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Indo-Atlantic plate accelerations around the Cretaceous-Paleogene boundary: A time-scale error, not a plume-push signal

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ABSTRACT

It has been suggested that plume arrival at the base of the lithosphere introduces a push force that overwhelms the balance of torques driving plate circuits, leading to plate-tectonic reorganizations. Among the most compelling evidence in support of a "plume-push" mechanism is the apparent coincidence between eruption of the Deccan flood basalts around 67–64 Ma and a short-lived increase in Indian (and decrease in African) plate speed. Using existing and newly calculated high-resolution plate-motion models, we show that plate divergence rates briefly increased throughout the Indo-Atlantic circuit, contrary to the expected effects of plume-push. We propose that this circuit-wide spike in divergence rates is best explained as the artifact of a magnetic reversal time-scale error around the much studied Cretaceous-Tertiary boundary, and that the period spanning chrons C29–C28 lasted 70% longer than currently assumed. Corrected for this error, the residual long-term patterns of Indo-Atlantic plate motions and accompanying plate-tectonic reorganization are explicable in terms of maturation of the circuit's spreading ridges, without invoking a significant plume-push force.

INTRODUCTION

A tectonic plate's motion is maintained by a balance of torques generated by its internal gravitational potential, that of the subducting material attached to it, and the pattern of flow in the mantle beneath the plate. Because plate boundaries and slabs are long-lived features, and mantle convection time scales are on the order of tens of millions of years, plate motion should evolve only gradually. Large and sudden changes in a plate's motion may thus be interpreted in terms of other mechanisms acting in the Earth system. One such mechanism may be a radial gravitational "plume-push" force related to lithospheric doming during the episodic rise of massive mantle plume heads. The arrival of the Deccan-Réunion plume beneath the southwestern part of the northward-moving Indian plate starting at 67 Ma (Fig. 1A) is the most-studied example.

The schematic velocity triangles in Figures 1B and 1C illustrate the effects of the introduction of a Deccan-Réunion plume-push force from the mantle (M), as suggested by Cande and Stegman (2011). Depicted by thick red arrows, the plume-push force opposes the preexisting motion of the African (AFR) plate, decelerating it, but it aligns with the preexisting motions of the Indian (IND) and, possibly, Antarctic (ANT) plates, accelerating them. These changes are represented by the lengthening of the IND-M and ANT-M vectors and shortening of the AFR-M vector between Figures 1B and 1C.

The changed vectors skew the triangles (Figs. 1B and 1C) to predict acceleration of the divergent motion of India relative to Africa (IND-AFR) and Antarctica (IND-ANT) and simultaneous deceleration of Africa's divergence from South America (SAM-AFR) and Antarctica (AFR-ANT). Therefore, if the arrival of the Réunion plume introduced a plume-push force at the southwestern edge of the Indian plate, its effects should be observable in the spacings of conjugate magnetic anomaly isochrons throughout the circuit, and not just those in the Indian Ocean.

Limited to the 10 m.y. resolution of O'Neill et al.'s (2005) models of absolute plate motion, van Hinsbergen et al. (2011) suggested that the Indian plate indeed accelerated northward over the mantle in the Late Cretaceous. Cande and Stegman (2011) presented better-resolved (~1–3 m.y.) evidence from the divergent IND-AFR and IND-ANT plate boundaries, both recording sharp increases in plate divergence rates at times coincident with plume arrival. They also used lower-resolution (3–6 m.y.) models of seafloor spreading data between Africa and Antarctica (AFR-ANT) and South America (AFR-SAM) to show decelerations in the 70–45 Ma period. Cande and Stegman (2011) also suggested that these relative plate-motion changes had wider consequences, by triggering a cascade of regional plate-tectonic events in the Indo-Atlantic circuit.

Here, we test in greater detail the proposal that the introduction of plume-related forces in the Indian Ocean led to large accelerations and decelerations in Indian and African plate motions. We do this by examining plate divergence rates calculated from a set of models of higher temporal resolution than those used by Cande and Stegman (2011). In turn, we discuss whether or not such plume-triggered divergence rate changes are necessary to explain the regional plate-tectonic reorganization around the Cretaceous-Paleogene boundary.

DATA AND METHOD

Seafloor spreading rate variations can be estimated from the spacings of magnetic reversal isochrons on individual ship-track profiles, but these are exposed to local variability and possible isochron misinterpretations. A more robust picture can be generated by calculating plate divergence rates from quantitative plate-motion models, which unite conjugate pairs of the isochrons identified in hundreds of ship profiles. The spreading rate curves presented by Cande and Stegman (2011) were derived from a set of models built using two differing techniques, here termed "Hellinger-Chang" (Hellinger, 1981; Chang et al., 1990), and "Shaw-Nankivell" (Shaw and Cande, 1990; Nankivell, 1997). In

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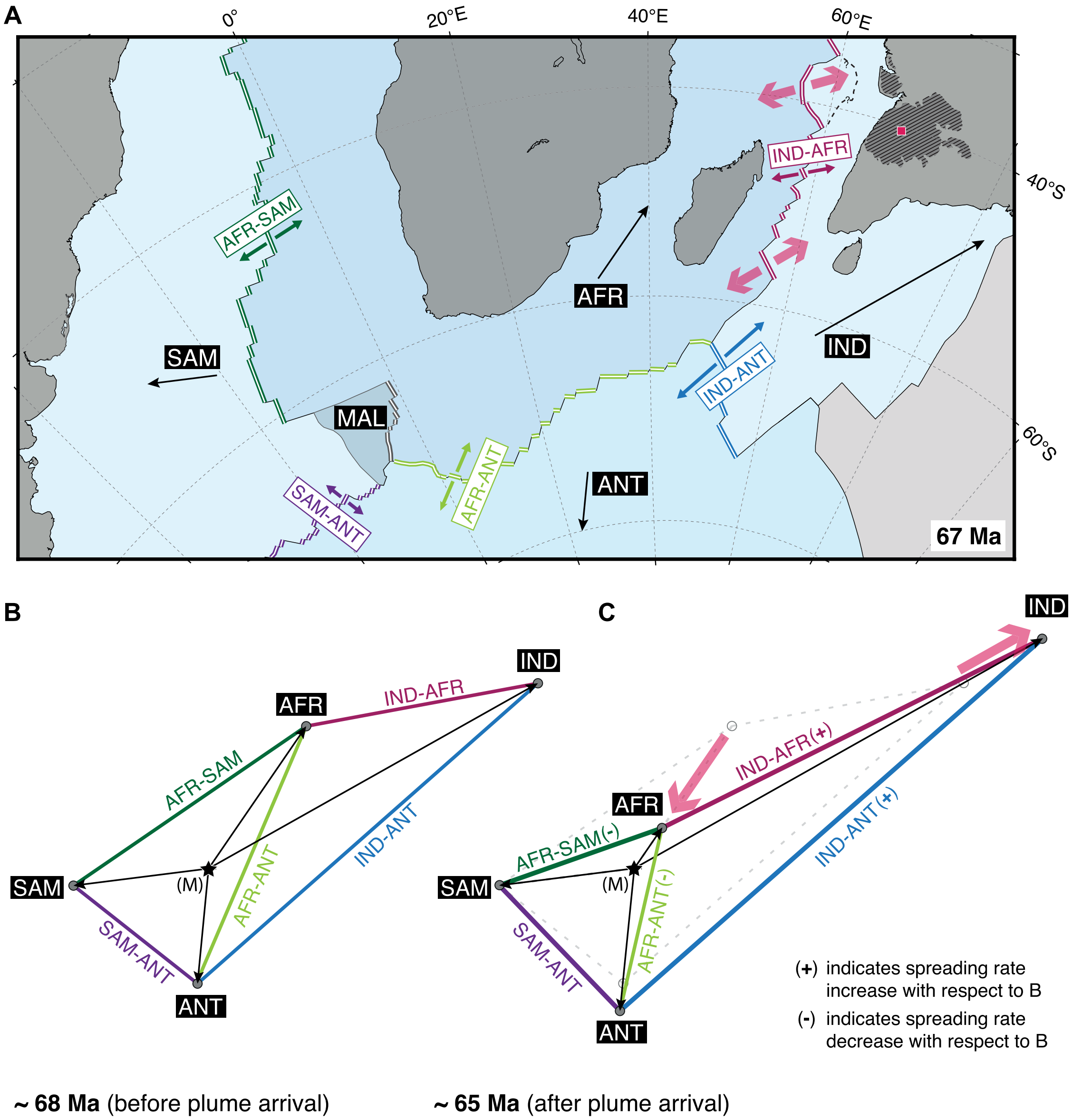

Figure 1. (A) Plate motions (see text for models used) in Indo-Atlantic plate circuit at 67 Ma, in hotspot reference frame of O'Neill et al. (2005). Red square and black hatching indicate approximate location of Réunion plume head and present-day extent of Deccan basalts, respectively. (B–C) Sketch velocity triangles describing plate motions with respect to mantle (M) in approach to and aftermath of Réunion plume arrival. Plates are African (AFR), Antarctic (ANT), Indian (IND), Malvinas (MAL), and South American (SAM).

the Supplemental Material[1], we use published examples for a detailed comparison of the two, showing that the Shaw-Nankivell technique produces models that are less noise-prone than their Hellinger-Chang counterparts.

All of the models we used were generated using the Shaw-Nankivell technique. As well as taking confidence from their stability, we also avoided the possibility of interpreting uncorrelated errors related to differing method assumptions and limitations. We calculated and compared rates for relative motions of the IND-AFR (Eagles and Hoang, 2013), AFR-ANT (Tuck-Martin et al., 2018), IND-ANT (Eagles, 2019), and SAM-ANT (Eagles, 2016) plate pairs. For the South Atlantic, we used a newly calculated model built with the specific aim to depict AFR-SAM divergence over the Deccan period (C30o–C25y, 68–57 Ma) in sharper detail than published alternatives.

For the new AFR-SAM model, we compiled a total of 2008 magnetic anomaly picks by reexamining previously unpicked marine magnetic profiles of varying vintages archived at the National Centers for Environmental Information (https://www.ngdc.noaa.gov/mgg/mggd.html), together with aeromagnetic data collected in 2006 and 2013 (Pérez-Díaz and Eagles, 2017; Thoram et al., 2019; see also Figs. S1 and S2 in the Supplemental Material). This represents an increase of 83% over the data set of Pérez-Díaz and Eagles (2014), and an increase of 16% over that of Cande et al. (1988), as archived by Seton et al. (2014). Crucially, 389 of our new magnetic picks are for isochrons within the critical time period between chrons C30o and C25y (68–57 Ma) that had only previously been modeled by visual fitting (Cande et al., 1988).

RESULTS

The IND-ANT and IND-AFR models reproduce previous observations of a short-lived divergence pulse centered at C29 (Fig. 2A). Divergence rates increase by 119% for IND-AFR (42–92 mm/yr), and 78% for IND-ANT (70.6–125.9 mm/yr). However, this pulse does not coincide with reductions in AFR-SAM and AFR-ANT rates, which would be expected if the African plate were decelerating as a result of an opposing plume-push force (Fig. 1). Instead, our new magnetic isochron data set confidently resolve an abrupt increase (~60%, 12.8–20.4 mm/yr) in apparent AFR-SAM divergence rate coincident with plume arrival. Similar short-lived episodes of fast divergence are observed in the AFR-ANT (~35% increase, 11.0–14.8 mm/yr) and SAM-ANT (~54% increase, 11.4–17.5)

[1]Supplemental Material. Magnetic isochron pick data set used in this study. Please visit https://doi.org/10.1130/10.1130/GEOL.S.12678923 to access the supplemental material, and contact editing@geosociety.org with any questions.

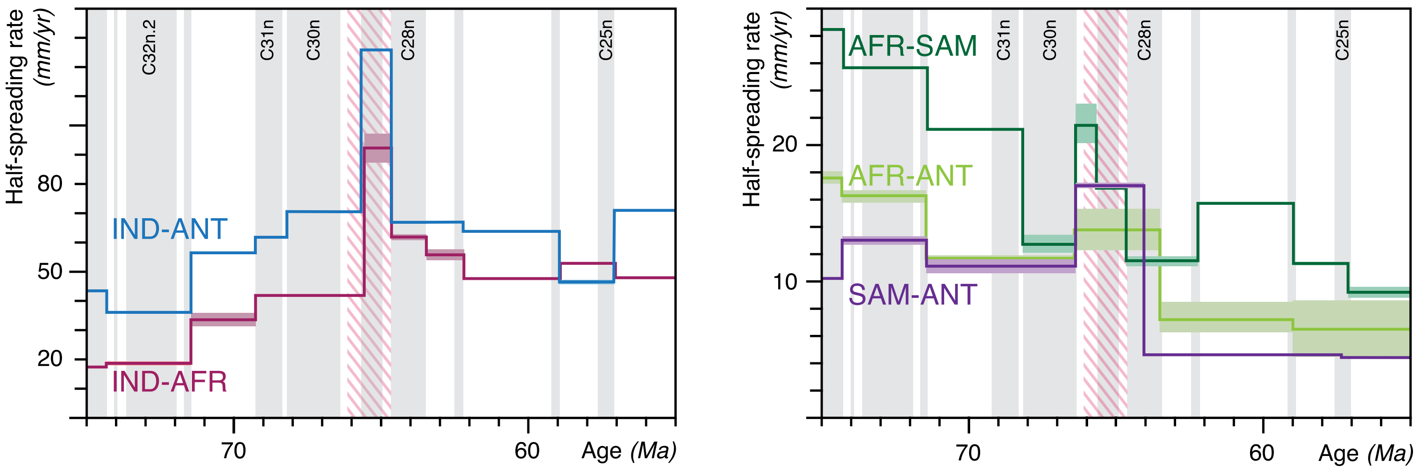

Figure 2. Ubiquitous 67 Ma acceleration in model divergence rates for five plate pairs in Indo-Atlantic circuit (see text for model references). Light-gray bars—magnetic reversal time scale of Gradstein et al. (2012), where C25n–C32n.2—magnetic chrons. Red hatching—Deccan volcanism. Plates are same as in Figure 1.

models. Our results thus depict a circuit-wide spike in plate divergence rates during chrons C29–28, following the arrival of the Réunion plume near the AFR-IND plate boundary.

Prior to the spike, rates along opposite sides of the African plate anticorrelate over a long period. Starting in Campanian times, IND-AFR and IND-ANT plate divergence rates (recorded in the central and eastern Indian Ocean) steadily increase, while AFR-ANT and AFR-SAM rates (recorded in the western Indian and South Atlantic Oceans) steadily decrease.

DISCUSSION

Likely Error in the Magnetic Reversal Time Scale

The plume-push hypothesis states that arrival of the Réunion plume head at 67 Ma caused sharp increases in the rates of the Indian plate's divergence from Africa and Antarctica, and a synchronous decrease in African divergence from Antarctica and South America. This pattern is not observable in our high-resolution results, which instead demonstrate that divergence rates between all the plate pairs briefly and synchronously increased (Fig. 2). Despite its temporal coincidence, explaining this ubiquitous spike in terms of the introduction of a Réunion plume-related push force is impossible. Instead, we propose that the spike is due to an error in the geochronological time scale affecting the dates assigned to magnetic reversal chrons C29–C28. In this scenario, the spreading spike should be a feature found at spreading ridges globally. We note that the southern Pacific rotations of Wobbe et al. (2012) and central North Atlantic rotations of Machiavelli et al. (2017) also deliver divergence rate peaks at C29 or C28, with caveats relating to the differing methods used in those studies.

The magnitude of this hypothesized time-scale error can be roughly estimated by considering our sample of apparent rate increases and the 2.904 m.y. duration of the C29r–C28n period (Fig. 2; Gradstein et al., 2012). The mean, median, and unweighted mode of these changes with respect to pre-Deccan rates are ~170%, ~160%, and ~157%, respectively. The time required to form the modeled swaths of C29r–C28n seafloor at rates that have been reduced by 57%–70% to account for a time-scale error is in the range between 4.6 and 4.9 m.y. The current boundaries of chrons C29r and C28n might thus be misplaced by a period of between 1.7 and 2.0 m.y. The Late Cretaceous to Paleogene magnetic reversal time scale is based on magnetostratigraphic correlations to the results of two separate astronomical tuning studies that are spliced during the reverse-polarity part of chron C29 (Husson et al., 2011; Gradstein et al., 2012). While consistent with the few available radioisotopic dates in this interval, the uncertainties and discrepancies of the correlations and the splice are the subject of ongoing debate. Our results should contribute to this debate, which is otherwise well beyond the scope of this study.

Long-Term Circuit Torque Balance

A corrected time scale between C29r and C28n (Fig. 3) would see modest increases in IND-ANT and IND-AFR plate divergence of 8% (70.6–76.3 mm/m.y.) and 50% (42.0–67.5 mm/m.y.), respectively. Conversely, AFR-SAM rates would decrease from 12.8 to 11.5 mm/yr (10%), and AFR-ANT rates would decrease from 11.0 to 6.9 mm/yr (35%). These figures complement the picture of a longer-term anticorrelation of plate divergence starting in the Campanian (80–75 Ma) and extend it into early Paleocene times (Fig. 3). Although these longer-terms signals have appropriate signs, attributing these steady trends to the gradual introduction of a plume-push force arriving at the base of the lithosphere at ca. 67 Ma would require the plume to have ascended at ~4.3–7 cm/yr through the upper mantle (~560 km over 8–13 m.y.). This is at least an order of magnitude slower than values predicted by geodynamic models (e.g., Steinberger and Antretter, 2006).

A more plausible link would need to be drawn to the evolving balance of plate-boundary torques in the Indo-Atlantic circuit. Numerous recent studies have attempted this for the Indian plate's Cretaceous–Paleogene acceleration to unusually fast rates (e.g., Kumar et al., 2007; Van Hinsbergen et al., 2011; Eagles and Wibisono, 2013; Jagoutz et al., 2015). Our observation of circuit-wide changes that correlate with this acceleration broadens the torque balance study region beyond the Indian plate, which cannot be pursued here. To produce the observed long-term changes of Figure 3, a system dominated by slab-pull forces must have favored subduction at the Neotethyan margins of India and Africa over the paleo-Pacific margin of South America. Alternatively, we note that the set of gravitational driving forces acting on the African plate, the only plate with shared boundaries in every branch of the circuit, was also undergoing change that is consistent with the trends in Figure 3. In Campanian–Paleogene times, these forces would have been increasing at the maturing (ca. 89 Ma onset) IND-AFR ridge but were at near steady state at its older (Late Jurassic and Early Cretaceous onset) AFR-SAM and AFR-ANT counterparts.

Indo-Atlantic Circuit Effects—Extinction of the Malvinas Plate

The large short-term changes in plate divergence rates around Deccan times that have been cited as primary evidence for a plume-push force are likely to be artifacts of the low-resolution plate-motion models used by Cande and Stegman (2011). However, several other events, together comprising a Cretaceous–Paleogene plate-tectonic reorganization, have been related to the Réunion plume's arrival. One of these is the incorporation of the Malvinas (MAL) plate into the African plate during C27o (62.5 Ma; Marks and Stock, 2001) by a large westward ridge jump along the Falkland-Agulhas Fracture Zone. Cande and Stegman (2011) argued that the introduction of a plume-push

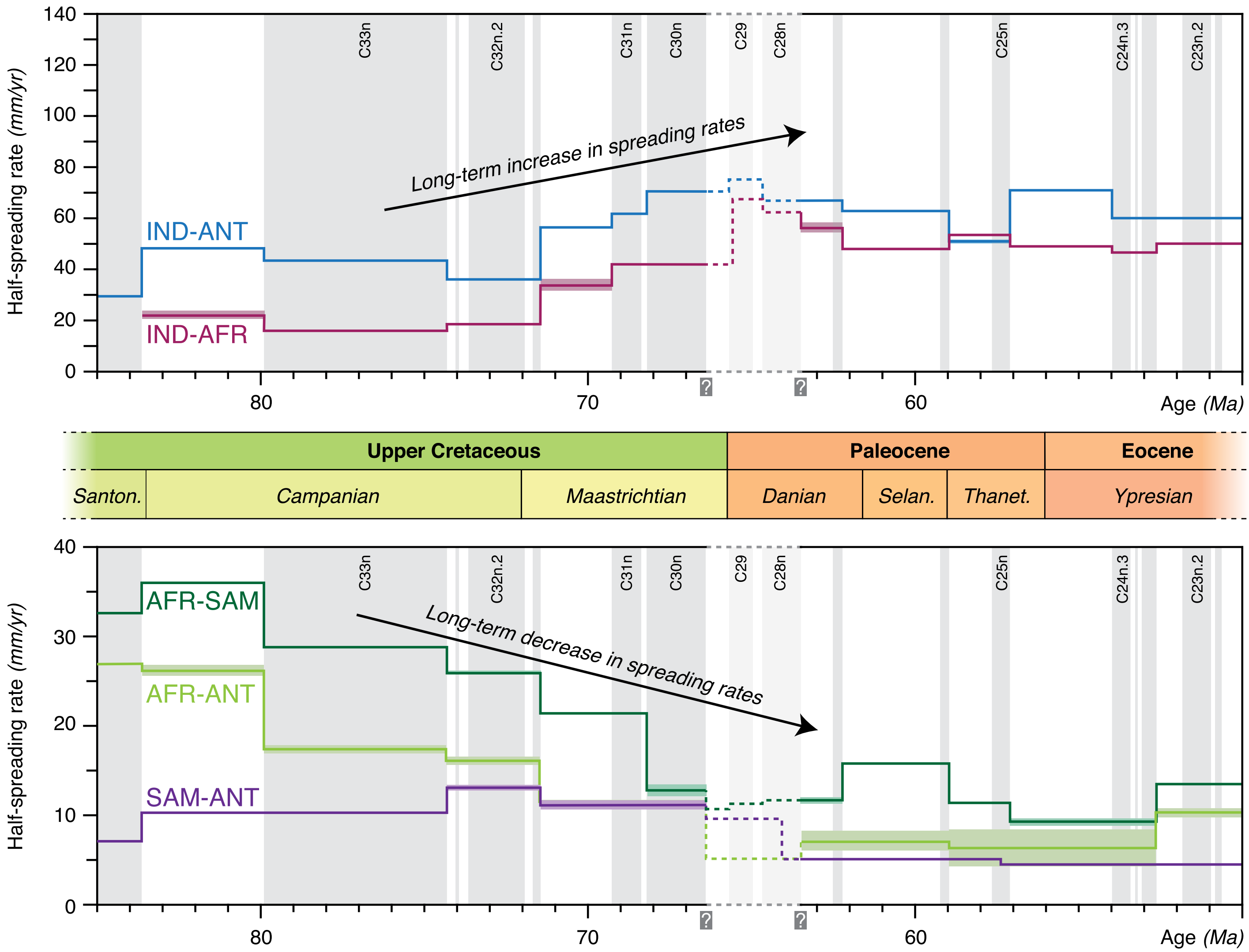

Figure 3. Adjusted model divergence rate changes for five plate pairs in Indo-Atlantic circuit. Dashed segments indicate that rates have been corrected to account for time-scale error affecting chrons C28–C29. Elsewhere, rates are same as those in Figure 2. Light-gray bars—magnetic reversal time scale of Gradstein et al. (2012), where C23n.2–C33n—magnetic chrons. Plates are same as in Figure 1. Santon.—Santonian; Selan.—Selandian; Thanet.—Thanetian.

force would have placed the fracture zone's transform segment under compression, raising a shear stress large enough to halt seafloor spreading at the MAL-AFR ridge in the Agulhas Basin.

We propose that this event is more simply explained as a consequence of the long-term evolution of the Indo-Atlantic circuit. Figure 4 shows stability analyses (McKenzie and Morgan, 1969) for the active MAL-AFR-SAM triple junction in the time preceding the Malvinas plate's demise. In Figure 4A, the AFR-SAM and MAL-AFR vectors are of similar lengths (the ridges were diverging at similar rates before C30, ca. 68.4 Ma), but their azimuths differ by ~25°. Their resultant suggests very slow and oblique divergence along the NW-striking MAL-SAM plate boundary (Fig. 4A). The triple junction has a stable ridge-transform-transform geometry. By C30n (66.4 Ma), continued AFR-SAM deceleration, which had been ongoing since 84 Ma (Fig. 3B), required the MAL-SAM boundary to increasingly accommodate N-S–directed convergence (Fig. 4B). The system entered into a new state requiring an unstable trench-transform-transform triple junction that was short-lived, ending with the westward ridge jump along the Falkland-Agulhas Fracture Zone and incorporation of the Malvinas plate into the African plate during C28 (ca. 64 Ma, by reexamination of six magnetic anomaly profiles over the extinct ridge crest; Supplemental Fig. S3).

SUMMARY

Spatial and temporal coincidences among a period of fast motion of the Indian plate, slower motion of the African plate, and the onset of Deccan Traps volcanism at ca. 67 Ma have led to suggestions that the arrival of plumes at the base of the lithosphere can introduce a push force that overwhelms the balance of forces driving the motions of entire circuits of plates, leading to plate-tectonic reorganizations. Using existing and newly calculated high-resolution models of plate motion, we instead show that records from spreading centers throughout the Indo-Atlantic plate circuit all record sudden short-lived plate divergence spikes at 67–64 Ma.

This ubiquitous increase is impossible to reconcile with the introduction of a plume-push force near the IND-AFR plate boundary, and it is best explained in terms of a previously unrecognized reversal time-scale error. Corrected for this error, the long-term spreading trends in the circuit may be easily explained by the slowly changing balance of torques generated at the circuit's mid-ocean ridges. The concomitant long-term gradual decrease in AFR-SAM rates also allows us to explain, without recourse to plume-related forces, the large westward ridge jump along the Falkland-Agulhas Fracture Zone that ultimately resulted in the extinction of the Malvinas plate.

The idea of plume-push forces as agents capable of precipitating plate-tectonic reorganizations

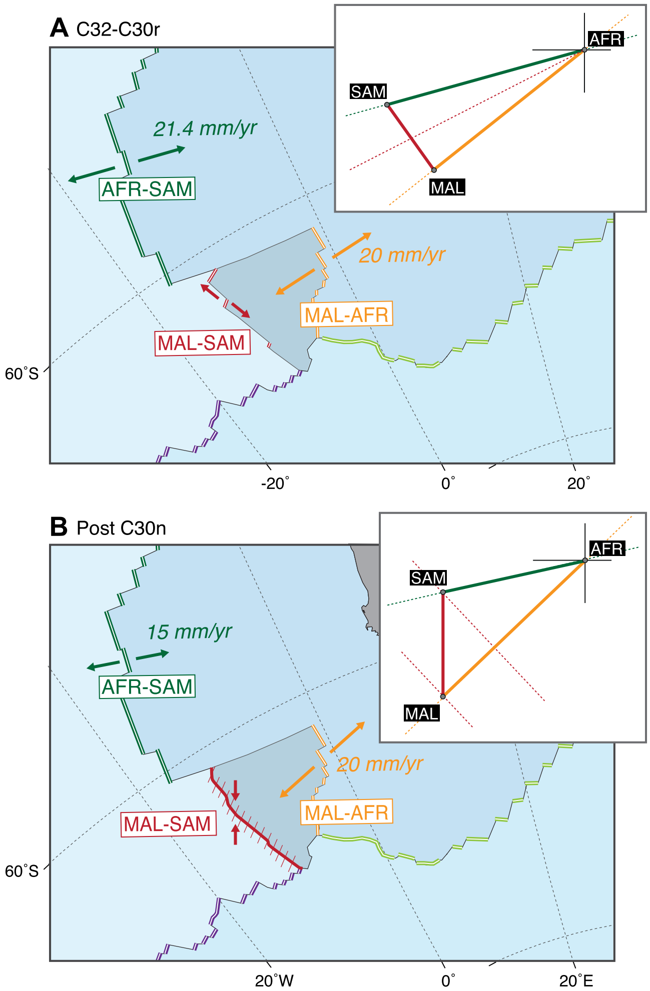

Figure 4. Velocity diagrams and triple junction stability analysis for the Malvinas–Africa–South America (MAL-AFR-SAM) triple junction, depicting change from divergence to convergence along SAM-MAL boundary as result of reduction in SAM-AFR spreading rates at chron C30.

by overwhelming the torque balances driving entire plate circuits should thus no longer be considered as plausible. In addition, the potential impact of a possible time-scale error such as the one identified by this study on the timing of critical events around the Cretaceous-Paleogene boundary adds urgency to a reevaluation of the time scale for the time period 67–63 Ma.

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