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Intracratonic stability: A comparison of paleomagnetic data from the north and the south of Dharwar Craton, India

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ABSTRACT

The prominent bend of Dharwar craton, India was recently suggested to post-date the ‘stabilization’ phase of the craton via a ~30°, anticlockwise, vertical-axis intracratonic rotation. The *prima facie* evidence for this rotation was the realignment of dyke trends following correction of the inferred deformation. The proposal also appeared to be consistent with the observed structural grain in the host Archean basement. We argue that using the trend of dyke swarms is not the ideal method to assess intracratonic rotation and instead we use variations in paleomagnetically determined declination data from these dykes. We find that multiple early Paleoproterozoic dyke swarms (the 2367, 2216, and 2082 Ma generations) preserve a systematic offset with a large uncertainty. The mean paleomagnetically permissible anticlockwise rotation is 19° ± 17°. Dykes emplaced during the ~1888 Ma LIP do not show the same offset, which suggests that rotation occurred prior to this time. Therefore, the 2082-1888 Ma interval brackets the window for any deformation and tectonism required to bend the Dharwar craton by about ~20°. No large-scale deformational events are documented in the Dharwar craton during this critical interval apart from the earliest stages of Cuddapah basin formation. We argue that the ‘observed’ rotation results from biases associated with how trends of dykes and their magnetic directions are compiled when age data are limited. The curvature of geological features in Dharwar craton is likely the tectonic inheritance of the Neoarchean collision between the Western Dharwar and Eastern Dharwar cratons.

1. Introduction

Lithospheric mobility on geologic timescales results in the interaction of lithospheric plates. Paleogeographic research strives to meticulously document the movement and interaction of the lithospheric plates over geologic time. Although the interactions of plates, and therefore orogenic effects, are principally focused along their margins, the interiors of plates do not escape deformation. Around 35 cratons have survived since the Archean (the so-called ‘puzzle pieces’ of Bleeker, 2003) and these are the relative pieces to consider when assessing intraplate, or rather intracratonic, deformation over the long term. Various datasets can be used to define ancient intracratonic deformation: the coherence of ancient sedimentary basins, metamorphic zones, or the geometric pattern of linear features such as dyke swarms and structural trends. Deformation of initially linear features may result in complex curvilinear structures (oroclines, Carey, 1955; Johnston et al., 2013). Discerning the timing and magnitude of bending is quantitatively assessed using paleomagnetic methods (Johnston et al., 2013). Within the powerful, simple framework of the geocentric axial dipole hypothesis (GAD; Meert, 2014), paleomagnetic results from across a craton can be examined for consistency. Craton-wide uniformity of paleomagnetic results would support hypotheses that involve little to no intracratonic rotation associated with deformation. This approach is exemplified in the comprehensive paleomagnetic, geometric, and tectonic examination of the Paleoproterozoic Superior craton (Evans and Halls, 2010), which found that the eastern half of the craton is best restored to the western half with a ~14° anticlockwise rotation. A necessary component to this style of analysis is a detailed paleomagnetic record from the craton in question.

Dharwar Craton is a large and well-studied block of ancient Archean crust that is exposed across much of Southern India (Meert et al., 2010a, 2010b; Naqvi and Rogers, 1987; Ramakrishnan and Vaidyanadhan, 2008). The craton can be roughly subdivided into the Eastern Dharwar Craton (EDC) and Western Dharwar Craton (WDC), based on differing major lithologies and ages of rocks (Chardon et al., 2008; Meert et al., 2010; Naqvi and Rogers, 1987; Swami Nath and Ramakrishnan, 1981); the main basement lithologies are TTG-granite-gneiss and greenstone belts. The EDC is primarily comprised of the granitic-gneissic Dharwar Batholith (~2.7–2.5 Ga; Chadwick et al., 2000) with linear greenstone belt arrays in the western part of the craton (Ramakrishnan and Vaidyanadhan, 2008). The WDC has more greenstone belts than the EDC, which fall into multiple generations from the Mesoarchean to Neoarchean. The TTG-gneisses which also comprise the WDC are relatively older (~3.5–3.3 Ga) than the Dharwar Batholith to the east (Bhaskar Rao et al., 2008; Peucat et al., 1993). The cratonic basement is intruded by numerous mafic dyke swarms with various geometrical trends. These dykes are separated into seven distinct temporal groupings based on decades of concerted paleomagnetic and geochronologic

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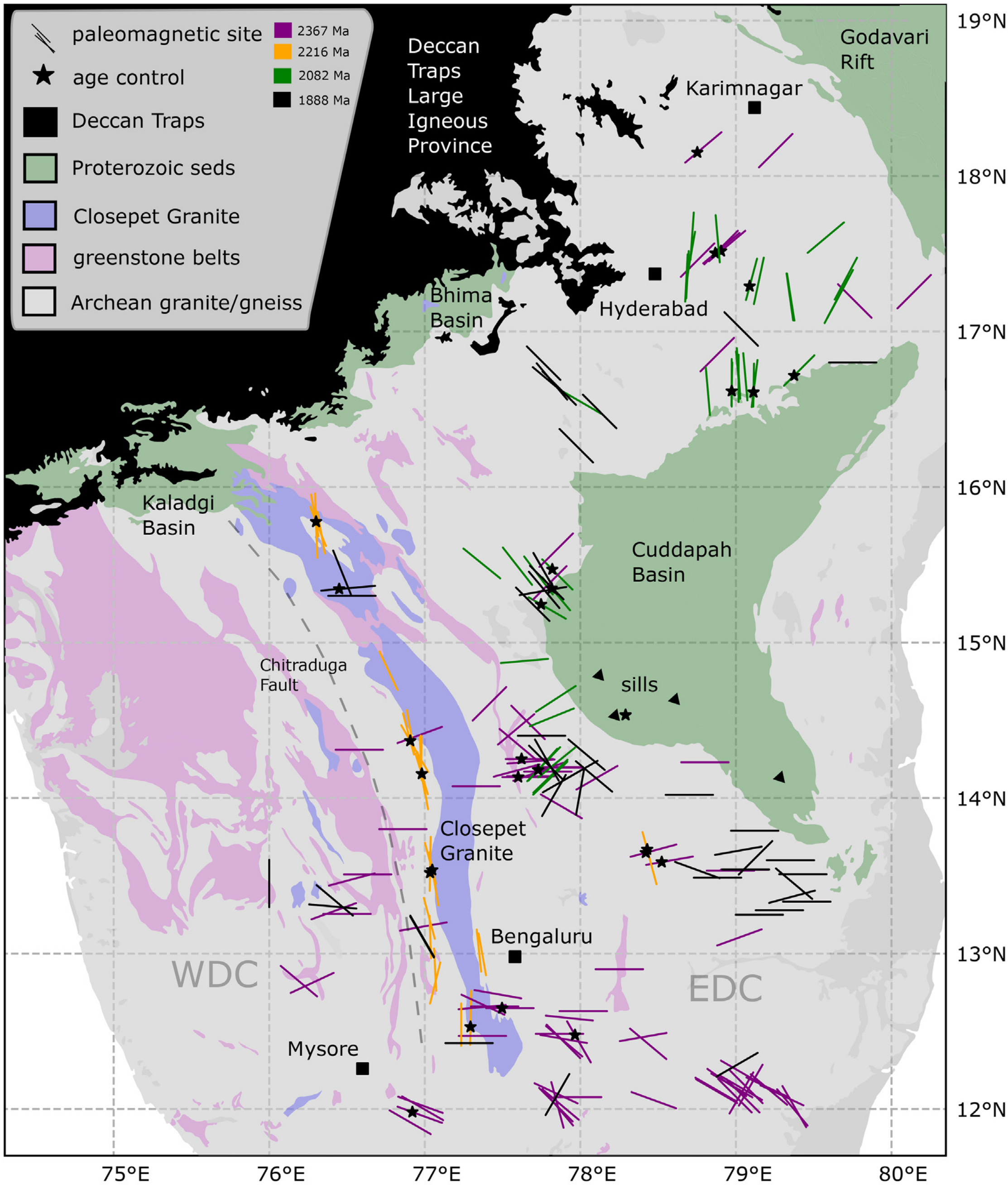

Fig. 1. Map of Dharwar craton showing the four major mafic dyke swarms that provided the paleomagnetic data used to test intracratonic rotation hypotheses. General geology of Dharwar craton from the 1:2,000,000 Geological Survey of India map; GSI 1:2M Map, 1998).

study (Fig. 1; Samal et al., 2015; Söderlund et al., 2019; Samal et al., 2019). The Dharwar craton additionally hosts a number of Proterozoic sedimentary basins including the Bhima, Kaladgi and Cuddapah.

A distinct feature of Dharwar craton is a curvilinear structural grain which bends from south to north through the craton (Fig. 1; Naqvi and Rogers, 1987). This curvilinear trend is easily recognizable in three features: the Chitradurga Fault (shear zone), the Closepet Granite, and the Andhra Karnataka Long Dyke (AKLD). Some greenstone belts in Dharwar craton also follow this trend. There are two end-member explanations for this: either this a primary (i.e. pre-stabilization, Archean) or secondary (i.e. post-stabilization, Proterozoic) feature. The possibility that Dharwar craton experienced an intracratonic rotation to produce this arcuate shape as a secondary feature was raised (Kumar et al., 2012a) and dismissed (Nagaraju et al., 2018b) in specific reference to the AKLD, a conspicuously curved 2216 Ma dyke which stretches > 400 km across the craton from north to south. Recent work again raised the issue of a secondary (i.e. post-stabilization, Proterozoic) relative rotation between north and south Dharwar craton (Söderlund et al., 2019). Söderlund et al. (2019) propose ~30° of anticlockwise vertical-axis rotation. According to their model, the correction transforms currently radiating 2367-2180 Ma dyke swarms into linear swarms. This approach relies on the assumption of original linearity of the 2367-2180 Ma dyke swarms.

In this paper, we examine the paleomagnetic data available from four major dyke swarms within Dharwar craton – the 2367, 2216, 2080 and 1888 Ma swarms – and their implications for relative intracratonic rotation. We undertake this analysis because we believe that quantitative paleomagnetic data provide a more robust test for rotation than does assuming an initial geometry of emplacement.

1.1. Assessing vertical axis rotation: direction-space and pole-space

The paleomagnetic database of Dharwar craton is now well-established, with robust results from mafic dykes in the north and south sectors of Dharwar craton (Fig. 1). We will not discuss the paleomagnetic data in detail here (for a discussion of the key paleomagnetic poles refer to Meert et al., in press). The myriad paleomagnetic studies used in this analysis are referenced at the end of this manuscript, and groupings are indicated in the attached data. We gathered site-level paleomagnetic data from the four major dyke swarms with large enough datasets to be useful and analyzed them using Python software with a specialized paleomagnetic package (Tauxe et al., 2016). Paleomagnetic directional data (declination and inclination) are ideal for assessing vertical-axis rotation of the craton (see Butler, 1992). This is achieved simply by comparing the observed paleomagnetic declination in a given region of questionable tectonic stability with the expected paleomagnetic declination from a stable reference area.

$$R = D_O - D_X$$

The difference between the declinations (R) is the amount of relative rotation. For our purposes, we compare the paleomagnetic declination of north versus south Dharwar craton. The southern sector of the craton (everything south of the latitude 14° N) serves as our 'stable' reference (Figs. 2 and 3).

Uncertainty on estimates of rotation (ΔR) is a function of uncertainty of paleomagnetic declination ($\Delta D_O$for the 'observed' direction and ΔD_X for the 'expected direction) along with a correction factor of 0.8 (Demarest, 1983). Directional data do not conform with a Fisher distribution (Tauxe and Kent, 2004; Deenen et al., 2014), and thus Fisher statistics are not appropriate for assessing the uncertainty on purely directional data. However, the use of A95, as calculated from the distribution of virtual geomagnetic poles (VGPs), which do conform to Fisherian statistics, enables us to use the Demarest (1983) uncertainty calculation method more appropriately. The main upshot is a slightly higher uncertainty on the paleomagnetic declinations and thus a larger interval where rotations are not statistically definable. If the amount of rotation (R) does not exceed the uncertainty on its estimate (ΔR), the directions compared are technically concordant even if R is non-zero. That is, the declination difference is paleomagnetically indistinguishable. If instead the defined rotation does exceed uncertainty, the directions are discordant, and a paleomagnetically definable rotation is suspected.

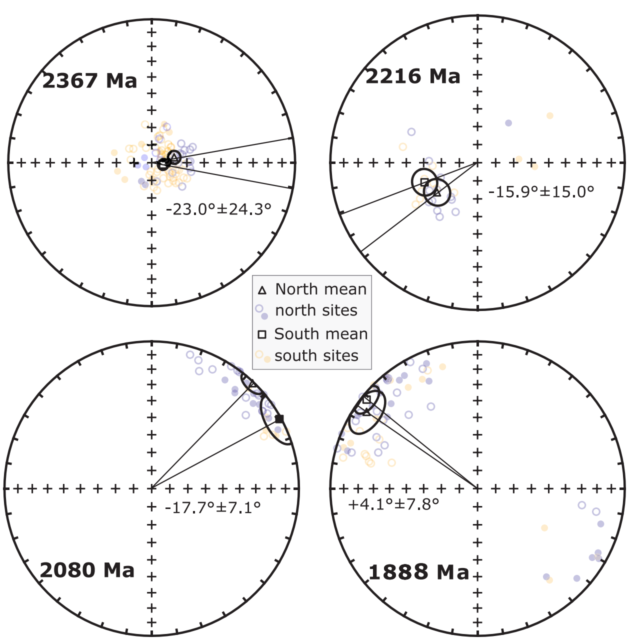

Fig. 2. Stereoplots of mean directional disparity among the four dyke swarms examined in this study. Black circles with confidence intervals represent the directional mean from north (triangle) and south (square), while the faded circles (blue = north and orange = south) represent site-level paleomagnetic data. Difference in declination between means are shown as lines radiating from the center of the plots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

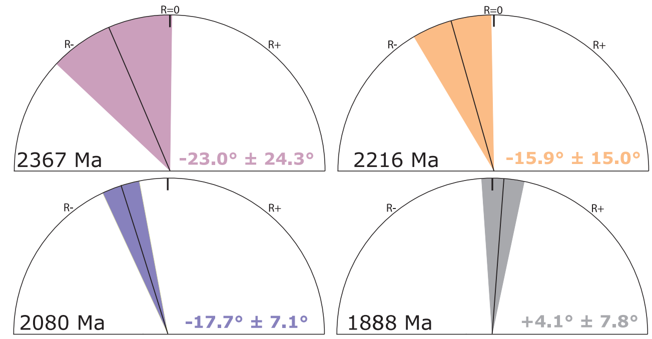

Fig. 3. Amount of rotation defined by the four major dyke swarms. North represents zero rotation; magnitude, direction, and uncertainty on rotation shown from the black line, left/right position from north, and shaded area. The three early Paleoproterozoic dyke swarms indicate anti-clockwise rotation, however, by 1888, concordant paleomagnetic results indicate that intracratonic rotation had ceased.

Paleomagnetic site-level data can also be used to calculate a paleomagnetic pole, which is generally assumed to represent the ancient position of the Earth's geographic pole with respect to a given area, subject to typical paleomagnetic uncertainties (Butler, 1992). We calculated paleomagnetic poles as the mean of virtual geographic poles (VGPs) calculated from each site mean (Supplementary Material). The paleomagnetic poles from north and south Dharwar craton are then compared in pole-space both before and after Euler rotations (Fig. 4). The hypothesized vertical-axis rotation between the north and south of the craton is best modelled as a Euler pole within the craton itself. We placed the pole at the hypothesized axis of rotation (Euler pole at 15° N, 75° E) of Söderlund et al. (2019) and examined both the amount of rotation hypothesized in their paper along with the rotation implied by paleomagnetic data (Fig. 4).

A summary of the paleomagnetic parameters of the total site-level datasets and calculations associated with this paper is attached as a Python notebook, along with the data used in this analysis (Supplementary Material).

1.2. Rotation evidence from paleomagnetism

The 2367 Ma Bangalore-Karimnagar dyke swarm is widespread throughout the entire Dharwar craton, from the Southern Granulite Terrane (SGT) (Fig. 1; Belica et al., 2014; Dash et al., 2013; French and Heaman, 2010; Halls et al., 2007; Pivarunas et al., 2019), through the rest of the craton (Kumar et al., 2012a; Söderlund et al., 2019) all the way into Bastar craton to the north (Liao et al., 2019). The trends of these dykes generally fan from NW-SE in the south to NE-SW in the north. Thus, it was originally proposed that these dykes are part of a radiating swarm with a center to the present geographic west of Dharwar craton (Halls et al., 2007). The 2367 Ma dykes, however, are mapped as more densely emplaced in Eastern Dharwar craton, which is hard to reconcile with a western plume center. Eastern and Western Dharwar have different dominant lithologies (granite-gneiss versus greenstones), which may have influenced the dyke distribution. The recent hypothesis of intracratonic rotation holds that the 2367 Ma swarm was roughly linear, and that the fanning of these dykes is a

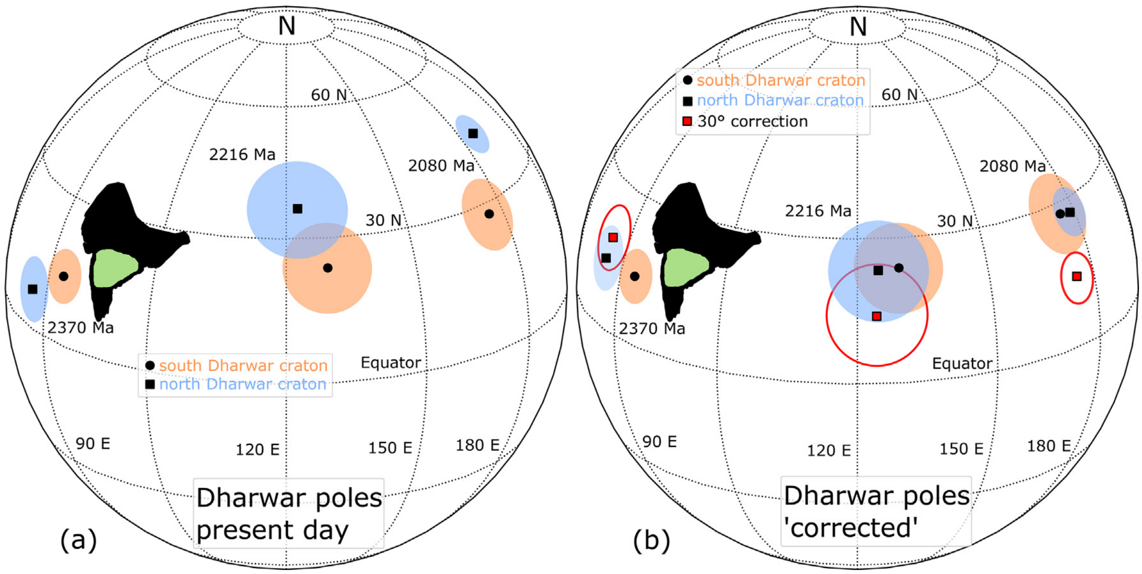

Fig. 4. Pole-space comparison of results from north and south Dharwar craton (squares with blue A95 are from north and circles with orange A95 are from south) in (a) present-day arrangement showing the relative separation in pole space and (b) 'corrected' for anticlockwise rotation using an Euler pole of [15, 75, −17.7]. The fit is quite noticeably improved for 2216 Ma and 2080 Ma results; however, the 2367 results do not improve significantly. Red squares indicate the illustration of a 30° clockwise correction as suggested by Söderlund et al. (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

secondary feature (Söderlund et al., 2019). If, in contrast, the dykes radiated away from an *eastern* plume center, the necessary rotation to bring them into their present-day arrangement would be substantially > 30°.

The total amount of rotation we can discern from paleomagnetic data is calculated as the difference between the mean declination in the northern (> 14° N) and southern sections (< 14° N). For the 2367 Ma dykes (N = 83), we find that R = –23.0° ± 24.3° (Table 1; Figs. 2 and 3). Although the sense of rotation is anti-clockwise, the magnitude of the uncertainty exceeds the apparent rotation and therefore the paleomagnetic data at 2367 Ma are not statistically discordant.

A 2216 Ma subswarm of dykes known as the Kandlamadugu swarm is a prominent member of ca. 2.2 Ga magmatism stretching across the craton (Kumar et al., 2012; Nagaraju et al., 2018a, 2018b; Srivastava et al., 2014b). Other swarms slightly post-dating 2216 Ma may represent the same event; however, due to the absolute rotation of Dharwar craton as a whole during this time interval, we only examine the precisely-dated 2216 Ma subswarm. For the 2216 Ma dykes (N = 25), we find that R = −15.9° ± 15.0° (Table 1; Figs. 2 and 3). In this case, the magnitude of rotation just rises above the level of uncertainty such that the paleomagnetic data at 2216 Ma are discordant. Detailed sampling of the AKLD, however, fails to show the expected local trend/declination relationship implied by intracratonic rotation post-emplacement (Nagaraju et al., 2018a).

The 2082 Ma Devarabanda dyke swarm mainly has been found to the north and west of Cuddapah Basin (Kumar et al., 2015). Dykes of this age are also found to the southwest of the Cuddapah Basin (Söderlund et al., 2019), but paleomagnetic results are lacking from this area of the swarm. For this reason, a boundary placed at 14° N results in no available paleomagnetic data from the 'southern' part of the craton. Thus, we consider a boundary at 15° N for this time period. For the 2082 Ma dykes (N = 34), we find that R = −17.7° ± 7.1° (Table 1; Figs. 2 and 3). This amount of rotation between north and south Dharwar craton reaches 'discordant' status. The trends of the 2082 Ma dykes, it should be emphasized, do not help define the hypothesized rotation between north and south Dharwar (Söderlund et al., 2019), this is only seen in the paleomagnetic data presented here.

A large igneous province (LIP) emplaced at ~1888 Ma (French et al., 2008), principally manifesting as the Hampi dyke swarm (sills/traps in the Cuddapah Basin), stretches across Dharwar craton and the neighboring Bastar craton to the north. A total of 54 dykes/sills were collected from this LIP since the inception of paleomagnetic studies in Dharwar craton (Belica et al., 2014; Meert et al., in press). For the 1888 Ma LIP, we find that R = +4.1° ± 7.8° (Table 1; Figs. 2 and 3)

Table 1
Paleomagnetic results and implied rotation from the north and south of Dharwar Craton.

Name	N	D (°)	I (°)	k	a95 (°)	Plat (°N)	Plon (°E)	K	A95 (°)	R (°)	ΔR (°)
2367N	26	76.6	−76.9	60.8	3.7	8.2	54.2	18.9	6.7	–23.0	24.3
2367S	57	99.6	−83.5	41.3	3.0	14.3	65.1	12.4	5.6		
2216N	13	233.8	−62.1	33.2	7.3	−36.3	302.9	16.9	10.4	−15.9	15.0
2216S	12	249.7	−58.5	37.9	7.1	–23.8	309.3	22.9	9.3		
2082 N*	27	43.7	−1.1	28.2	5.3	43.5	186.5	37.2	4.6	−17.7	7.1
2082S*	7	61.4	1.3	32.9	10.7	27.8	174.7	64.4	7.6		
1888N	39	308.7	−3.8	13.1	6.6	36.2	334.1	19.5	5.3	4.1	7.8
1888S	23	304.7	−9.2	9.8	10.2	31.9	333.6	14.7	8.2		

Notes: Name = age of dyke swarm, N indicates upper craton, S indicates southern craton; N = site-level data incorporated into mean directions; Dec = paleomagnetic declination, Inc = paleomagnetic inclination, k = kappa precision parameter (Fisher, 1953); a95 = cone of 95% confidence about the mean direction, PLat = virtual geomagnetic pole latitude, PLon = virtual geomagnetic pole longitude (these last two calculated from directional data and site location); K = kappa precision parameter (Fisher, 1953); A95 = circle of 95% confidence about the paleomagnetic pole; R = paleomagnetic rotation seen in directional space; ΔR = 95% confidence limits on paleomagnetic rotation (Demarest, 1983).

and shows no discordance. Thus, on the basis of paleomagnetism, no intracratonic deformation is indicated after 1888 Ma.

We take the mean ($\bar{R}$) of the 2367, 2216, and 2082 Ma dyke swarms to evaluate the amount of intracratonic rotation permissible. Given the high variance of the calculated confidence intervals for two of three estimates of rotation, we present the pooled uncertainty ($\Delta\bar{R}$) as follows in order to account for the uncertainty on the estimates:

$$\Delta\bar{R} = \sqrt{\frac{\sum \Delta R_i^2}{N}}$$

$$\bar{R} \pm \Delta\bar{R} = -18.9^\circ \pm 16.9^\circ$$

This range encompasses, within confidence limits, the previous estimate for N-S intracratonic anticlockwise rotation of ~25° (Kumar et al., 2012b, cf. Nagaraju et al., 2018a), and the 30° proposed by Söderlund et al., (2019). It is also compatible with negligible rotation. We also note, this number relies on the necessary movement of the geographic dividing line for the 2082 Ma dyke swarm in order to cope with data availability.

For comparison in pole-space, our vertical-axis correction (a clockwise rotation) is derived from the 2082 Ma dykes (R = −17.7°) since this is the datum with the most reasonable confidence limits. The present-day offset between north and south poles is noticeable in mean pole positions (Fig. 4a). When corrected for 17.7° of anti-clockwise rotation, the fit of the 2216 and 2082 Ma paleomagnetic poles is improved (Fig. 4b). We also used the 30° clockwise rotation (Söderlund et al., 2019) for comparison that 'overcorrects' the paleomagnetic data with the exception of the 2367 Ma data.

2. Discussion

Given the rather large confidence intervals on the paleomagnetic rotation data, particularly for the high-latitude results which characterize Dharwar craton in the early Paleoproterozoic, they are nominally compatible with the hypothesis of intracratonic rotation. The 2082 Ma dykes provide the most robust data; however, they required a different latitudinal position for the dividing line between north and south. The 1888 Ma dykes show no evidence of rotation. Thus, any large-scale intracratonic deformation of Dharwar craton pre-dates 1888 Ma.

The analysis is dependent on the choice between dykes that make up the north and south regions of the Dharwar craton. For example, if we adjust the boundary for the 2367 Ma dykes to 15° N, there are fewer dykes in the northern sector (only 9 of 83 units), and R = +9.9° ± 27.0°. This is the opposite sense of rotation from what is 'expected' and disagrees with results using the 14° N boundary; the statistical threshold for discordance is not reached in either case. The same is true for the 2216 Ma dykes. If we adjust the boundary to 15° N, our calculation changes to R = +20° ± 41.1° which is also the opposite sense of rotation. Since this situation occurs for both the 2367 Ma and 2216 Ma results at the 15°N sector boundary, this may be an artifact of comparing steep-intermediate inclination directional means from drastically different sample sizes. For 2082 Ma dykes, changing the boundary is a fruitless exercise given that no paleomagnetic results for 2082 Ma dykes exist below 14° N. This exercise in boundary condition adjustment should give one pause before unequivocally accepting the paleomagnetic data as strong evidence for rotation. For 1888 Ma dykes, we find R = −0.4° ± 7.3°, which is similar to a 14° N boundary in both concordance of directional data and indication of no rotation; this is expected given that the datasets have comparable numbers for both cases. Thus, the only dataset that is not strongly influenced by boundary conditions is also the dataset which illustrates a *lack* of rotation.

We also should examine the uncritical use of dyke trends as an analogue for age. The Söderlund et al. (2019) hypothesis of intracratonic rotation relies on empirically unsupported assumptions regarding trends of dykes throughout Dharwar craton. For example, 2367 Ma dykes from southernmost part of the craton (Halls et al., 2007; Dash et al., 2013; Belica et al., 2014; Pivarunas et al., 2019), do not show 'improved' linearity after rotating northern trends clockwise by 30° and were not rigorously assessed in the prior analysis (see Fig. 5 of Söderlund et al., 2019). The NW-SE trend observed in the northern SGT dykes (which is simply an extension of Dharwar craton; see Pivarunas et al., 2019) remains unchanged given an axis of rotation at 15° N, 75° E. One can always rotate a portion of a radiating dyke swarm back to linearity with another portion through an appropriate angle of rotation. For example, if the 2367 Ma dyke swarms represent a giant-radiating swarm, only ~60° (the south-to-north change in dyke trends) of the total radiation is present. Thus, arguing that central and northern Dharwar craton dykes become approximately linear after ~30° of relative rotation is still consistent with a radiating dyke swarm, and is not *prima facie* evidence for either original linearity or subsequent deformation.

As an example of trend-age problems, India hosts the spectacular Deccan large igneous province (LIP) – a comparatively modern analogue – where the lack of a preferred orientation of Deccan feeder dykes indicates that we should not necessarily expect a preferred trend-age relationship for Proterozoic dyke swarms (Vanderkluysen et al., 2011). This is abundantly clear in India from the coincidence of 2367 Ma and 1888 Ma trends (Samal et al., 2015; Samal and Srivastava, 2016). Besides the geochronological and paleomagnetic differentiation of these swarms, geochemical evidence also points to a disparate genetic history (Srivastava et al., 2014a). It is likely that both dyke swarms exploited preferred zones of weakness in the crust (Pivarunas et al., 2019). The pulsed generations of Proterozoic dykes could either represent the remnants of plumbing systems of older LIPs or be related to extensional tectonics (Ernst, 2014). Similarly, the ~1.2 Ga Harohalli alkaline dykes (Pradhan et al., 2008) share a general N-S trend with many 2.2 Ga mafic dykes (Kumar et al., 2012; Nagaraju et al., 2018a, 2018b). The 2080 Ma dykes from around Cuddapah Basin have a generalized radiating structure that does not produce linearity after 'correcting' for the hypothesized deformation (Söderlund et al., 2019). Untangling the secondary effects of regional deformation on the basis of dyke swarms must take into account deviations from ideal 'one-trend-one-age' behavior.

Furthermore, it is important to remember that most mafic dykes lack radiometric ages. A common practice is to group directional data on the basis of comparison to dykes that are well-dated *and* have paleomagnetic data. Occasionally, the dykes are also correlated on the basis of geochemical similarities (see, for example Liao et al., 2019) or trends without any reference to paleomagnetic data. This results in somewhat circular criteria for including dykes in a given dataset, with directional comparison likely the most inclusive (not always a good thing!) metric. Directional comparison likely results in artificial tightening of directional groupings to some degree, but also may result in an artificial loosening of groupings if a broad directional definition is used. Thus, statistical differences in declination can be caused by artificially small confidence intervals or the natural consequences of a highly-scattered dataset. On the other hand, relying solely on trends of dated dykes, or geochemical similarities can also create artificial 'lumping'. This is well-illustrated by the southernmost 2367 Ma dykes in Dharwar craton; they either help define a radiating swarm, or else are conjugate to an otherwise linear swarm. It would be ideal, albeit impractical, to date every single paleomagnetically sampled dyke. We simply stress caution in the uncritical use of these approaches and note that the apparent rotations in the Dharwar craton should be viewed with caution.

Our final point relates to tectonic matters, the *corpus delicti* which should accompany intracratonic rotation. Thus, we emphasize that the most important results from this analysis are the apparently 'positive' test for 2082 Ma dykes and the 'negative' test for rotation at 1888 Ma.

These endpoints provide a temporal framework, a 'tectonic window', for evaluating potential tectonic triggers for either oroclinal bending or protracted shearing (Söderlund et al., 2019) in the Dharwar craton. In other well-documented examples of intracratonic deformation, the zone of accommodation is recognizable and falls within the proper temporal framework (Li and Evans, 2011; Evans and Halls, 2010). Thus, for Dharwar Craton, a simple question arises. *Where is the deformation?*

Evidence for deformation within the Dharwar craton during the 2100-1900 Ma interval is lacking. This time period does coincide with the early formation of the Cuddapah Basin (early sedimentary rocks therein are intruded by 1888 Ma sills). The present-day structural grain in the Cuddapah basin is opposite in sense to the proposed rotation of Söderlund et al. (2019); however, it is likely that the deformation producing the crescent shape of the region occurred later in the Proterozoic. Thus, we have an apparent solution (paleomagnetically defined rotation) in search of a major deformational accommodation. One option is that 2367 Ma and 2216 Ma dykes simply each produce a similar apparent anticlockwise rotation given the scatter inherent in the averaging of paleosecular variation at relatively high latitudes. In this case, the 2082 Ma rotation – which is statistically better defined – may have resulted from more localized accommodation around the Cuddapah Basin. The pole-space results are more intriguing, given that both 2216 Ma and 2082 Ma paleomagnetic poles show improved fit after the northerly results are corrected for the proposed rotation (Fig. 4). This gives us higher confidence in the 2216 Ma results, which only just exceed uncertainty in directional-space. We note that the 2216 Ma declination difference does not exceed uncertainty (14.8° ± 17.1°) if a more stringent compilation (N = 21) of dykes is used (Meert et al., in press).

The Neoproterozoic 40° clockwise rotation of the South and West Australia cratons (SAC and WAC) with respect to North Australia craton (NAC) provides an excellent example of harmony between tectonic and paleomagnetic data (Li and Evans, 2011). A cross-continental megashear zone is visible within the Neoproterozoic Paterson and Petermann orogenies (Myers et al., 1996). In this case, there is both a clear post-rotation fit from the paleomagnetic data and a clear zone of deformation accommodating the rotation. Another example of Proterozoic cratonic rotation is within Superior Craton (Evans and Halls, 2010). This rotation, although relatively 'small' (~14°), is accommodated by a major deformational area, the Kapuskasing Structural Zone (KSZ).

The major tectonized regions of the Indian shield that may be relevant to Dharwar craton rotation include the Central Indian Tectonic Zone (CITZ) and the Eastern Ghats Province (EGP). The CITZ suffered cryptic deformation at around 2.5 Ga in the Sausar Mobile Belt (Stein et al., 2004, 2006), but major tectonic activity took place between 1.6 and 1.5 Ga and again during the assembly of proto-India around the Mesoproterozoic-Neoproterozoic transition (Bhowmik, 2019). Deformation in the EGP is broadly coeval with that in the CITZ (Dobmeier and Raith, 2003). Thus, major Proterozoic deformation in both of these provinces post-dates the paleomagnetically defined hard lower limit on rotation in Dharwar craton (1888 Ma).

There have been multiple suggestions that the structural grain of Dharwar craton pre-dates the Proterozoic. Chadwick et al. (2000) posited a plate-tectonic paradigm for the assembly of Dharwar craton and credit a Neoarchean collision between the eastern and western nuclei of Dharwar craton with creating the present curved structural grain. Chardon et al. (2008), disagreed with the mechanism and some interpretations of previous workers, yet still favored late Archean timing for development of the Dharwar craton crustal architecture. These scenarios are plausible hypotheses for the formation of the curvilinear structural grain that do not require major post-stabilization intracratonic rotation. A detailed structural analysis of Eastern Dharwar craton granitoid rocks by Das et al. (2019) found major ductile deformation in the late Neoarchean (D1-D3) related to final cratonization (D3 at ~2524 Ma), while limited brittle deformation (D4-D5) post-dates Paleoproterozoic mafic dykes. The D4-D5 brittle deformation, therefore, seems insufficient to drive a ~20-degree craton-wide rotation.

3. Conclusions

Dyke trends provide insufficient evidence for diagnosing intracratonic rotation. Paleomagnetic studies provide a more robust analysis because any rotation should be apparent from changes in declination. There is limited evidence for an anti-clockwise rotation of the northern Dharwar craton based on paleomagnetic results between 2367 and 2082 Ma. The offset is dependent on the division of Dharwar craton into 'north' and 'south' sectors. Depending on where the boundary is drawn, the datasets show either limited evidence for anti-clockwise rotation or the opposite sense of rotation (clockwise). Rigorously honoring statistical constraints, the best evidence for rotation via paleomagnetic results is from the 2082 Ma dykes and suggests ~17° of counterclockwise rotation, but uses a different geographic dividing line than used to separate older (2367-2216 Ma) dykes. By 1888 Ma, the declinations indicate no relative rotation. Therefore, any event or long-term tectonic driver for rotating the northern Dharwar craton is constrained to between 2082 Ma and 1888 Ma. At present, there are no reasonable mechanisms for craton-wide deformation during this interval. Given the ambiguities of the paleomagnetic data, we suggest that a more parsimonious conclusion wherein the structural grain of Dharwar craton pre-dates emplacement of the dykes resulting from 'indentor' tectonics between the EDC and WDC during the Neoarchean. We believe the paleomagnetic data preclude significant deformation of the Dharwar craton nucleus post-Archean.

4. Data availability

Excel files of site-level paleomagnetic information used in this analysis is provided, along with a Jupyter notebook that provides reproduction of analyses reported in this paper. If there are any questions related to the use of the notebook, please direct them to AFP, the corresponding author.

Declaration of Competing Interest

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.precamres.2020.105858.

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