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Palaeomagnetic Inclination Anomaly in the Deccan traps and its geodynamic implications over the Indian Plate

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Abstract

Rapid northward drift of the Indian plate during Deccan volcanism assumes a gradual equatorward shallowing of the paleomagnetic inclinations amongst subsequently younger lava flows. Compilation of palaeomagnetic database and using 1062 statistically significant site mean directions from the Deccan Volcanic Province discovered an inclination anomaly of +10 degrees during the Deccan main phase eruptions (DE_M within Chron C29r at 66.398 Ma to 65.688 Ma). This anomaly represents northward tilt during C29r followed by its restoration by C29n (~65 Ma). This anomaly is explained here by the Indian lithospheric response to Réunion plume head during DE_M. A sequence of coincident geodynamic instances including: i) biostratigraphically constrained 'the brief inland seaway', ii) development of a regional southward dips for the lava flows, iii) major drop in sea level at the southern tip of Peninsula and iv) accelerated spreading and convergence rates during C29r to 29n transitions; substantiate the effect of lithospheric tilt and its restoration. We present a plume-lithospheric evolutionary model to explain the anomaly and its wider implications over the Indian lithospheric plate.

Keywords: Deccan traps; Palaeomagnetism; Indian plate; Réunion hotspot; Late Cretaceous

1 Introduction

Recent studies on mantle plume-lithosphere interactions have indicated that the spreading plume heads below lithosphere can develop significant asthenospheric flows to exert ‘plume-push’ force and act as potential drivers for accelerated plate motions and/or subduction initiation (e.g., Cande and Stegman 2011; van Hinsbergen *et al.* 2011; Pusok and Stegman 2020). The Deccan Large Igneous Province (LIP) is a product of such lithospheric interactions with Réunion hotspot during the northwardly drift of the Indian plate in the Late Cretaceous and early Paleogene (Courtillot *et al.* 1986; Basu *et al.* 1993). LIPs are characterized by short-lived (<1-5 Ma) igneous pulses responsible for large volume (>75%) magma outpourings (Bryan and Ernst 2007). Geochronological records indicate a peak in tholeiitic basalt eruptions of Deccan volcanism during 66.4-65.4 Ma (Sprain *et al.* 2019 and references therein), precisely within the geomagnetic Chron C29r. This peak is widely referred to as the Main Deccan eruption phase (denoted here as DE_M) representing the bulk Deccan volcanism (~80%, Renne *et al.* 2015; Schoene *et al.* 2015; Sprain *et al.* 2019) which is also evident from abundance of palaeomagnetic reversal records of C29r (e.g., Vandamme et al. 1991; Chenet et al., 2009).

Several aspects on Deccan volcanism largely dealt with stratigraphy, petrology, structures and morphology; and the geodynamic implications of Réunion mantle plume over Indian lithospheric plate is inadequately explored (e.g. Raval and Veeraswamy 2019). The rapid northward drift of the Indian plate, along with its rotation, during Deccan encounter, has been previously studied by many workers (Cande and Stegman 2011; van Hinsbergen et al 2011; Pusok and Stegman 2020) using various computational models. Extensive palaeomagnetic data has been produced from Deccan basalts since 50s representing the classical geomagnetic polarity sequence of C30n-29r-29n (e.g., Clegg *et al.* 1955; Wensink 1973; Vandamme *et al.* 1991; Chenet *et al.* 2008; 2009). In this study, we have examined the palaeomagnetic data by compilation of over 1600 significant site mean palaeomagnetic directions from over 76 published records from Deccan trap (Fig. 1 and Supplementary data file) for its possible geodynamic implication.

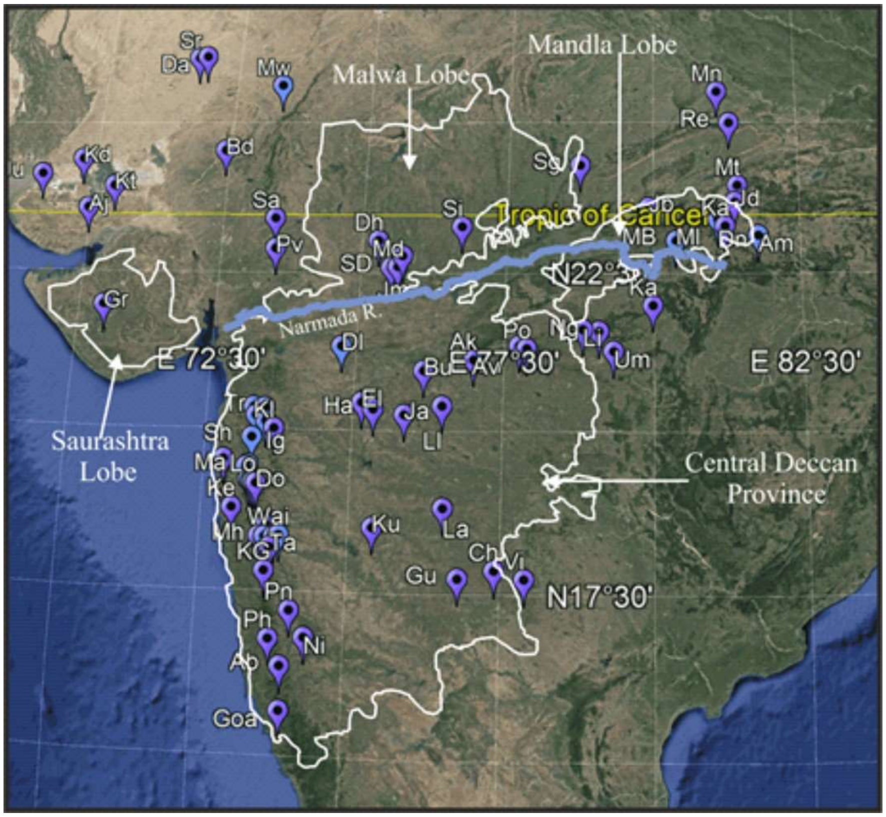

Figure 1: Map showing present-day extent of the Deccan traps into four distinct sub-provinces (Malwa, Mandla, Saurashtra and Central Province). The dots with abbreviations (expanded below) are the sites where paleomagnetic studies were undertaken by previous workers and taken into consideration for present analysis (details in SDF Table D6). The sub-provinces north of the Narmada/Tapi rifts (i.e., Malwa, Mandla and Saurashtra) dominantly exhibit the records of earliest eruptions belonging to Chron C30n as a result of northward drift of the Indian plate after its breakup from Gondwana. In the northern region of the central province, majority of the normal polarity flows overlay the reverse polarity, and rest of the occurrences with prominent reverse polarity (C29r) compile the tripartite subdivision of the Deccan traps into the C30n-C29r-C29n sequence. Stratigraphically thicker (/longer) records of C29r are most widely documented in the Central province. *Site Abbreviations*- Amboli (Ab) , Anjar (Aj), Akola (Ak), Ambenali (Al), Amarkantak (Am), Amravati (Av), Badargarh (Bd), Buldhana (Bu), Chincholi (Ch), Dandali (Da), Dhar (Dh), Dhule (Dl), Dindori (Dn), Dongargarh (Do), Ellora (El), Goa (Goa), Girnar (Gr), Gulbarga (Gu), Harsul (Ha), Igatpuri (Ig), Jalna (Ja), Jabalpur (Jb), Jodhpur (Jd), Jamdarwaza (Jm), Jumara (Ju), Karopani (Ka), Khairi (Ka), Kalodungar (Kd), Kelgar (Ke), Khumbharli Ghat (KG), Khandala (Kh), Kalsubai (Kl) , Khodala (Ko), Khopoli (Kp), Kanthkote (Kt), Kurduwadi (Ku), Latur (La), Linga (Li), Lonar lake (Ll), Lonavala (Lo), Matheran (Ma), Mandla Bridge (MB), Mandaleshwar (Md), Mahabaleshwar (Mh), Mandla (Ml), Manikpur (Mn), Mokhada (Mo), Mohtara (Mt), Mumbai (Mu), Mundwara (Mw), Neral (Ne), Nagpur (Ng), Nipani (Ni), Panchigani (Pa), Phonda (Ph), Panhala (Pn), Pohor (Po), Pavagadh (Pv), Rewa (Re), Rajahmundry (Rj)Sadara

(Sa), Sahastra Dhara (SD), Sagar (Sg), Shahapur (Sh), Singarchori(Si), Sarnu (Sr), Tapola (Ta), Trimbak (Tr), Umred (Um), Varandha Ghat (VG), Vikarabad (Vi), Wai (Wai).

Finally, a compilation based on 56 widely referred publications (See Supplementary data file) with details on analytical treatments and statistical operations was selected for the present analysis. After compilation, the data was classified into the geomagnetic Chrons: C30n, C29r and C29n for further processing. Details on methods, treatment, classification and filtering of the data is discussed below and given in Supplementary data file (SDF). As mentioned, the Chron 29r (66.398 Ma – 65.688 Ma) represents highest number of data points in agreement with the abundance as a result of bulk of lava eruption during D_{EM} (e.g. Vandamme *et al.* 1991; Chenet *et al.* 2008; 2009; Renne *et al.* 2015; Schoene *et al.* 2015; Sprain *et al.* 2019). This robust compilation observed an unambiguous inclination anomaly of more than 10º and clockwise/anticlockwise rotations of 2 to 5 degrees during C29r (see Tables 1 and 2). Aim of this work is therefore to report this inclination anomaly and explain its possible geodynamic implications over the Indian plate.

2 Methodology

The work was initiated by preparation of database by complete documentation of the palaeomagnetic data published since 1955. Over 76 publications including thesis presenting the palaeomagnetic studies from Deccan traps (and dykes) till date were reviewed and the data base presented in excel file format for the processing. The vast majority of these publications unambiguously reported the palaeomagnetic directions (Declinations and Inclinations or D/I) in agreement with the N-R-N sequence of the C30n-29r-29n geomagnetic polarity time scale. The data was independently produced by various teams during over last 65 years, and majority of the analysis performed in reputed national/international laboratories with standard instrumental setups (information given in SDF). We elaborate below the criteria and methods adopted to compile and treat this data with a discussion on the sources of error justifying the anomaly.

The high ferrimagnetic concentration within Deccan basalt mineralogy offers distinct demagnetization spectra measurable with moderate magnetometer sensitivity, and helps easy discrimination of Characteristic remanence (ChRM) components considered as primary remanence.

Majority of the published papers presented the demagnetization data (using thermal and/or alternating fields methods), identification of ChRM directions and the site mean calculations using routine statistical methods with spherical distribution (e.g., Fisher 1967, 1987). The parameters of statistical significance (e.g., alpha-95, precision parameter and maximum angular deviations) describe the scatter, facilitating filtering of the data for higher reliability and quality (McElhinny 1964; Fisher 1967, 1987; Tarling 1983). In majority of cases, the reverse polarity is unambiguously assigned to C29r, the reversal followed by normal to C29r-29n, and the normal followed by reversal to 30n-29r polarity chrons. The data was supported by field stratigraphic knowledge, chemostratigraphy and the isotope geochronology wherever available, by these authors (list of references given in SDF).

For present analysis, we complied only the declination/inclination (D/I) values from the published data, facilitating the site mean data points (See SDF). This is because, the NRM intensities can show large variation due to the style of presentation, various laboratory standards and instrumental sensitivities from individual attempts (discussed in SDF). The palaeomagnetic analysis involve various protocols of demagnetization adopted by different workers and instrumental sensitivities (Collinson, 1983; Tarling 1983; Butler 1992; McElhinny et al 2000; Tauxe 2010; Dunlop and Ozdemir 1997). Therefore, the standardization and comparison of NRM intensities across different attempts is not feasible. However, since our inferences are founded entirely on the D/I data, the NRM intensities are therefore neglected.

2.1 *Sources of Error*

The data were retrieved and rechecked several times avoiding typographic errors. Further below, we discuss the sources of errors based on which the filtering strategy was adopted.

1) Manual error: The first and foremost source of error is generally developed during the collection of oriented samples in the field. The oriented samples are collected manually (oriented hand samples) or by gasoline-driven portable rock coring machines (manually handled). The samples are marked carefully using either the compass north or by the sun compass. This has a greater chance of introducing manual errors at various stages from marking in the field till creating the standard cylindrical specimens in laboratory. Manual errors can also be introduced during laboratory handling of the specimens for analysis, as for most of the spinner magnetometers, the specimens are to be handled over six directions of measurement strategy. There is no clue to define the manual error, although it may be reflected in the final data as scatter and can be refined by the statistical distribution or calculation of means from large number of specimens. We find majority of the data is not tilt corrected, since the tilt is regional and non-measurable at outcrop level unless mapped (e.g., See Chenet et al 2009 p. 5 mention). This has encouraged to record the physical tilt of the palaeomagnetic data as discovered in this work.

2) Laboratory standards: The palaeomagnetic data in Deccan traps are produced from various laboratories that are commonly equipped with spinner magnetometers. High NRM intensities amongst Deccan trap basalts often permit pronounced demagnetization paths, even with low sensitivity magnetometers (e.g., Minispin from Molspin UK, Sensitivity: 0.05 mA/m). The other commonly used spinner magnetometers with better sensitivities are DSM-Schonstedt (~10e-4 A/m) and JR- 4 to 6 versions of AGICO Czech (~2.4 x µA/m). Both of these later versions provided better details of demagnetization trajectories over a large number of palaeomagnetic specimen. Whereas, the quality of older data which was meticulously produced from other instruments such as Astatic magnetometers, is also ascertained by excellent repeatability over stronger intensities of the Deccan basalt samples. Recently, the fully automated magnetometers AGICO (JR 6A) prevented manual errors from sample positioning; and the standardized data interface software with statistical and plotting provisions allowed rapid, error-free data processing. The cryogenic magnetometer (e.g., 2G) gives the finest sensitivity in paleomagnetic analysis; however, the strong remanence in Deccan basalt does not compel such analysis unless the studies like paleointensity and secular variation are intended.

The detailed palaeomagnetic analysis involve demagnetization of a large array of specimens to produce statistically significant data by the removal of noisy results (Collinson 1965; Butler 1992; Tarling 1983; Tauxe 2010). The two most commonly used methods of demagnetization are thermal and alternating field (af) demagnetizations. While thermal demagnetization can introduce laboratory-induced errors during heating and cooling, alternating field (af) demagnetization is the most commonly used in Deccan traps due to majority of soft ferrimagnetic- primary and secondary components (Vandamme et al., 1991). Individual workers have used different protocols of demagnetization strategy, and the demagnetizers themselves can introduce spurious fields during analyses, producing deviations rather than direct errors. Furthermore, the skills and experience of individual workers during interpretation varies, which may lead to some manual bias error component.

3) Geomagnetic variability and transitional fields: Some authors have indicated secular variation or the non-dipole fields as the source of error in paleomagnetic directions acquired by few samples. However, such samples showing spurious directions are most likely to be rejected, as the palaeomagnetic directions for Deccan traps are very well known and constrained. Similar is the case for the transitional polarity instances that are developed during normal to reversal or vice versa producing intermediate and mixed polarities. These directions are also likely to be rejected by individual authors, and if they are present in the data, the filtering criteria used in this paper has taken care for removal of such intermediate and noisy directions.

4) Geotectonics: The shield type geometry of Deccan province in general refutes any major intra-shield tectonics to significantly affect the palaeomagnetic directions. No major internal rotations and deformation have so far been reported within palaeomagnetic data from the Deccan province. Chron C29r is the main focus of this study, and majority of the palaeomagnetic data for this chron belong to the main/central Deccan province, which does not show such intra-shield tectonic deformations to significantly influence the palaeomagnetic data. Nevertheless, if such incoherence is present, it will be reflected by the internal deviations of D/I values, and our filtering criteria (discussed below) has taken care.

2.2 *Data Reduction (rejection) and Filtering*

The Deccan traps represent one of the richest databases over a short geological time interval of less than 5 Ma, and is marked by the distinct polarity sequence of N-R-N for the Late Cretaceous/Paleogene. The ample data thus produced from the Deccan traps, from various laboratories therefore is in close agreement. Previously, Vandamme *et al.* (1991) produced Deccan Super pole based on the compilation of the available data. With the updated database (till 2020), we further recalculated the Deccan Super pole, which is in close agreement with Vandamme *et al*. (1991) (see Table 1) depicting a central tendency. Therefore, a simple filtering and reduction criteria was used based on the qualitative parameters (Alpha-95, k and MAD) derived from the routine statistical methods in palaeomagnetism (Tauxe 2010). The deviation of values seen in this table (Table 1) is mainly due to enrichment from new data points added during the latter 30 years (1062 points in this study against the 163 points of Vandamme et al., 1991). Therefore, considering these Super pole directions as central tendency, we further defined the limits/windows for filtering of the data in this work given in Table 2. The data was classified into the chrons C30n, C29r and C29n and then the central tendency (Table 1) was used to filter the data by a declination window of +/-36^0 (i.e., 10% of 360^0) and inclination window of +/-18^0 (i.e., 10% of 180^0) and is presented in Table 2.

Table 1: An account of the mean paleomagnetic data recalculated from the database presented in Supplemental data file (SDF).

	Total data points	**Mean D/I**	**Super-pole**	**Mean Inclination Data**		
				C30n	**C29r**	**C29n**
Vandamme *et al*. (1991)	163	154/43 (antipode: 334/-43)	281˚E 37˚N	D/I ----	D/I 154/44	D/I 333/-48
This Study	1062	152/56 (antipode: 332/-56)	284˚E 27˚N	333/-38	157/47	341/-32

Table 2: Considering the means for whole data in 5^{th} to 6^{th} columns of Table 1 as the central tendency for the updated database (SDF), we further applied filters to remove the noise in mean data due to the possible errors described in the text. The data for C30n, C29r and C29n are filtered individually in a declination window of +/- 36 (10% of 360) and inclination window of +/-18 (10% of 180).

	Chron 30n		**C29r**		**C29n**	
	D	**I**	**D**	**I**	**D**	**I**
Central Tendency	333	-38	157	47	341	-32
Window	297-366	20-56	121-193	29-65	305-377	14-50
Mean after applying the Filter.	338	-38.7	153.3 (333.3 antipode)	47.4	334.8	-35.1
Scatter	α-95: 2.5; k = 21.37, N:153		α -95: 1.1, k = 36.05, N: 451		α -95: 4.3, k:21.61, N: 54	
Anomaly with Vandamme *et al.* 1991	+4 (clockwise)	-5 (shallow)	-0.7 (anti-clockwise)	+5 (deeper)	+0.8 (clockwise)	-8 (shallow)
Anomaly with Réunion latitudes*		$+1^0$		$+10^0$		-2^0

Note: α-95: 'size of the cone in degrees within which the true palaeomagnetic direction is expected to lie with 95% confidence'; k: 'measure of the concentration of the distribution about the true mean direction', N: number of samples/sites/stratigraphic time horizon. *: Considering the Reunion latitude of 21^0, the inclination of $\sim 37.5^0$ can be derived using Geocentric axial dipole model reference frame of Torsvik et al (2012), calculated using IAPD 2014 Software.

3 The Inclination Anomaly and Rotation

It can be noted from the table 2, that the observed mean inclination for C29r is significantly higher than the anticipated paleolatitude derivative of 37º at Reunion latitudes. This inclination anomaly of the order of 10^0 is further attested by various approaches given in Table 3.

Table 3: The Inclination Anomaly for C29r with respect to 30n and 29n, using various approaches described in text and table 2. The mean of central tendency after filtering for C29r is taken as 47^0.

Reference	**Inclination in degrees**	**C29r Anomaly Amount in Degree**
w.r.t. Expected latitudes using *Tan I = 2 Tanλ (λ = 20.5 to 21.5 for Reunion)*	~36 to 38	11 to 9
w.r.t. C30n from Table 1	38	9
w.r.t. C29n from Table 1	32	15
w.r.t. C30n Filtered Mean (Table 2)	38.7	8.7
w.r.t. C29n Filtered Mean (Table 2)	35.1	12.3
w.r.t. Reunion latitude mean	37	10.4
Average anomaly from various approaches		$10.78^0 \sim +11^0$ or $+10^0$

Finally, we consider this inclination anomaly of '+11º' or broadly '+10º' as mathematical expression for significant northerly/northeasterly dip achieved by the Indian plate during C29r. Further its restoration is evident from the negligible anomaly near the expected inclination for the chron C29n. The C29r anomaly is therefore much oversighted in the context of equatorward drift of the Indian plate, which anticipated either inclination shallowing or the inclination values intermediate between C30n and C29n within the Deccan sequence. Moreover, no evidence for such large magnitude changes during the Late Cretaceous geodynamo exists (Coe *et al.* 2000; Pechersky *et al.* 2010; Velasco-Villareal *et al.* 2011), and therefore refutes such anomalous geodynamo behaviour related explanations. In contrast, coincident geological evidences from the Indian subcontinent endorse the anomaly by possible effect of plate tilting (described later).

Similar to inclination anomaly, the declination data finds anomalies (See Table 4) depicting 5º clockwise rotation during C29r with respect to C30n and 2º anticlockwise rotation in C29n with respect to C29r. Based on this palaeomagnetic information, we present a cartoon model (fig. 2) to depict the geodynamic interaction of the Indian lithospheric plate with Réunion plume head, and in order to explain the evidences of anomaly in the text.

Table 4: Rotational anomaly (+: clockwise, -: anticlockwise) derived from the central tendency and filtered data (depicted in tables 1-3).

Chron	**Filtered Mean**	**Wrt Reference North**	**Inferred Indian plate rotation**
C29n	334.8	-25.2	2 degree anticlockwise w.r.t. 29r
C29r	333.3	-26.7	5 degree clockwise w.r.t. 30n
C30n	338	-22	
During 80 to 60 Ma		-12	

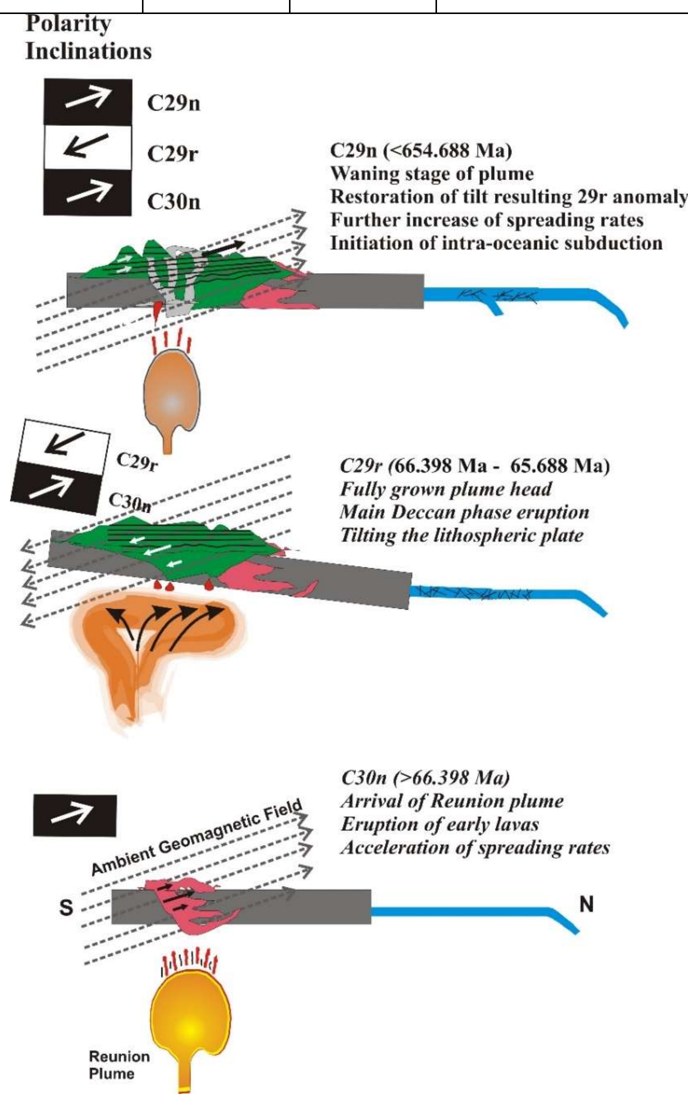

Figure 2. Cartoon model showing Reunion plume head-lithospheric interaction for Indian plate during Deccan eruption. The model depicts geodynamic mechanism to impart the inclination anomaly

as described in text. During C30n, the subcontinent approached the impinging mantle plume, and is recorded by alkaline magmatism in the northern Deccan province. The plate interaction with fully developed plume head during C29r resulted in north/northeast tilt. As the plate moved farther from the waning plume, the tilt was restored, and reverse inclination steepened, producing the inclination anomaly of C29r.

4 Geodynamic Implications

Considering the tilt and rotation estimates based on palaeomagnetic data (Tables 1 to 4 and SDF); the cartoon model (Fig. 2) explains the possible geodynamic mechanism with implications to Reunion plume-lithospheric interactions. This follows the coincident geological evidences from the published records discussed below.

Very high inclinations (D/I=140/60º) during C29r were reported from the Deccan traps in southern latitudes of Deccan province (Mishra *et al.* 1989). Although the data is inadequate and the precise chronology not available; it suggests an existence of southern/ plate wide extent of the tilt. The pre-Deccan, Late Cretaceous strata from Cauvery Basin in the southern Peninsula record a shallower inclination (338/-38, N=80) (Venkateswarulu 2020), further substantiate existence of Deccan anomaly relative to the pre- Deccan strata. Whereas, the inclinations for C29n and C30n agrees well with the anticipated paleolatitudes (Table 3), which indicates that the tilt was absent in C30n and restored during C29n as the Indian plate drifted away from the Réunion plume head (e.g., see Fig. 2). The regional southward dip for the Deccan lava flows (Fig. 3c and d) is widely documented (Jay and Widdowson 2008; Shoene *et al.* 2015) that verify the proposed model (Fig. 2) based on the palaeomagnetic information.

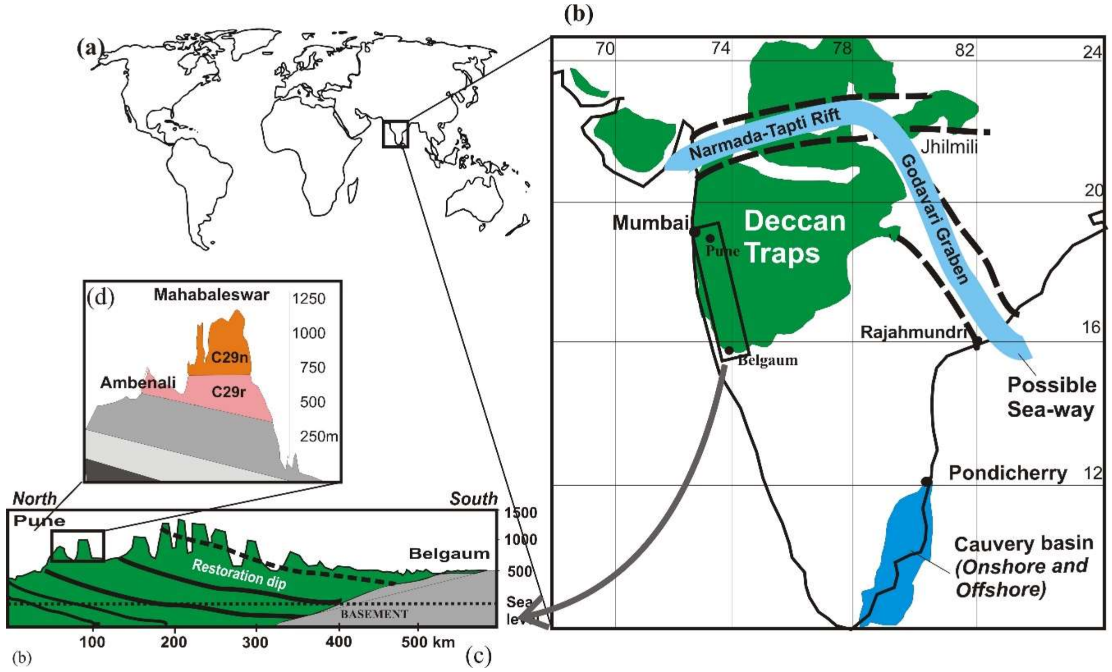

Figure 3. (a) World map showing the location of Deccan Province, (b) Part of Indian plate marking the present extent of Deccan trap province and the possible seaway as reported from biostratigraphic records discussed in text. The broad location of Cauvery Basin is shown which documented significant drop in sea level during the Late Cretaceous. The widely reported Pune to Belgaum (N-S) profile (c) depict a regional southward dip, explained here as a result of tilt restoration (discussed in text). Inset (d) shows the dip discordance between C29r (Ambenali Formation) and C29n (Mahabaleswar Formation) marked by Schoene *et al.* (2021), as evidence of tilt and its restoration.

4.1 *Magmatic records of plume head arrival and the Plate tilt*

There is close temporal and spatial linkage between voluminous LIPs, their tholeiitic and alkaline magmatism and mantle plumes (e.g., Bryan and Ernst 2007). LIPs are typically characterized by large volume (>75%) magma outpourings within very short time interval (<1-5 Ma, Bryan and Ernst 2007). The relatively rapid drift of the Indian plate did not permit its longer exposure to the Reunion plume. Whereas the highly effusive and voluminous outpouring of magma suggest a buoyant lithospheric interaction, and hence a significant geodynamic response of the Indian plate during Deccan volcanism is anticipated.

Alkaline rocks associated with LIPs are typically formed due to low degree of partial melting owing to minor thermal effects from an impinging or receding mantle plume (e.g., Gibson *et al.* 2006).

The impact of Réunion plume over Indian plate is in close agreement with this convention through the observed episodes of tholeiitic and alkaline magmatism. The initial impact of the Réunion plume head started ~0.2 million years before the DE_M and produced nepheline syenites and alkali gabbros during these early Deccan eruptions (Fig. 3). This corresponds to terminal C30n and early C29r stage. Recent high-precision geochronological data (Renne *et al.* 2015; Sprain *et al.* 2019) indicated outpouring of bulk Deccan tholeiites between 65.4 and 66.4 Ma within C29r. This rapid extrusion requires higher amounts of partial melting under a considerably elevated geothermal gradient during a fully developed plume head, which precisely coincides with the duration of C29r (Cande and Kent 1995). Small-volume, volatile-rich magmatism of lamprophyres and carbonatites between 65.8-65.2 Ma (Fig. 3), which were mostly emplaced towards the terminal part of the $DE_{M,}$ typically intruded the Deccan lavas. This terminal phase is an artifact of small-fraction melting caused by thermal weakening during the waning stage of the Réunion plume. The occurrence of DE_M precisely within C29r therefore elucidates the short span of geodynamic interaction of the plume head with the Indian plate. The rapid impact of plume head below the western margin of the Indian plate therefore appears to have resulted in a major geodynamic activity as recorded by the tilt and rotation in the paleomagnetic data inferred here.

Further, the lithospheric tilt and its restoration had been physically recorded by the flows showing a southerly tilt. Apart from other widely reported field evidences for the regional dip (e.g., Jay and Widdowson 2008), recently Schoene *et al.* (2021) reported discordance between C29n and 29r flows (reproduced in Fig. 3d) that indicate the restoration of tilt during C29n. It is also likely that the restoration may not be complete and the residual tilt is reflected in the southeasterly flows of the major Peninsular rivers (except Narmada which flows in rift). The questions remain unsolved in this context of the relative adjustments of Malwa plateau with Central Deccan province separated by the Narmada rift. So detailed investigations are also necessary to estimate a possible component of sea level rise in the southern stratigraphy during tilt restoration. Investigations are also needed to find the relationships amongst post- buoyant subsidence, rotation and relative sea level changes.

4.2 *Accelerated convergence at the end of C29r*

Sea floor spreading anomalies document accelerated spreading rates in the Indian Ocean reaching a maximum between ~66 and 63 Ma during C29n (Cande and Stegman 2011; compiled and redrawn in Fig. 4). The initial anomalously high rates of drift of the Indian plate from less than 100 mm/y to ~160 mm/y during 68 to ~66 Ma were explained by the arrival of the plume head (Eagles and Hoang 2014). However, the later increase in the drift (up to 180 mm/y after ~66 Ma) during the waning and withdrawal stages of the plume/plume head remains little explored. We suggest the later increase due to convergence as a result of a combination of different factors including *i)* the termination of resistance from plume-induced rotational and tilt components to the northward drifting kinematics, *ii)* the establishment of double subduction (explained below) in front of Indian plate easing out the northward drift of the Indo-Australian plate. This demands a detailed estimates using kinematic modeling to elaborate the above contentions arising out of the Deccan tilt, and is beyond the scope of the present work.

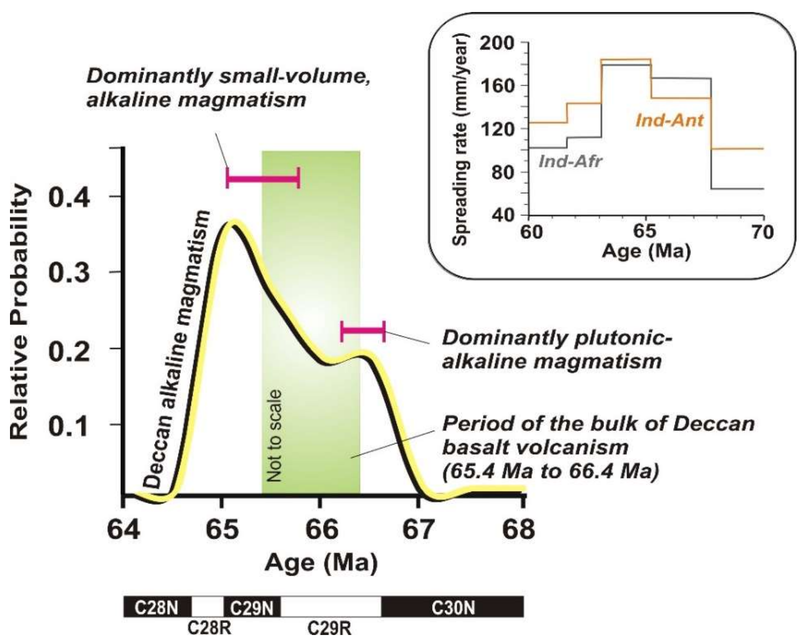

Figure 4. Relative probability of alkaline and small-volume, volatile rich magmatism spatially and temporally related to the Deccan LIP based on high-precision $^{40}Ar/^{39}Ar$ and U-Pb determinations (n=12) (adopted from Dongre, *et al.* 2021). The period of bulk Deccan basalt volcanism is also shown in green

(from Sprain *et al.*, 2019). *Inset*: Spreading rates between India-Antarctica and India-Africa ridges (After Cande and Stegman, 2011).

4.3 *Acceleration of the intra-oceanic subduction*

Mantle plumes have been considered as drivers of regional subduction initiation (Gerya *et al.* 2015; Pusok and Stegman 2020; van Hinsbergen *et al.* 2021, Rodriguez *et al.* 2021). Multiple and the double subductions are evident for the India-Asia convergence (See Hafkenscheid *et al* 2006; Bouilhol *et al* 2013; Replumaz *et al* 2014; Jagoutz *et al* 2015 and 2019;; Searle 2019; Rodriguez *et al* 2021). The final subduction around ~66 Ma to 65 Ma is little explored in the context of Deccan volcanism and the Réunion plume push force. We infer that the quick geodynamic response of the Indian plate to Réunion plume head during DE_M marked by the tilt and counter (clockwise/anticlockwise) rotations during C29r might have exerted significant changes in the pre-existing plate kinematics at the India-Asia subduction interface. The possible resultant deformation due to plate tilt and rotation added to the rapid changes in rates of convergence may have significant repercussions on the colder/brittle/thinner ocean floor in front of the northern Indian continental margin to deform leading to an intra-oceanic subduction (Fig. 2). In absence of any detailed study, therefore we postulate that the Réunion plume lithospheric interaction was significant enough to accelerate the convergence during late subduction.

4.4 *Brief Opening of inland 'Sea-way'*

Based on paleontological finds, a short-lived 'seaway' associated with Deccan traps precisely at the end of C29r has been widely reported (e.g. Keller *et al.* 2009, 2012 and references therein). This inland 'sea-way' formation (/marine influence) along pre-existing rift valleys (i.e. Narmada and Godavari Rifts, shown in Fig. 3) is evident by the stressed marine fauna. The brief north/northeastward tilting of the Indian plate therefore offers a possibility to explain the formation of the brief inland 'sea-way'.

Biostratigraphically, the well-documented localities ~800-1000 km inland of the Narmada and Godavari rifts contain brief and stressed planktic foraminiferal assemblages within terrestrial palustrine to freshwater facies (Keller *et al.* 2009, 2012). The absence of benthic species among these localities (Keller *et al.* 2012) indicates only a brief marine incursion; which can be explained due to the coincident lithospheric tilt and submergence of the rift valley. The contemporary low base levels of Godavari and

Narmada rifts would have facilitated the dramatic relative sea level change in response to the tilt for the reported marine incursions. The paleosols developed immediately over this zone of marine excursion (Keller *et al.* 2012) designate upland conditions by withdrawal of sea and further support the restoration of tilt during C29n (depicted in Fig. 2).

The late Maastrichtian rocks of Cauvery basin at the southern tip of Peninsular India represent fluvial formations overlain by marine to estuarine formations and record a vertical sea level fall of 80 m (Raju *et al.* 1994; Nagendra and Reddy 2017). Thus, upliftment of the southern peninsular tip of the Indian plate is documented and marked by a rapid sea level fall during the deposition of Kallamedu Formation (Late Maastrichtian) in the Cauvery Basin. The 80m fall in sea level reported by Raju et al (2005) is therefore coincident and can be postulated as a result of northward tilt of the Indian plate as it moved over, passing the Reunion plume head to cause northern/NE dip uplifting the southernmost part of the plate. Briefly the plume appears to have buoyantly uplifted this southern part of the Indian plate, while the northern and northeastern part dipped. The contemporaneous upliftment of the southern end of the Indian plate along with downward tilt in northern and northeastern Deccan provinces can therefore be related to the geodynamic causes coincident with the Reunion plume lithospheric interactions discussed above. We finally summarize this sequence of events in table 5 with a note for more detailed studies to test several hypothesis arising out of the explanations of coincident geological instances during/after the tilt reported here. On the other hand, more supporting and conflicting geological signatures are to be gathered to further discuss the anomaly and its implications.

Table 5: A summary of sequence of events presented in this paper.

Time	**Stage**	**Event**
C30n	Plume early stage	Indian plate encountered the Réunion hotspot
Late 30n to Early 29r	Emerging plume-lithosphere interaction	Indian plate encountered the plume over western continental margin and rotated possibly by thermal expansion (and uplift) of the lithosphere in the plume region. Eruption of early lavas and alkaline rocks. Acceleration of spreading rates.
Early to Late 29r	Fully developed plume head	Maximum exposure of the plate to plume, eruption of bulk of Deccan basalts, possible upliftment of the southern Peninsular part of the Indian plate along with tilting in the N/NE part of

		the plate, biostratigraphic evidences of 80m drop in sea level in south and opening of the seaway in N/NE periphery of Deccan. Quick clockwise-anticlockwise rotations along with northward tilt appears to have developed a weak (/fracture) zone possibly leading to the latest subduction in the India-Eurasia zone.
29n		Waning stage of the plume, restoration of tilt, regional south dip of Deccan, closure of seaway, onset of secondary subduction

Conclusion

We report a palaeomagnetic inclination anomaly of the order of 10 degrees during the Chron C29r (66.398 Ma – 65.688 Ma) depicting lithospheric tilt for Indian plate and its restoration during C29n (immediately after ~65.7 Ma). At regional scale geological evidences presented here suggest this anomaly as an artifact of the Indian lithospheric response to Reunion plume during the main phase of Deccan eruption. The widespread geological incidences during the N/NE tilting of the Indian plate, during Late C29r Chron includes: i) short. inland, marine incursion in the northern Deccan province in contrast to the sea level fall in the Southern Peninsula, ii) the regional southward dip of C29r lava flows and iii) the initiation of double subduction at the northern margin of Indian plate. The geodynamic interaction of the Reunion hotspot with Indian lithospheric plate deduced from the long term palaeomagnetic database from Deccan basalts further demands detailed kinematic modelling to establish a relationship amongst the plume push force, Deccan volcanism, Indian ocean spreading and the late Himalayan subduction.

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Authors Statement

SJS, AB and AND conceptualized and planned the study. AB compiled the data, and with SJS curated the data by processing, corrections and presentation. AND, SJS, AB developed the model and DCM added discussions and guidance. All the authors involved in inputs including concepts, writing, discussion, ideas, interpretations, revisions and the presentation of diagrams and tables.

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