Drift rate partitioning indicates anomalous high velocities for the Indian plate during ~65 Ma

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Key Points:

- **Very high drift rates for the Indian subcontinent during the Deccan Trap eruption are reported.**
- **Dynamics of the reported drift rates are explained.**
- **Present day location of the lithospheric root delaminated from the Indian subcontinent is proposed.**

Abstract

A rapid northward drift of the Indian plate after 130 Ma has also recorded significant plate rotations due to the torques resulting from multiple vectorial forces. Magnetic anomaly, seismic tomography and palaeomagnetic database is used here to constrain drift velocities, tilt and lithospheric root delamination at different temporal snapshots. It results into estimates of 263.2 to 255.7 mmyr^{-1} latitudinal drift, 234 to 227.3 mmyr^{-1} longitudinal drift and 352.2 to 342.1 mmyr^{-1} diagonal drift, for the period from ~66 to 64 Ma during the Chrons C30n.y–C29n.y. Alternative models suggest active driving forces arising from *i)* slab pull, *ii)* ridge push from eastern-, western and southern plate margins, and *iii)* Reunion plume-push force; in addition to delamination of the lithospheric root during approximately 65$\pm$2 Ma. Delamination amplified the buoyancy of the Indian plate in contrast to sudden loading from Deccan basaltic pile that resulted into complex drift dynamics expressed by hyper plate velocities within global plate circuit.

Plain Language Summary:

Paleomagnetism has proved indispensable in plate tectonic reconstructions. Often the seafloor spreading rates are calculated from the Marine magnetic anomalies in the ocean basins. However, it is possible that these robust features of the global conveyor belt may at times miss events which are significant in magnitude occurring within a short time span. Here, we present one such event during the Deccan trap eruption. It is well established that the highest plate velocities that can be achieved by drifting plates range around

180-200 mmyr^{-1}. However, in the present study based on paleomagnetic data, we present drift rates that are in excess of 300 mmyr^{-1}, these drift rates result from contemporary existence of multiple plate driving forces that acted on the Indian plate during the K-Pg event. Slab pull combined together with plume push, ridge push and lithospheric root delamination propelled the Indian plate at tremendously high velocities which resulted in multiple course corrections along within a short span of ~1.5 Ma.

Introduction:

The Indian plate presents one of the most dynamic trajectories of plate motion by its rapid northward drifts and clockwise/anticlockwise rotations (Patriat and Acache 1984, Eagles and Hoang 2013, O'Neill et al 2003). Multiple surges in the plate velocities are recorded at 130, 85 and 65 Ma (Van Hinsbergen et al 2011, Eagles and Hoang 2013, Gibbons et al 2013, Gibbons et al 2015, Jagoutz et al 2015, Cande et al 2010, Cande and Stegman 2011, Demets and Merkouriev 2021, Eagles and Wibisono 2013) and are related to Indian plate encounters with three well established mantle plumes. The 130 Ma event was caused by the Kerguelen plume forming the Rajmahal (Kale 2020, Ghatak and Basu 2011, Taludkar and Murthy 1971) traps in India, Bunbury basalts in Australia (Frey et al 1996, Ingle et al 2002, Zhu et al 2009, Olierook et al 2016) and Kerguelen plateau in the Southern Indian Ocean. This resulted in rifting of India from East Gondwana (Aitchison et al 2007, Acharyya 2000, Argus et al 2011, Bardintzeff et al 2010) forming the Indian subcontinental block comprising (India + Madagascar + Seychelles). This rifting was followed by the Marion plume arrival at the End Cretaceous (~90-85Ma) (Torsvik et al 1998, Georgen et al 2001, Storey 1995), resulting in separation of India + Seychelles block from Madagascar.

The final Reunion plume encounter led to India-Seychelles separation and eruption of the Deccan flood basalts at ~65.5 Ma (Sangode et al 2022, Vandamme et al 1991, Jay and Widdowson 2006, Chenet et al 2007, Chenet et al 2008).

Drift, rotation and tilt of the Indian plate

Based on marine magnetic anomaly data it has been established that the Indian subcontinent moved at extreme velocities during the period from C32 to C28 at highest speeds of ~185- 200 mm/yr recorded during Chron C29r (Cande and Stegman 2011, Pusok and Stegman 2020, Sangode et al 2022, Rodriguez et al 2021, Van Hinsbergen et al 2015). These velocities are anomalous when compared with the fastest spreading rates obtained from the East Pacific Rise (~140mm/yr) existing today (Lonsdale 1977, Clennett et al 2020). This high drift velocity for the Indian plate has been classically attributed to its interaction with the Reunion plume and the Deccan eruption event, which amplified the existing rapid velocity of the Indian plate.

Primarily, the drift rates are calculated from the Marine Magnetic Anomalies (MMA) in the ocean basins; however, in situations where anomaly data are sparse the drift rates are calculated from paleomagnetic measurements based on land values. Present work is built up on the database of Sangode et al (2022), who discovered the Deccan inclination anomaly from a compilation and analysis of existing paleomagnetic data from the Deccan Traps. They discovered that the paleomagnetic inclinations for the chrons C30n, C29r and C29n differ significantly for such a short-time span, with C29r depicting highly anomalous inclination values. This inclination anomaly was attributed to the ~10 tilt of the Indian plate towards north leading to short episode of epicontinental marine transgression along the Narmada rift (Kumari et al 2020, Keller et al 2021). This tilt is attributed to the arrival of the Reunion plume at the NW-W periphery of the Indian subcontinent resulting in uplift of southern tip of peninsular India and dipping of the northern edge of the subcontinent for a very brief time spanning C29r. The tilt was restored back to normal during C29n, resulting in normal inclination values for the same.

Constrains from paleomagnetic database

Statistical analysis of the paleomagnetic data leads to 2 differing results which contrast not only in position but also significantly differ in the drift velocities for the Indian subcontinent. 'Model A' explains the results obtained from Central tendency data, while 'model B' explains the results obtained from the Filtered mean data. As it is not clear when the Deccan volcanism event precisely initiated, we have considered the initial position of the Indian subcontinent for our calculations at the end of Chron C30n while the final position at the end of C29n signifying the end of main phase eruption of Deccan tholeiites. This provides us with a ~1.5 Ma (1.518 Ma for GTS2020; 1.563 for MQSD20) time window to monitor the movements of the Indian subcontinent spanning C29r and C29n. The co-ordinates for Nagpur in Central India were used as a reference point for calculating movement of Indian plate.

For 'model A' (Central tendency data), the D/I value are 333/-38 at C30n.y and 341/-32 at C29n.y. The initial position of the Indian subcontinent at C30n.y is exactly southwest of the final position at C29n.y. This agrees well with the established literature, except for the fact that the displacement of India for the specified time period is massive. The differences in initial and final positions depict a latitudinal drift of 6° and a longitudinal drift of 8°. Simple trigonometric calculations reveal a diagonal drift of about 10° which is colossal when compared with the highest drift rates that have been recorded for India-Eurasia convergence. Assuming 1° = 111 km, latitudinal, longitudinal and diagonal drifts can be calculated as 666 km, 888 km and 1110 km respectively. These results when compared with the above-mentioned timespan, evolve into drift rates which have not been directly documented earlier. These are presented in the Table 2 and figure 3.

'Model B' (Filtered mean data) however indicates an altogether different result. The D/I values are 338/-37.8 and 334.8/-35.1 respectively for the final and initial positions (i.e., C30n.y and C29n.y). This presents smaller drift rates when compared with 'model A'. However, there appears to be some sort of disparity when analysing the drift directions. The final and initial positions differ in the convergence trend that is generally accepted for India-Eurasia. The subcontinent appears to have moved towards northwest with respect to its initial position at C30n.y. This is in contrast with the results from 'model A' which shows a northeast convergence for the above-mentioned timespan. The drift values calculated from the initial and final positions reveal a 3.6° latitudinal, 3.2° longitudinal and 4.82° diagonal drifts respectively for the 'model B'. These values equate to displacements of 399.6 km, 355.2 km and 534.65 km respectively and are shown in Table 2 and figure 4.

Recent studies have attributed these high drift rates to multiple factors, most prominent being the convergence of India towards Eurasia owing to the multiple subduction zones present at the southern Eurasian margin (Aitchison et al 2000, Aitchison and Davis 2004, Baxter et al 2016, Bouilhol et al 2013, Gibbons et al 2015, Buckman et al 2018). The enormous slab pull experienced by the Indian plate towards north has been postulated by many to be the major driver of rapid movement of India. This could possibly be the case if the lithospheric plate experiencing slab pull was entirely oceanic in character and did not carry a significant continental landmass such as India (Pusok and Stegman 2020, Van Hinsbergen et al 2015, Zahirovic et al 2012). The negative buoyancy of the Indian subcontinent could possibly not have allowed such a high drift rate based merely on slab pull of the downgoing oceanic slab attached to the Indian plate (Forsyth and Uyeda 1975, Morgan and Parmentier 1984).

Slab pull or Ridge push?

Amongst the forces acting on the Indian plate during Late Cretaceous, slab pull appears to be the major driver; as the velocity of a drifting plate is directly proportional to the length of subduction zone attached to it. This is evident as there existed a long subduction zone all along the southern Eurasian margin. This more than ~10,000 km subduction zone would have acted as a major driver for the plate motion of India since its rifting from Madagascar (~85-90 Ma), only to be modified/interrupted by the Reunion plume (67-64 Ma). The western spreading centre being younger would be more vigorous and thereby have a dominant role in driving the Indian plate as compared to the eastern spreading centre during the Late Cretaceous. This coupled together with the push emanating from the southern spreading ridge and the slab pull from the north would have resulted in a northerly – northeasterly drift of the Indian subcontinent.

However, based on the analysis of the Declination data in 'model B', it appears that this dominant drift direction might have been affected severely or it altogether changed although for a short time interval. This implies that a plume head upon interaction with continental lithosphere can significantly affect the directions of plate movement, by overcoming the existing plate driving forces. This is confirmed by the lithospheric tilting recorded within the DVP (Sangode et al 2022), which depicts that the incipient plume push arising from the first interaction of a mantle plume with continental lithosphere can result in tilting of the continental block. Along with this tilting there appears to be an additional sideways component associated, more likely to result in the sideward drift/slip with velocities that surpass existing plate tectonic speed limits. Thus, the plume push force originating from the Reunion plume not only enhanced the drift velocity of the Indian plate with respect to Eurasia, but it could have also caused a previously unnoticed westward drift/slip for ~1.5 Ma with velocities as high as ~352 mm/yr $^{-1}$.

This is possible as the plume made its first contact along the North-western fringes of the Indian subcontinent thereby resulting in a northward tilting, where maximum part of the subcontinent was positioned. This was followed by a slip towards west along periphery of the plume, where the point of contact between the plume head and subcontinent acted as a pivot thereby rotating the continental block. After C30n.y the subcontinent moved beyond the sphere of direct influence of the plume, restoring the slab pull and ridge push forces resulting in north-eastward drift of India. The drift rates were however significantly enhanced with renewed push from the Reunion plume resulting in the rates that were higher than what they were before the Reunion encounter, but significantly lower than what it was during the event which lasted about 1.5 Ma.

Tomographic hunt for the lost root

Another possible explanation for this rapid drift could be attributed to the absence of a thick cratonic root beneath the Indian subcontinent (Kumar et al 2007, Dessai and Griffin 2021, Jaupart and Mareschal 1999). This can be expected in our case as Indian subcontinent has had 3 major encounters with mantle plumes within less than 70Ma (Dessai and Griffin 2021, Griffin et al 2009, Paul and Ghosh 2021). The multiple encounters could possibly have led to thermal erosion of the continental lithospheric root. The lithospheric roots act as anchors for the continents in the mantle, once removed or lost, it is difficult for the continents to retain the coefficient of friction with the asthenospheric or mantle drag (Stoddard and Abbot 1996). A buoyant continental mass deprived of its root can prove to be an excellent candidate for this continental “MotoGP”.

We present surface wave tomographic models along a traverse in the Indian ocean at co-ordinates (25°S, 55°E) and (15°N, 75°E). These models have been derived using Submachine an open-source seismic tomography software. S-wave models provide better resolution in the upper mantle, which explains the choice of our models. The results show a distinct cold-high velocity anomaly at the reunion latitudes in the upper mantle enclosed by lower velocity material highlighted by the dashed enclosures. The shape of this anomaly does not correspond to a subducted slab of oceanic lithosphere, nor there have been any reported subductions at those latitudes in the past 100 Ma. We say 100 Ma as the slab is yet lying in the upper mantle and has not ventured below 1000 km. The horizontal alignment also defies any chances of a subducted slab at such shallow depths in the mantle. Besides the direction of elongation corresponds to that of the movement of the Indian subcontinent. We therefore propose that this could possibly be the delaminated lithospheric root of the Indian subcontinent, which was removed by the Reunion plume resulting in reduced coupling between the Indian plate and the underlying asthenosphere. This loss of lithosphere effectively increased the efficiency of slab pull experienced by the Indian plate thereby resulting in enhanced velocities followed by the Deccan event.

Based on the above 4 models it appears that bottom of the anomaly lies at depths of 660 km to 710 km barring HMSL-S06 which gives a maximum depth of 535 km. Assuming sinking rates of 10 $mmyr^{-1}$ and 20 $mmyr^{-1}$, the models predict that the outlined anomaly subducted somewhere between 66-33 Ma (3D2016_09Sv), 68-34 Ma (GyPSuM-S), 53.5-26.725 Ma (HMSL-S06) and 71-35.5 Ma (SL2013sv). All of these age ranges except HMSL-S06 closely fit with timing of the Deccan event. Thus, it is highly unlikely, that the occurrence of a cold high-density anomaly exactly around Reunion latitudes with a geometry that does not resemble a subducted lithospheric slab and mantle sinking rates that when backtracked lead to a delamination age of 70-66 Ma, which is precisely the age for Deccan-Reunion event is a mere coincidence. This therefore strengthens the argument that the Indian plate cratonic root was completely removed during the Deccan event. This decoupling led to a decrease in the asthenospheric drag on the Indian plate, which combined with the slab pull and plume push forces resulted in tremendously high velocities.

Conclusions

Paleogeographic reconstruction positions India in close proximity to spreading centres at the western and southern margins before the plume interaction at ~70-65 Ma (Van Hinsbergen et al 2019, Rodriguez et al 2021, Cande and Stegman 2011, Parsons et al 2021). The Indian subcontinent formed less than ~50% (roughly about 35-40%) of the total area of the Indian plate, which was dominantly comprised of oceanic lithosphere. Zahirovic et al (2015), explained based on numerical models that plates with a significant portion of the plate boundary involved in subduction zone experienced higher drift velocities compared to plates with no active subducting margins. If the subducting plate happens to carry a continental block, the size of the block would in turn decide the velocity of the moving plate. From the paleo-reconstructions it is obvious that Indian plate had a massive subduction zone at its northern boundary (Hafkenschied et al 2004, Van der Meer et al 2018, Gibbons et al 2015) thereby placing an active propellant for the plate velocities.

Based on our calculations, we propose that the Indian subcontinent travelled at exceedingly high velocities which had never been recorded earlier directly. The Indian subcontinent experienced a brief pulse of hyper-spreading velocities when it encountered the Reunion plume-head (end of C30n to the end of C29n). The positive buoyancy created by the plume head and the negative buoyancy due to Deccan basalt loading, both appear to have encouraged the larger displacements besides tilting of the continental block by ~10^0. Once the plate moved away substantially from the plume head, lower velocities facilitated by lithospheric cooling are observed. The torques resulting from the multiple force vectors acting simultaneously are expressed by the clockwise/anticlockwise rotations and suitably derived from longitudinal and latitudinal drift components of the Indian plate during the same time. Thus, finally we report here one of the highest ever recorded plate velocities although for a short time span resulting from a combination of factors with changing intensities that modified plate movement including the directions precisely at 65$\pm$2 Ma.

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Table 1: Data table showing the results obtained after statistical treatment of paleomagnetic data.

	Chron 30n.y D I	C29r.y D I	C29n.y D I			
Central Tendency						
Window Mean after applying the Filter.	-366	-56	-193 (333.3 antipode)	-65	-377	-50
Scatter	-95: 2.5; k = 21.37, N:153	-95: 1.1, k = 36.05, N: 451	-95: 4.3, k:21.61, N: 54			
Anomaly with Vandamme *et al.* 1991	+4 (clockwise)	(shallow)	(anticlockwise)	+5 (deeper)	+0.8 (clockwise)	(shallow)
Anomaly with Réunion latitudes*		$+1^0$		$+10^0$		^{0}

Table 2. Calculated drift rates from the inclination data for Central tendency and filtered mean data respectively for GTS2020 and MQSD2020 timescales.

	Central Tendency (Latitudinal drift)	Filtered Mean (Latitudinal drift)	Central Tendency (Longitudinal drift)	Filtered Mean (Longitudinal drift)	Central Tendency (Diagonal drift)	Filtered Mean (Diagonal drift)
Distance covered in degrees	^{0}	^{0}	^{0}	^{0}	^{0}	^{0}
Distance covered in kilometres	km	km	km	km	km	km
Spreading rate (GTS 2020)	mm yr^{-1}	mm yr^{-1}	mm yr^{-1}	mm yr^{-1}	mm yr^{-1}	mm yr^{-1}
Spreading rate (MQSD20)	mm yr^{-1}	mm yr^{-1}	mm yr^{-1}	mm yr^{-1}	mm yr^{-1}	mm yr^{-1}

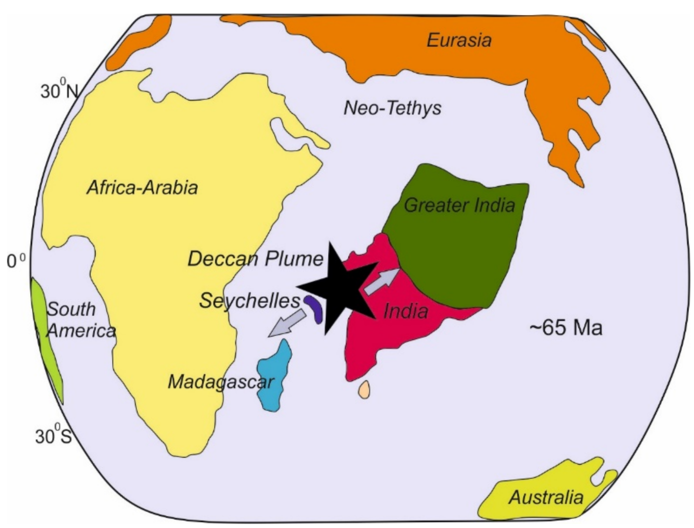


Fig 1. Position of the Indian subcontinent during the Deccan Trap Volcanism during 65 Ma (redrawn after Van Hinsbergen et al 2011).

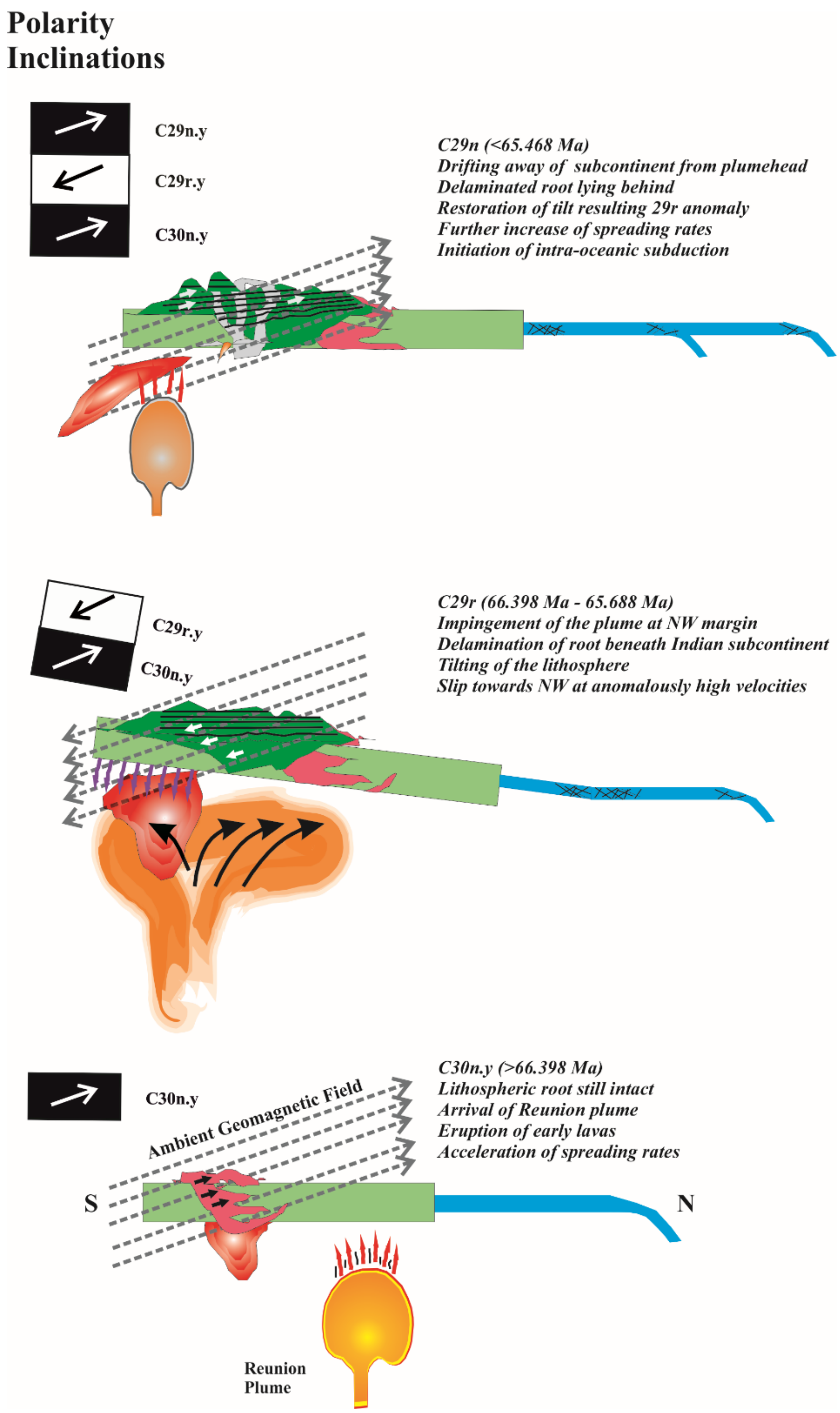


Fig 2. The mechanism of Deccan inclination anomaly modified after

Sangode et al 2022. At C30n the plume-head arrives beneath the Indian subcontinent resulting in minor alkaline intrusives. This is followed by the main phase of eruption at C29r which led to tilting of the Indian subcontinent towards north by ~10°, along with the delamination of the lithospheric root below the subcontinent. The root delamination led to an increase in buoyancy, further contributing to the anomalous drift rates and slip towards NW. At C30n during, the subcontinent moved away from the plume-head, restoring normal inclination values along the northeastwardly march of Indian subcontinent.

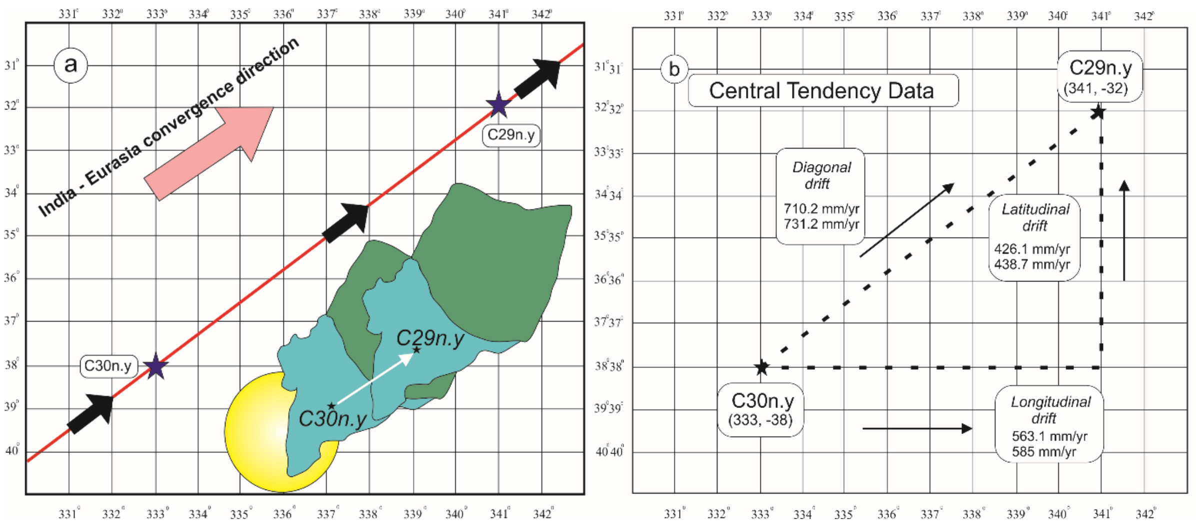


Fig 3. Model A: North-eastward drift of the Indian subcontinent can be observed along with the calculated drift rates based on inclination data. a)The blue stars indicate initial and final positions for the Indian subcontinent during the chrons C30n.y and C29n.y. The black arrows point the directions of drift calculated from the present study. The larger grey arrow indicates the established convergence direction of Indian subcontinent with respect to Eurasia, while the red line marks the trace of the drift direction as deduced from the paleomagnetic data. The yellow circle represents Reunion plume, blue portion indicates the present day extent of Indian subcontinent and the green portion indicates subducted continental part of Greater India. The small black stars represent the position of present day city of Nagpur in central India, which was used as a reference point to conduct the calculations. The small white arrow depicts the relative motion of the subcontinent at initial and final positions, showing the northeastward drift of India. b) The black stars mark the initial and final positions of the Indian subcontinent. Longitudial (563.1 and 585 mmyr^{-1}), latitudinal (426.1 and 438.7 mmyr^{-1}), and the diagonal

(710.2 and 731.2 mmyr^{-1}) drift rates have been calculated by extrapolating the vectors from initial and final positions along respective directions. Two different spreading rates result from using the dates for chrons C30n.y and C29n.y for MQSD20 and GTS 2020, where the above mentioned period spans 1.518 and 1.563 Ma respectively, resulting higher drift rates for MQSD20 and slightly lower rates for GTS2020.

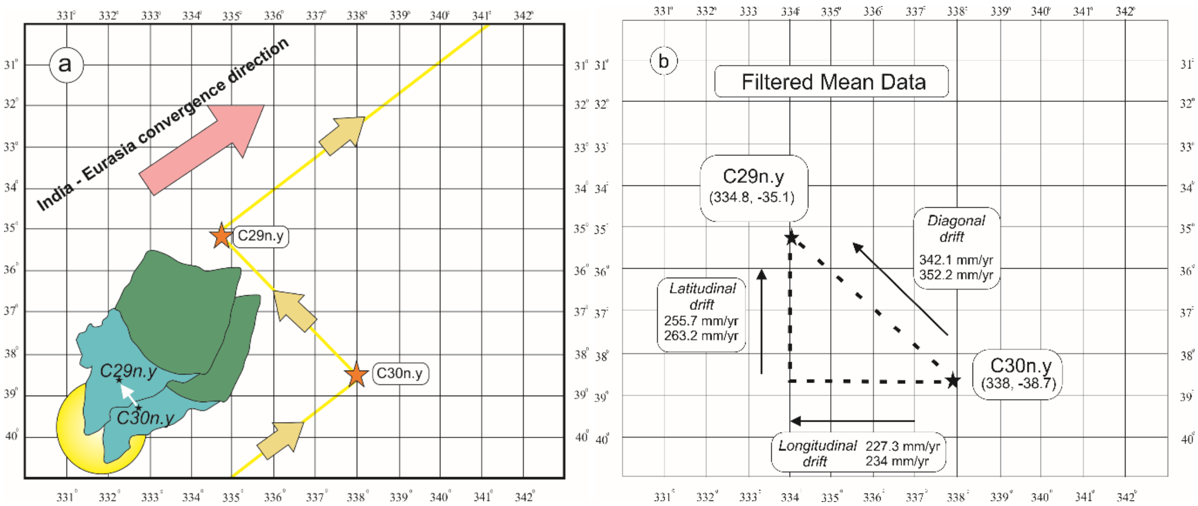


Fig 4. Model B: North-westward drift of the Indian subcontinent can be observed along with the calculated drift rates based on inclination data. *a)* The orange stars indicate initial and final positions for the Indian subcontinent during the chrons C30n.y and C29n.y. The smaller arrows point the direction of drift calculated from the present study. The larger grey arrow indicates the established convergence direction of Indian subcontinent with respect to Eurasia, while the yellow line marks the trace of the drift direction as deduced from the paleomagnetic data. The yellow circle represents the Reunion plume, blue portion indicates the present day extent of Indian subcontinent while the green portion indicates subducted continental Greater India. The small black stars represent the position of present day city of Nagpur in central India, which was used as a reference point to conduct the calculations. The small white arrow depicts the relative motion of the subcontinent at initial and final positions. It can obeserved clearly that the northeastward motion of India was interrupted when it encountered the Reunion plume at ~65Ma leading to a change of convergence direction at anomalously high velocities. The model thus predicts that the plume push emanating from the Reunion plume did overcome the slab pull and ridge push forces acting on the Indian plate during its encounter for a short period of time. This change in direction was corrected once the Indian subcon-

tinent moved away from the sphere of direct influence of the Reunion plume. *b)* The black stars mark the initial and final positions of the Indian subcontinent. Longitudial (227.3 and 234 mmyr^{-1}), latitudinal (255.7 and 263.2 mmyr^{-1}), and diagonal (342.1 and 352.2 mmyr^{-1}) drift rates have been calculated by extrapolating the vectors from initial and final positions along respective directions. Two different spreading rates result from using the dates for chrons C30n.y and C29n.y for MQSD20 and GTS 2020, where the above mentioned period spans 1.518 and 1.563 Ma respectively, resulting higher drift rates for MQSD20 and slightly lower rates for GTS2020.

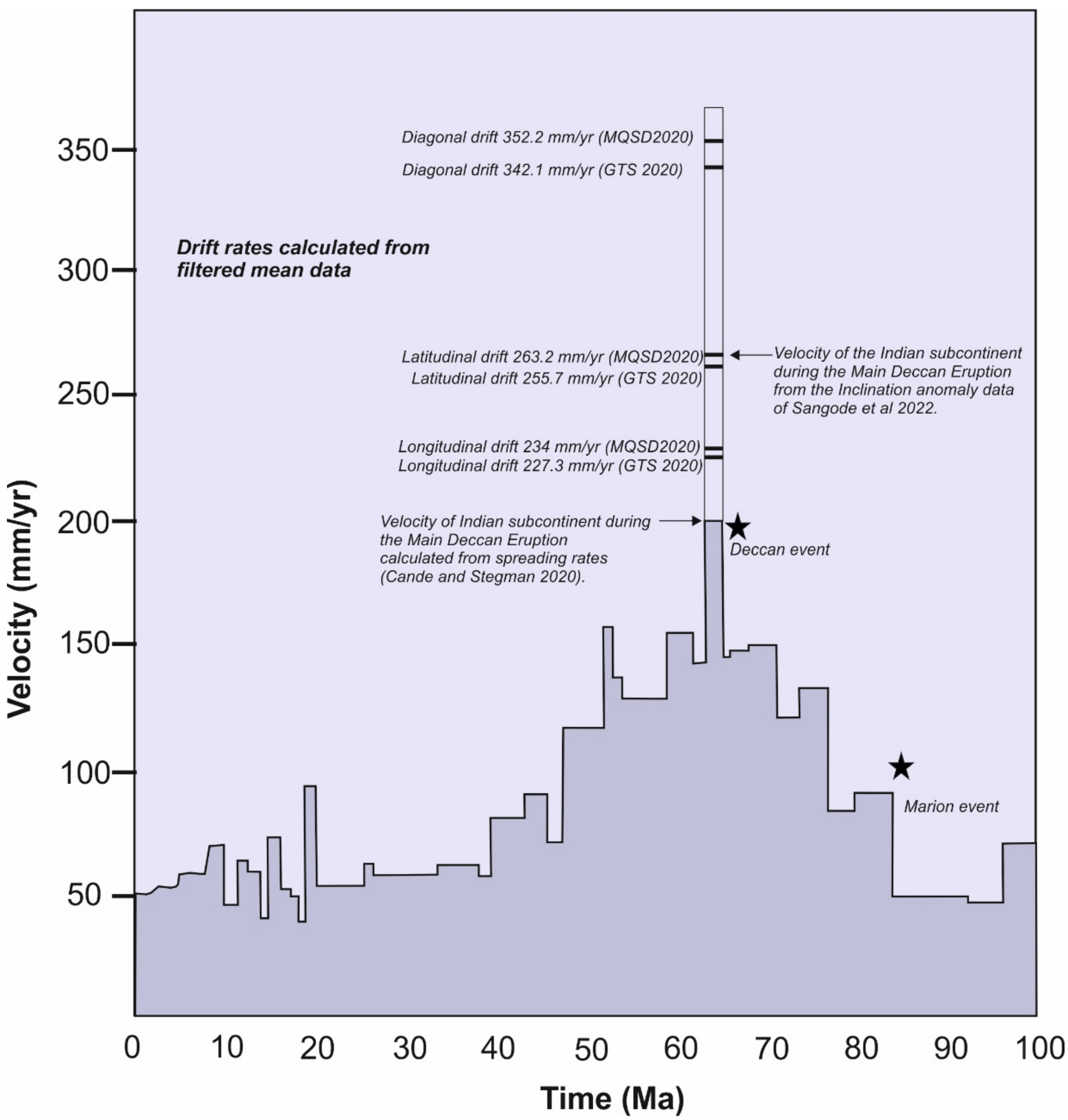


Fig 5. A plot showing spreading rates versus time of the Indian plate for the past 100 Ma, modified after White and Lister (2012). At the Deccan event, the new data has been plotted to depict the newly discovered drift rates from the filtered mean data for the Indian Subcontinent. The black stars mark mantle plume events. The drift rates for the Indian subcontinent peak at the Deccan event, following which there is a considerable decrease in drift rates. This has been attributed to the moving away of the subcontinent from the Reunion hotspot leading to increasing viscosity of the asthenosphere beneath the Indian subcontinent acting as an obstruction to the rapid drift.

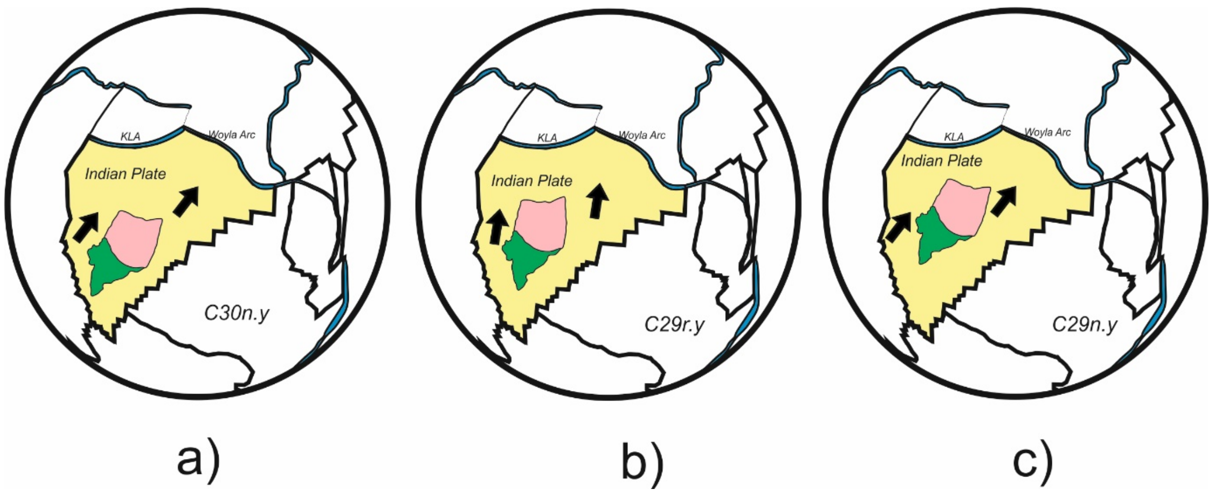
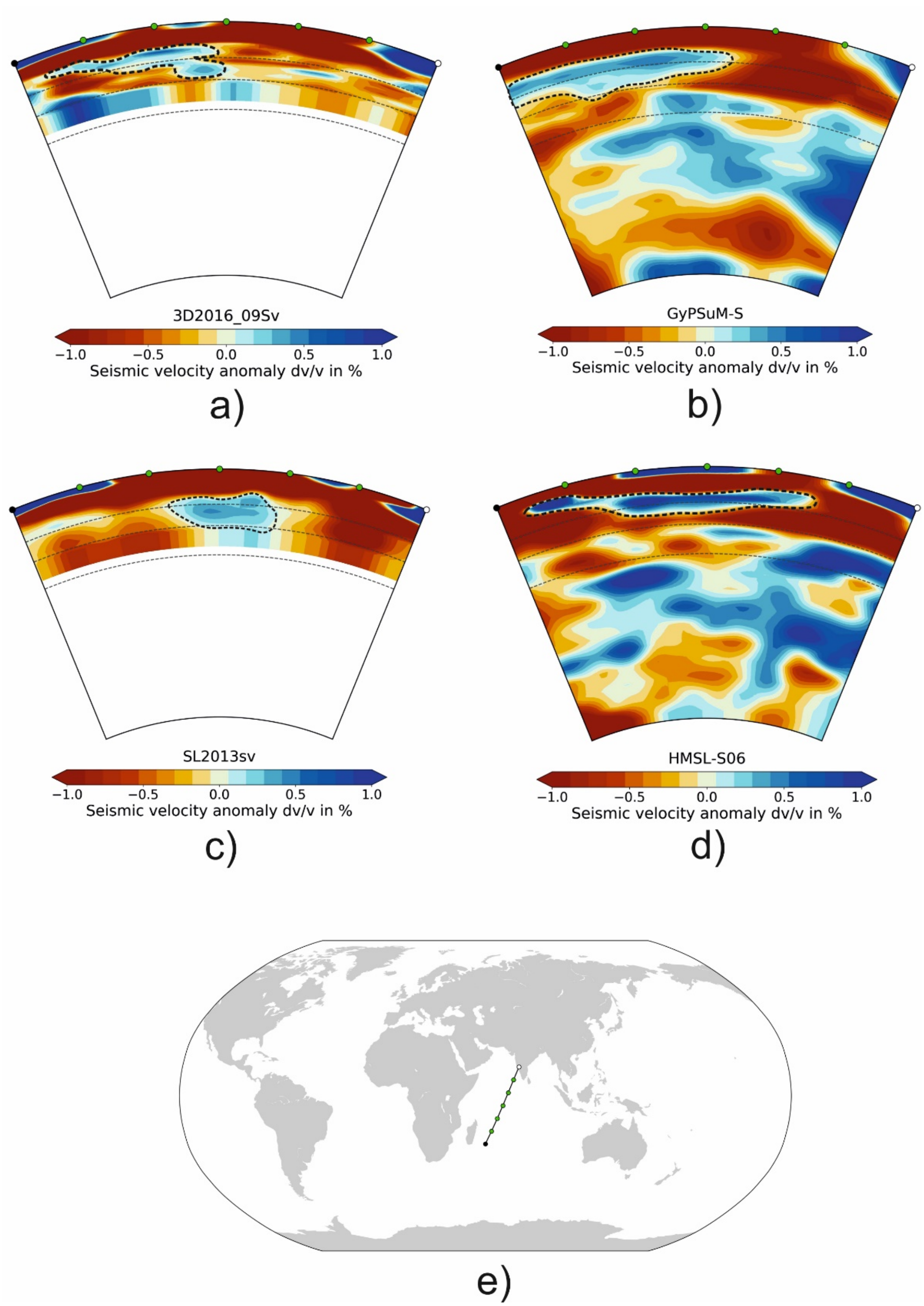


Fig 6. Arrangement of the plate boundaries for Indian plate at time of interaction with the Reunion plume (after Gibbons et al 2015). The convergence directions for C29r depicting a slight change for the Indian subcontinent which was restored substantially back to normal after the Deccan event.

Fig 7. A seismic tomographic cross section of the upper mantle from the model SL2013sv (Schaeffer and Lebedev, 2013) for the present-day Indian subcontinent along 80°E from 30°N to 0°, showing absence of any high-density material below the Indian subcontinent hinting towards the absence of a cratonic root, which if present would have impeded the plate velocities.



3D2016_09Sv
−1.0 −0.5 0.0 0.5 1.0
Seismic velocity anomaly dv/v in %
a)
GyPSuM-S
−1.0 −0.5 0.0 0.5 1.0
Seismic velocity anomaly dv/v in %
b)
SL2013sv
−1.0 −0.5 0.0 0.5 1.0
Seismic velocity anomaly dv/v in %
c)
HMSL-S06
−1.0 −0.5 0.0 0.5 1.0
Seismic velocity anomaly dv/v in %
d)
e)

Fig 8. Seismic tomographic s-wave profiles for the mantle. Cross sections from (25°S, 55°E) and (15°N, 75°E) based on (3D2016_09Sv), (GyPSuM-S), (HMSL-S06) and (SL2013sv), depicting the proposed lithospheric root/keel dislodged from the Indian subcontinent during the Deccan episode.