepest point on Earth's solid surface, is so deep is unclear, but part of the reason must be the age and density of the downgoing plate. Northwest Pacific oceanic crust subducting in the Izu-Bonin-Mariana Trench is Cretaceous and Jurassic, but the age and nature of Pacific oceanic crust subducting in the southernmost Mariana Trench remains unknown. Here we present the first study of seafloor basalts recovered by the full-ocean-depth crewed submersible *Fendouzhe* from the deepest seafloor around the Challenger Deep, from both the overriding and downgoing plates. $^{40}Ar/^{39}Ar$ ages indicate that downgoing basalts are Early Cretaceous (ca. 125 Ma), indicating they are part of the Pacific plate rather than the nearby Oligocene Caroline microplate. Downgoing-plate basalts are slightly enriched in incompatible elements but have similar trace element and Hf isotope compositions to other northwest Pacific mid-ocean ridge basalts (MORBs). They also have slightly enriched Sr-Nd-Pb isotope compositions like those of the Indian mantle domain. These features may have formed with contributions from plume-derived components via plume-ridge interactions. One sample from the overriding plate gives an $^{40}Ar/^{39}Ar$ age of ca. 55 Ma, about the same age as subduction initiation, to form the Izu-Bonin-Mariana convergent margin. Our results suggest that 50%–90% of the Pb budget of Mariana arc magmas is derived from the subducted MORBs with Indian-type isotope affinity.

INTRODUCTION

Subducted oceanic slabs play key roles in compositional variations of arc magmas and crust-mantle cycling (Hauff et al., 2003; Kawamoto et al., 2012; Keppler, 2017). During subduction, slab-derived components are selectively transferred into the overlying mantle wedge by aqueous fluids, siliceous melts, and supercritical fluids, leading to compositional diversity of arc magmas (Kawamoto et al., 2012; Keppler, 2017; Kessel et al., 2005). The Izu-Bonin-Mariana arc system has developed since 50–55 Ma and is a natural laboratory for studying convergent-margin magmatism (Stern et al., 2003), but the nature of the subducting oceanic crust in the southernmost Mariana Trench and what role this might have played in forming Earth's deepest point, the Challenger Deep, are unknown.

Dramatic compositional changes of Early Cretaceous Pacific mid-ocean-ridge basalts (MORBs) from Pacific-type to Indian-type isotope affinity has been proposed to account for DUPAL-like signatures (high $\Delta 8/4$ and $\Delta 7/4$; Δ notation from Hart, 1984) in Izu-Bonin arc magmas (Straub et al., 2009). Compiled data demonstrate that Pb isotope compositions of Mariana arc magmas exhibit a continuum from a high–$^{206}Pb/^{204}Pb$ end member with low $\Delta 8/4$ to a low–$^{206}Pb/^{204}Pb$ end member with high $\Delta 8/4$ (see details below), indicating input of a DUPAL-like component. Published data, however, demonstrate that northwest Pacific oceanic crust subducting in the Izu-Bonin-Mariana Trench has distinct Pacific-type isotope affinity and is older than 127 Ma (Durkin et al., 2020; Koppers et al., 2003a; Miyazaki et al., 2015; Straub et al., 2009). Recent dives with full-ocean-depth crewed submersible *Fendouzhe* recovered seafloor basalts near the trench axis in the Challenger Deep, which is the deepest known place on Earth at ~10,909 m below sea level recorded by diving (Du et al., 2021).

To reveal the age of this seafloor as well as slab inputs and thus the origin of compositional variations of Mariana arc magmas, we combined detailed petrography and geochemical data of 24 basalt samples recovered around the Challenger Deep by the crewed submersible *Fendouzhe* as well as those from ~40–50 km southeast of the trench axis by the crewed submersible *Jiaolong* and compared these with northwest Pacific MORBs, Mariana arc magmas and forearc basalts (FABs), Ontong Java–Manihiki–Hikurangi Plateau (Ontong Java Nui) basalts, and Deep Sea Drilling Project (DSDP) Site 57 basalts of the Cenozoic Caroline plate. We show that the downgoing basalts in the southernmost Mariana Trench are ca. 125 Ma and show mean MORB-like trace element compositions and Indian-type isotope affinity. We use these results to explore the nature and origin of these seafloor basalts and their implications for understanding the boundary between the Caroline and Pacific plates near the southernmost Mariana Trench and the evolution of Mariana arc magmas.

BOUNDARY BETWEEN THE CAROLINE AND PACIFIC PLATES NEAR THE SOUTHERNMOST MARIANA TRENCH

We analyzed 23 basalt samples from six dive sites on the downgoing plate and one sample from the overriding plate (Fig. 1; sample details, analytical methods, and results are provided in the Supplemental Material[1]). Most samples are aphyric basalt, except for some with minor

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[1]Supplemental Material. Supplemental Figures S1–S6 and Tables S1–S4, and extended information about samples, methods, and results. Please visit https://doi.org/10.1130/GEOL.S.22782917 to access the supplemental material, and contact editing@geosociety.org with any questions.

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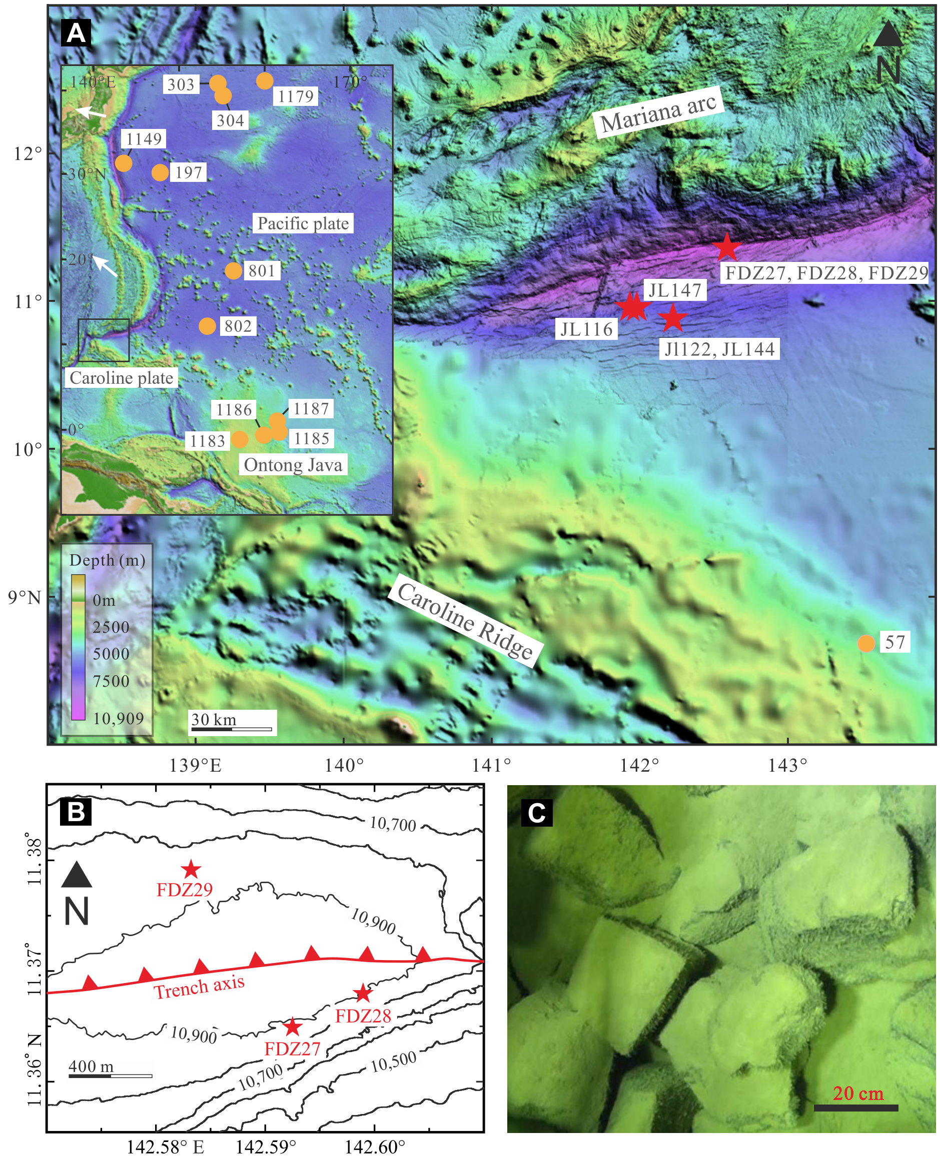

Figure 1. (A) Location map for the southern Mariana subduction system. Filled circles represent Deep Sea Drilling Project Sites (57, 197, 303, 304) and Ocean Drilling Program Sites (801, 802, 1149, 1179, 1183, 1185–1187), and filled stars represent dive locations in this study. Relative motion of the Pacific plate with respect to the Philippine Sea plate is shown with white arrows (Stern et al., 2003). (B) Bathymetric map around the Challenger Deep with dive locations (contours at 100 m intervals). (C) Representative photo of seafloor basalts from dive FDZ28 taken by crewed submersible *Fendouzhe*.

to abundant phenocrysts of plagioclase and clinopyroxene (Fig. S1 in the Supplemental Material). Basalt samples recovered from the downgoing plate in the southernmost Mariana Trench generally have major and trace element characteristics similar to those of other northwest Pacific MORBs. Plagioclase from sample FDZ28-G3 yielded a $^{40}Ar/^{39}Ar$ plateau age of 125.6 ± 6.5 Ma (2σ, MSWD = 1.15; Fig. 2A), indistinguishable from Ocean Drilling Program (ODP) Site 1149 basalts (127.0 ± 1.5/3.6 Ma, n = 1, 2σ internal/absolute error; Koppers et al., 2003a) from the Nadezhda Basin close to the Izu-Bonin-Mariana Trench (Fig. 1A inset). These basalt samples have mean-MORB-like rare earth element (REE) patterns ($[La/Sm]_N$ = 0.80–1.07; N = normalized to CI-chondrite. Fig. 2C), trace element patterns (Fig. S2), trace element ratios (e.g., Ti/Eu, Y/Ho; Fig. S4), and Hf isotope compositions that are similar to those of other northwest Pacific MORBs (Fig. 3). These results are consistent with magnetic anomaly patterns indicating that this part of the westernmost Pacific plate formed in Late Jurassic and Early Cretaceous time (Nakanishi et al., 1992).

The great depth of the Challenger Deep is believed to be controlled by its great age and a tear in the downgoing Pacific slab (Fryer et al., 2003; Gvirtzman and Stern, 2004; Hilde and Uyeda, 1983). Compared to the ca. 125 Ma basalts in this study, much younger basalts (ca. 23 Ma) recovered from DSDP Site 57 (Fig. 1A) on the northern flank of the Caroline Ridge exhibit distinctly higher light REEs relative to heavy REEs (Fig. 2C) and higher $\varepsilon_{Nd}(t)$ for given $\varepsilon_{Hf}(t)$ (Fig. 3B) (Ridley et al., 1974; Zhang et al., 2020). This suggests that a cryptic boundary between the Oligocene Caroline plate in the south and Early Cretaceous Pacific MORBs studied here lies somewhere between them, i.e., south of 10.89°N (*Jiaolong* dive sites JL122 and JL144).

NATURE AND ORIGIN OF MID-CRETACEOUS PACIFIC MORB

Oceanic crust subducting in the Izu-Bonin-Mariana Trench has Pacific-type isotope signatures (Durkin et al., 2020; Koppers et al., 2003a; Miyazaki et al., 2015; Nakanishi et al., 1992; Straub et al., 2009). Note that the ca. 125 Ma Pacific MORBs subducting in the southernmost Mariana Trench in this study have similar Hf isotope compositions to other northwest Pacific MORBs but distinct Sr-Nd-Pb isotope compositions like those of the Indian mantle domain (Figs. 3A and 3B). These ca. 125 Ma basalts generally have higher $^{208}Pb/^{204}Pb$ for given $^{206}Pb/^{204}Pb$, lying above the Northern Hemisphere Reference Line (NHRL) and thus having a "DUPAL-like signature" (Fig. 3A; Δ8/4 = 31–60, except one sample with Δ8/4 = 9), and lower $\varepsilon_{Nd}(t)$ and $^{206}Pb/^{204}Pb$ for given $\varepsilon_{Hf}(t)$ (Figs. 3B and 3C), plotting in the Indian mantle domain. They also have lower $\varepsilon_{Nd}(t)$ than the older northwest Pacific MORBs for given initial $^{87}Sr/^{86}Sr$ (Fig. 3D). The above signatures are consistent with their enrichment in incompatible elements relative to older northwest Pacific MORBs (e.g., elevated $[La/Yb]_N$ and Nb/Y; Figs. 2C and 3E).

A DUPAL-like signature and enrichment in incompatible elements in MORBs have long been suggested to be related to ridge suction of plume-derived components during plume-ridge interactions (Sun et al., 1975), given that deep mantle plume–derived high-temperature, hydrous magmas can carry components enriched in incompatible elements into nearby spreading ridges (Gibson and Richards, 2018). The contemporaneous Ontong Java Nui in the western equatorial Pacific, which is the world's largest large igneous province, has long been proposed to be related to a mantle plume (e.g., Isse et al., 2021). Sr-Nd-Pb isotope diagrams (Figs. 3A, 3B, and 3D) show trends that start from a typical Pacific MORB composition and go toward Ontong Java Nui basalts. If, as appears likely, this trend reflects plume-ridge interaction, it indicates the involvement of plume-derived components that are similar to the Ontong Java Nui plume source.

Incompatible-element ratios, such La/Sm, La/Yb, and Nb/Y, are effective proxies of plume-derived enriched components in MORBs (Sun

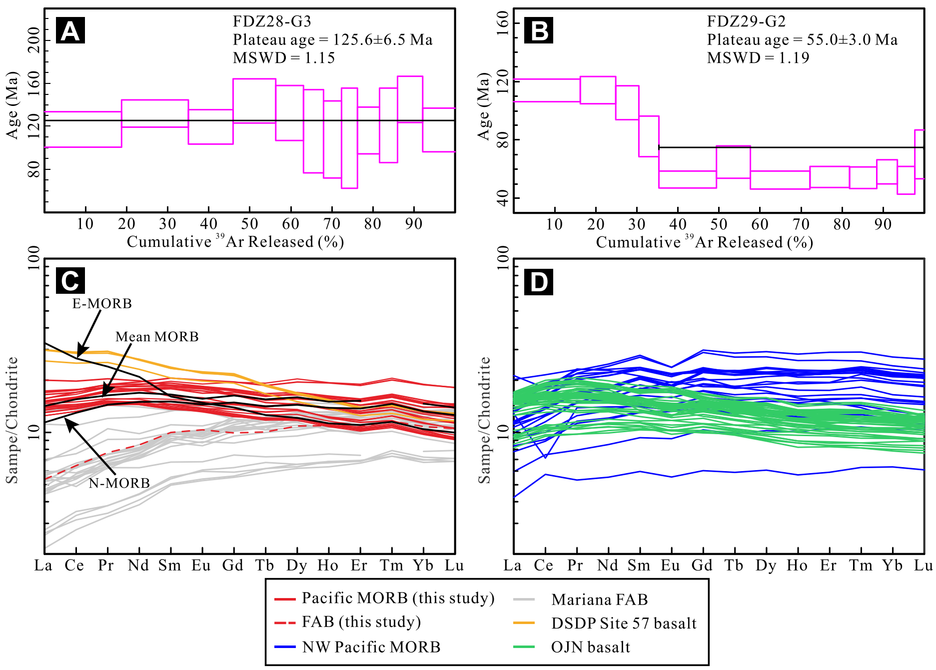

Figure 2. (A, B) High-resolution incremental-heating $^{40}Ar/^{39}Ar$ age spectra of plagioclase for samples FDZ28-G3 and FDZ29-G2, respectively. (C, D) Rare earth element patterns normalized to C1 chondrite (Taylor and McLennan, 1985) for the basalts in this study, compared with northwest Pacific mid-ocean-ridge basalts (MORBs), Mariana forearc basalts (FABs), Deep Sea Drilling Project (DSDP) Site 57 basalts, and Ontong Java Nui (OJN) basalts. Compositions of mean MORB, normal MORB (N-MORB), and enriched MORB (E-MORB) are from Gale et al. (2013). Data sources are from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/); we preferentially consider data sets with both major and trace element contents (loss on ignition <2.5 wt%) and isotope data, and this is the same in Figures 3 and 4.

et al., 1975; Tatsumi et al., 1998). Modeling using Nb/Y and $[La/Yb]_N$ suggests that addition of ~1–5 wt% plume-derived component explains the trace element compositions of ca. 125 Ma Pacific MORBs in this study (Fig. 3E; see details in the Supplemental Material). We favor a model in which ca. 125 Ma Pacific MORBs subducting in the southernmost Mariana Trench formed with contributions from plume-derived components via plume-ridge interaction (Fig. S6). This agrees with the fact that ODP Site 802 basalts in the East Mariana Basin (114.6 ± 3.2 Ma; Castillo et al., 1994) have Sr-Nd-Pb isotope compositions within the range of those of Ontong Java Nui basalts, suggesting they may share a similar plume source (Fig. 3).

IMPLICATIONS FOR THE EVOLUTION OF MARIANA ARC MAGMAS

One of the most important characteristics of basalts in many regions of the western Pacific, including the Izu-Bonin-Mariana arc, Shikoku and Parece Vela Basins, and Mariana Trough, is that their isotopic characteristics resemble those of the Indian mantle domain and are distinct from those of older Pacific MORBs (Durkin et al., 2020; Hickey-Vargas, 1998). The Pb isotope composition of Mariana arc magmas exhibits a continuum from a high–$^{206}Pb/^{204}Pb$ end member with low Δ8/4 (~0) to a low–$^{206}Pb/^{204}Pb$ end member with high Δ8/4 (as high as 51) (Figs. 3A, 4C, and 4D), indicating input of a DUPAL-like end-member component; similar relationships are seen for Δ7/4 (Fig. S4B). Decoupling of Nd and Hf isotope compositions in Mariana arc magmas is also clear, with significantly lower $\varepsilon_{Nd}(t)$ for given $\varepsilon_{Hf}(t)$ like those of the Indian mantle domain (Fig. 3B).

Hf is thought to be immobile relative to most elements in subduction-related aqueous fluids, whereas Nd is more soluble, suggesting that Nd-Hf covariations could be strongly influenced by slab-derived components (Pearce et al., 1999). Pacific plate seamounts near the Mariana Trench generally have low $\varepsilon_{Nd}(t)$ (about –4 to 8) (Koppers et al., 2003b) and are candidates for introducing less-radiogenic Nd into the mantle wedge. Therefore, the decoupling of Nd and Hf in Mariana arc magmas could reflect the input of less-radiogenic Nd from the subducting slab, while the Hf isotope composition of Mariana arc magmas may largely be inherited from the subarc mantle.

The observation that Mariana arc magmas systematically plot closer to the NHRL with increasing $^{206}Pb/^{204}Pb$ indicates that components other than pelagic sediments play a key role in Mariana arc magma Pb isotope compositional variations. Volcaniclastics and seamounts outside the Mariana Trench, such as the Magellan Seamounts, could have introduced high–$^{206}Pb/^{204}Pb$ and low–Δ8/4 components into the mantle wedge (Figs. 4C and 4D); this is also consistent with sediments recovered from ODP Site 801 outboard of the Mariana arc, which consist of >40% (by mass) of HIMU (high-μ; $\mu = {}^{238}U/^{204}Pb$) volcaniclastics (Ishizuka et al., 2007). The increase in $^{206}Pb/^{204}Pb$ and decrease in Δ8/4 of post–10 Ma Mariana arc magmas may indicate subduction of such seamounts (Straub et al., 2015). Alternatively, older Pacific MORBs with Pacific-type isotope compositions could also contribute a low–Δ8/4 component to Mariana arc magmas (Fig. 4).

A variety of sources can account for the DUPAL-like signature in Mariana arc magmas, including asthenosphere flowing from the Philippine Sea plate outward to feed southern Mariana lavas (Ribeiro et al., 2017). Trends in Figures 4C and 4D suggest that ca. 125 Ma basalts subducting in the southernmost Mariana Trench are candidates for introducing a low–$^{206}Pb/^{204}Pb$ and high–Δ8/4 component into the mantle wedge. Mariana Trough basalts generally have lower $^{206}Pb/^{204}Pb$ with increasing Nd/Pb (Fig. 4A); the Mariana Trough basalts with low $^{206}Pb/^{204}Pb$ and high Nd/Pb, which were least affected by slab-derived components, indicate their mantle sources have low $^{206}Pb/^{204}Pb$ and high Δ8/4 (Fig. 4B). Although the mantle source beneath the Mariana Trough may introduce a low–$^{206}Pb/^{204}Pb$ and high–Δ8/4 component into the Mariana wedge, MORB-derived components are more effective for transporting such a component into the mantle wedge (Kawamoto et al., 2012; Keppler, 2017; Kessel et al., 2005). Modeling using $^{206}Pb/^{204}Pb$ and Δ8/4 suggests that 50%–90% of the Pb budget of Mariana arc magmas is derived from subducted slab with similar geochemical compositions to the ca. 125 Ma basalts in this study (Fig. S5B).

SUBDUCTION INITIATION AT THE SOUTHERN MARIANA TRENCH

Basalt sample FDZ29-G2 from the overriding plate exhibits FAB-like geochemical affinities (Reagan et al., 2010), such as light-REE-depleted patterns (Fig. 2C) and low Ti/V of 19.6 (Fig. 3F), and gives a complicated $^{40}Ar/^{39}Ar$ plateau age of 55.0 ± 3.0 Ma (Fig. 2B); this is slightly older than, but overlaps with, ages reported for other Izu-Bonin-Mariana FABs at ca. 48–52 Ma (Ishizuka et al., 2011). Zircons from one gabbro sample (5876 m below sea level) from the Mariana forearc southeast of Guam gave a weighted mean age of 51.8 ± 0.7 Ma (Reagan et al., 2013). Currently, studied forearc rocks from the Izu-Bonin-Mariana forearc are shallower than 7000 m below sea level, and the ages of deeper crustal rocks are unknown. The FAB-like sample in this study suggests that the first

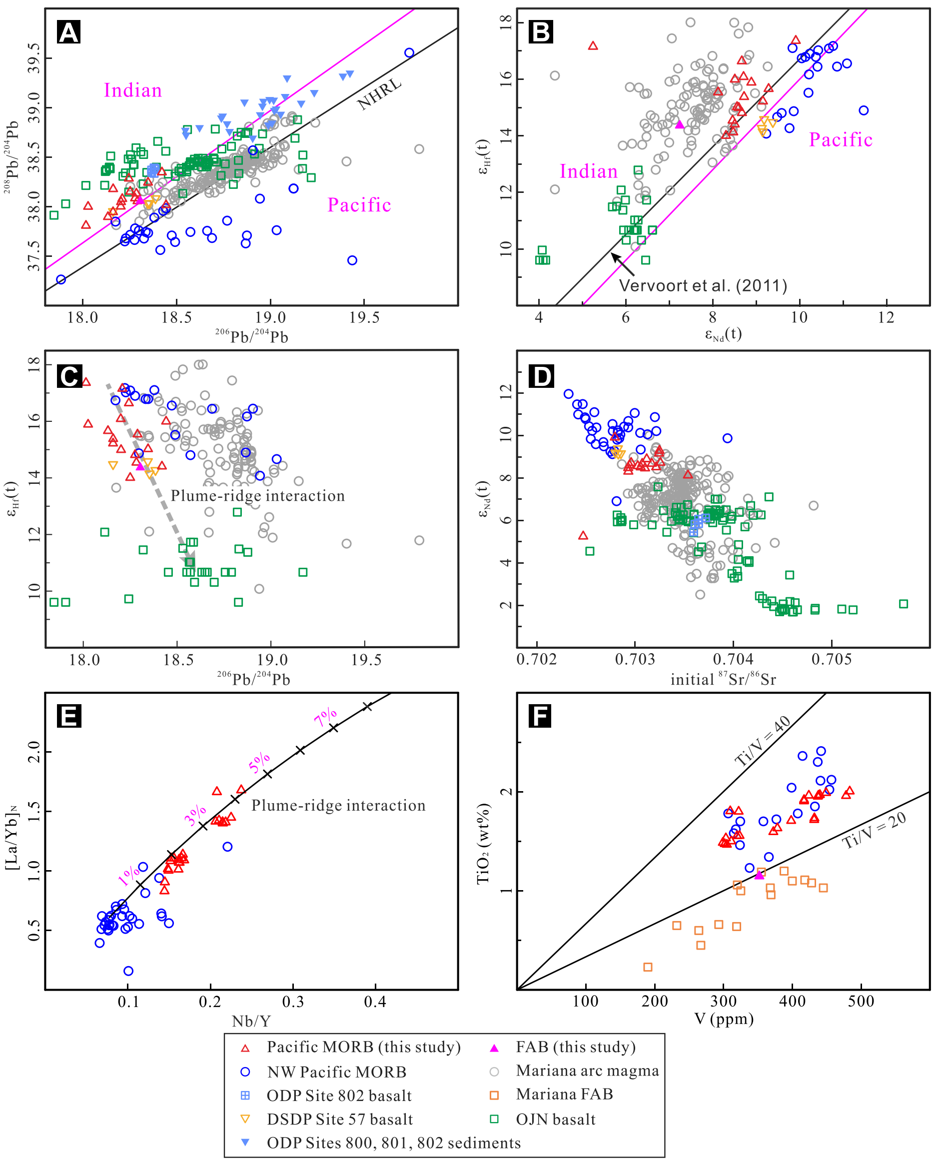

Figure 3. $^{208}Pb/^{204}Pb$ **versus** $^{206}Pb/^{204}Pb$ **(A),** $\varepsilon_{Hf}(t)$ **versus** $\varepsilon_{Nd}(t)$ **(B),** $\varepsilon_{Hf}(t)$ **versus** $^{206}Pb/^{204}Pb$ **(C),** $\varepsilon_{Nd}(t)$ **versus initial** $^{87}Sr/^{86}Sr$ **(D),** $[La/Yb]_N$ **(normalized to C1 chondrite; Taylor and McLennan, 1985) versus Nb/Y illustrating contributions of plume-derived component (1%–5%) for the ca. 125 Ma Pacific MORB (E), and** TiO_2 **versus V (F) for the basalts in this study, compared with northwest Pacific mid-ocean-ridge basalts (MORBs), Ocean Drilling Program (ODP) Site 802 basalts, Deep Sea Drilling Project (DSDP) Site 57 basalts, sediments from ODP Sites (800, 801, 802), Mariana arc magmas, Mariana forearc basalts (FABs), and Ontong Java Nui (OJN) basalts. Pink line represents the geochemical boundary between Pacific and Indian mantle domains (Pearce et al., 1999), the Northern Hemisphere Reference Line (NHRL) is from Hart (1984), and the mantle array is from Vervoort et al. (2011). The gray dashed arrow in Fig. 3C shows a trend that starts from a depleted Pacific MORB composition and goes toward Ontong Java Nui basalts. Data sources are as described for Figures 2C and 2D.**

basaltic magmatism during subduction initiation at the southernmost Mariana Trench was produced at ca. 55 Ma, although further studies are needed to test this suggestion.

CONCLUSIONS

Newly identified ca. 125 Ma Pacific MORBs subducting in the southernmost Mariana Trench formed with contributions from deep-sourced, mantle plume–derived magmas via plume-ridge interaction, resulting in enrichment in incompatible elements (e.g., light REEs, Sr, Pb) and corresponding Sr-Nd-Pb isotope compositions of these basalts. This idea may be extended to the origin of MORBs that experienced plume-ridge interaction and have enriched Sr-Nd-Pb isotopes. Our results suggest that 50%–90% of the Pb budget of Mariana arc magmas is derived from the subducted MORBs with Indian-type isotope affinity. Further work is needed to identify the boundary on the subducting plate between Early Cretaceous lithosphere in the north and ca. 27 Ma crust of the Caroline plate in the south and to understand the significance of a ca. 55 Ma age for overriding plate FAB.

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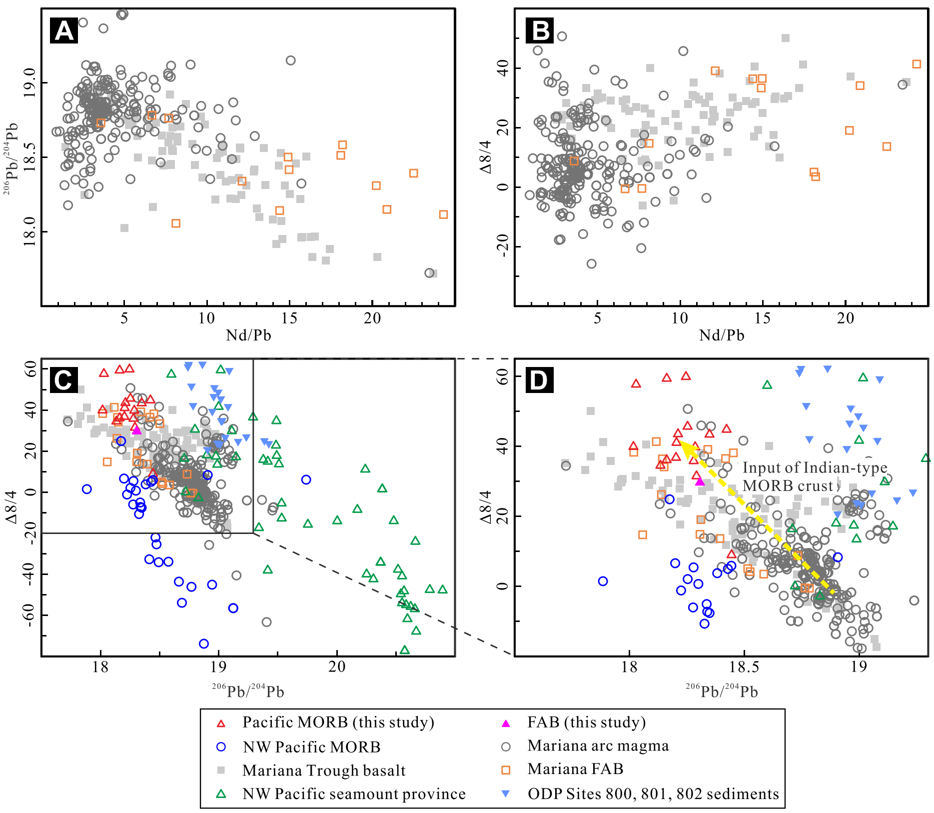

Figure 4. **^{206}Pb/^{204}Pb versus Nd/Pb (A), Δ8/4 (Δ notation from Hart, 1984) versus Nd/Pb (B), Δ8/4 versus ^{206}Pb/^{204}Pb (C), and closeup from C (D) illustrating source components that contributed to the Pb budget of Mariana arc magmas. Data are for the basalts in this study, compared with northwest Pacific mid-ocean-ridge basalts (MORBs), Mariana Trough basalts, northwest Pacific seamount province, Mariana arc magmas, Mariana forearc basalts (FABs), and sediments from Ocean Drilling Program (ODP) Sites (800, 801, 802). Data sources are as described for Figures 2C and 2D.**

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