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The complex Rodrigues triple junction migration since ca. 8 Ma: A response to episodic Amsterdam–St. Paul hotspot tail capture by the Southeast Indian Ridge?

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ABSTRACT

The mutual intersection of three plate boundaries, so-called triple junctions, has long been recognized as crucial boundaries for unraveling the spatiotemporal motion of tectonic plates. Yet, the dynamic and tectonic processes ruling their migration remain enigmatic. At the Rodrigues triple junction, the Southwest Indian Ridge lengthens northeastward in response to the unsteady linearity of the Southeast Indian Ridge–Central Indian Ridge dueling ridge system. This mechanism is episodically compensated by the southeastward propagation of the Central Indian Ridge and alternating stages of recession and progression of the Southeast Indian Ridge. This has led to an apparent length constancy of the first Southeast Indian Ridge segment over the past ca. 8 Ma. These multiple ridge propagation episodes, from northwest, southwest, and southeast, result in a net northeastward migration of the Rodrigues triple junction. Here, we suggest that its migration since ca. 8 Ma is a consequence of short-term readjustments of its plate boundaries induced by transitory motion changes of the Capricorn plate, driven by episodic push forces exerted from ephemeral captures of the Amsterdam–St. Paul plume tail by the Southeast Indian Ridge at the southeastern part of the Capricorn plate (77.3°E–78.6°E).

INTRODUCTION

The Rodrigues triple junction (RTJ) defines a unique structural region among the mid-ocean ridge system (Fig. 1). It has quickly migrated northeastward at $\sim$35 mm yr^{-1} since at least ca. 40 Ma (Bernard et al., 2005) and developed a wide morphotectonic diversity ranging from deep and rough terrains for its slowest-spreading branches (Central Indian Ridge [CIR] and Southwest Indian Ridge [SWIR]) to a shallow, smooth seafloor for its fastest-spreading limb (Southeast Indian Ridge [SEIR]; Fig. 1B). Its peculiar asymmetrical upper-mantle seismic wave velocity structure (Barruol et al., 2019) is also reflected in crustal thickness (West et al., 1995) and mid-ocean-ridge basalt (MORB) chemical composition variations along the individual limbs (e.g., Michard et al., 1986). The RTJ has been a key factor in Indian Ocean tectonic evolution since ca. 96 Ma (Bernard et al., 2005), but the mechanisms behind its nucleation and its different modes of migration are still unknown. Here, we report evidence retrieved from earlier geophysical surveys (e.g., Sauter et al., 1997) and new surveys of BGR's INDEX exploration program (2011–2019) suggesting that morphological changes in its migration pattern since ca. 8 Ma are due to far-field forces emanating mainly from the Amsterdam–St. Paul (ASP) plume tail inducing shifts in both speed and direction of motion of the Capricorn plate (Fig. 1A).

EVOLUTION OF THE DUELING CIR-SEIR PROPAGATION SYSTEM (<ca. 2 Ma)

At first glance, the CIR-SEIR system appears to behave as a dueling ridge propagation system (e.g., Lonsdale, 1989) with repeated retreat and propagation episodes resulting in a net slow migration toward the southeast. These fast, repetitive events produced a partial obliteration of morphological structures, particularly obvious on the CIR propagator (Fig. 1B). The CIR limb (C_1) is indeed characterized by a deep (4040 $\pm$ 82 meters below sea level [mbsl]), disorganized, and asymmetrical terrain, while its SEIR counterpart (S_1) has a shallower (3779 $\pm$ 121 mbsl), symmetrical, and typical abyssal-hill organized fabric. Their past contact positions on the Capricorn plate (i.e., the RTJ's trace) track their relative migration (Fig. 1B). For the past 1.07 m.y. (Fig. 1C), the northwest-directed V-shape pattern of this boundary expresses a rapid advance of S_1 at the expense of C_1 culminating near 0.78 Ma, associated with a higher magma supply to the south (Fig. S1 in the Supplemental Material[1]) as inferred from gravimetric and calculated thickness variations (West et al., 1995). Indeed, a northwest-directed, half V-shape pattern, delineated by variations in P-wave seismic travel time residuals (Sato et al., 1996; Fig. S1), also reflects mantle migration underneath the Capricorn plate from a hotter mantle in the southeast (S_1) to a colder mantle in the northwest (C_1). Contemporaneously, the bending of the subparallel abyssal hill fabric observed on the Capricorn plate compensates for the difference in spreading rates between the CIR and SEIR (Fig. 2A) until the non-transform discontinuity (NTD) formation at 1.07–0.78 Ma, which is followed by an abrupt CIR advance (Mendel et al., 2000). This dynamic behavior of the dual system induced passive lengthening of the third ultra-slow SWIR branch into the SEIR/CIR lithosphere and its valley relocation toward the northeast at 0.78 Ma (Figs. 1B and 1C).

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[1]Supplemental Material. Supplemental references for age compilation of Figure 2, compositions of lavas from SEIR of Figure 4, and Figures S1–S8. Please visit https://doi.org/10.1130/GEOL.S.23304170 to access the supplemental material, and contact editing@geosociety.org with any questions.

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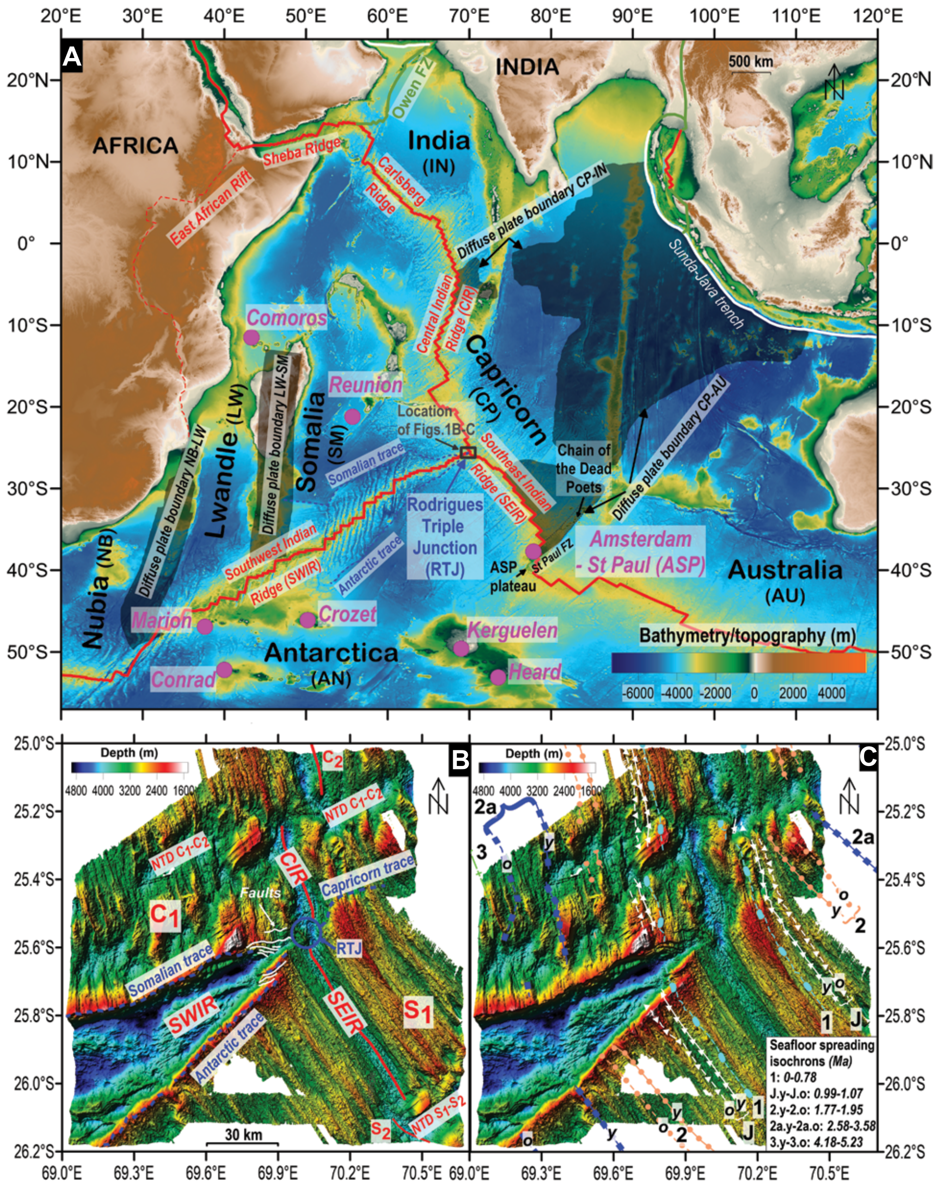

Figure 1. (A) Bathymetry of the Indian Ocean computed from General Bathymetric Chart of the Oceans (GEBCO; https://www.gebco.net/) data. Dark bluish-gray areas are diffuse plate boundaries (Conder and Forsyth, 2001); pink dots, hotspot locations. ASP—Amsterdam–St. Paul; FZ—fracture zone. (B) Three-dimensional surface map of Rodrigues triple junction (RTJ) computed from ship-based multibeam echosounding (MBES) bathymetry data acquired during 2011–2019 INDEX cruises, supplemented by older surveys (Sauter et al., 1997; Mendel et al., 2000). NTD—non-transform discontinuity; C_x, S_x—Central Indian Ridge (CIR), Southeast Indian Ridge (SEIR) segments; white lines—faults; blue dotted lines—RTJ traces; red lines—segment axes. (C) Same map including oceanic crust isochrons (Mendel et al., 2000).

PLUMES, RTJ, AND CAPRICORN PLATE MOTION

Multiple episodes of ridge propagation toward the cold RTJ (Fig. S1) might be driven by converging thermally driven asthenospheric material fed by the nearest hotspots (Crozet, Réunion, and ASP; Fig. 1A) probably anchored in the African superplume (Tsekhmistrenko et al., 2021). However, morphotectonic, geoid, geochemical, and seismic variations (e.g., Nicolaysen et al., 2007; Sauter et al., 2009; Machida et al., 2014; Wamba et al., 2021) do not show any hotspot influence in the vicinity of the junction. However, a synchronicity of eruptive hotspot history with the RTJ's tectonic phases since ca. 8 Ma linked with eventual plate tectonic changes (Fig. 2C) might attest to their far-field influence on the RTJ's mode of migration.

The offset cycle of the CIR-SEIR system marks each change in the RTJ's mode of migration (intermittent versus continuous; Fig. 3A; Mendel et al., 2000). From 8 to 3.58 Ma, the RTJ unsteadily migrated with a NTD offsetting the SEIR and CIR during a drop-off period in the eruption frequency for most Indian Ocean hotspots (Figs. 2A and 2C). At 6.8–6.5 Ma, the CIR's southeast migration was halted by the SEIR's lengthening until 5.33–4.8 Ma, as inferred from strike variations of the RTJ traces (Sauter et al., 1997; Fig. 3B). During this time, the spreading rates of SEIR and CIR rapidly increased, with a maximum reached for SEIR at 4.18–5.23 Ma (Fig. 2A). The SEIR then slightly shortened up to 3.48 Ma (Fig. 3B). At 6.73 Ma, the Capricorn plate motion accelerated toward the north until a deceleration at 3.6 Ma (Fig. 2B; DeMets et al., 2005, 2020; Iaffaldano et al., 2018). This period coincided with a revival of most Indian Ocean plumes (3.6–3.8 Ma; Fig. 2) and the ridge-ridge-ridge–like steady configuration restoration (3.58–2.58 Ma) by offset reduction through a CIR jump, followed by a CIR segment creation at the junction. The SEIR spreading rate increased at 3.58 Ma, followed by the CIR reaching a similar rate at 2.58 Ma (Fig. 2A). Their spreading asymmetry abruptly reversed, becoming larger on the Antarctic and Somalian plates (Fig. S2). Since then, the SEIR poorly lengthened until the NTD restoration (1.07–0.78 Ma), coinciding with a change in Somalian-Antarctic plate motions (DeMets et al., 2015) and a tectonic reorganization at the junction (Mitchell and Parson, 1993).

For the past 8 m.y., the changes in the RTJ's mode of migration appear synchronized with those in Indian Ocean hotspot eruption frequency and/or tectonic reorganizations. At 3.58–2.58 Ma, its step-like to continuous transition might also have resulted from its progression from a cold mantle in the west toward a hotter mantle in the east (Fig. S1; Sato et al., 1996). The alternate lengthening of its dual branch system (SEIR-CIR) cannot be easily linked to eruption frequency changes but occasionally appears to have correlated with motion changes of its bounding plates, in particular with the onset of Capricorn plate's superfast motion at 6.73 Ma (Iaffaldano et al., 2018). This last event was preceded by an abrupt change in the Capricorn-Somalian plate angular rotation rate at ca. 8 Ma (DeMets et al., 2005, 2020).

SEIR-ASP TAIL CAPTURE CAUSING A FAST ROTATION AND SPEED-UP OF THE CAPRICORN PLATE

The Capricorn plate's accelerated motion has been attributed to a surge in asthenosphere flow fed by the Réunion tail since ca. 11 Ma (Iaffaldano et al., 2018). However, its eastward-directed lateral flow at 50–80 km depth (as identified by azimuthal seismic anisotropy; Barruol et al., 2019; Fig. S3) could not have triggered its change in motion from east to north at ca. 8 Ma (DeMets et al., 2005). In contrast, the progressive tail capture of the small ASP plume (diameter = 80 km) by the SEIR ca. 9.7–6.3 Ma

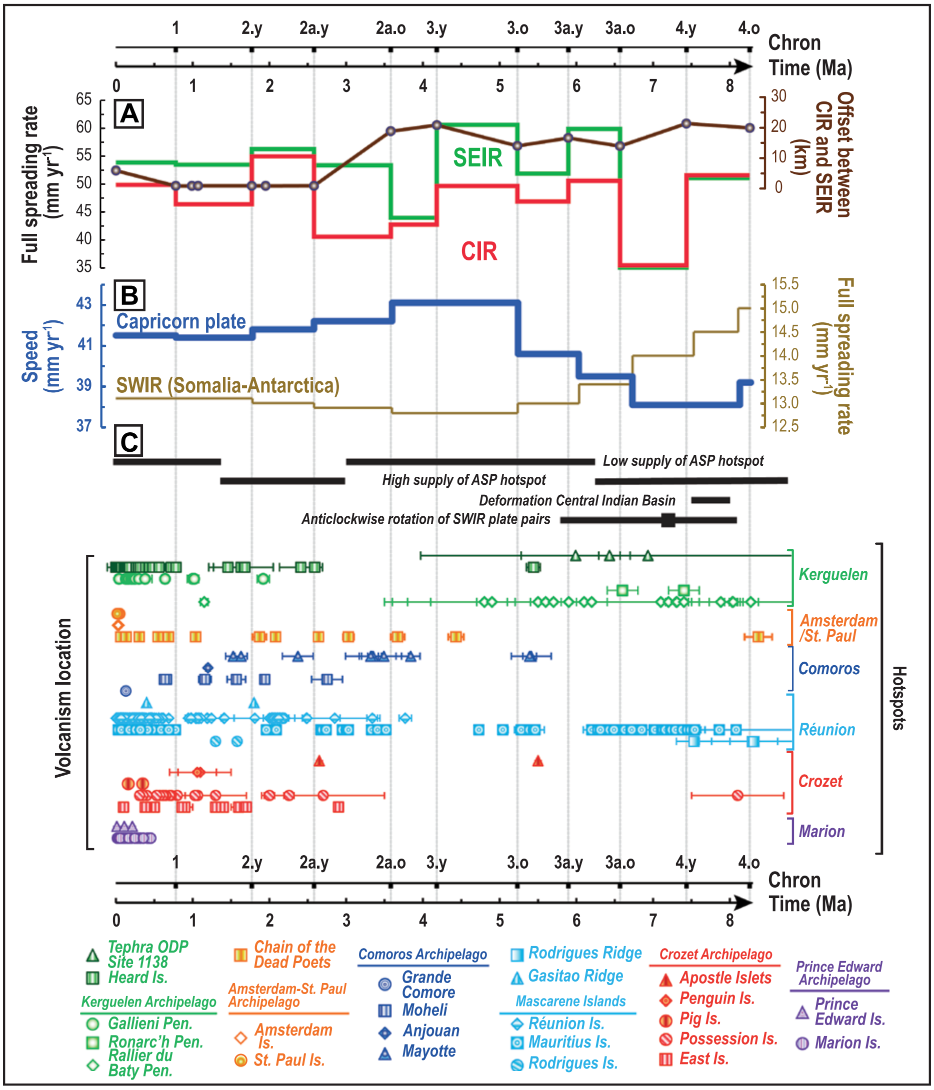

Figure 2. (A) Evolution of full spreading rates for Central Indian Ridge (CIR) and Southeast Indian Ridge (SEIR) as well as of their associated apparent offset (in brown) for the past 8 m.y. (Mendel et al., 2000). (B) Evolution of Capricorn plate speed compared to full spreading rates for Somalian-Antarctic plate pair. SWIR—Southwest Indian Ridge. (C) Comparative geochronology of post–8 Ma oceanic island volcanism (see list of references S9 [see text footnote 1]), as well as timeline of various events occurring in the Indian Ocean. The error bars represent the uncertainties reported for each age in the literature. ASP—Amsterdam–St. Paul; ODP—Ocean Drilling Program; Is.—Island; Pen.—Peninsula. Oceanic crust isochrons are defined as in Figure 1.

near the diffuse boundary at the St. Paul fracture zone between the Capricorn and Australian plates (Conder and Forsyth, 2001) is associated with a short-term increase in plume-fed asthenospheric flow as inferred from gravity-derived crustal thickness variations (Fig. S4; Maia et al., 2011). This might have caused the counterclockwise rotation and acceleration of the Capricorn plate (Fig. 1A).

To the north of the ASP plateau, the emergence of the largest seamounts (Boileau and La Bruyère) of the Chain of the Dead Poets at 8.7–9 Ma, their northeastward displacement relative to the hotspot trace at 8–9 Ma (Fig. 4A), the ASP-like mantle component carried by the Sr-Nd-Pb isotopic signatures of their lavas, and their alignment (N65°E) and elongated morphologies (Fig. S5; Janin et al., 2011, 2012) all support the existence of a dominant, northeastward-directed ASP plume flow component. This channeled stream remains active as evidenced by an ASP plume-like He-Sr-Nd-Pb MORB signature (Fig. S5; e.g., Nicolaysen et al., 2007), low mantle Bouguer anomaly, high relief at the H segment of the SEIR (Fig. 4A) contiguous to the Amsterdam FZ northeast of the hotspot locus (Boomerang Seamount). As much as 60% of northeastward-directed Poiseuille flow at 300 km depth is numerically forecast under the ASP region (Fig. S6; Natarov and Conrad, 2012). This pressure-driven motion stems from the presence of a narrow, SW-NE low-shear-speed band at 100–200 km depth (Fig. S7; Wamba et al., 2021). Poiseuille and Couette flows would be one way in this region (Natarov and Conrad, 2012). The flow (<340 km wide) must then move faster than the Capricorn plate to impose a viscous drag at the lithospheric-asthenospheric boundary (LAB) in its direction (Höink et al., 2011). Indeed, the Capricorn plate motion in the hotspot reference frame (9.3 cm yr^{-1}) exceeds the spreading rate of the SEIR (5.94 cm yr^{-1}; Janin et al., 2011). The greater residual depth observed over a narrower area than for the Réunion hotspot (Fig. S8) would also require a much faster flow rate (>10 cm yr^{-1}, calculated after Iaffaldano et al., 2018). The ridge-tail capture would transmit a greater torque than in an intraplate tail position (van Hinsbergen et al., 2011). If the Réunion hotspot could trigger a plate acceleration of ~5 cm yr^{-1}, the same would also be true for the ASP hotspot.

Reaching this acceleration might also be favored by the amplification of ridge push–slab pull effects due to weakening of the LAB below the diffuse plate boundary. Tail-ridge interaction increases the ridge-push force by two to three times (Bott, 1991). This force (~5–8 × 10^{12} N m^{-1}, calculated after Buck, 2007) for ASP might have briefly surpassed the net current slab-pull force (2.5 × 10^{12} N m^{-1}; Copley et al., 2010) exerted on the whole Indo-Australian plate by subduction zones, exceeding the threshold (2 × 10^{9} N m^{-1}) for compressing the lithosphere. A plate driving force emanating from the ASP plume might hence be responsible for the north-south, fast contractional deformation episode in the northern diffusive zone of the Capricorn-Indian-Australian plate system (78.8°E–87°E) between 7.5 and 8.0 Ma coinciding with the maximum uplift of the Tibetan Plateau (Fig. 1; e.g., Bull et al., 2010). This is in line with the interpretation of DeMets et al. (2005, 2020) that forces acting on the Capricorn plate rather than the Indian plate were responsible for this deformation.

The Poiseuille flow propagation associated with the Capricorn plate motion change might have caused far-field viscous stresses under adjacent plates (Lithgow-Bertelloni and Richards, 1995). This effect is registered by the counterclockwise rotation (5° ± 2°) in the plate slip direction of all SWIR plate boundaries (Nubia-Antarctic, Lwandle-Antarctic, and Somalian-Antarctic) at 7.2 ± 1.4 Ma (Fig. 2) as well as by the contemporaneous gradual counterclockwise rotation of the Indian-Somalian plate slip direction (DeMets et al., 2015, 2020). The motion change further correlates with a SWIR spreading slowdown (DeMets et al., 2015), the initiation of the step-like migration of the RTJ (chrons 4a.y-4.y, 8.7–7.4 Ma; Mitchell and Parson, 1993), and an increase in

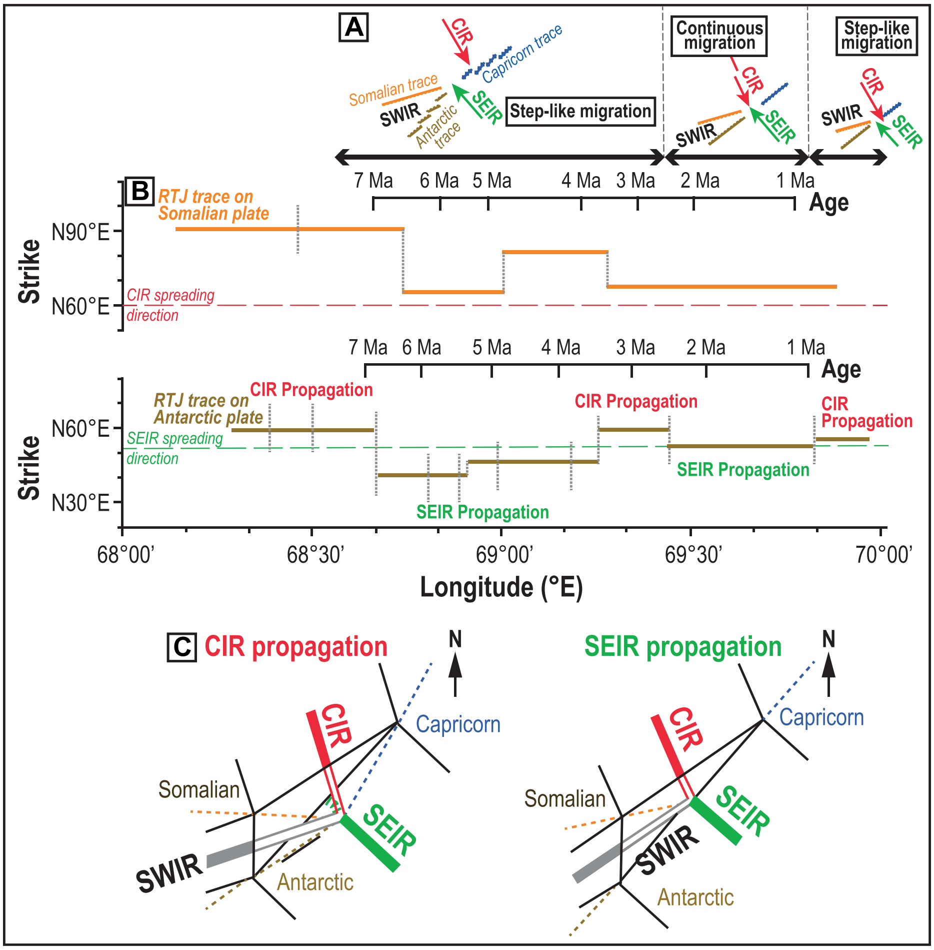

Figure 3. (A) Rodrigues triple junction (RTJ) evolution sketch for the past 8 m.y. (B) Strike variations of RTJ traces on the Somalian and Antarctic plates compared to spreading directions of Central Indian Ridge (CIR) and Southeast Indian Ridge (SEIR) (Sauter et al., 1997). Vertical gray dashed lines are trace offsets. (C) Velocity-space diagrams with thin black lines corresponding to isochrons at time *t* and thick colored (gray, green, red) double lines corresponding to plate boundaries (axes of SWIR, SEIR, and CIR) at a time *t* + *dt* (Patriat and Parson, 1989). Dotted lines are predicted triple junction traces. SWIR—Southwest Indian Ridge.

crustal production rate at the CIR at ca. 7.3 Ma (Dalton et al., 2022).

FAR-FIELD EFFECTS OF ASP CAPTURE ON THE RTJ DYNAMIC

From 8 to 7.2 ± 1.4 Ma, the sinistral rotation of the Capricorn plate and African subplates driven by ASP-ridge capture probably slowly increased the oblique spreading at the SWIR and CIR, stretching the SEIR by 6.5–6.8 Ma (Fig. 3B). At 5.33–4.8 Ma, the RTJ trace directions slightly rotated clockwise, leading to a small SEIR retreat (Fig. 3B). This could have been due to the waning of the ridge-push force due to SEIR drift away from the plume from 6.3 to 3 Ma (Maia et al., 2011; Fig. S4) or to its compensation by an eastern-directed, increased Poiseuille flow, fed by the Réunion plume. The volcanic rebirth in Mauritius from 5.5 to 4.7 Ma might indicate a flux rise (Fig. 2C). At 5.23 Ma, an intra-ridge grew inside the NTD's junction as the CIR lengthened (Mendel et al., 2000). The successive CIR jump at 3.44–2.48 Ma (Mendel et al., 2000) might also have been due to a flux increase, as the eruption rate rose at Mauritius over this time. However, these spurts are not correlated either with eruptions inside the pathway from Mauritius to the CIR or with Capricorn plate speed-up (Fig. 2; Fig. S8). Indeed, the Capricorn plate's deceleration started at 3.6 Ma (Fig. 2B). At ca. 3–2.58 Ma, the ASP tail recaptured by a SEIR jump released sudden voluminous magmatism at the plateau as registered by crustal thickness reaching as much as 11 km (Maia et al., 2011; Fig. S4). Its plateau asymmetry at this time can be attributed to across-axis Poiseuille flow focusing mantle upwelling beneath its leeward rather than windward side (as modeled by Conder et al., 2002). As observed at 6.5–6.8 Ma, this event is correlated with a small lengthening of the SEIR as shown by the strike (N52°E) of the Antarctic plate trace (Fig. 3B) but also with a ridge-ridge-ridge–like restoration. However, no plate motion change or speed-up of the Capricorn plate (Fig. 2B) was registered at that time. The offset return to RTJ at 0.78 Ma was preceded by a change in Capricorn-Somalian plate motion (as suggested by the strike change between chrons 2.y and J.o over the Capricorn plate; Fig. 1C) correlating broadly with a volcanic resurgence at Gasitao Ridge at 1.8 Ma (Fig. 2C). It might also have been synchronous with a Somalian-Antarctic plate motion change (DeMets et al., 2015), as recorded by a spreading direction swing at the Atlantis II fracture zone (Dick et al., 1991) and a tectonic reorganization at the junction (Mitchell and Parson, 1993), involving a relocation of the SWIR valley northeastward to its present location (Mendel et al., 2000). A new Poiseuille flow surge heading east from the Réunion hotspot might have driven these mechanisms, as suggested by the volcanic resurgence at Mauritius Island and a slight acceleration of the Capricorn plate (Fig. 2).

Since 8 Ma, the Antarctic plate trace's anticlockwise rotations coupled to SEIR lengthening occur at the same time as ASP-SEIR captures. However, only the first capture (9.7–6.3 Ma) is unambiguously associated with a regional tectonic reorganization, in which simultaneous rotations of African subplates and Capricorn plate likely modified the RTJ configuration, and the Capricorn plate suddenly accelerated. By itself, this does not establish a causal relationship. However, the occurrence of a change in the RTJ's configuration and SEIR lengthening at the same time as the bulk formation of the ASP plateau also suggests that these events might be related to a plate-driving force emanating from the ASP tail. Due to the low ASP buoyancy flux (0.02 Mg s^{-1}; King and Adam, 2014), this driving effect would be greatly diminished at the time of the second capture (3–2.58 Ma) because of a more vigorous upper-mantle convection flow field strengthened by numerous plume discharges feeding the Indian asthenosphere (Fig. 2C). Instead, due to its higher buoyancy flux (0.07 Mg s^{-1}), the Réunion hotspot might transiently dominate this background convection. Sudden drainages of the ASP hotspot branch anchored in the African superswell, and perhaps occasionally of its Réunion counterpart, might cause fast lateral propagation of asthenospheric waves exerting viscous drag strong enough to change the Capricorn plate motion and, by cascade effect, the RTJ dynamic evolution. Future high-resolution tomographic, magnetic, and geochemical studies will allow for fine-tuned and improved quantitative modeling of the role exerted by pulsations of the African superswell on Earth's tectonic plate motion evolution.

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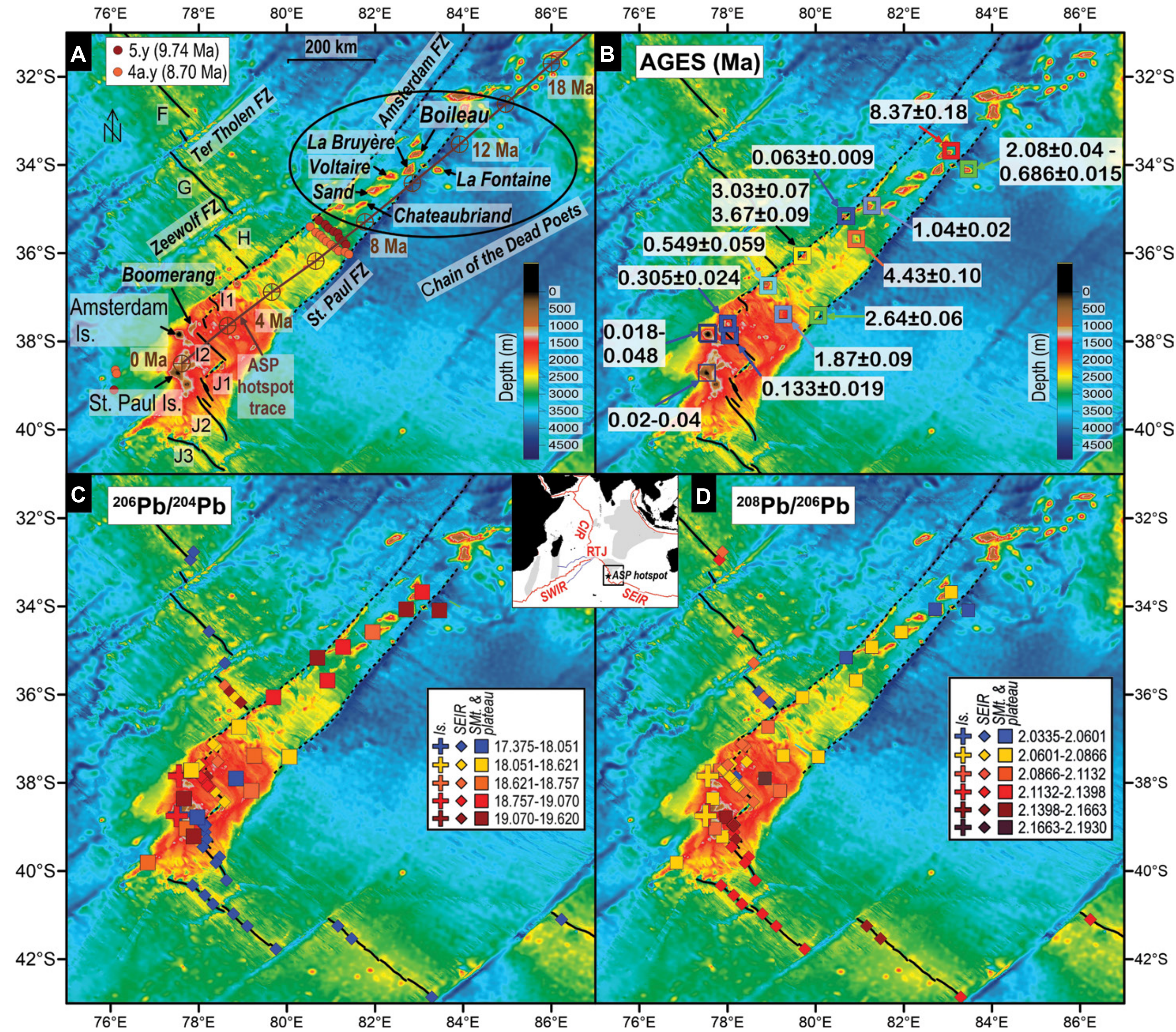

Figure 4. (A) Bathymetry of the Amsterdam–St. Paul (ASP) region. Southeast Indian Ridge (SEIR) segmentation tagged as F to J3 as well as magnetic lineations for isochrons 5.y (9.74 Ma) and 4a.y (8.70 Ma) and ASP hotspot path (in brown) are from Maia et al. (2011). FZ—fracture zone. (B–D) Same map with geochronological ages of lavas erupted over the ASP region (Janin et al., 2011) (B), and the distribution of their $^{206}Pb/^{204}Pb$ (C), and of their $^{208}Pb/^{206}Pb$ (D) (see Fig. S5 for details and and list of references S10 [see text footnote 1]. Is.—island; SMt—seamount. Inset shows regional location of the study area (box): CIR—Central Indian Ridge; SWIR—Southwest Indian Ridge; SEIR—Southeast Indian Ridge; RTJ—Rodrigues Triple Junction.

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