Impact of Deccan Volcanism on Reorganization of the Indian plate kinematics

Amarjeet Bhagat[1], Satish Sangode[1], and Ashish dongre[1]

[1]Savitribai Phule Pune University

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Western Indian Ocean basin shows one of the most complex signatures of the ocean floor anomalies by juxtaposition of the rapidly evolving, multiple spreading ridges, subduction systems and microcontinental slivers. This study based on ocean floor magnetic anomalies, gravity gradient map, tomographic profiles and geometrical kinematic models reports a significant westward drift of the Central Indian Ridge (CIR) segments. Documented precisely between the latitudes 17°S and 21°S the drift is coincident with the Deccan volcanism at ˜65±2 Ma and we further explain its bearing on the Indian plate kinematics. The progressive stair-step trend of the ridge segments towards NE is marked by anomalous deflection to NW for a brief distance of ˜217 km between these latitudes represented by the anomalies C30n-C29n. The observed length of the ridge segments moving NW at 17°S match the calculated NW drift rates of Indian plate (Bhagat et al., 2022). We infer that the NW drift and its restoration towards NE triggered short Plume Induced Subduction Initiation along the Amirante trench. Further a plume induced lithospheric tilt of the Indian plate (Sangode et al 2022) led to restoration of subduction along the Sunda trench at ˜65 Ma imparting new slab pull force over the Indian subcontinent besides the NE trend for CIR. This episode resulted into anticlockwise rotation of the Indian plate along with accelerated drift rates due to vector addition of the plume push and the slab pull forces from Eurasian as well as Sunda subduction systems after 65 Ma. The Deccan eruption thus resulted in major geodynamic reorganization that altered the kinematics of Indian plate; and the signatures of which are well preserved over the ocean floor.

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Amarjeet R. Bhagat[1], S. J. Sangode[1*], Ashish Dongre[1]

Department of Geology, Savitribai Phule Pune University, Pune, India

***Corresponding author: Satish Sangode (sangode@unipune.ac.in)**

Abstract

Western Indian Ocean basin shows one of the most complex signatures of the ocean floor anomalies by juxtaposition of the rapidly evolving, multiple spreading ridges, subduction systems and microcontinental slivers. This study based on ocean floor magnetic anomalies, gravity gradient map, tomographic profiles and geometrical kinematic models reports a significant westward drift of the Central Indian Ridge (CIR) segments. Documented precisely between the latitudes 17°S and 21°S the drift is coincident with the Deccan volcanism at ~65±2 Ma and we further explain its bearing on the Indian plate kinematics. The progressive stair-step trend of the ridge segments towards NE is marked by anomalous deflection to NW for a brief distance of ~217 km between these latitudes represented by the anomalies C30n-C29n. The observed length of the ridge segments moving NW at 17°S match the calculated NW drift rates of Indian plate (Bhagat et al., 2022). We infer that the NW drift and its restoration towards NE triggered short Plume Induced Subduction Initiation along the Amirante trench. Further a plume induced lithospheric tilt of the Indian plate (Sangode et al 2022) led to restoration of subduction along the Sunda trench at ~65 Ma imparting new slab pull force over the Indian subcontinent besides the NE trend for CIR. This episode resulted into anticlockwise rotation of the Indian plate along with accelerated drift rates due to vector addition of the plume push and the slab pull forces from Eurasian as well as Sunda subduction systems after 65 Ma.

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Keywords: Deccan eruption, Indian ocean, plate kinematics, ocean floor gravity anomaly, marine magnetic anomaly.

1. Introduction:

Bhagat et al. (2022) reported very high drift rates for India during the Deccan event at C29r along with a hitherto unnoticed sudden westward drift during the same time period (Patriat and Acache 1984, Klootwijk 1992, Gaina et al 2013, Gibbons et al 2015). This departs from the widely accepted convergence direction for India-Eurasia during the K-Pg boundary (Patriat and Acache 1984, Klootwijk 1979, Gaina et al 2015, Gibbons et al 2015). The accelerated drift rates are explained as a consequence of plume push (Cande and Stegman 2011), lithosphere delamination (Kumar et al 2007, Paul and Ghosh 2021), combined together with slab pull and ridge push (Eagles and Hoang 2013, Jagoutz et al 2016, Van Hinsbergen et al 2012). The delamination of the cratonic root along the western and southern regions resulted in slightly positive buoyancy of India (Dessai et al 2020, Dessai and Griffin 2021, Singh et al 2021 and references therein), which in turn resulted in tilting by ~10 degrees (Sangode et al 2022). This positive buoyancy combined with loss of coupling between the subcontinent and asthenospheric mantle led to the hyper spreading velocities (van Hinsbergen et al 2011, Cande and Stegman 2011, Eagles and Wibisono 2013, Cande and Patriat 2015, Cande et al 2010). However, overall the westward drift remains unexplained in literature with following questions remaining unanswered.

i) What could have caused this change in direction of drift of the Indian plate

ii) Are there any evidences other than the Paleomagnetic records of the Deccan traps wherein the vestiges of this event can be found?

While looking for the possible explanations of the westward force that resulted in the sudden westward drift of India, the following constraints have to be explored.

1. The force should have been activated precisely at the initiation of the Deccan-Reunion plume event.
2. It should have lasted long enough for India to achieve required drift velocities.
3. It should have ceased or lost its potency at the end of the Deccan eruptions.

In the above context, we first present a primordial overview of the forces and then discuss the main drivers of this westward drift. The forces that are capable of causing major change in plate kinematics are: a) Mantle Plume push; b) Ridge Push and c) Slab Pull

In this paper we explain the events that could have been responsible for this sudden change in the convergence directions with evidences visible from the ocean floor.

The present study thus, is an analogy based on the above existing information on the Indian plate movements during the Deccan event and can be summed up in the following three points.

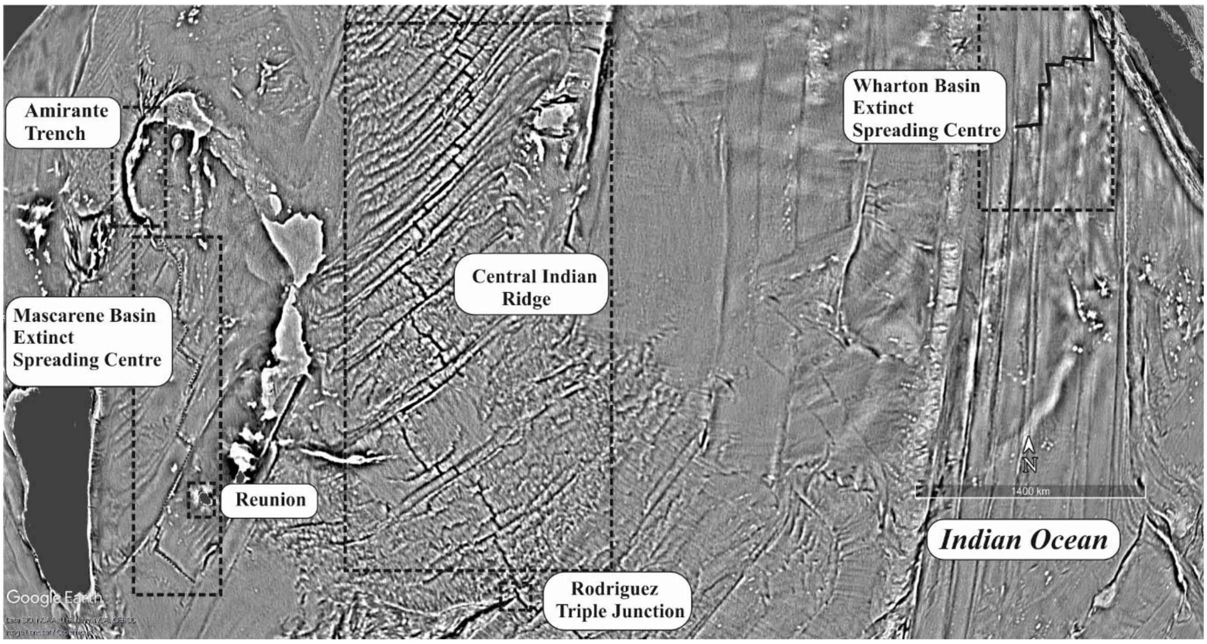


Figure 1. A gravity gradient map of the western Indian ocean after the gravity model of Sandwell et al (2014) showing prominent tectonic features in the Indian Ocean basin.

The present study is based on critical observations encompassing various maps, satellite imageries and anomaly maps besides tomographic profiles in key regions to explore: i) the formation of Seychelles microcontinent along with its relation to the evolution of Amirante ridge trench system in the Indian ocean; ii) subduction initiation along India-Arabia transform plate boundary; and iii) presenting a comprehensive model for the sudden change in drift direction of India and its remarkable restoration towards NE.

2. Forces acting on the Indian Plate:

2.1. The forces related to Mantle Plume encounter

The most likely candidate for the above exploration is the Reunion (Deccan) mantle plume. However as pointed out by previous studies, the Deccan plume propelled India forward towards N-NE directions (Gibbons et al 2015, Gaina et al 2015, Cande et al 2010, Cande and Stegman 2011). The plume thinned the Indian craton, and could have pushed/propelled India towards west, with anticlockwise rotation. However, the plume itself being positioned on the western continental margin of India, it seems unlikely that it would drag the subcontinent towards west. Although it is possible that there could have been a torsional effect exerted on India arising from the toroidal flows in the asthenospheric mantle surrounding the plume, which could have possibly rotated the subcontinent anticlockwise towards west. The removal of cratonic root beneath India did not support anchoring in the mantle flow. Such anchoring could have encouraged absolute torsional rotation. Further given the geodynamic positioning of the plume towards the western margin, it seems highly unlikely that the plume would entirely rotate the subcontinent towards west. If the plume were to rotate the subcontinent wholly then it would be a much larger effect something comparable to the lithospheric tilting of the Indian subcontinent (e.g., Sangode et al 2022). Thus, from all the above evidences and analogical inferences it appears to be unlikely that the Reunion plume was solely responsible for the westward drift of India during the Deccan eruptions. However, the inferences need holistic consideration of all the possible major forces for Indian plate kinematics that can be evident from the observations of the oceanic lithosphere surface.

2.2. Forces related to Mid Ocean Ridge activity

The spreading history of the western Indian ocean can be viewed as an artifact of two major spreading ridges viz., i) Mascarene Spreading centre (MSC) and ii) Central Indian ridge (CIR)

Spreading rates in the Wharton basin would not have accounted for much as it was in the waning phases. A similar predicament prevails for the Mascarene spreading centre. However, any significant contributions from the MSC would result in enhanced motion of India towards east eliminating any chances of a westward motion and the proto-CIR might possibly have played a role in this westward migration. The spreading in MSC slowed down by ~68.5 Ma (anomaly C31n), and a ternary rift system came into existence off the west coast of India in the form of **Laxmi ridge-Gop ridge-Narmada rift.** Spreading in the Northern Mascarene basin ceased completely by 62.5 Ma, the time by which Seychelles was completely stripped off of India (Bhattacharya and Yatheesh 2015). In Southern Mascarene basin the spreading stopped somewhere around ~60.9 Ma and the spreading centre jumped north between southern end of the Laccadive plateau and the northern boundary of the Mascarene basin to relocate itself closer to the hotspot.

Based on the relative movements between spreading ridges and hotspots, three major interactions in the Indian ocean have been identified here as described below (Small 1995).

a) Ridge migration towards the hotspot.

b) Ridge captured by the hotspot Or Ridge situated above a hotspot.

c) Ridge migrating away from a hotspot.

If the hotspot remained/existed within moderate distance of a ridge, the ridge moved through a series of ridge jumps and remained (through spreading asymmetry) above or in close proximity to the hotspot (Small 1995). This moderate distance seems to depend on the strength of the hotspot e.g., extinction of MSC and the opening of the Carlsberg ridge in response to the arrival of Reunion hotspot, that can be envisioned as 1000-1500 km ridge jump.

Prior to the Deccan event, the hotspot was located NE of the Ridge while at the Deccan event it was below the ridge and following the main phase of Deccan eruptions, it was situated southwest of the ridge. As mentioned earlier, the ridge jumping and relocation of a spreading centre took place which resulted in shift of spreading axis ~1000-1500 km shift towards east.

Another interesting fact that needs to be considered here is the time required for a ridge jump. It is found to be of the order of 10^5-10^6 years for fixed or migrating ridges (Mittelstaedt et al 2001). Once a ridge jump occurs, the hotspot and ridge migrate together for time periods that increase with magma flux. However, in the present case, after the ridge jump occurred, the magma flux was reduced causing decoupling/separation of the ridge from hotspot. The magmatic heat flux from the Reunion plume would have been sufficient enough to initiate the ridge jump, from which spreading in the Mascarene basin ceased. In the event if the ridge jump happens, there could be a temporary change/distortion in the existing plate kinematics. This discordance could possibly result in disfigured motions albeit for a short while, which would be long enough for India to produce the observed directional drift due to high drift rates. Once the new spreading regime along the CIR is established, restoration of the drift directions might take place and India continued its NE journey unimpeded. But, the fact that the reorganization of the spreading systems occurred around 60-62 Ma and not at 65-66 Ma, rules out the reorganization of the spreading centres as the sole cause for the observed westward drift of India.

2.3. Forces related to Subduction

Establishment of a new subduction zone would definitely change the force balance in a plate kinematic framework. However, as there was already a massive pre-existing subduction system existing along the Northern margin of the Indian plate i.e., the Neo-Tethyan subduction system, any new subduction system would prefer to be in the proximity of the established system. Along with this mother system there existed some other smaller intra-oceanic subduction systems along the northern margin of India, these systems contributed to the northward drift as well. The challenge is to how exactly did the existing subduction systems all of a sudden exerted an unprecedented westward pull over the Indian plate, and why would this pull stop shortly after the Deccan episode thereafter resuming the old drift direction. Therefore, the major questions that need to be addressed here are as follows:

1. Which subduction zone was responsible for this short westward drift?
2. What caused an increase in the slab pull, that could possibly overpower the Reunion plume push?
3. Why did this slab pull decrease suddenly or become non-existent at the end of Deccan episode?

Many previous studies have proposed for an intraoceanic subduction system to have initiated at the Deccan episode owing to the Reunion plume (Jagoutz et al 2016, Gnos et al 1998, Rodriguez et al 2019, 2020,Pandey et al 2019, Gaina et al 2015). However, despite the extensive research that has been conducted, there have been no successful candidates so far. Although 3 systems do appear in the vicinity of India (Fig. 2) at the Deccan episode, they are still surrounded by controversies regarding their age and origin. All the three are aligned along the western margin of India, this makes them worthy contenders.

1. Bela-Waziristan-Muslim Bagh-Kabul subduction system (Gaina et al 2015, Gnos et al 1998, Mahmood et al 1995).
2. Amirante Trench system (Rodriguez et al 2019, 2020, Plummer 1996).
3. Laxmi Basin Fore Arc sequence (Pandey et al 2019)

Rodriguez et al (2020) hypothesized that the Reunion plume in its pre-Deccan state at ~90-100 Ma formed an arcuate subduction system that broke into 3 distinct limbs, viz., The Northern, North-western and Southern limbs. Of these the North-western branch drifted off to form the Troodos and Semail ophiolites, the northern branch drifted to form subduction systems resulting in the formation of ophiolites along the Indus suture zone; and the Southern branch drifted southward along the NW frontier of India to form the string of ophiolites scattered along Bela-Waziristan-Muslim Bagh-Kabul ophiolite belt.

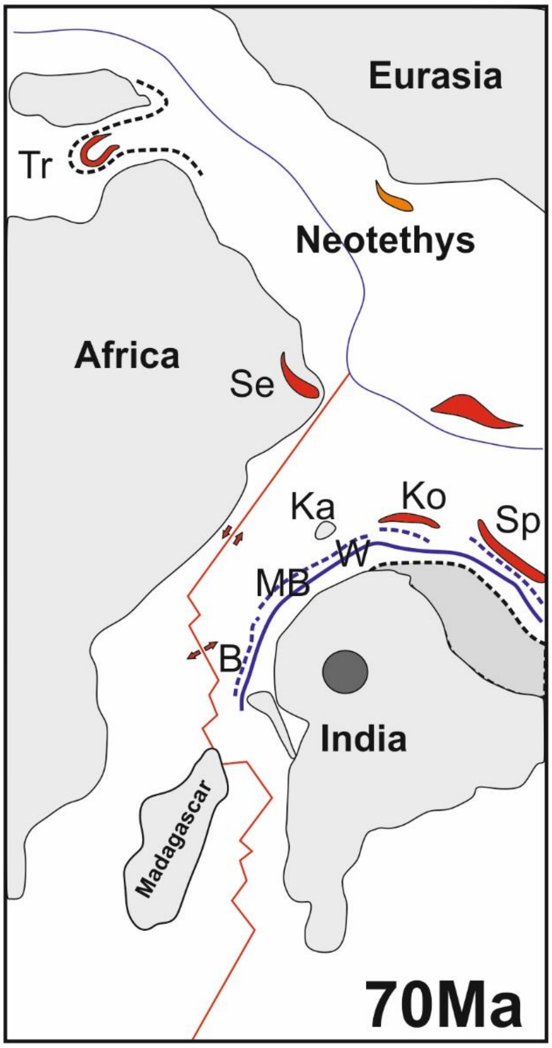


Figure. 2 The distribution of ophiolites along the NW margin of India modified after Rodriguez et al 2020. Note that the Mascarene spreading centre gives way to the India-Arabia transform boundary that ends at the Neo-Tethyan subduction. B-Bela, MB-

Muslim Bagh, W- Waziristan, Ka- Kabul, Ko- Kohistan, Sp- Spongtang, Tr- Troodos, Se- Semail.

It is interesting to note here that Gnos et al (1998) proposed the age of subduction initiation at ~70-68 Ma and the age of ophiolite emplacement at ~66-65 Ma for the Bela ophiolite. Gnos et al (1998) proposed that the Reunion plume was responsible for initiation of subduction along the NW margin of India. However, as interesting it may appear, we are left to wonder if the subduction initiated at ~70 Ma then why did the change in course occur at C29r and that too for a very short time spanning ~700-800 ka. The ophiolites in general depict obduction due to higher drift rates, their ages above restricted to 66-65 Ma are to be explained. What happened after C29r, and why did the westward drift stop so abruptly if the subduction system was active? If the subduction along Bela belt caused this drift, why did it not continue after the Deccan episode? These questions beg certain answers that the Bela system fails to provide. We are therefore forced to look beyond this system for a possible answer.

Pandey et al (2019) detected Fore Arc Basalt (FAB) and Boninite like signatures from the basalts in the Laxmi basin off the west coast of India **(Fig. 3)**. These basalts although did not entirely exhibit Boninite or FAB signatures, they however displayed eerily similar trace element signatures. This led them to concur that the crust in the Laxmi basin was relict of a failed subduction system which could not be sustained owing to rapid slab rollback within the proposed subduction zone and the collisional events along the Northern subduction margin. This could have been the possible subduction system we are looking for; however, the extent of the active margin and duration of the event make it rather unsuitable for the scale of tectonic disturbance we are dealing here. In addition to this, the proposed site of subduction initiation lies very close to the continental margin of India. This makes it unsuitable for accommodating the displacement and the rotational torques arising out of the plume induced rotation.

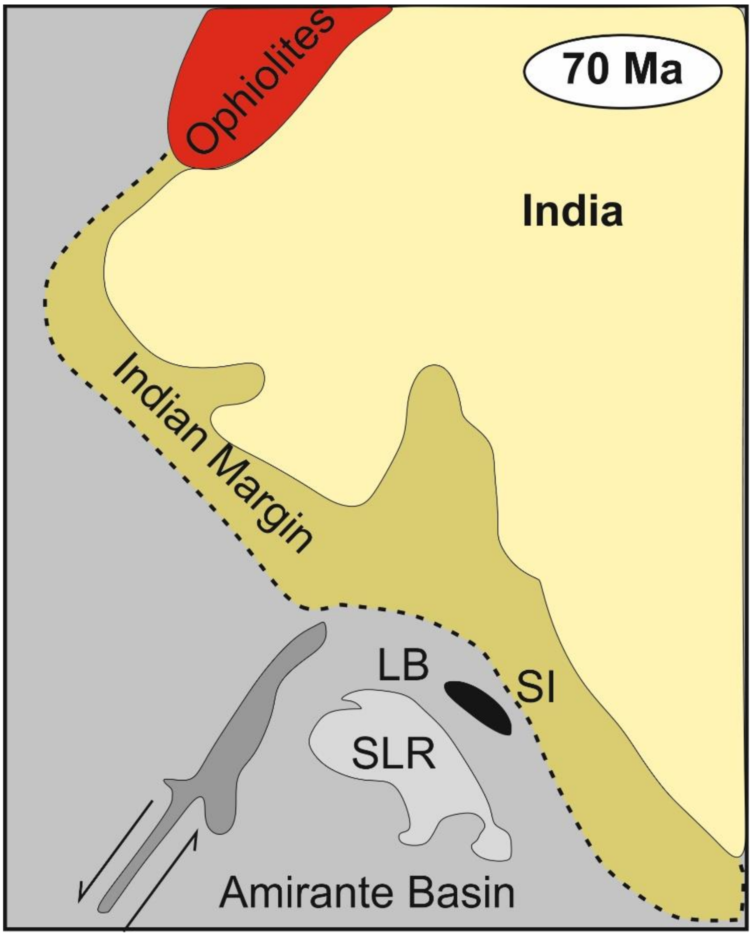


Figure. 3 The proposed point of Subduction initiation in the Laxmi Basin along the continental margin of India. The region highlighted by the black enclosure marks the point where Pandey et al (2019) reported signatures of Boninite like and Fore Arc Basalt

like rocks, this was the hypothesized subduction initiation point at ~70 Ma. LB- Laxmi Basin, SI- Subduction Initiation, SLR- Seychelles Laxmi Ridge.

There was another important Neo-Tethyan system along the Indian plate active during the Cretaceous which could have had a profound effect on the drift of India after the Deccan event. This was the Sunda subduction system active along the north-eastern margin (McCourt et al 1996, Gibbons et al 2015, Crameri et al 2020). The Sunda subduction system experienced a subduction lull from 75-65 Ma during the accretion of the Woyla terrane, following which there was a pause in subduction along the entire margin of the Woyla arc for a period of ~10 Ma (Muller et al 2016). This period of quiescence came to an end after ~65 Ma which is precisely the Deccan event **(Fig. 4)**. The reactivation of subduction in the Sunda system enhanced the NE slab pull on the Indian plate thereby causing the NNE drift of India. This might explain the sudden switch in plate movement towards NE, and also to some extent contribute towards the cessation of NW drift of India. However, this still leaves the origins of the Northwest drift unresolved.

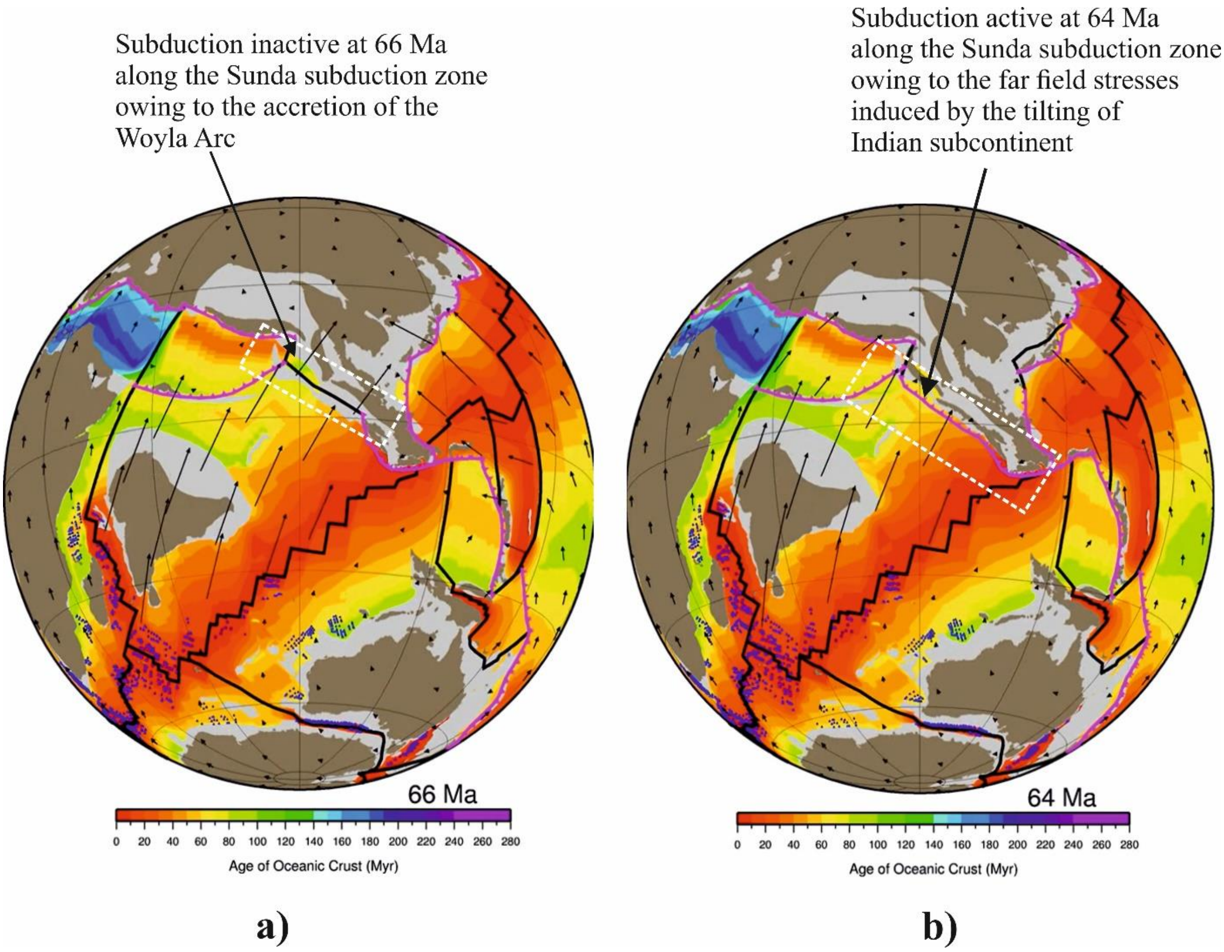


Figure. 4 Paleogeographic reconstructions of the Eastern Neo-Tethys showing evolution of the Sunda subduction zone. The Woyla Arc collided with Sundaland at ~75 Ma impeding subduction along the boundary for ~10 My. This was further restored at ~65-64 Ma owing to the lithospheric tilting of the Indian subcontinent at the Deccan episode following the interaction of India with Reunion plume. a): The Sunda subduction zone at 66Ma before the lithospheric tilting of India. b): The Sunda subduction zone at 64 Ma after the lithospheric tilting of the India.

The Amirante ridge trench system in the Indian ocean **(Fig. 1)** between the latitudes 3-10^{0}S presents an interesting arcuate feature in the above context. The origins of this arcuate body have long been debated. The curvature resembles that of an arcuate subduction zone, while there are no significant island arc rock assemblages associated with it, that could conform its origin as a subduction zone. However, in the current study we propose that the Amirante represents a failed system that could not be sustained despite being originated in the close vicinity of an active margin.

3. Paleolatitudes, Angular Rotations and Drift Rates

In this section we calculate different angular velocities for the drift of India during the Deccan event based on model 'A' and 'B' of Bhagat et al (2022). Further considering the inclination data we constrain the paleolatitudes for India during the Deccan event. We also constrain finite angular rotations between the initial and final positions of India for the Deccan encounter.

We ran the paleomagnetic Database of Sangode et al (2022), through the "Paleomagnetic Analysis Program V4_Chunfu Zhang" to calculate the paleolatitudes for Deccan event. The two models (A and B) produced the following paleolatitude estimates for C29n and C30n. We do not consider the paleolatitude derived from C29r owing to the "Inclination anomaly", as it would lead to incorrect results. Therefore, we produce paleolatitudes only for C30n and C29n.

	CT	FM	CT	FM

Initial Position C30n(Dec/Inc)	333/-38	338/-38.7	-21.34 (21° 20' 24")	-21.83 (21° 49' 48")
Final Position C29n(Dec/Inc)	341/-32	334.8/-35.1	-17.35 (17° 21' 0")	-19.36 (19° 21' 36")
Difference			3.99	2.47

Table 1. The paleolatitudes for Central India calculated from DI database of Sangode et al 2022. CT- Central Tendency Data, FM- Filtered Mean Data.

The paleolatitudes derived for C30n **(Table.1)** fall exactly at the present-day Reunion latitudes. This validates the accuracy of the database and ensuing calculations. Following this, the data was then subjected to finite rotation and angular velocity calculations through "GPlates" an open-source software programme for plate tectonic modelling. The results thus obtained agree well with the drift rates calculated from inclination anomaly data of Bhagat et al (2022). A total angular displacement of 8.783 degree was obtained for Central tendency dataset, and 4.4161 degree for the Filtered mean dataset. These values together equate to the angular velocities presented in **(Table.2)**.

	CT	FM
Drift Rates GTS20	291.758893	180.612648
Drift Rates MQSD20	283.358925	175.412668
Angular displacement	8.783	4.4161
Angular Velocity in deg (GTS20)	5.7859025 deg/Ma	2.90915679 deg/Ma
Angular Velocity in deg (MQSD20)	5.61932182 deg/Ma	2.28539987 deg/Ma

Table 2. Angular velocities calculated for India from the Paleomagnetic Database. CT- Central Tendency, FM- Filtered Mean.

4. Central Indian Ridge Dynamics

In model 'B' (Filtered Mean dataset) of Bhagat et al (2022), it can be observed that the NE movement of India was modified towards NW as the plate approached Reunion plume. The Central Indian Ridge between the latitudes 17^0S and 21^0S shows a unique distribution of ridge segments **(Fig. 5)**. There appears a sudden change in segmentation/offset pattern of the ridge segments at the above-mentioned latitudes. The ridge segments tend to offset successively towards west rather than NE. This appearance of shorter length ridge segments depicting westward rather than eastward migration as shown by rest of the ridge seems to have been influenced by an unidentified force at the Deccan event. The sudden break in ridge axis is spontaneous, for a length of about 217 km towards West after which the ridge appears to have made a course correction, with successive segments breaking off at NE bearings. The NW change in segmentation could be an artifact of the sudden Westward drift of India as postulated by Bhagat et al (2022). The drift rates calculated from inclination data match very closely with the observed displacements of mid ocean ridge segments.

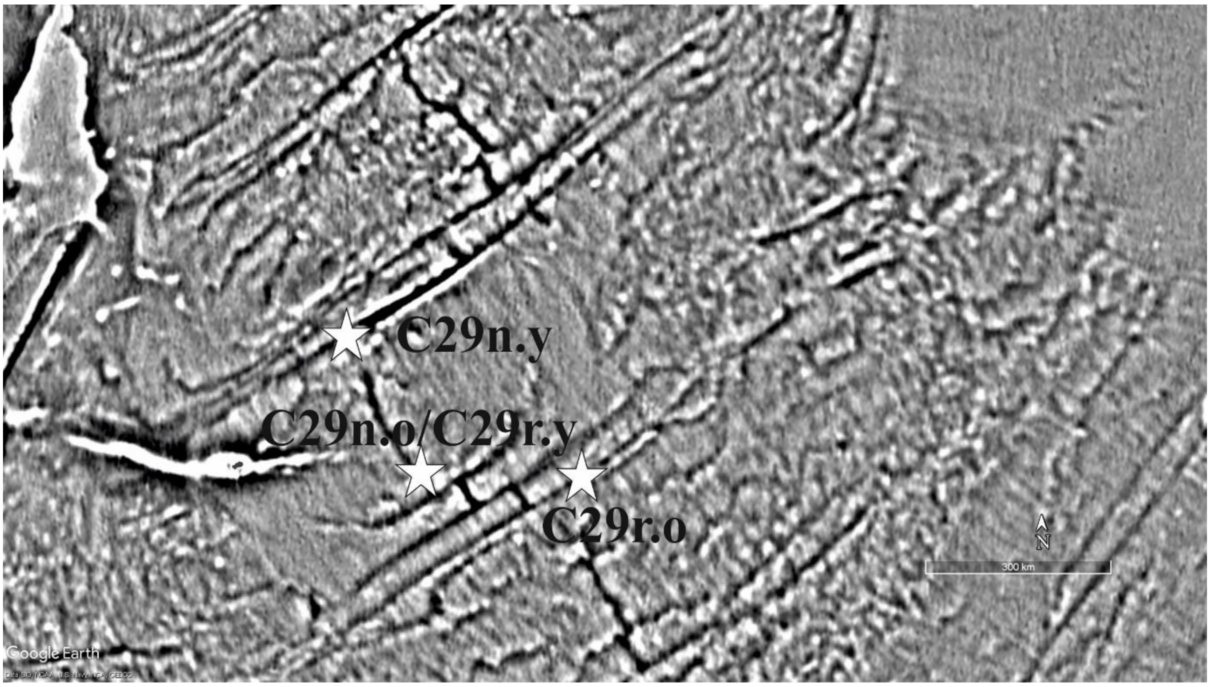
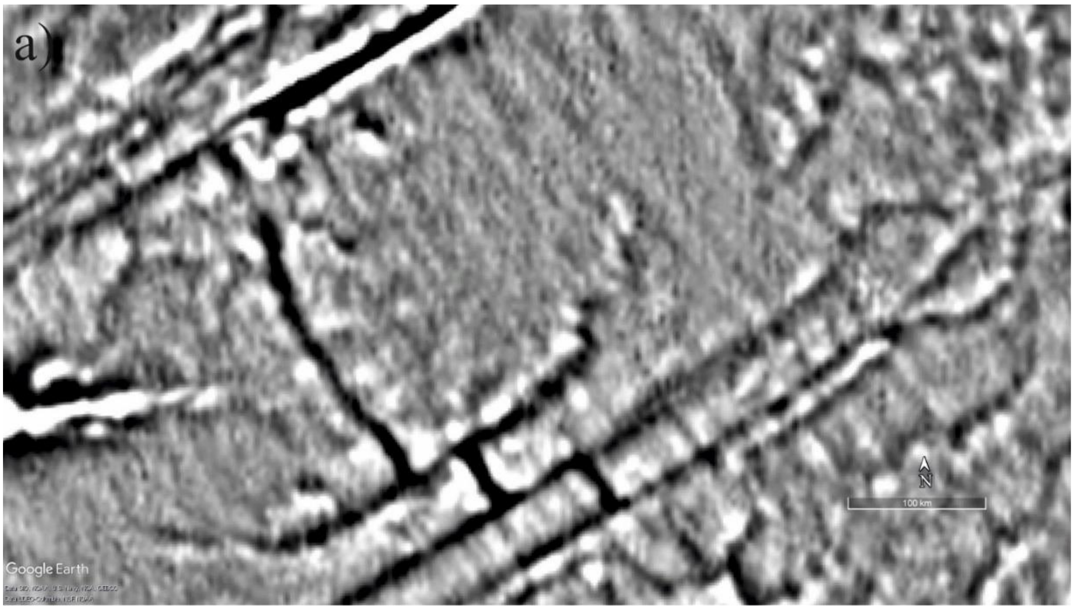


Figure. 5 Gravity map of the Central Indian Ridge after Vertical Gravity Gradient model of Sandwell et al (2014). The three white stars indicate changing positions of India at the onset and

end of Main phase of Deccan eruptions. Towards lower right, the star marks the position at C29r.o i.e., at the beginning of the Main phase of the Deccan eruptions. The central star indicates the position at the end of C29r and the top left star depicts the position of India at the end of Main phase of Deccan eruptions. The southernmost star marks the shift towards west, while the northernmost star indicates the revival of NNE drift of India.

The transform fault to the south would then possibly indicate the onset of C29r while its northern counterpart the end of C29n. This is further strengthened by the first westward jump of the ridge axis depicted by the stepping geometry of the Central Indian Ridge at southern end, and further by the resumption of MOR segmentation pattern towards NE. As we move across the equator towards north, it becomes apparent that no such sudden directional changes took place on the Central Indian Ridge, other than the transition at 1-3^{0}N where Central Indian Ridge gives way to the Carlsberg Ridge. The above discussion thus presents the fact that, the segment of Central Indian Ridge axis between latitudes 17^{0}S and 21^{0}S formed during the Deccan episode. The bounding latitudes are also similar to the paleolatitudes calculated from the paleomagnetic database of Sangode et al (2022). Thus, if we were to take the two observations and form a connection between them, hypothetically it could be assumed that the southern fault marks the onset of C29r (C29r.o) and the northern fault marks the end of C29n (C29.y), thereby spanning a time period of ~1.5 Ma.

The **figures 6a and 6b** accurately depict the ridge morphology and make it possible to identify the fracture zones. The length of the sinistrally climbing ridge segments originating at the southern fault calculated from satellite altimetry data equates to about 217 km on the map. Which if hypothetically considered to be the portion of the ridge propagated during C29r accompanying the Westward drift of India translates into spreading rates ranging between (259-280 $mmyr^{-1}$). This falls very close to the absolute drift rates calculated from the inclination data from the Deccan Traps by Bhagat et al (2022) (s.s. 255.7-263.2 $mmyr^{-1}$).



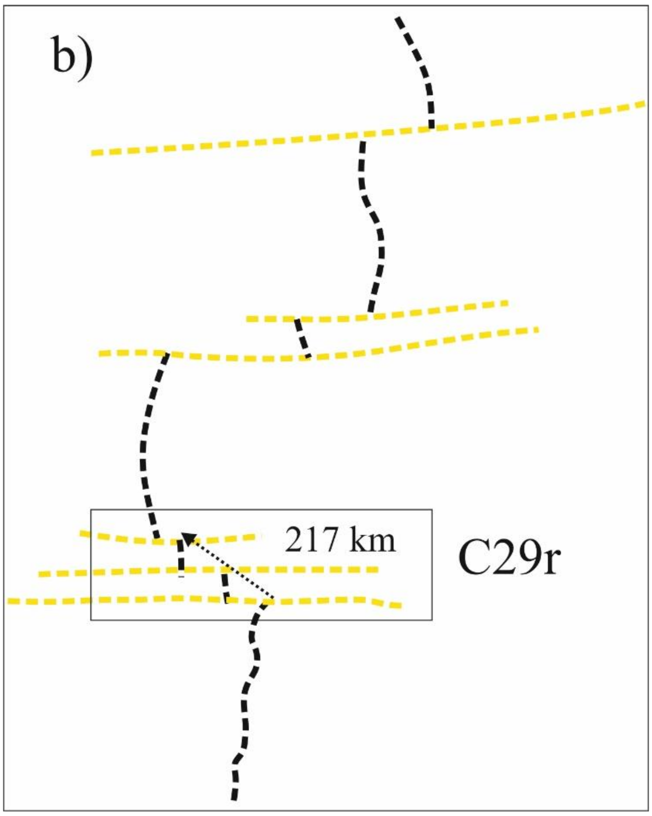


Figure. 6 a) Satellite gravity image of the Central Indian ridge along 17°S, showing stair stepping geometry of the ridge segments migrating westwards. b) Trace of the satellite gravity image of the Central Indian Ridge. The distance between the initial and final position of ridge disjuncts that migrate towards west as measured from satellite altimetry is 217km. This distance when compared with the length of C29r reveals drift rates of (259-280 mmyr^{-1}) which fall very closely to the latitudinal drift values of India during the Main phase of Deccan eruption.

The changing force dynamics in the region were bound to introduce changes in the plate kinematic circuit which can be observed in the form of changing force vectors resulting from the variation in intensity of the different plate driving forces before-during-after the Deccan event are presented in **Fig. 7** These are rightly preserved and reflected in the segmentation pattern of the Central Indian Ridge which is discussed below. The events have been divided into 3 stages as pre-, syn- and post main phase events. The pre-main phase event covers the timespan before C29r, syn-phase spans C29r-C29n and post-main phase heralds beginning of C28r.

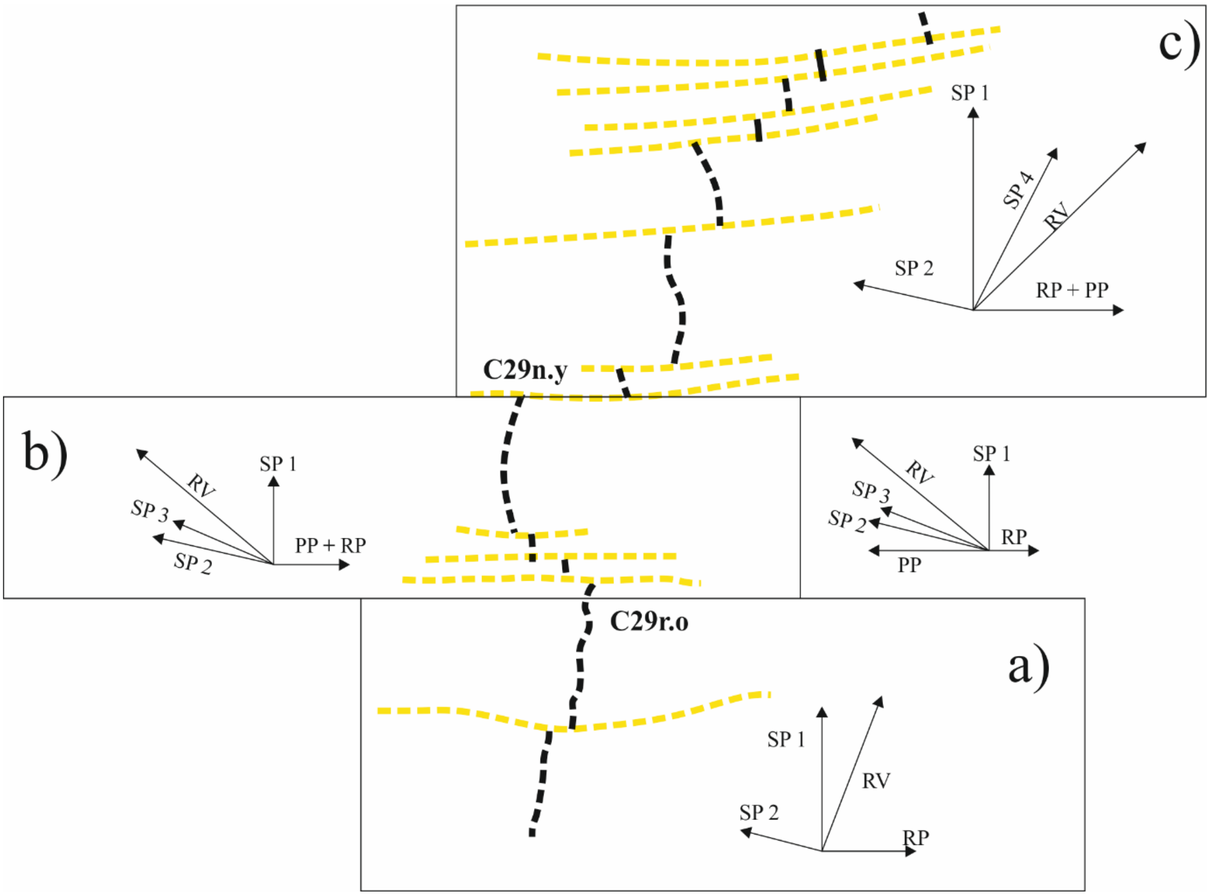


Figure. 7 The figure shows a trace of the Central Indian Ridge with vector distribution of the plate driving forces before and after the Deccan event. The acronyms are as follows: SP1- Slab pull exerted by the Eurasian Trench at the southern margin of Eurasia north of India, SP2- Slab Pull exerted by the NW subduction along the Bela-Waziristan-Muslim Bagh ophiolite belt, SP3- Slab Pull exerted by the Amirante system, SP4- Slab Pull exerted by the Sunda subduction system, PP- Plume push from the Reunion plume, RP- Ridge Push exerted by the Mascarene Ridge, RV- Resultant Vector of all the driving forces. a) The orientation of force vectors before the Main phase of Deccan event b) The orientation of force vectors during the Main phase of Deccan event c) The orientation of force vectors after the Main phase of Deccan event.

Before C29r, the drift of India essentially appears to have been driven by the slab pull arising out of the Neo-Tethyan subduction system and the ridge push exerted by the dying Mascarene ridge (RP). India follows a predominantly North-northeasterly drift direction before the Reunion encounter, this however changed when India arrived over the Reunion hotspot. The north-northeasterly drift direction can be ascertained from the distribution of segments successively towards east which abruptly terminates at the 21°S. This arrangement of ridge segments is relict of the existing plate kinematic setup and the dominant driving forces (**Fig.7a)**. We propose this change in segmentation to have occurred at the end of C30n (C30n.y) and beginning of C29r (C29r.o).

The positioning of India above Reunion hotspot led to a change of force balance in the existing plate Kinematic circuit. The driving force shifted from the Eurasian subduction (SP 1) to the Amirante system (SP 3). This adds an additional component in the accepted theory for the Deccan geodynamics. It is generally accepted that India moved northwards after the Reunion encounter, however the geodynamics at the Deccan event are somewhat sketchy. The first effect Reunion had on India was the lithospheric tilting (Sangode et al 2022), secondly it was the delamination of the cratonic root beneath India (Bhagat et al 2022) and thirdly it was the rapid NW drift of India much, faster than ever recorded. We attribute this westward drift lasting for ~1.5 Ma to the Amirante system, a failed subduction zone in the Southwestern Indian Ocean lying between

Seychelles and Madagascar that initiated exactly when India came over the Reunion hotspot. Following the massive outpouring of the Deccan basalts, India moved away from the hotspot restoring the force balances in regional plate circuit. This led to cessation of the westward drift of India, and resumption of the original northward drift with renewed vigour owing to the plume push. After India passed over the hotspot, the lithospheric tilt was restored leading to cessation of the Amirante system at the end of C29r (C29r.y) and the beginning of C29n (C29n.o) (**Fig.7b)**.

Interestingly the subduction across the Woyla arc in the Sunda subduction zone which had paused since 75 Ma, resumed after 65 Ma (Muller et al 2016), following the accretion of Woyla arc onto Sundaland. We think this could possibly be related to the restoration of tilt of the Indian subcontinent, that led to transfer of far field stresses all the way across the Indian plate to the Sunda subduction system. This resumption of subduction along the Sunda subduction zone along with the combined pull of Eurasian subduction system was more than capable enough to restore the N-NE drift of India and overcome any drag towards west **(Fig.7c)**.

This switch in drift direction is evident in the rearrangement of the ridge segments towards east again compatible with the restoration of lithospheric tilt, cessation of subduction in Amirante system and resumption of subduction along the Sunda subduction zone at the end of Main phase of Deccan eruptions coinciding with the end of C29n (C29n.y).

5. The Amirante system

The Amirantes Arc is a 600 km long arcuate trench shaped feature in the Western Indian Ocean southwest of Seychelles. Its shape strongly resembles that of an island arc over a subduction zone. However, dredge samples of basalts obtained over the ridge classify them as tholeiitic basalts thereby strongly contradicting against the subduction zone origin Fisher et al. (1968). The calc-alkaline diorite, syenite and microgranite suite of rocks encountered along the north-western flanks of the Seychelles plateau represent partial melting and subsequent intrusion in the microcontinent Baker and Miller (1963).

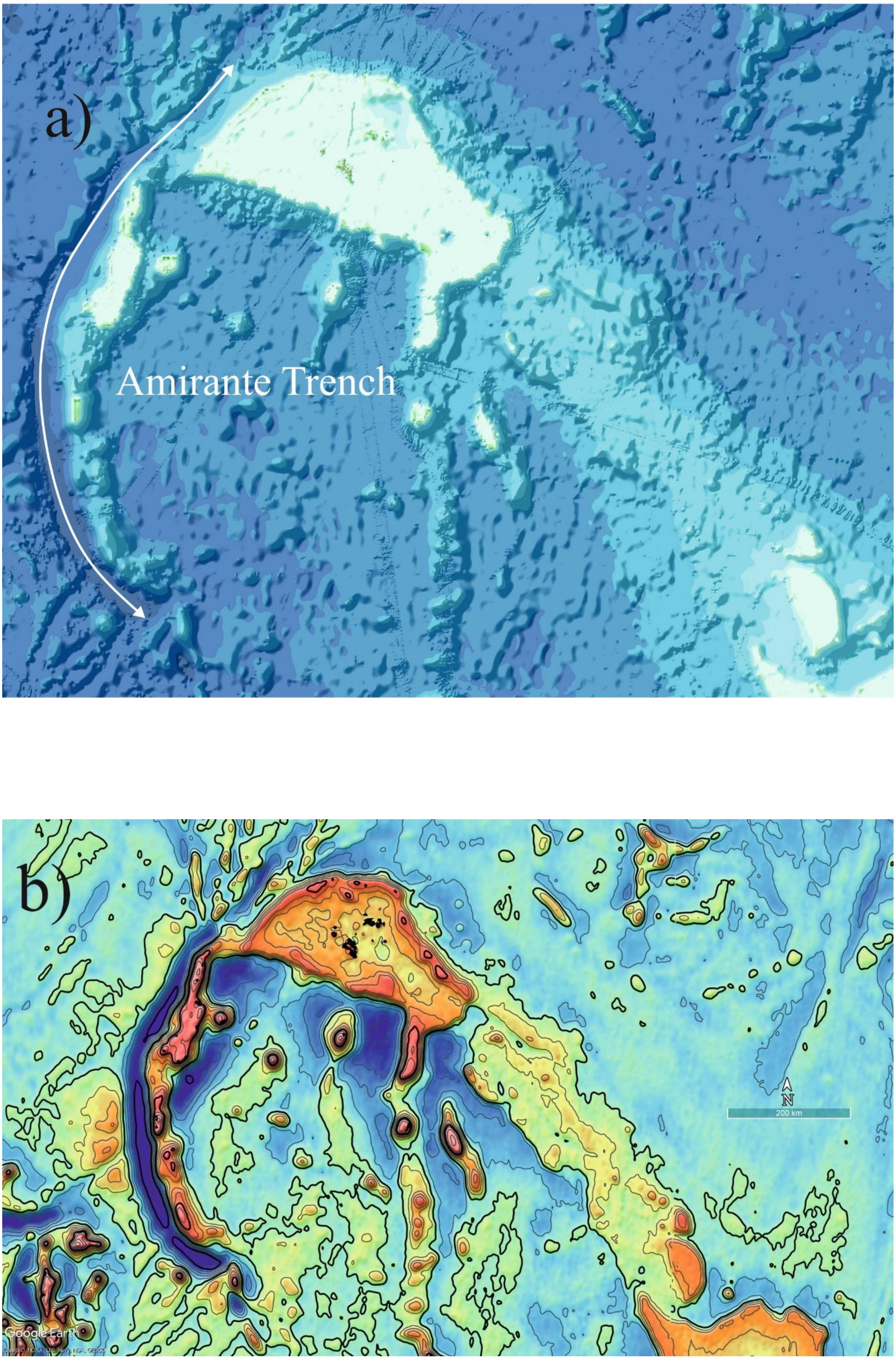

a)
Amirante Trench
b)
N
200 km
Google Earth

Figure. 8a) GEBCO bathymetry map of the Amirante-Seychelles system showing a perfect arcuate subduction zone topography. b) Free Air gravity map of the Amirante trench shows gravity lows in the trench while contrasting with the positive gravity values over the adjacent ridge. This depicts an ideal ridge trench setup, peculiar of the western Pacific mature subduction systems.

Norton and Sclater (1979) suggested that the arc might represent an extinct subduction zone that may have been active before the Seychelles breakoff from India. Miles (1982) compared the Free Air gravity signatures over the Amirante trench, with those from the Lesser Antilles, Tonga and Hellenic arc in the Eastern Mediterranean and the new Hebrides trench. Of the above-mentioned trenches, the new Hebrides trench showed a comparable gravity anomaly signature, however the amplitude of the Hebrides was about 200-250 km while it is ~75 km in the Amirante trench. The gravity values range from -200 mGal over the trench to +200 over the adjoining ridge for the Amirante trench **(Fig. 9)**. When compared with the globally observed gravity values of ±500 mGal this is less than half the global average. The presence of parallel ridge and trench structures along a subduction zone is a peculiar feature of many modern-day subduction zones in the western Pacific **(Fig. 8a & b)**.

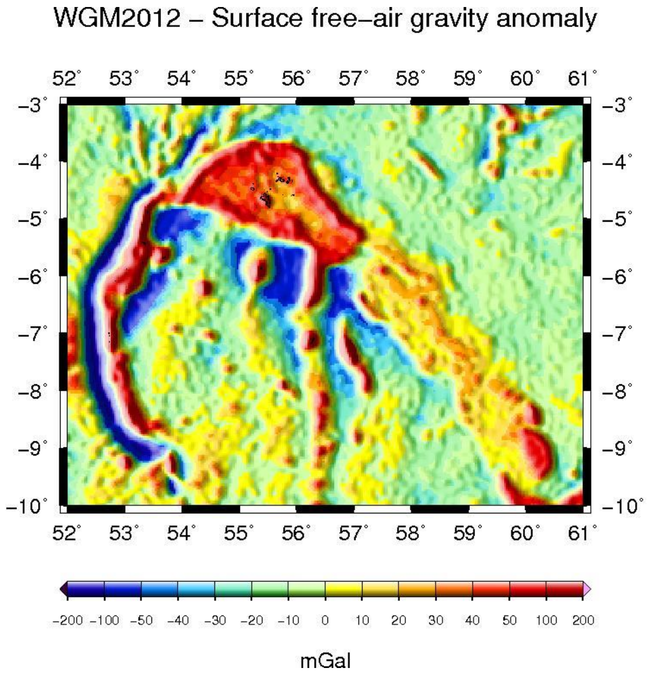


Figure. 9 Free Air Gravity Anomaly plot of the Amirante system showing gravity values around -200 mGal in the Amirante trench contrasting with~200 mGal over the Amirante ridge, derived from the World Gravity Model 2012.

Mart (1988) proposed, the Seychelles microcontinent rifted from India due to sea-floor spreading and collided with the oceanic crust of the Mascarene basin. The resulting collision could have formed an elongated structure at first, which would have subsequently developed into a subduction zone. This subduction caused the development of Amirante system, followed by the intrusion of syenite and microgranite into Seychelles. The absence of younger intrusive rocks with further alkaline signatures suggests that the subduction system would have terminated abruptly.

Plummer (1996) was the first to propose a holistic model for the development of the Amirate structure creating the Amirante system. He proposed that the Amirante basin developed independently of the Mascarene basin, which itself had an independent origin regardless of the Somali basin to its NW. Spreading in the Mascarene basin started in the late Cretaceous around ~83-84 Ma in response to the rifting of India from Madagascar. Initially the Somali and Mascarene basins were separated from each other by sinistral transform fault which resulted in the southward migration of Madagascar with respect to India. This strike-slip motion induced a zone of compression adjoining the western margin of Seychelles leading to the development of a pull apart basin i.e., the Amirante basin. Accordingly, the Amirante basin did not develop from a spreading centre, rather it developed from compressional tectonics. Differential spreading rates within the northern and southern reaches of the Mascarene basin coupled together with the coeval independent formation of the Amirante basin created a zone of compression along the transform fault separating the Somali and Mascarene basins. These basins resulted in subduction of the Somali basin crust under the Mascarene basin crust further owing to counter-clockwise rotation of the Seychelles microplate, leading to the formation of Amirante trench. The arcuate Amirante system thus developed in response to the counter-clockwise rotation of the Seychelles micro-continent along the transform boundary with the adjacent Somali Basin. This plate kinematic alignment lasted till ~65 Ma, until the arrival of the Carlsberg ridge which introduced significant changes in the plate configuration of the Indian ocean plate circuit.

Moving on from the above discussion, we would like to postulate that the Amirante trench system is the possible cause for sudden westward drift of India at the Deccan encounter, vestiges of which are recorded in the Central Indian Ridge between the latitudes 17-21°S **(Fig. 6a)**. Based on recent advances in the knowledge about the initiation of subduction zones and the behaviour of oceanic lithosphere with increasing age and depth, we propose our geodynamic model for the plate kinematic setup in the Western Indian Ocean along WCMI. This model explains the evolution of plate boundaries in a rapidly evolving kinematic framework.

6. Geodynamic model

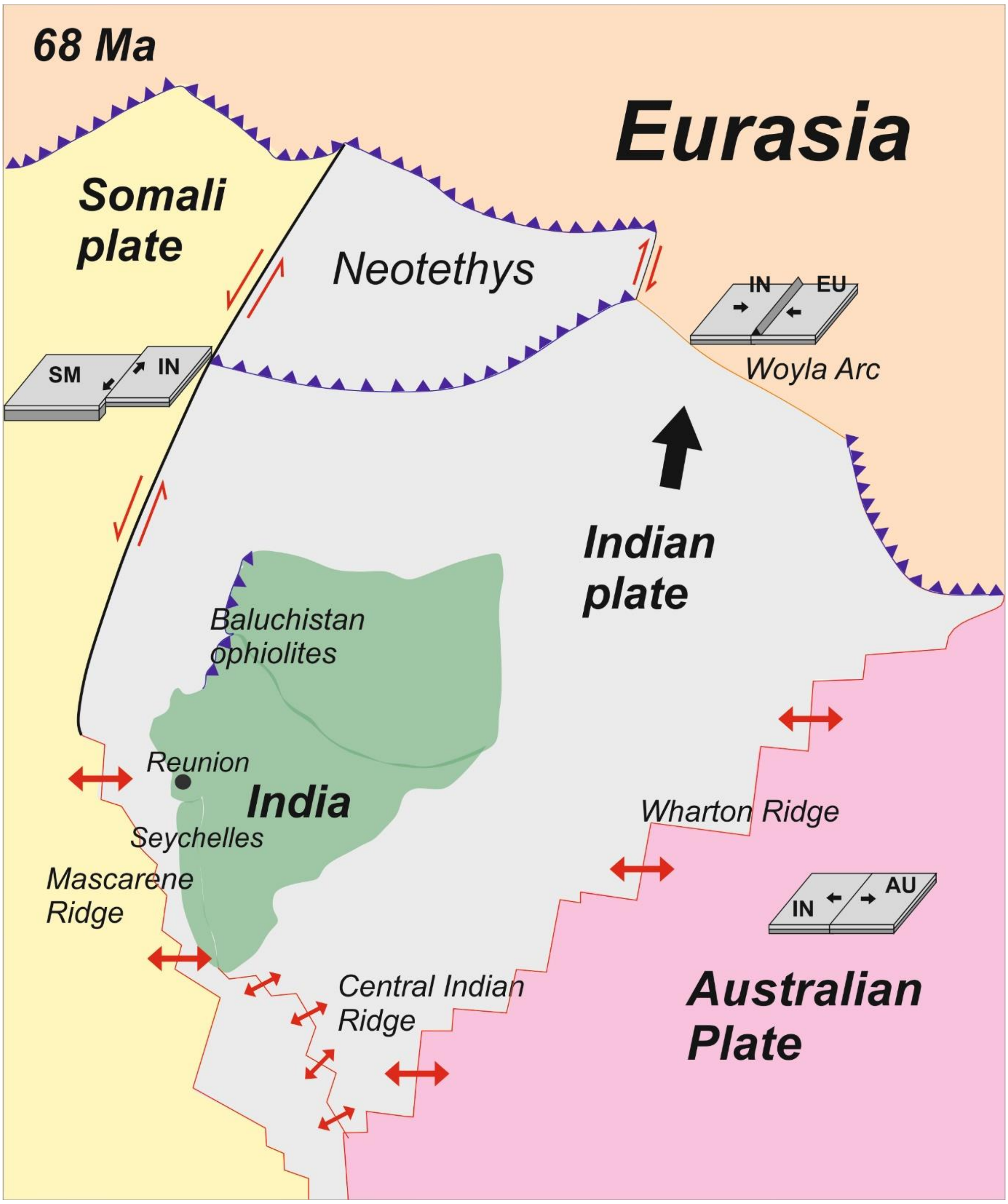


Figure. 10 The alignment of plate boundaries surrounding the Indian plate. At 68 Ma, the India -Somalia boundary is a left lateral strike slip fault in the north and a spreading centre in the south. The northern margin of the transform fault meets first the intraoceanic subduction between India and Eurasia, and further north ending in the subduction zone at the southern margin of Eurasia. The southern region ends in a triple

junction where the Indian Australian and African (Somali) plates meet. The boundary between Indian and Australian plates is a spreading ridge (Wharton basin spreading centre). The northern end meets the Neo-Tethyan subduction system, while the southern meets the triple junction in the Southern Indian Ocean. The boundary between Indian and Eurasian plates is a subduction in the NW followed by a dextral transform fault which connects it to a suture zone along the Woyla arc in the North which on moving further eastwards evolves into a subduction zone.

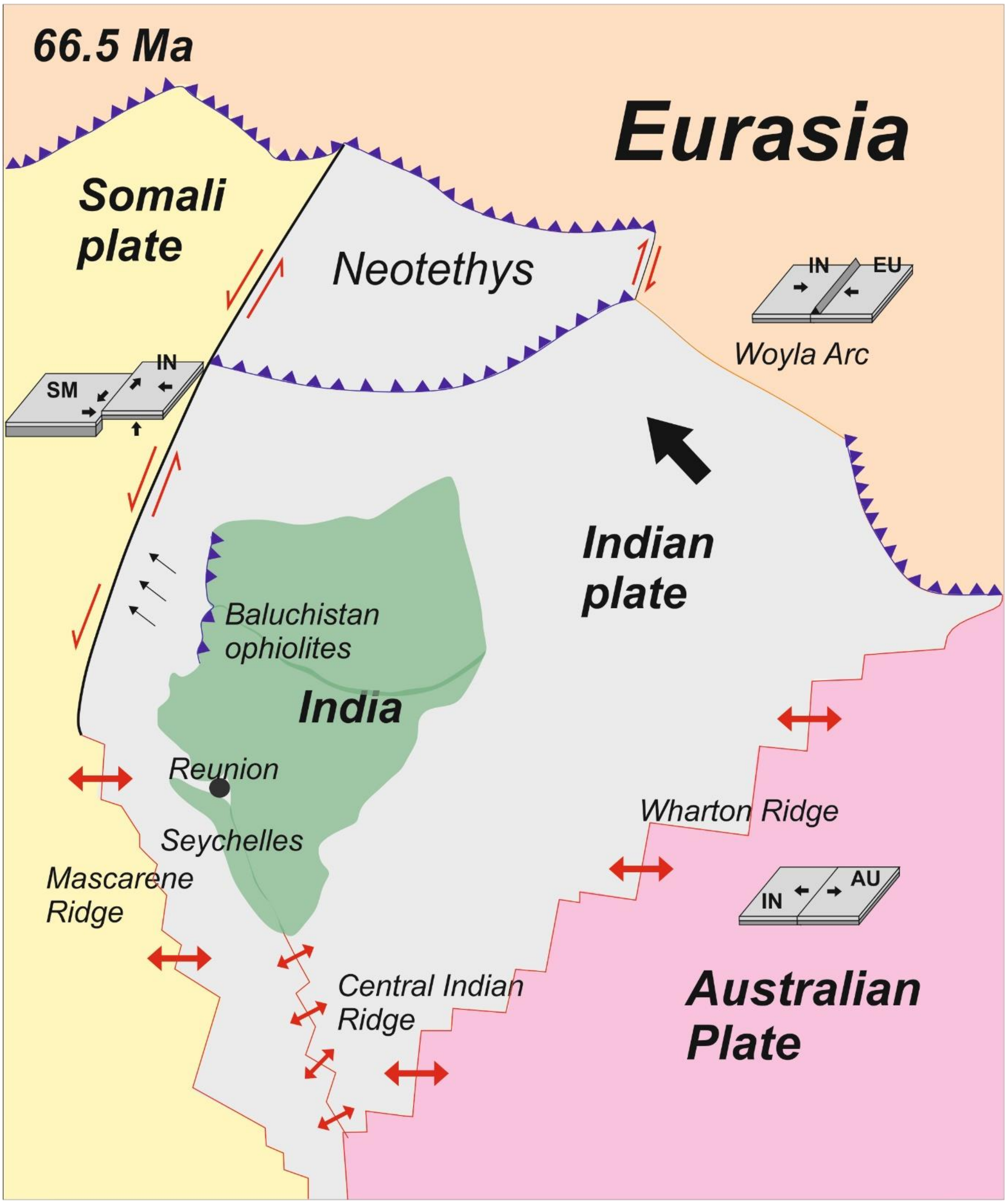


Figure. 11 At 66.5 Ma the Indian subcontinent arrives over the Reunion hotspot. This leads to tilting of India towards North resulting in rotational and compressional stresses along the India-Somalia transform fault, leading to anti-clockwise rotation of India. Early phase rifting of Seychelles commences due to plume induced thermal instability along the pre-existing weak zones.

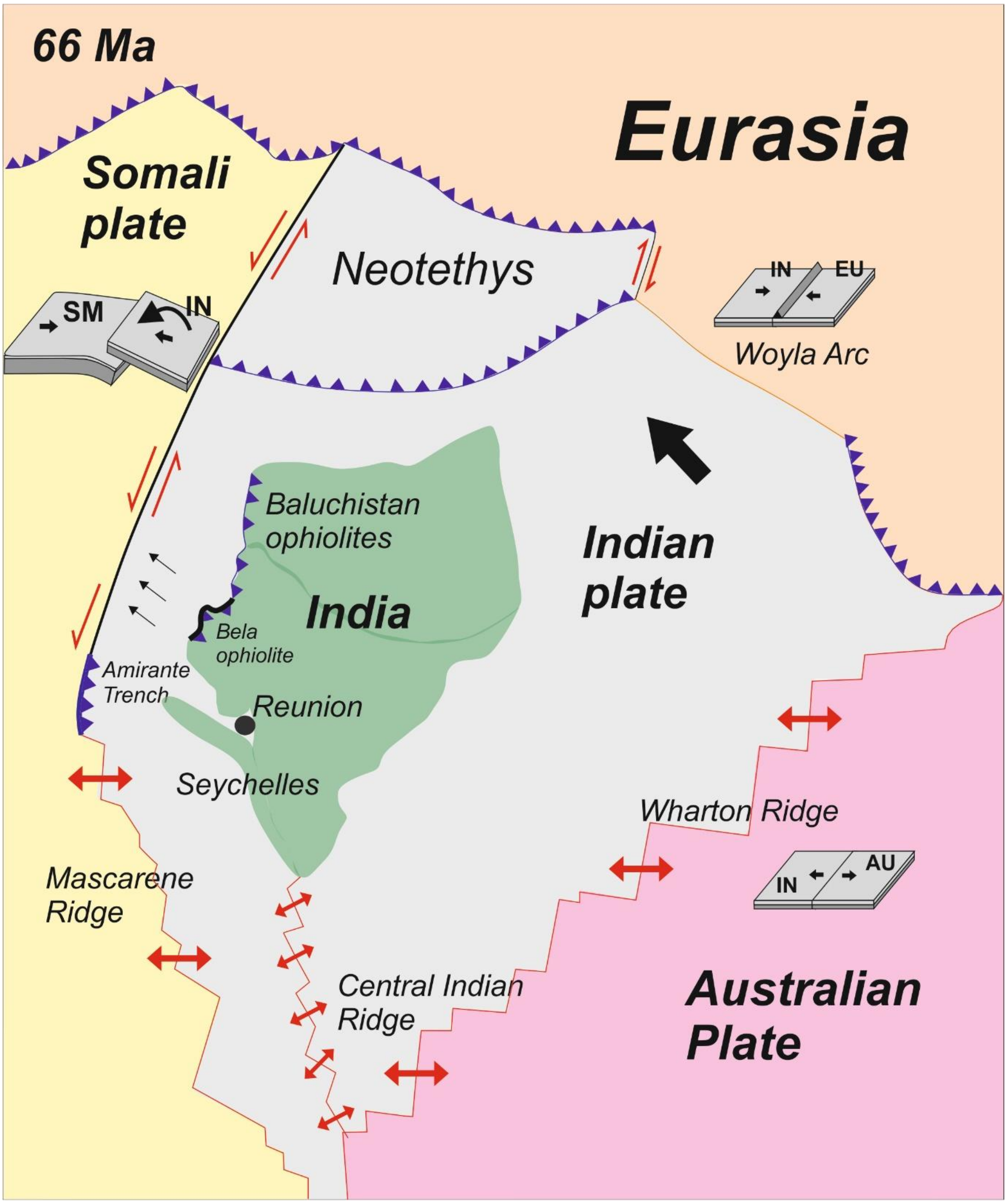


Figure. 12 At 66 Ma the plume induced tilting leads to initiation of subduction in the Amirante basin along the India-Somalia transform fault. This causes India to abandon its NE drift and follow a NW course towards the newly initiated subduction zone. The

Bela ophiolite sequences start obducting along the Northwestern margin of India, another consequence of the plume induced tilting.

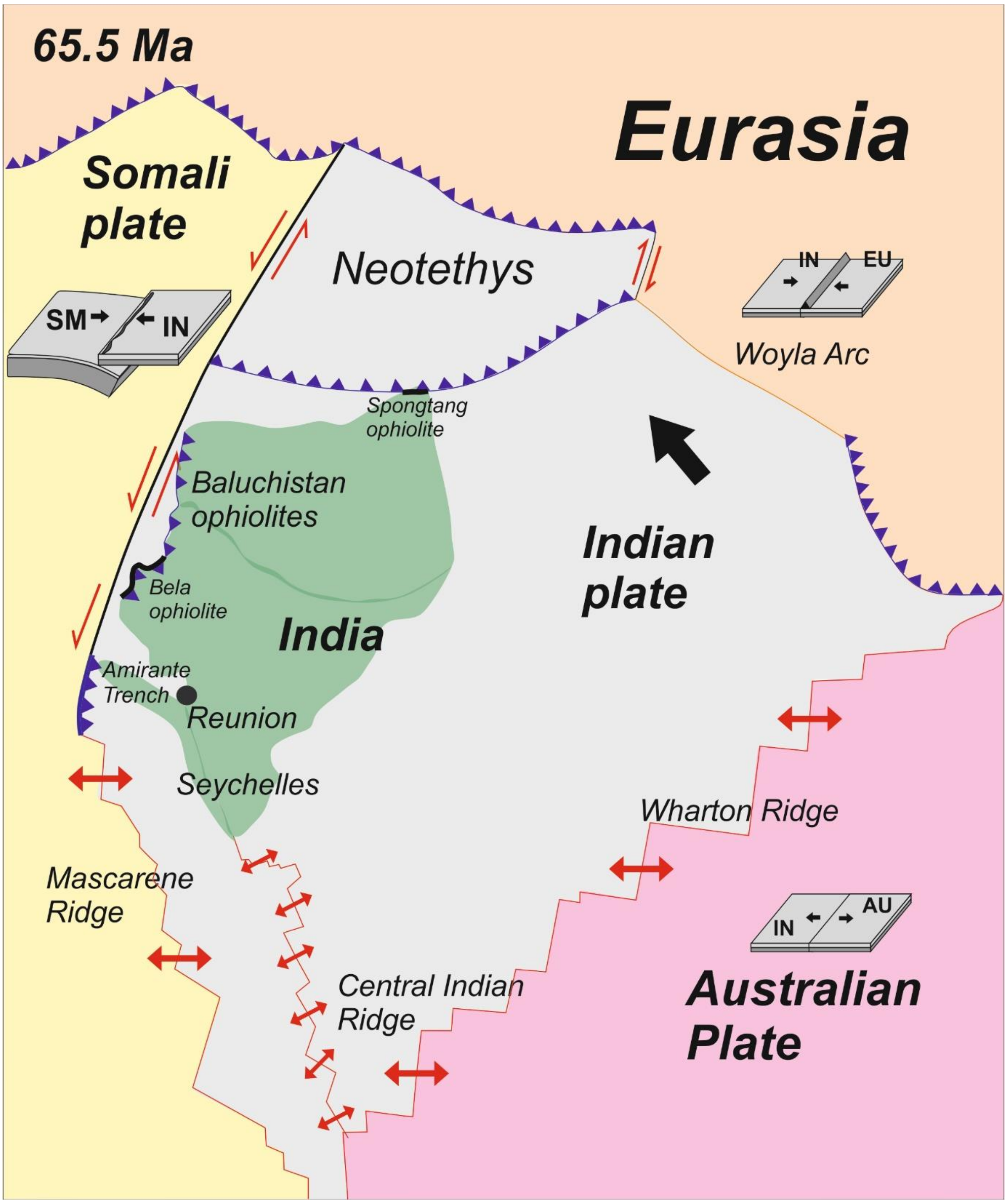


Figure. 13 The NW drift gets recorded in the alignment of spreading ridge axis of the Central Indian Ridge. The Northern portion of Seychelles microcontinent arrives in the Amirante subduction zone. The northern extremity of Greater India approaches the Neo-Tethyan intra-oceanic subduction resulting in obduction of Spongtang ophiolites along the Northern margins.

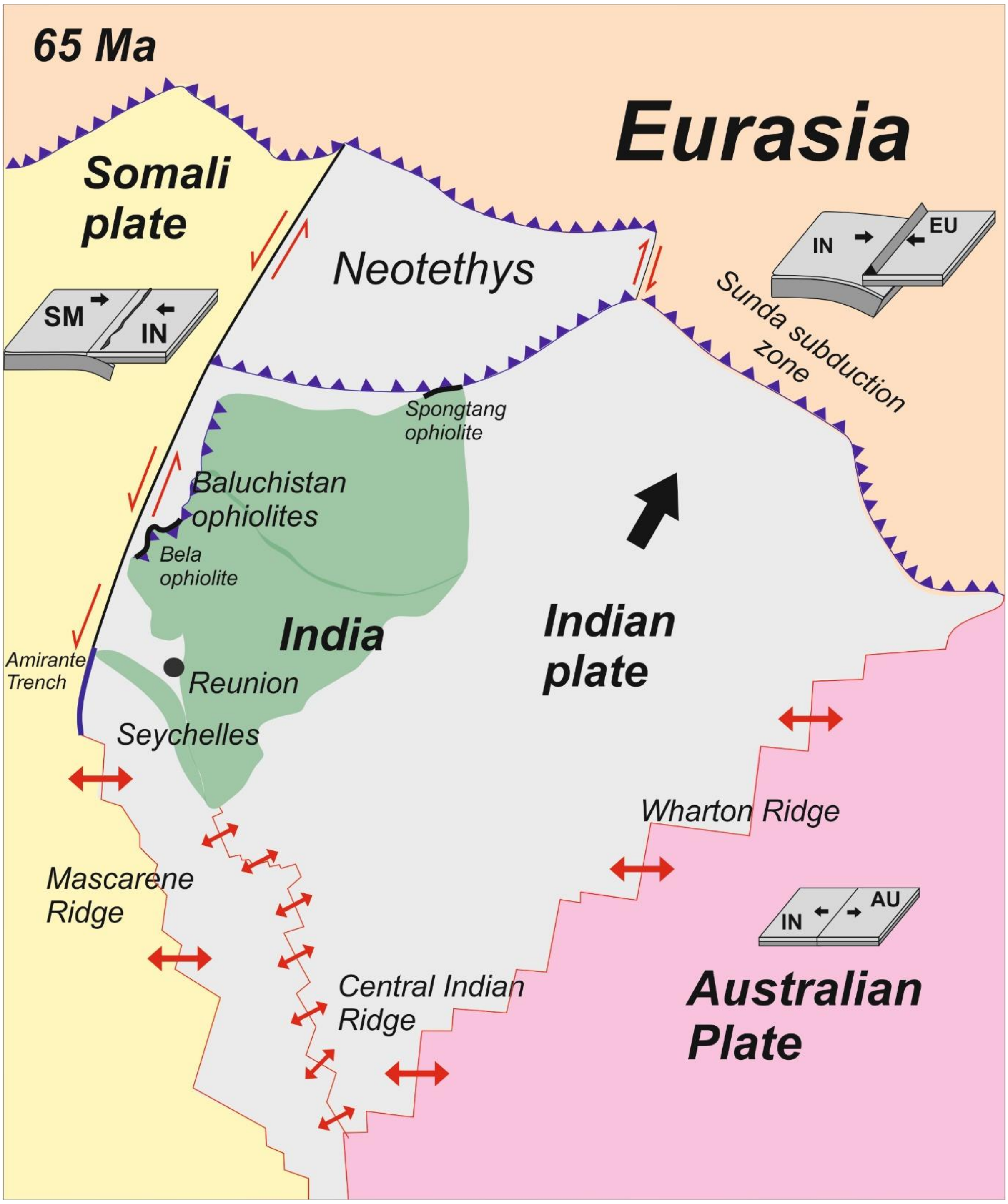


Figure. 14 Arrival of Seychelles in the subduction zone causes its cessation ending the NW drift of India. The NE plate boundary along the Woyla arc activates from the transference of lithospheric stresses resulting from tilting of the Indian plate leading to initiation of subduction and forming the Sunda subduction zone. The initiation of subduction along Sunda zone re-established the NE convergence of India.

At ~67-68 Ma **(Fig. 10 and Fig. 15a)** before the main phase of the Deccan event, the Reunion plume was placed along the northwestern margin of India close to present day Saurashtra. There was an active subduction along the NW towards Baluchistan, active since early Cretaceous which had obducted the Kabul Muslim-Bagh-Waziristan ophiolites onto the continental margin of India. Along with this, the Eurasian subduction system was active all along the northern margin of India, except for the NE where the accretion of Woyla arc was almost complete, convergence had paused temporarily along the Sunda subduction zone. In addition to this, spreading in the Mascarene basin was waning and the proto-Central Indian ridge was in its youthful stage. The sinistral movement along the transform fault separating Mascarene and Somali basins had created a zone of compression in its northern reaches, resulting in possible convergence along the NW Indian margin and obduction of the Baluchistan ophiolites.

The arrival of Reunion plume under India ~66.5 Ma **(Fig. 11 and Fig. 15b)**, resulted in delamination of cratonic root beneath the western and southern parts of the peninsular region, leading to additional positive buoyancy. This newly acquired positive buoyancy resulted in northward tilting and counter-clockwise rotation of India. This tilting of India led to an enhancement of the compressional regime along NW resulting in ophiolite obduction along the southernmost Baluchistan ophiolites- the Bela ophiolites. However, the tilting induced stresses were not limited to this region, rather they had far-reaching tectonic implications.

The buoyancy contrast created by loss of cratonic root led to an overall rise of the subcontinent, along the western and southern peninsular tip. The transform plate boundary between Mascarene and Somali basins that also formed the boundary between the Indian and Arabian plates underwent subduction initiation.

Collapse of oceanic transform fault separating the older Somali basin (Arabia) lithosphere from the younger Mascarene basin (India) lithosphere resulted in the sudden initiation of an east verging subduction zone at ~66 Ma, where the older Somali oceanic lithosphere started subducting under the younger Mascarene lithosphere **(Fig. 12 and Fig. 15c)**. This nascent subduction zone is the present day Amirante trench which exhibits a typical arc-trench morphology. This young subduction zone however, was destined to fail as it would never achieve stability. Since, for a subduction zone to be able to achieve stability, oceanic floor segments older than 20-30 Ma need to be present across the subduction interface. In this case the Somali basin lithosphere was sufficiently aged ~Jurassic to Early Cretaceous age; however, the Mascarene basin lithosphere was younger than 20 Ma (~15-16Ma). This young-weak lithosphere fragment being hotter and more buoyant than older and denser slabs which characterize mature subduction zones, resulted in density contrast with the surrounding mantle unable to advance beyond the nascent subduction stage. Another impeding factor would be the slower rate of convergence less than ~2 mm/yr, which would have been limited below the threshold value owing to younger age of the lithosphere and high positive buoyancy of the overriding plate. Thus, formation of a full-fledged mature subduction along the Amirante trench was highly improbable, leading to the failed subduction and the remanent superficial arc-trench profile.

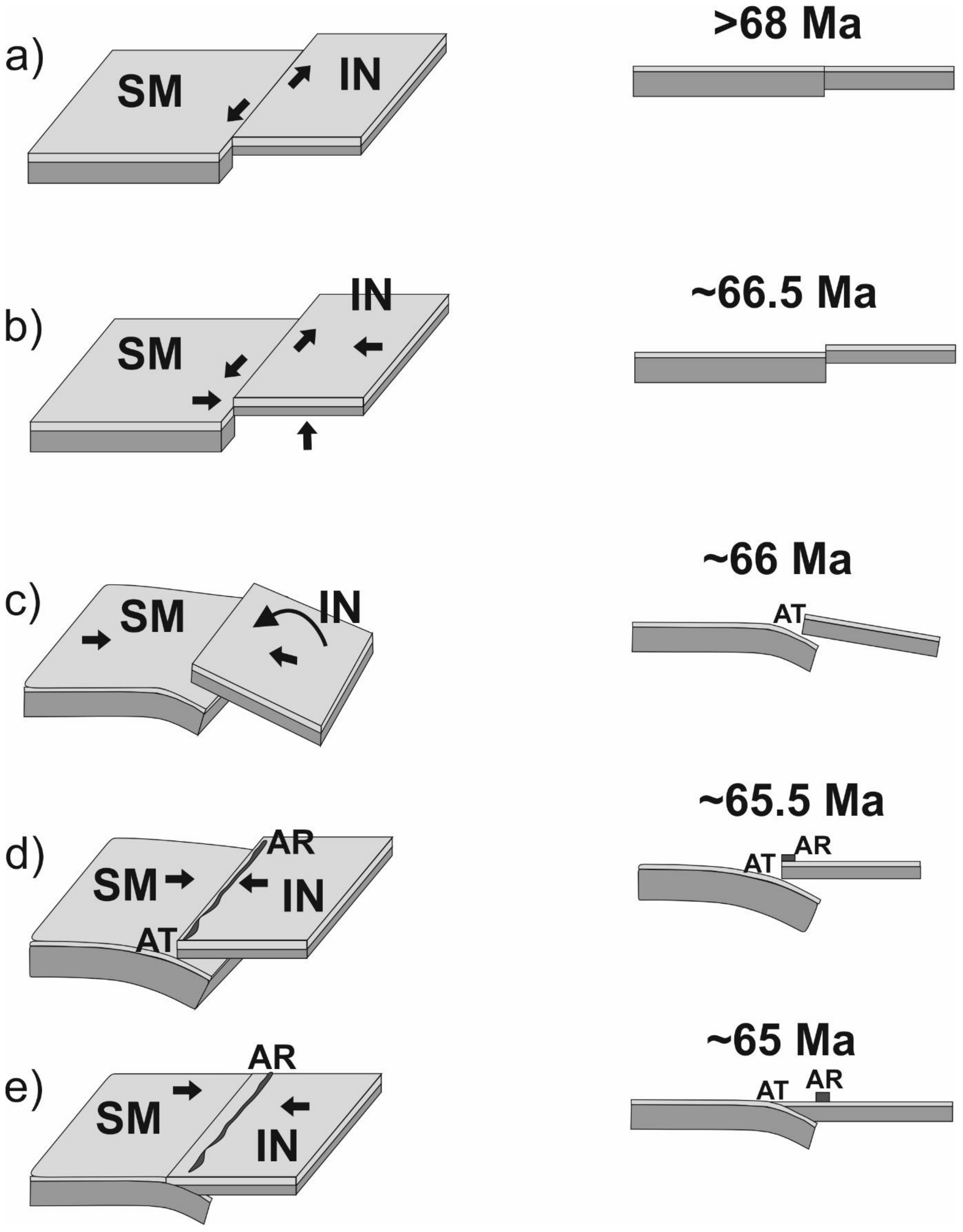


Figure. 15 Model showing the evolution of India-Somalia (Arabia) boundary at the Deccan event, along the western margin of India below the Baluchistan subduction zone. a) The boundary between Indian and Arabian plates is essentially a sinistral transform fault, with the Somali (Arabia) block moving downwards and the Indian plate moving

northwards. b) The arrival of the Reunion plume under the western margin of the India exerts an upward push on the Indian plate leading to tilting towards North. c) The imbalance created by the tilting is balanced by the initiation of subduction at the India-Somalia plate boundary. d) The juxtaposition of younger and lighter oceanic crust of the Indian plate against the denser and older crust of the Somali plate, leads to the sinking of the Somali basin crust under the Indian plate owing to the stresses produced by the anticlockwise rotation of the Indian plate along with plume induced tilting. e) At the end of Deccan event the lithospheric tilt is restored back to normal resulting in cessation of the subduction along the Amirante subduction zone. IN-Indian plate, SM- Somalia (Arabia) plate, AT- Amirante trench, AR- Amirante ridge.

The slip along Amirante system once activated would have lasted ~1-1.5Ma, this duration would have been sufficient enough to initiate the NW drift of India combined together with the pull from the Baluchistan subduction zone and the counterclockwise rotation induced by the compressional forces arising from the Reunion plume. This westward pull would have its maximum impact on the Seychelles microcontinent, as the anchoring cratonic root would be completely lost owing to thermal erosion of the Reunion plume, and plume induced rifting would lead to its stripping off from the Indian margin. Once the rifting commenced, it would continue until the Seychelles arrived in the subduction thereby causing cessation of the subduction zone **(Fig. 13 and Fig. 15d)**. This explains the semi arcuate shape of the Seychelles microcontinent. The northern portion would have been first to come in contact with the subduction zone, while the rest of it was still attached to India. Thus, once the northern region collided with the trench, it caused the cessation of the trench, thereby leaving behind a curved northern region while more or less linear southern region. The boundary along India-Arabia interface was intermittently convergent and transform (Pandey et al 2019) which explains the sudden cessation of the subduction zone and end of WNW drift of India at the end of main phase of Deccan eruptions. The active convergent margin along the Amirante trench would be converted to a fossil subduction zone and retain the arc trench morphology.

The cessation of Amirante system at the end main phase of Deccan eruptions would mark the end of westward drift. This phase was followed by the renewed NNE drift of India activated by the Sunda subduction. The tilting of India would have exerted tremendous stresses across the Indian plate all the way to the Sunda subduction zone, where subduction had paused for ~10 my owing to the accretion of the Woyla arc onto the Sundaland margin. The tilting would have induced compressive stresses and revoked the flexure of the lithosphere which resulted in reinitiating the subduction of the Indian plate below the Sundaland margin along the Woyla arc. Once initiated, this reactivated subduction would have exerted a massive slab pull force on the Indian plate combined together with the Eurasian subduction system overcoming the pull from the Baluchistan convergent margin. The push from the Reunion plume would only help accelerate the NNE drift of India by lowering the viscosity of asthenosphere beneath India.

Thus, establishing the unique drift of India towards Eurasia **(Fig. 14 and Fig. 15e)**.

7. Conclusions

The Deccan Traps form one of the most spectacular geological features of the Indian subcontinent. Significant amount of work focusses on the volcanism and petrological aspects of the large igneous province leaving several lacunae in understanding its geodynamic impact over the Indian plate, the Indian ocean basin and its subduction regimes. In this paper we have presented the observations on the ocean floor anomalies to explain the kinematic changes in terms of drift velocities and directions of the Indian plate, and the interaction of the subduction zones and spreading ridges as the plate encountered the Reunion plume. A significant westward drift has been reported here precisely at the Deccan event as an anomaly to the NNE drift. The relicts of this drift are scattered across the Western Indian Ocean. We investigated the CIR for the same and discovered that the ridge segments between 17-21°S exhibit a segmentation pattern that is distinct from the rest of the ridge. Below 21°S the ridge breaks off at NE bearings and starting 21°S the ridge breaks off at NW bearings and this is again reversed to NE at 17°S. Paleolatitude calculations revealed that the site of eruption of main phase of Deccan Traps falls almost exactly between the above latitudes. We estimate the length of ridge segments trending towards west equivalent to the length of the drift of Indian plate previously reported by Bhagat et al (2022). Amongst the possible forces that could have brought about this directional change, subduction forms the most plausible option. The initiation of Amirante subduction system and its cessation within a short span of less than ~1.5 Ma exactly at the Deccan event makes it geodynamically the best candidate for this position. Further the activation of the Sunda arc at the Deccan event owing to the lithospheric tilting reinstated the NNE drift of the India. Based on the ocean floor records and the postulations presented here, we indicate that the westward drift of India at the Deccan event reflects the kinematic reorganization of the Indian plate which further demands detailed computational modelling as future studies in this region.

Declarations:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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