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GR letter

Preliminary report on the paleomagnetism of 1.88 Ga dykes from the Bastar and Dharwar cratons, Peninsular India

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ABSTRACT

We report the results of a preliminary paleomagnetic study on well-dated 1.9 Ga dykes from the Bastar craton, India. This suite of NW–SE trending dykes was linked to similarly-aged magmatic activity in the Dharwar craton and Cuddapah basin in India as part of a large igneous province. This igneous activity may have extended across many cratons in the "Columbia" supercontinent including the North China craton, Laurentia, Baltica, Australia, Siberia and the Kaapvaal and Zimbabwe cratons (southern Africa). The Bastar dykes along with the Cuddapah traps and dyke yield a dual-polarity magnetization with D = 126°, I = +15.2° (k = 27, α_{95} = 11.9°) and a corresponding paleomagnetic pole at 31° N, 330° E (dp = 6.3°, dm = 12.2°). The relatively robust paleomagnetic and geochronologic database at 1.85–1.90 Ga allow us to test one of the configurations of the supercontinent "Columbia". There are some critical differences between our paleomagnetically-based reconstruction and the archetypal and geologically-based "Columbia" configuration of Zhao et al. (2004). Most notably, Siberia, India and Australia cannot be linked to Laurentia in the archetypal Columbia fit. Proposed links between western Australia and the Kaapvaal and Zimbabwe cratons are possible as is the fit between Baltica and Laurentia. The robust paleomagnetic data reported in this paper require that either the Columbia supercontinent did not exist at 1.9 Ga or requires major modification. Given that our data provide only a snapshot on the Paleoproterozoic, we conclude that the Columbia supercontinent remains a viable possibility although relationships between individual elements should be re-evaluated as more data become available.

1. Introduction

Dykes are useful igneous bodies for deciphering the geological evolution of cratonic blocks, extensional tectonics, mantle chemistry and magma transport history. In addition, dykes are ideal recorders of the Earth's magnetic field due to their quick cooling history and the ability to obtain precise U–Pb emplacement ages. Numerous dyke swarms intrude all the major cratonic blocks within Peninsular India (Fig. 1a). Although there are numerous paleomagnetic studies on many of the Indian dykes, it is only recently that the dykes received detailed attention in terms of establishing a strong geochronologic framework for their emplacement in conjunction with paleomagnetic studies (for examples see Pradhan et al., 2008, 2010; Halls et al., 2007; French et al., 2008; French and Heaman, 2010; Lubnina et al., 2010a,b; Piispa et al., in press; Pradhan et al., in review).

Peninsular India (the Indian Shield) can be subdivided into five major cratonic nuclei, namely the Aravalli in the northwest, the Bundelkhand in the north, the Dharwar in the south, the Singhbhum in the east and the Bastar in southeast (Fig. 1a; Meert et al., 2010). The Bastar craton, where part of our study was carried out, is one of the least studied due to inadequate infrastructure, insurgency and security concerns in the area. We have carried out a preliminary paleomagnetic study in the region and hoped to return for more detailed sampling; however due to the hostilities in the region additional sampling cannot take place in the foreseeable future. Therefore, we present our preliminary results in this paper because we feel that, although limited, they provide useful information on the paleogeographic position of India at ~1.9 Ga.

2. Geological setting

The Bastar craton is an almost a square (500 km^2) crustal block in SE India, bounded to the north by the Central Indian Tectonic Zone (CITZ) and to the south by the Eastern Ghats Mobile Belt. The eastern and western boundaries are defined by two Phanerozoic rift systems, the Mahanadi Rift to the east and Godavari Rift to the west (Fig. 1a). The oldest rock units in the Bastar craton are undifferentiated tonalite–trondjhemite gneisses, exposed in the southern and western parts and popularly known as the Gneissic Complex (Ghosh, 1941; Crookshank, 1963 and see also Ramakrishnan and Vaidyanadhan, 2008). The 3509 + 14/−7 (Sarkar et al., 1993) and 3561 ± 11 Ma (Ghosh, 2004) U–Pb zircon ages attest to the early Archaean status of

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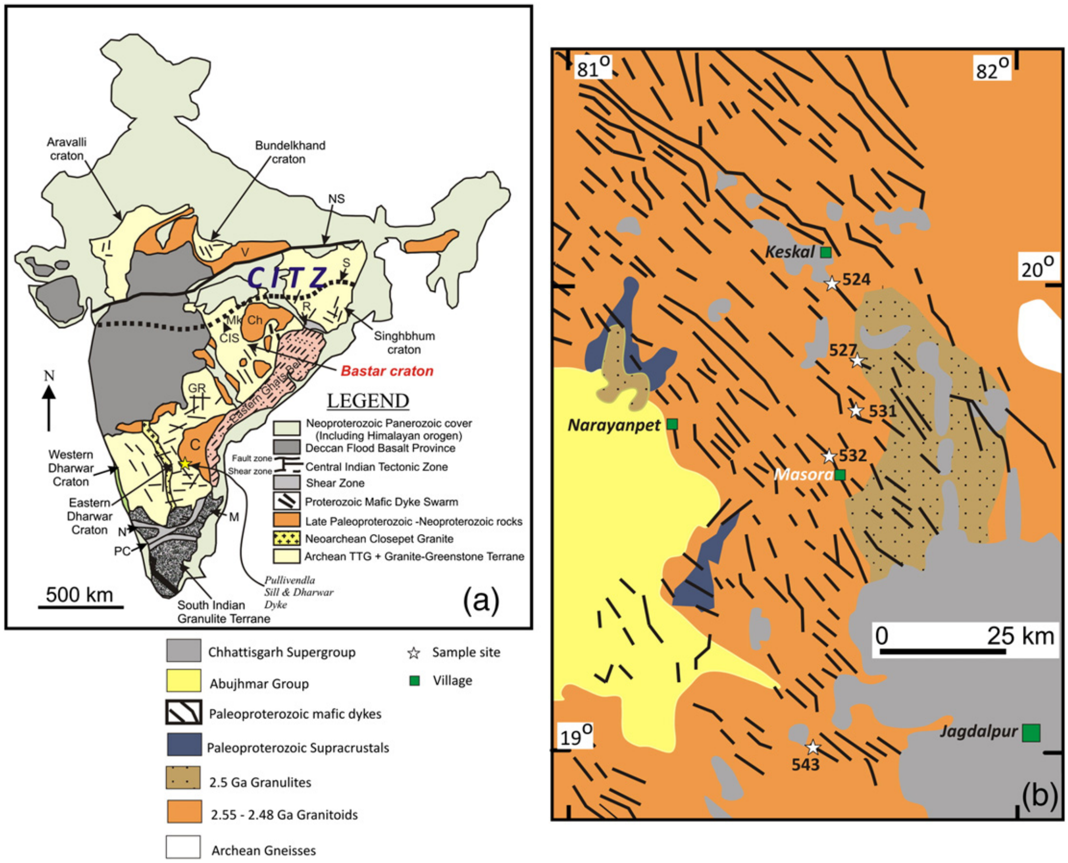

Fig. 1. (a) Generalized geologic map of Peninsular India showing the major cratons and various dyke swarms intruding those cratons. The Bastar craton (focus of this study) is located in east-central region (adapted from French et al., 2008). The Pullivendla sill, Cuddapah traps and Dharwar dyke are represented by the yellow star (b) field area for the present study of Bastar dykes near Keskal. Paleomagnetically sampled dykes are indicated by white stars. The reversely magnetized dyke at Site 543 was dated by French et al. (2008) to 1883.5 ± 4.4 Ma.

the basement gneisses. This high-grade gneissic terrane forms the basement for supracrustals represented by phyllite, schist, quartzite and meta-carbonate interbedded with meta-basalts. Stratigraphic relationships of these supracrustal sequences remain debated on account of two contrasting views. Crookshank (1963) subdivided into an older Sukma Series and younger Bengpal Series, which was in contradiction to the proposal of Ghosh (1941) who considered all the supracrustal rocks as simple facies variants and grouped them under Bengpal Series. Ramakrishnan (1990) reported an angular unconformity between Sukma and Bengpal rocks and observed differences in the grade of metamorphism to call them as two separate stratigraphic entities. However, most studies, including the present one, have followed the classification scheme of Ghosh (1941). The basement gneisses and 'older' supracrustals are intruded by a number of Proterozoic granitoids (Malanjkhand Granite, Kanker Granite, and Dongargarh Granite) that are conspicuous in the southern part of the craton and dated to 2480 ± 3 Ma (zircon U–Pb) by Sarkar et al. (1993). This end Archaean/earliest Paleoproterozoic granitic magmatism is thought to mark a significant accretionary event in the region and overlaps with the widespread end-Archaean granite plutonism recorded in other cratonic blocks in the Indian shield, such as 2.56–2.44 Ma Berach Granite in the Aravalli craton (Wiedenbeck et al., 1996) and 2.51 Ga Closepet Granite in Dharwar craton (Jayananda et al., 2000). Meert et al. (2010) considered that the terminal Archaean marked a major stabilization phase in Peninsular India that could have resulted from either reworking of the older crust or collisional tectonism.

The overlying metasedimentary sequence comprising slate, phyllite, schist and banded iron formations (BIF) is named as the Bailadila Group. The Bailadila Group represents an Early Proterozoic sedimentary ensemble. Mafic dykes represent the youngest magmatic event in the region as they cross-cut all the older rock units. The dykes are concentrated in the southern sector of the Bastar craton and show a dominant NW–SE trend (Fig. 1b). In addition to the mafic dykes, mafic volcanics were reported in previous studies (Ramakrishnan, 1990; Srivastava et al., 1996; Hussain et al., 2008). Several Proterozoic-age intracratonic basins were developed over the granite–gneiss terrane in the Bastar craton including the extensive Chhattisgarh basin in the north and Indravati basin in the south (Fig. 1a and b). Sedimentation in the Chhattisgarh and other "Purana" basins closed near the end of the Mesoproterozoic (Patranabis-Deb et al., 2007; Basu et al., 2008; Malone et al., 2008). The generalized stratigraphy of the Bastar craton is summarized in Table 1 (compiled from French et al., 2008; Ramchandra et al., 1995; Ramakrishnan and Vaidyanadhan, 2008).

Table 1
Generalized stratigraphy of the Bastar craton.

Unclassified mafic dykes	
Younger dolerite dykes (~1.88 Ga)	
Mafic volcanics	Abujhmar Group
Conglomerate, sandstone, shale	
Older meta-basic dykes (~2.1 Ga)	
BIF	Bailadila Group
Slate, phyllite, schist	
~2.5 Ga granites	
Schist, gneisses, conglomerate, quartzite	Bengpal Group
TTG gneisses, undifferentiated crystalline basement (>3000 Ma)	

3. Mafic dyke swarms

Mafic dyke swarms outcrop in the southern part of the Bastar craton where they cross-cut the older Archaean and early Paleoproterozoic granites and gneisses (Fig. 1b). The dyke swarms have a dominant NW–SE to WNW–ESE trend (Fig. 1b) with subordinate NE–SW to almost N–S orientations (Ramchandra et al., 1995; Ramakrishnan, 1990). The dyke swarms are reported to extend over a strike length of 150 km (Ramchandra et al., 1995), and individual dykes sampled in the present study are typically 15–20 m thick (reaching up to 200 m) and can be traced along strike for several kilometers. Emplacement of the dykes parallels the NW–SE trend of the Godavari Rift suggesting they are exploiting a long-lived weakness in the crust. This NW–SE regional tectonic grain in the region can be identified as predominant lineaments in the satellite imagery of the area (Rajurkar et al., 1990). The predominant trend of the dykes in the northeastern part of the Bastar craton is also to the NW–SE, but is oblique to the trend of Mahanadi Rift (Biswal and Sinha, 2003).

Earlier studies on the Bastar craton mafic dykes identified metamorphosed and un-metamorphosed dykes and at least two episodes of dyke intrusion (Crookshank, 1963; Chatterjee, 1970; Ramakrishnan, 1990). Ramchandra et al. (1995) classified the NW–SE trending dykes from the Keskal area as predominantly quartz-normative tholeiites with subordinate proportions of olivine- and nepheline-normative dykes. Srivastava and Singh (2003, 2004) identified three major suites of mafic dykes; (a) older suite of metamorphosed dykes (amphibolites), (b) a younger suite of relatively fresh and unaltered dolerites and (c) and a suite of high-Mg boninite dykes. In a more recent study, Hussain et al. (2008) ascribed the nearly coeval emplacement of the amphibolite and dolerite dykes as part of a subduction complex. Hussain et al. (2008) based their conclusions on chemical variations in the rare-Earth element (REE) enrichment levels of the dykes. They claimed independent mantle sources (shallow level for dolerite and deeper for amphibolites) that were variably modified by slab and/or sediment derived fluids during melting. Until recently, the Proterozoic ages for mafic dykes were based solely on cross-cutting relationships and tentative regional correlations across central India. French (2007) reported a 2100 ± 11 Ma U–Pb rutile age for a metamorphosed dyke that he interpreted as the minimum age of emplacement for this suite. More recently, French et al. (2008) presented precise U–Pb baddeleyite and zircon ages of 1891.1 ± 0.9 and 1883 ± 1.4 Ma for two dolerite dykes from southern part of the Bastar craton near Dantewara. French et al. (2008) also dated the Pullivendla sill (Cuddapah basin) at 1885.4 ± 3.1 Ma (Fig. 1a) and considered that the Bastar–Cuddapah mafic igneous activity represented a large igneous province emplaced in the Dharwar and Bastar cratons at ~1.9 Ga. This igneous activity includes the Cuddapah traps mafic volcanism.

4. Geology of Keskal dyke swarm

Mafic dykes for the present study were sampled from the Keskal area (Fig. 1b) where host rocks include undifferentiated crystalline basement and gneisses, migmatites, and quartzites of Bengpal Group (see also Ramchandra et al., 1995). The predominant schistosity in the basement trends NW–SE with steep to sub-vertical dips. In most cases, the contact between dykes and the host rocks is concealed under dyke derived boulders with chilled contacts rarely well-preserved. The trend in the majority of mafic dykes is parallel to sub-parallel to the regional schistosity and the dykes generally terminate close to the contact between Bengpal and Bailadila Groups. There are subordinate NE–SW trending dykes. The dykes are vertical and with a modal width of 20–30 m with occasional dykes of up to 200 m in thickness. Individual dykes can be traced for a few tens of meters to several kilometers and are easiest to trace near major villages where some infrastructure (road cuts) were preserved. The dykes show only low-grade alteration (uralitization and saussuritization). The most common texture is glomeroporphyritic ophitic to subophitic and less commonly porphyritic (Ramchandra et al., 1995). In porphyritic varieties phenocrysts (mainly plagioclase) do not exceed 5% modal abundance. Mineral compositions (plagioclase + uralitized clinopyroxene) are consistent with largely gabbroic and subordinate noritic (plagioclase + hypersthenes altered to tremolite and chlorite) compositions. Randomly distributed titanomagnetite is the main magnetic mineral and traces of pyrrhotite, pyrite and chalcopyrite are also present in some dykes.

5. Paleomagnetic methods

Dyke samples were drilled in the field using a portable gasoline-powered drill and oriented using both sun and magnetic compasses. Sample site are shown in Fig. 1b and paleomagnetic results are given in Table 2. Individual samples were then cut into cylindrical specimens and natural remanent magnetization was measured on a Molspin spinner magnetometer or 2G 77R cryogenic magnetometer at the University of Florida. A small group of paired cores from the same sample were either thermally demagnetized using an ASC TD-48 thermal demagnetizer or AF (alternating field) demagnetized using a home-made AF demagnetizer. Based on the behavior of these partner samples, the remaining samples were stepwise treated using either AF or thermal methods. In the case of the Bastar dykes, thermal treatment resulted in a better isolation of the vectors.

Rock magnetic studies were conducted to determine the magnetic carriers in the samples. A KLY-3S susceptibility bridge with a CS-3 heating unit was used to measure Curie temperatures on rock powders and isothermal remanent acquisition studies (with backfield IRM) were performed on previously AF-demagnetized cores.

6. Results

We combine our pilot results (5 dykes) with paleomagnetic data from the Cuddapah traps volcanics (Clark, 1982) and a dyke adjacent to the Cuddapah basin and the Pullivendla sills that are both considered part of the same ~1.9 Ga large igneous province (Kumar and Bhalla, 1983; Chatterjee and Battacharji, 2001; French et al., 2008). Results from the previous studies (Clark, 1982 and Kumar and Bhalla, 1983) were of a single polarity to the NW and shallow up. Means for the Cuddapah traps was Dec = 299°, Inc = −6° (k = 18, a95 = 16°) and for the Cuddapah dyke the mean direction was Dec = 317°, Inc = −32° (k = 97, a95 = 25°).

Stepwise thermal demagnetization of our samples revealed a near uni-vectorial high-temperature component that unblocked at temperatures between 500° and 575 °C (Fig. 2a–i). In a few samples, a low-temperature component could be isolated (see Fig. 2g) that was directed to the north and intermediate down inclination that is very similar to the present-Earth's field direction in the region.

Rock magnetic studies on the dykes show nearly reversible Curie temperature runs characteristic of magnetite (Fig. 3a and b). Isothermal remanence acquisition studies along with backfield coercivity of remanence are characteristic of magnetite. Saturation is reached between 0.2 and 0.35 mT and backfield coercivity of remanence values ranged between 0.062 and 0.12 mT (Fig. 3c).

Two different polarities were present in the dykes, either to the NW and shallow-up (Fig. 2a and b) or to the SE and shallow-down (Fig. 2d, e, g, and h). For simplicity, we refer to sites with NW-shallow negative inclinations as 'reverse' and those with SE-shallow positive inclinations as 'normal'. Three of our dykes had normal polarity and two had reverse polarity directions. Due to the large geographic area, we reduced all directional data to a common site mean (19° N, 81.5° E). A combined normal direction (3 sites, 25 samples) was Dec = 130.9°, Inc = +14.4° (k = 28, a95 = 23.5°, Fig. 4) and the mean reverse direction (4 sites, 46 samples) was Dec = 302.8°, Inc = −15.8°

Table 2
Paleomagnetic results.

Sample	Slat	Slong	N	Dec	Inc	A95	k	Plat	Plong	Ref.
1.9 Ga suite										
Cuddapah traps	14.3° N	78.2° E	15	299°	−6°	16°	18	27° N	337° E	Clark (1982)
NE-Cuddapah dyke	14.4° N	77.7° E	9	317°	−32°	25°	97	37° N	312° E	Kumar and Bhalla (1983)
NW–SE dyke Bastar (532)	19.6° N	81.6° E	5	142°	+25°	7°	122	40° N	313° E	This study
N–S dyke Bastar (543)	18.9° N	81.5° E	14	297°	−24°	8°	26	18° N	331° E	This study
NW–SE dyke Bastar (524)	20.1° N	81.6° E	14	120°	+5.4°	8°	27	27° N	338° E	This study
NW–SE dyke Bastar (527)	19.8° N	81.6° E	9	132.1°	+10°	7°	56	37° N	329° E	This study
NW–SE dyke Bastar (531)	19.7° N	81.6° E	8	292°	0.5°	8°	54	27° N	341° E	This study
Mean (7 sites)[a]	19° N	81.5°	74	126.3°	15.2°	11.9°	27	31° N	330° E	This study

Notes: Slat = site latitude, Slong = site longitude, N = number of samples, Dec = declination, Inc = inclination, A95 = cone of 95% confidence about the mean direction, k = kappa precision parameter (Fisher, 1953), Plat = pole latitude, Plong = pole longitude.
[a] The mean is calculated using a common site at 19° N, 81.5° E.

(k = 22, a95 = 20.3°, Fig. 4). The reversal test (McFadden and McElhinney, 1990) was classified an "Rb" with $\gamma = 7.9°$ and $\gamma_{crit} = 27.9°$. While not definitive, a positive reversal test supports a primary magnetization in these dykes and volcanic rock.

Combining all results (after inverting the 'reverse' directions and using the common site mean) yields a mean declination = 126.3°, inclination = +15.2° (k = 27, $\alpha_{95} = 11.9°$). The paleomagnetic pole falls at 31° N, 330° E (dp = 6.3°, dm = 12.2°) for seven widely separated sites and lends support to the notion of a large igneous province in the Dharwar and Bastar cratons (Fig. 5). Based on the dual-polarity magnetization in these samples, the lack of resemblance to younger magnetic directions from India and the relatively unaltered mineralogy of the dykes, we argue that the magnetization is of a primary nature and represents the 1.90 Ga position of the Bastar craton.

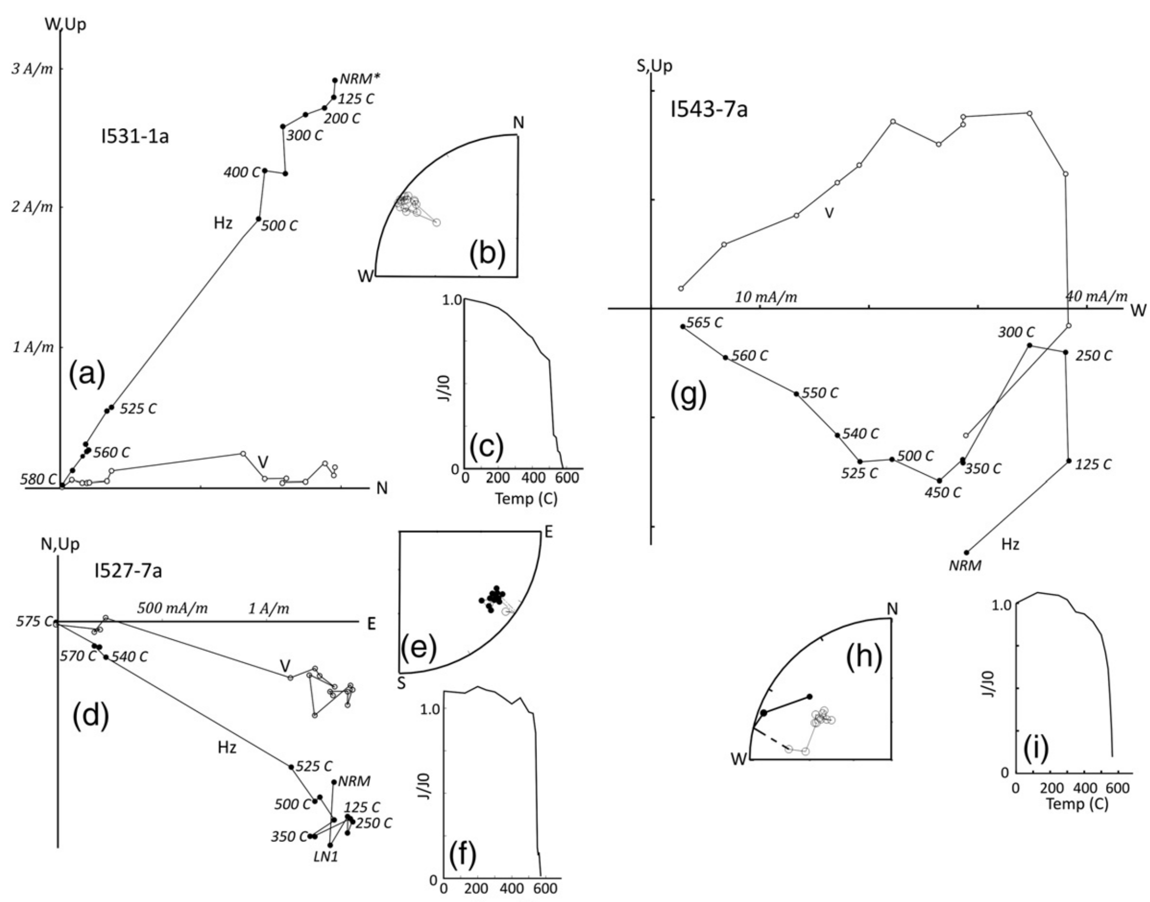

Fig. 2. (a) Zijderveld plot of sample I531-1a 'reverse' polarity showing near uni-vectorial decay at temperatures above 500 °C; Horizontal vector indicated by H and closed circles, vertical vector indicated by V and open circles; (b) stereoplot of demagnetization for sample I531-1a; (c) intensity decay plot for sample I531-1a; (d) Zijderveld plot of sample I527-7a 'normal' polarity showing near uni-vectorial decay at temperatures above 525 °C; Horizontal vector indicated by H and closed circles, vertical vector indicated by V and open circles; (e) stereoplot of demagnetization for sample I527-7a; (f) intensity decay plot for sample I527-7a; (g) Zijderveld plot of sample I543-7a 'reverse' polarity (dated by French et al., 2008 to 1883.5 ± 4.4 Ma) showing near uni-vectorial decay at temperatures above 525 °C; Horizontal vector indicated by H and closed circles, vertical vector indicated by V and open circles; (h) stereoplot of demagnetization for sample I543-7a; (i) intensity decay plot for sample I543-7a.

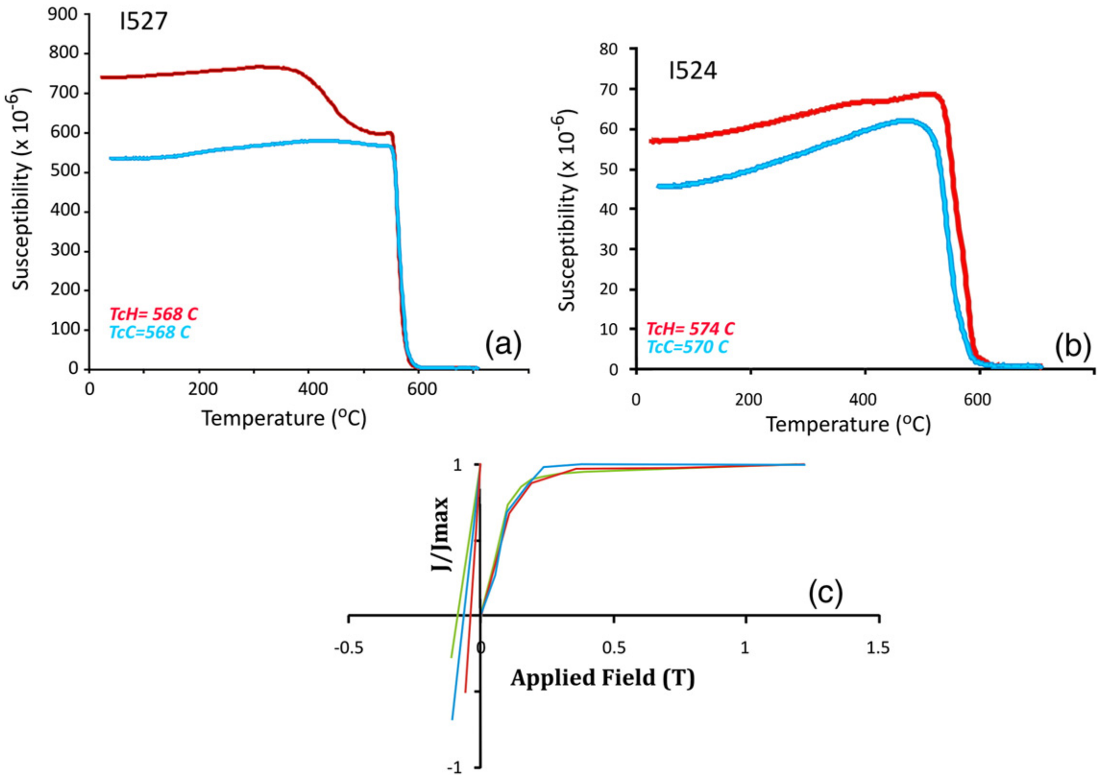

Fig. 3. (a) Curie temperature run on a dyke sample from Site 523 exhibiting slight alteration on heating with identical heating and cooling Curie temperatures of 568 °C. (b) Nearly-reversible Curie temperature run on dyke sample from Site 524. Heating curve Curie temperature of 574 °C is slightly higher than the cooling curve Curie temperature of 570 °C. (c) Isothermal remanence acquisition curves and back-field IRM for dyke samples from 524 (red), 523 (blue) and 543 (green). All samples reach saturation between 0.25 and 0.4 T. Coercivity of remanence values ranged from 0.062 to 0.12 T.

7. Paleogeography at 1.9 Ga

Any attempt at global reconstructions in the Proterozoic is difficult due to the paucity of paleomagnetic data, the inherent polarity ambiguity of paleomagnetic data and the lack of longitudinal control on the positioning of continents (Meert, 2002; Van der Voo and Meert, 1991). In addition, many of the larger present-day continents are an amalgam of older cratonic nuclei that were not fully assembled until Mesoproterozoic or later time. In spite of these hurdles, reconstructions are sometimes made on the basis of geological comparisons of major features such as orogenic belts, large igneous provinces and

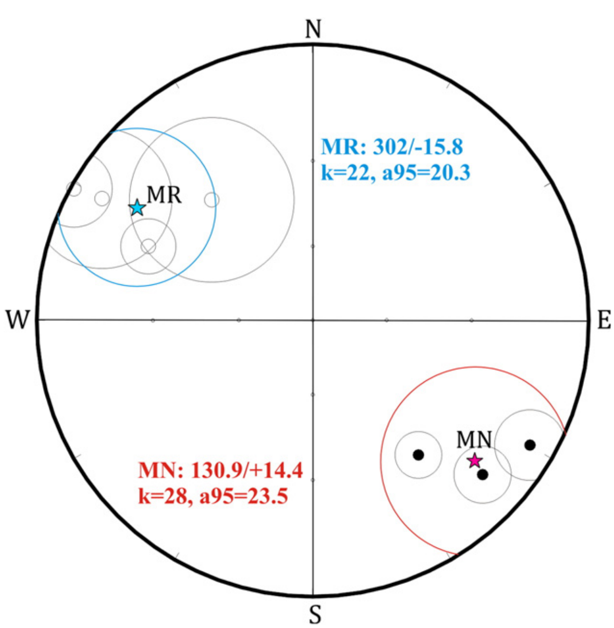

Fig. 4. Stereoplot of mean directions from the Bastar dykes, Cuddapah traps (Clark, 1982) and NE-trending Cuddapah dyke (Kumar and Bhalla, 1983). The stars represent the mean 'normal' direction (MN) and the mean 'reverse' direction (MR). Directional data have been reduced to a common site location at 19° N, 81.5° E. The reversal test (McFadden and McElhinney, 1990 is classified as R_b). See Table 2 for individual directions.

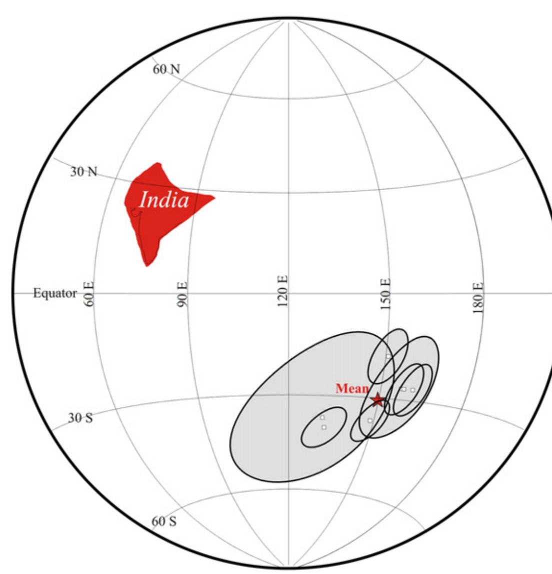

Fig. 5. Map (Schmidt projection) of virtual geomagnetic poles from this study along with those of Clark (1982) and Kumar and Bhalla (1983) along with the mean paleomagnetic pole calculated in this study (see Table 2).

patterns of mafic dyke swarms (Rogers and Santosh, 2002, 2009; Zhao et al., 2002, 2004; Kusky and Santosh, 2009; Ernst et al., 2010; French and Heaman, 2010; Hou et al., 2008). In particular, the reconstruction of Zhao et al. (2002, 2004) is argued on the basis of geological connections between cratonic nuclei and the presence of 2.1–1.8 Ga orogenic belts (Fig. 6a).

The paleomagnetic database for the Paleoproterozoic improved over the past decade as more attempts focused on the integration of paleomagnetic data with precise age constraints. This improvement was possible due to the ability to find, separate and date small uranium-bearing accessory minerals in mafic dykes (see reviews in Söderlund et al., 2010). Below we discuss some recent well-dated paleomagnetic results from other cratonic blocks that yield a glimpse into the global paleogeography at 1.9 Ga (Table 3).

Our new paleomagnetic results from the Bastar/Cuddapah region of India allow us to position the Dharwar, Singhbhum and Bastar cratons of India at 1.9 Ga. Although these blocks may have connected much earlier, the Bastar–Singhbhum cratons were united by at least 2.5 Ga and the paleomagnetic and geochronologic data presented here and by French et al. (2008) support an existing connection between the Bastar–Singhbhum and Dharwar cratons at 1.9 Ga.

There is some debate regarding the timing of collision between the Aravalli and Bundelkhand cratons (the northern Indian blocks) with the Bastar–Dharwar–Singhbhum cratons (the southern Indian blocks; Meert et al., 2010). The Central Indian Tectonic Zone (CITZ, Fig. 1a) represents the locus of the collision between the northern and southern blocks. Stein et al. (2004) argued that the major phase of collision was completed by 2.5 Ga. Other authors argue for a younger 1.9–1.6 Ga collision between the northern and southern blocks (Acharyya, 2003; Naganjaneyulu and Santosh, 2010; see also Zhang et al., 2011). We note that even the models that argue for a Paleo-Mesoproterozoic assembly of India place the northern and southern Indian blocks in close proximity by 2.3 Ga. Thus we argue that most of Peninsular India, with the exception of small parts of the southern granulite region was assembled by at least 1.9 Ga and most likely earlier.

The Plum Tree volcanics in northern Australia (Pine Creek Inlier) were dated at 1.82 Ga and a preliminary pole was cited in Idnurm and

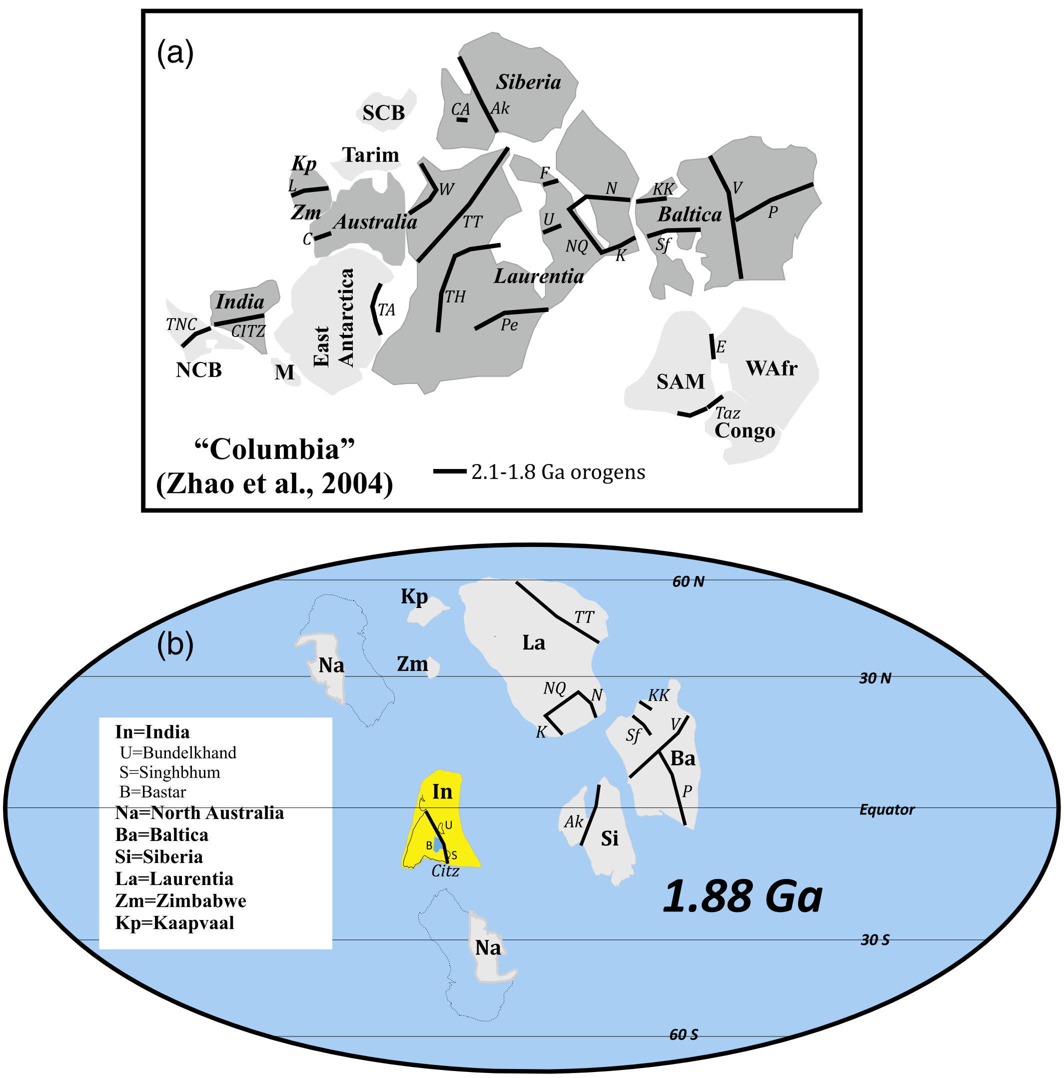

Fig. 6. (a) Columbia reconstruction according to Zhao et al. (2002, 2004). Dark-shaded cratons have paleomagnetic data available at 1.9 Ga and lighter shaded cratons have no paleomagnetic data (Table 3). Legend Kp = Kaapvaal craton; Zm = Zimbabwe craton; NCB = North China Block; SCB = South China Block; M = Madagascar; SAM = South America blocks (Amazonia, Rio de la Plata); WAfr = West Africa; 2.1–1.8 Orogens (smaller italics); TNC = Trans North China; CITZ = Central Indian Tectonic Zone; TA = Transantarctic; C = Capricorn; L = Limpopo; CA = Central Aldan; Ak = Akitkan; W = Wopmay; TT = Taltson-Thelon; TH = Trans-Hudson; Pe = Penokean; F = Foxe; U = Ungava; NQ = Nugssugtoquidian; K = Ketilidian; Sf = Svecofennian; V = Volhyn; P = Pachelma; KK = Kola-Karelian; E = Eburnean; Taz = Trans Amazonian. (b) Paleogeographic reconstruction based at ~1.9 Ga based on the paleomagnetic poles given in Table 3. Note that Northern Australia is shown using both polarity options. Select orogens are included for comparative purposes to Fig. 6a.

Table 3
Ca. 1.88 Ga paleomagnetic studies.

Pole name	Continent	Age	Plat	Plong	A95	Ref.
Bastar dykes	India	1.88 Ga	31° N	330° E	12°	This study
Plum Tree volcanics	Australia	1.82 Ga	29° S	195° E	14°	Idnurm and Giddings (1988)
Akitan Group	Siberia	1.87 Ga	31° S	99° E		Didenko et al. (2009)
Molson dykes-B	Laurentia	1.87 Ga	27° N	219° E	4°	Halls and Heaman (2000)
Mean Baltica	Baltica	1.88 Ga	41° N	233° E	5°	Pesonen et al. (2003)
Post-Waterberg	Kaapvaal	1.87 Ga	9° N	015° E	14	Hanson et al. (2004); de Kock (2007)
Black Hills	Kaapvaal	1.88 Ga	9° N	352° E	5	Lubnina et al. (2010)
Mashonaland Sills	Zimbabwe	1.88 Ga	8° N	338° E	5°	Bates and Jones (1996)

Giddings (1988) and Idnurm (2004) without analytical details. Slightly younger poles (~1.79 Ga) from northern Australia yield lower paleolatitudes and Schmidt and Williams (2008) proposed a progression of poles for the region starting with the Plum Tree volcanics pole. We note the tentative nature of this pole, but use it in our reconstruction (Fig. 6). The assembly of the Australian continent was not completed at 1.8 Ga (Cawood and Korsch, 2008) although some contiguity was suggested for the northern Australian blocks and southern Australian blocks. Our reconstruction uses only northern Australia with the caveat that both Western Australia and southern Australia may have been in close proximity at this time (Korsch et al., 2011).

Siberia's paleolatitude is well-constrained at 1.878 ± 0.004 Ga based on recent results from the Akitan Group (south Siberia). This paleomagnetic result has a positive fold test and an intra-formational conglomerate test (Didenko et al., 2009). The Siberian craton was assembled during the interval from 2.1 to 1.9 Ga and the two major Archaean blocks (Aldan and Anabar shields) were united along with several smaller "building blocks" during that interval (see Gladkochub et al., 2006).

Paleomagnetic studies on the Molson dykes of the western Superior craton (Laurentia) provide a latitudinal constraint for the Superior craton. Halls and Heaman (2000) document several poles from this swarm and argue that the Molson-B dykes pole dates to 1.87 Ga. These dykes were emplaced into the Superior craton during the latter phase of the Trans-Hudson orogeny in a back arc rift setting. The Trans-Hudson orogen represents the collision of the Slave–Rae–Hearne blocks with the Superior craton. The other large craton of Laurentia is the Wyoming craton that was incorporated with the Slave–Rae–Hearne blocks at about 1.86 Ga although the collision may have been protracted with final assembly around 1.77 Ga (Mueller et al., 2005). Given that all three of the major Laurentian nuclei were in close proximity at 1.86 Ga, we use the Molson-B pole as representative for Laurentia (including Greenland).

Paleomagnetic data from Baltica are derived from the compilation of Pesonen et al. (2003). The Baltica pole is a mean pole based on results from the 1.87–1.89 Ga Vittangi, Kiuruvesi, Pohjanmaa and Jalokoski gabbros and diorites.

The remaining paleomagnetic poles used in our reconstruction are from the Kaapvaal and Zimbabwe cratons of southern Africa (Hanson et al., 2004; de Kock, 2007; Lubnina et al., 2010; Bates and Jones, 1996). The Black Hills dykes and post-Waterberg dykes have similar paleomagnetic poles and are well-dated to 1.87–1.88 Ga (Söderlund et al., 2010). The welding of the Kaapvaal and Zimbabwe cratons took place sometime between 1.90 Ga and 2.06 Ga (Lubnina et al., 2010) so poles from the Zimbabwe craton and Kaapvaal craton should be fairly similar at 1.88 Ga. Bates and Jones (1996) established a pole for the Mashonaland sills of the Zimbabwe craton (1.88 Ga) with a pole that is only slightly different than the Black Hills Kaapvaal craton pole. These results support the idea that the 1.88 Ga magmatic activity in both the Zimbabwe and Kaapvaal cratons was also spatially linked.

The reconstruction shown in Fig. 6b can be compared to the prediction of Zhao et al. (2002, 2004) for the supercontinent of Columbia (Fig. 6a). The existence of the Columbia supercontinent is based on geological arguments and principally upon the existence of 1.8–2.1 Ga orogenic belts within its constituent cratons (Fig. 6a). In an attempt to test the Columbia configuration we position the continents with respect to their orientation and latitudinal position based on the paleomagnetic data in Table 3. The continents are then moved longitudinally into position so that we can compare our reconstruction with the Columbia model of Zhao et al. (2002, 2004).

There is very little resemblance to Columbia with the exception of the relationship of Baltica and Laurentia. The model of Zhao et al. (2002, 2004) requires that India should be positioned at high latitudes along with Australia and the South African blocks and adjacent to the North China craton (Zhao et al., 2003; Hou et al., 2008). According to the paleomagnetic data in Table 3, India is located at equatorial latitudes, northwest Australia and the Kaapvaal/Zimbabwe cratons at mid latitudes (either north or south depending on polarity choice). Zhao et al. (2002, 2004) have Kaapvaal/Zimbabwe cratons adjacent to Western Australia (Fig. 6a). Thus, although neither South Africa nor Australia is positioned in the location prescribed by the Columbia model, their latitudinal disposition with respect to each other is consistent with the relationships proposed by Zhao et al. (2002, 2004).

In the Columbia model, Siberia is positioned along the present-day Arctic margin of Laurentia. The paleomagnetic data of Didenko et al. (2009) place Siberia at the equator at 1.88 Ga that is inconsistent with the reconstruction of Zhao et al. (2002, 2004).

Although there are only limited paleomagnetic data from a small number of cratons at 1.88 Ga, most of the poles are well-constrained in time and space. Thus we cannot dismiss the possibility of a Columbia supercontinent during the Paleoproterozoic, though we can confidently reject some of the relationships between cratons shown in the model of Zhao et al. (2002, 2004) at 1.9 Ga.

8. Conclusions

Paleomagnetic results from a pilot study of dykes intruding the Bastar craton combined with coeval volcanic and dyke rocks at the margins of the Cuddapah basin (Dharwar craton) support the notion of French et al. (2008) that they are temporally and spatially linked and may have been part of a large igneous province. This province was tentatively linked with both Laurentia and North China (Zhao et al., 2003; Hou et al., 2008; French et al. 2008) on the basis of geometric relationships of radiating dykes. We can discard the correlations between Laurentia and India, but the North China craton lacks paleomagnetic data from this time period and so the links between India and North China as proposed by Zhao et al. (2003) remain paleomagnetically untested. We do note that paleomagnetic data from India at ~1.8 Ga and a slightly younger pole from North China (Halls et al., 2000; Pradhan et al., 2010) both yield low-latitude directions supporting the correlations of Zhao et al. (2003, 2004) and Hou et al. (2008).

There are several robust paleomagnetic poles for this same time period from northern Australia, Laurentia, Baltica, Siberia and the

Kaapvaal and Zimbabwe cratons that allow us to test one possible Columbia configuration. There are some key differences in the model of Zhao et al. (2002, 2004) and the relationships between the cratons discussed in this paper. This would require (a) the dismissal of the Columbia supercontinent or (b) that the supercontinent has a different configuration than the one proposed by Zhao et al. (2002, 2004) or (c) that Columbia assembly was not complete until 1.8 Ga and therefore our reconstruction yields a snapshot of that assembly process. Thus we feel it is more reasonable to use the reconstruction of Zhao et al. (2002, 2004) as a starting point that can be modified as new well-dated poles are added to the database.

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