Indian Dykes
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A Cautionary note on the Age of the Paleomagnetic pole obtained from the Harohalli Dyke swarms, Dharwar Craton, Southern India

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Abstract

Radiometric dating of mafic intrusive and extrusive rocks poses a problem due to the paucity of dateable minerals. A significant amount of paleomagnetic work has been done for the Precambrian mafic dyke swarms in the Harohalli-Bangalore region (Dharwar craton, southern India). Two suites of dykes are present in the Harohalli region. The first, a series of ~E-W trending doleritic dykes were previously assigned an Rb-Sr whole rock isotopic age of 2370±230 Ma and U-Pb ages of 2365.5±1.1 Ma and 2370±1 Ma. Isotopic ages reported for the ~N-S trending younger suite of dykes range between 800-850 Ma.

We sampled three dykes in the Harohalli region with the goal of providing a robust age for the younger alkaline dykes and also to add additional sites to the paleomagnetic pole. A grand mean paleomagnetic pole is calculated at 24.9° S, 258° E (A95=15°). A secondary component observed in this and previous studies yields a paleomagnetic pole at 76.5° S, 68.8° E (α_{95}=8.4°) that we interpret as a remagnetisation of Ediacaran age.

Two of the dykes yielded zircon crystals and fragments for U-Pb dating using LA-MS-ICP-MS methods. Six laser spots from three different zircons yielded a concordant U-Pb age of 1192±10 Ma. In addition, a discordia fit using these grains and several fragments yielded a lower intercept age of 506 $^{+18}/_{-19}$ Ma and an upper intercept at 1212 $^{+20}/_{-21}$ Ma. The lower age may represent Pb-loss event associated with the final assembly of Gondwana and the upper intercept is interpreted as being close to the preferred 1192 Ma crystallisation age of the dykes. A second dyke yielded a total of 15 concordant zircons with an age of 2941±14.2 Ma (MSWD=1.3) reflecting inheritance from the Peninsular gneisses.

The implications of this new age for the Harohalli alkaline dykes means that previous conclusions regarding true polar wander during the Neoproterozoic and Rodinia reconstructions need to be re-evaluated. A tentative reconstruction at ~1.2 Ga places Laurentia, Australia and India at intermediate to high latitudes in a configuration quite different from archetypal Rodinia.

Keywords: Paleomagnetism, Age, Harohalli, Dyke swarms, Dharwar craton, Southern India.

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Introduction

The Precambrian basement of the south Indian peninsular shield is made up of granite-greenstone belts which are crisscrossed by several generations of dolerite, and alkaline dykes (Halls, 1982) NOT IN THE LIST. These mafic intrusive dykes, particularly from the Harohalli region of the Dharwar craton exposed south of Bangalore city, are the source of some high-quality paleomagnetic data from India for the Proterozoic (Fig. 1). Accordingly, a rather robust paleomagnetic dataset had been generated by various groups of workers for these Meso- to Neoproterozoic mafic intrusives (Naqvi et al., 1974; Hargraves and Bhalla, 1983; Radhakrishna and Mathew, 1993; Dawson and Hargraves, 1994; Radhakrishna and Mathew, 1996; Halls et al., 2007). The main problem is that there is a paucity of robust radiometric ages for the younger of these paleomagnetically significant dykes.

The local geological setting of the Harohalli region consists of a basement gneissic complex (~2900 Ma BGC-Peninsular gneisses) and the elongated body of the Closepet Granite (~2500 Ma), both trellised by various dyke intrusions. Separate geochronological studies had been carried out and two distinct sets of dykes have been reported in the area by various workers. The older set of dykes consists of a series of ~E-W trending doleritic dykes that were dated by Rb-Sr whole rock methods at 2370±230 Ma by Ikramuddin and Stueber (1976) and have been more recently dated by U-Pb methods at 2365.5±1.1 Ma by French et al. (2004). Additional work on correlative dykes by Halls et al. (2007) yielded a robust U-Pb age of 2370±1 Ma. Halls et al. (2007) refers to these older dykes as the Bangalore dyke swarm and we follow that terminology in our paper. The younger dykes are referred to as the Harohalli alkaline dykes.

The Harohalli alkaline dykes, trending in ~N-S directions (Fig. 1) were dated by Ikramuddin and Stueber (1976) at 814 ± 34 Ma (Rb-Sr whole rock) and 810 ± 25 Ma (K-Ar whole rock). Later Anil-Kumar et al. (1989) reported a whole rock-feldspar Rb-Sr age of 823 ± 15 Ma. These results were considered to represent strong evidence for an 850-800 Ma age for the alkaline dykes of Harohalli. The ages are cited by numerous authors investigating the assembly of Gondwana, the breakup of Rodinia as well as geodynamic models positing rapid true polar wander (Meert and Powell, 2001; Meert, 2003; Meert and Torsvik, 2003; Li et al., 2004; Maloof et al., 2006; Piper, 2007).

Igneous intrusive events in the Dharwar craton are not limited to the Harohalli dykes. A series of dykes and igneous intrusions can be found in many areas throughout the Dharwar craton, but most have poor age control. We call attention to some recent studies with robust geochronology from the Dharwar craton. Kumar et al. (2007) reported precise U-Pb perovskite and Rb-Sr phlogopite ages of 1.1 Ga for the kimberlites from eastern Dharwar craton, which they linked with a short-lived mantle plume activity that took place in this region. Dykes from the Bastar and Dharwar cratons were recently shown to be part of a large 1883-1891 Ma large igneous province by French et al. (2007). Patranabis-Deb et al. (2007) examined igneous rocks capping the Chattisgarh basin and argued that this particular Purana basin was some 500 Ma older than assumed. The ages obtained from the Chattisgarh basin are in the range from 990-1020 Ma.

The present study of the Harohalli alkaline dykes attempt to examine the igneous history of the younger suite of dykes using LA-ICP-MS geochronologic methods and provide robust constraints on the age of the Harohalli alkaline dyke swarm paleomagnetic pole.

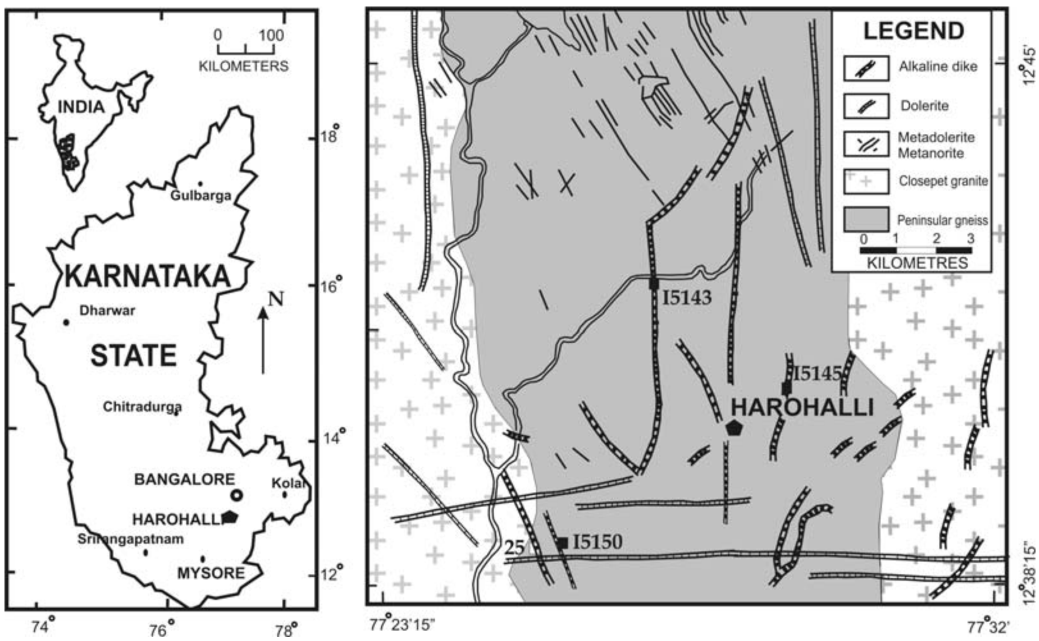

Figure 1: Map of the Harohalli region in Karnataka showing the location of dikes used in this study (after Dawson and Hargraves, 1994). Site 25 (white box) is a sample from Radhakrishna and Joseph (1996). Geochronologic samples that yielded zircon are I5143 and I5145.

Paleomagnetism of the Harohalli Alkaline Dykes

The dykes sampled for geochronologic study were also sampled for paleomagnetic study. Samples were drilled in the field using a water cooled gasoline-powered hand drill and oriented using both sun and magnetic compass. Due to deep tropical weathering in the region, samples were removed from ‘boulders’ of dyke that looked to be in place. In the case of dykes I5145 and I5150 there was no ambiguity about the *in-situ* nature of the sampled material. I5143 was sampled carefully, but it was not always clear whether or not the material sampled was in place or boulders. Samples were then cut and measured using a Molspin spinner magnetometer at the University of Florida. Pilot samples were subjected to detailed stepwise alternating field (AF) or thermal demagnetisation and the remaining samples were treated based on the best response.

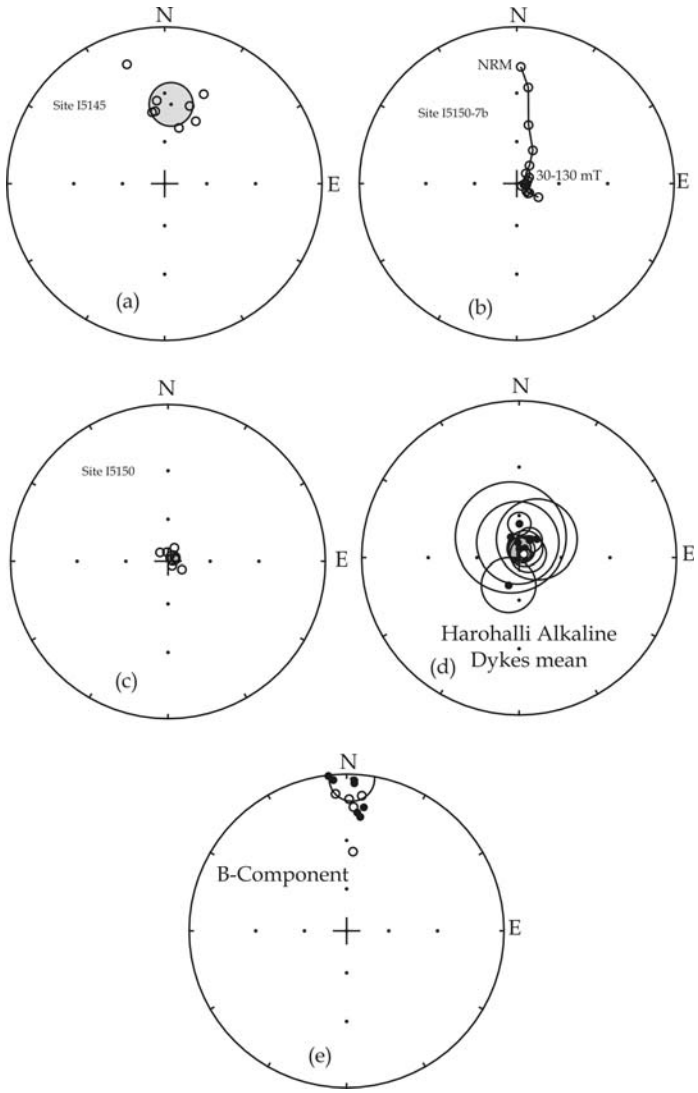

Figure 2: (a) Stereoplot of directions obtained from the dike at Site I5145 (b) example of alternating field demagnetisation of sample I5150-7b from site I5150 showing removal of a northern and shallowly directed overprint and a great-circle trend towards an easterly and steeply up direction. (c) Individual samples and mean direction for site I5150 (d) Compiled results from 3 studies on the alkaline dikes at Harohalli (overall mean direction is shaded). (e) stereoplot of B-component directions reported here and in Halls et al. (2007) converted to a common site location at 12.6° N, 77.4° E. In all stereoplots open/closed circles represent up(-)/down(+) inclinations.

Dyke I5143 yielded no consistent paleomagnetic directions although individual samples were well behaved. The results confirmed our suspicion that the boulders we sampled were not all *in-situ*. Dawson and Hargraves (1994) also sampled this dyke but did not obtain any useful paleomagnetic results. Dyke I5145 gave consistent directions that were to the north and intermediate up with a mean declination=4.6° and inclination=-36.2° (k=21, α95=12.6°; n=8; Fig. 2a; Table 1). Dyke I5150 shows a low coercivity direction to the north and shallow up (Table 1; Dec=6.4°, I=-8.1°, k=253, α95=3.8°, n=7). This direction is distinct from the present earth's field direction, but comparable to the B-direction obtained by Halls et al. (2007). Halls et al. (2007) interpreted the ubiquitous B-component observed in the Bangalore swarm as an Ediacaran-Cambrian remagnetisation (Fig. 2e). The remaining I5150 dyke samples were treated by AF demagnetisation. Dyke I5150 yielded a well-defined high-coercivity grouping with a mean declination=52.3° and inclination= -85.7° (k=134, α95=4.8°, n=8) with a resultant virtual geomagnetic pole at 7.3° N, 70.6° E (Fig. 2b and 2c). The direction and pole are similar to the directions reported from the adjacent dyke (site 25; Fig. 1) by Radhakrishna and Mathew (1996).

Table 1: Paleomagnetic Results from Alkaline Dikes near Harohalli.

Site	N	Dec	Inc	k	α_{95}	Plat	Plong	Reference
18	5	18.4°	83.9°	65	9.5°	23.8° S	261.6° E	Dawson & Hargraves, 1994
21	6	32°	82.0°	28	12.8°	25.6° S	266.8° E	Dawson & Hargraves, 1994
17	5	30.9°	75.2°	77	9.0°	35.8° S	274.7° E	Radhakrishna & Mathew, 1996
19	3	337.9°	73.9°	11	38°	39.9° S	243.3° E	Radhakrishna & Mathew, 1996
20*	4	200.5°	68.5°	43	19°	23.4° N	244° E	Radhakrishna & Mathew, 1996
21	3	355.1°	79.1°	18	29°	33.4° S	255.5° E	Radhakrishna & Mathew, 1996
22	3	0.5°	65.7°	239	8°	54.5° S	258.2° E	Radhakrishna & Mathew, 1996
24	4	43.7°	71.5°	12	28°	35.1° S	285.5° E	Radhakrishna & Mathew, 1996
25	3	67.4°	-82.8°	28	13°	6.9° N	64.4° E	Radhakrishna & Mathew, 1996
I5150-low	7	6.4°	-8.1°	253	3.8°	72.1° S	56.2° E	This study-B Component
I5150-high	8	52.3°	-85.7°	134	4.8°	7.3° N	70.6° E	This study-A Component
I5145-high	8	4.6°	-36.2°	21	12.6°	57° S	69.5° E	This study-B Component
Mean- B**	12	2°	-1.6°	27	8.4°	76.5° S	68.8° E	This study and Halls et al., 2007
Mean	8 N	10.4°	81.1°	33	9.8°	29.7° S	261° E	This study-A
Mean	2 R	61.5°	-84.3°	---	---	7.1° N	67.4° E	This study-A
Overall Mean	*10*	*2.3°*	*83.6°*	*34*	*8.4°*	*24.9 S*	*258°E*	*This study-A*

*Recalculated pole originally reported incorrectly at 7.8° S, 251.3° E.
**Calculated for a site at 12.6°N, 77.4° E.
Dec=declination, Inc=inclination, k=kappa precision parameter; α95=cone of 95% confidence about the mean Direction, Plat=Paleopole latitude, Plong=Paleopole longitude

Two separate high-latitude paleomagnetic poles have been published for the Harohalli/Bangalore dykes. The paleomagnetic pole for Bangalore suite of dykes was reported by Dawson and Hargraves (1994) at 9.5° S, 242.4° E (α_{95}=9.0°). Multiple studies on the Harohalli alkaline dykes (Dawson and Hargraves, 1994; Radhakrishna and Mathew, 1996) yield a grand mean result with a declination of 2.3° and an inclination of +83.6° (k=34,

$\alpha95$=8.4°; n=10 including one new site from our visit in 2005; Table 1; Fig. 2d). The resultant mean paleomagnetic pole is located at 24.9° S, 258° E (A95=15°). We note that while the overall mean result from these dykes has a good grouping and small α_{95}, four of the ten dykes had α_{95} values exceeding 15° and 4 dykes had only 3 samples. Nevertheless, this pole is typically cited as a key ~823 Ma pole for India and has been used to make a variety of tectonic/geodynamic conclusions (Li et al., 2004; Maloof et al., 2006).

The paleomagnetic poles obtained from the ~2370 Ma Bangalore dyke swarm overlap with the younger alkaline suite and this led Dawson and Hargraves (1994) to speculate about possible remagnetisation of the Bangalore suite of dykes. A more detailed examination of coeval dykes throughout the region by Halls et al. (2007) concluded that the older Bangalore suite of dykes carry a near primary magnetisation that is fortuitously coincident with the directions from the younger Harohalli alkaline dykes.

Geochronology of the Harohalli Dykes

For the current study, four dyke samples varying in composition from alkaline to dolerite were analysed for their U-Pb isotopic signatures (Fig. 1). Zircon grains were concentrated through standard gravity and magnetic techniques from pulverized samples. The doleritic samples were first crushed, disk milled and sieved to a fraction of grain size < 125µm to liberate as many zircon grains as possible. These were then rinsed, followed by water table treatment with slow sample feed rates. This was followed by heavy liquid mineral separation with multiple agitation periods to reduce the number of entrapped grains in the lower density fraction. The final step involved repeated passes on a Frantz Isodynamic separator up to a current of 1.0 A (2-4° tilt). Approximately 30-50 fresh looking, euhedral to almost anhedral zircon grains were handpicked from the two samples labeled I5143 and I5145 under an optical microscope to ensure the selection of only the clearest grains and fractions of grains, mounted first in resin and then polished to expose median sections. The plugs were sonicated and cleaned in nitric acid to remove any common Pb surface contamination. U-Pb concentrations were collected and analysed using the University of Florida Nu LA-MC-ICP MS system. Data calibration and drift corrections were based on the Forest Centre-1 (Duluth Gabbro) zircon standard, dated at 1099.1±0.5 Ma (Black et al., 2003) NOT IN THE LIST, and corrected for common Pb using the $^{207}Pb/^{206}Pb$ correction outlined in Williams (1998). FC-1 which is used as the zircon standard for calculation of all the ages are typically large, clear, colorless, inclusion free and sector zoned. A laser beam diameter of 40µm and laser energy density of ~10 J/cm^2 was applied to analyse the samples I5143-a, b and c. A few of these analyses were discarded on account of high levels of observed discordance interpreted to reflect incorporation of common lead.

All isotopic analyses were performed on a "New Wave" 213 nm Laser Ablation-Multi Collector-Inductively Coupled Plasma Mass Spectrometer (LA-MC-ICPMS) at University of Florida. The ablated material was mixed with Ar gas (~1.3L/min) after the ablation cell and introduced in the plasma. The isotopic ratio data were acquired in static mode using 5 Faraday collectors using TRA (time resolved analysis) software. The isotopic data was corrected for elemental fractionation, gas-flow drift and mass bias using a raster ablation protocol with the help of simple empirical correlation factor derived for an external zircon of known age and applying it to the unknown sample (Jackson et al., 1996; Ketchum et al., 2001; Knudsen et al., 2001) NOT IN THE LIST. The measured Pb/U ratios for the used FC-1 zircon standards were $^{206}Pb/^{238}U$=0.18503 and $^{207}Pb/^{235}U$=1.94286 respectively.

The corrected Pb/U ratios for the sample $R_{sample}(true)$ was then derived using this correction factor from the calculated ratios of known $R_{std}(true)$ and averaged measured $R_{std}(meas)$ values for FC-1 by the following relation:

$$[\ (R_{sample}(true) = (R_{sample}(meas) * (R_{std}(true)/\ (R_{std}(meas.)\ ]$$

Zircons may have high ratios of radiogenic Pb to common Pb. A robust common Pb correction is therefore essential for the application of U-Pb geochronology to mineral that contains appreciable amounts of common Pb. We corrected our isotopic data for the common lead using the $^{207}Pb/^{206}Pb$ correction outlined in Williams (1998). All analyses were done by using previous measured blanks determined on pure Ar gas.

Geochronologic Results

U-Pb ages from the zircon were determined for two out of five Harohalli alkaline dyke samples. The first dyke (I5145) yielded zircon blades and fragments. A second N-S trending dyke (I5143) near Harohalli yielded one well-faceted zircon and several fragments/tips of zircon (Fig. 3a).

Six laser spots from three different zircons (sample I5143) yielded a concordant U-Pb age of 1192±10 Ma (2σ; MSWD=2.4; Fig. 3a). Six spots on 3 fragments and tips (sample I5143) yielded discordant ages ranging from from 580-1139 Ma. A discordia fit using these grains (forced through the three concordant grains noted above) yielded a lower intercept age of 506 $^{+18}/_{-19}$ Ma and an upper intercept at 1212 $^{+20}/_{-21}$ Ma (MSWD=1.15; Fig. 3b). The lower age may represent Pb-loss event associated with the final assembly of Gondwana (Collins et al., 2007; Meert, 2003) and the upper intercept is within error of the 1192±10 Ma crystallisation age of the dyke. Analytical data are given in Appendix A.

Dyke I5145 yielded 15 grains of zircon which gave a concordant age of 2941±14.2 Ma (2σ; MSWD=2.2; Fig. 4). The implication of this age is discussed below. Analytical data are given in Appendix B.

Discussion

The paleomagnetic pole from the alkaline suite of the Harohalli dykes has been updated and recalculated at 24.9° S, 258° E (A95=15°). The paleomagnetic directions from 10 dykes show a dual-polarity magnetisation. The mean of 8 normal polarity dykes yields a declination=10.4° and an inclination of +81.1° (Table 1). Two reverse polarity dykes yielded a mean declination=61.5° and an inclination of -84.3°. A reversal test (McFadden and

McElhinny, 1990) was negative (critical angle λ_c=7.0°; observed angle λ_o=15.8°) signifying that the angle between the normal and reverse directions is much larger than required for a common mean direction. Because of the limited number of reversely magnetized sites, the test may simply be an indication that those two dykes did not adequately average secular variation.

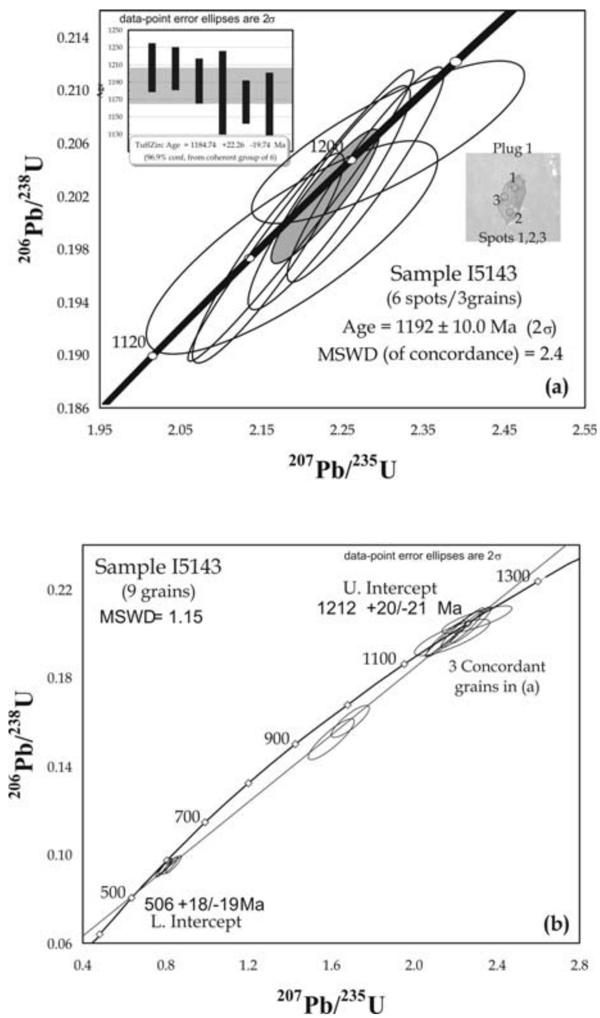

Figure 3: (a) U-Pb concordia diagram for concordant zircons from sample I5143. inset: '*tuffzirc*' analysis (Ludwig, 2003) for the concordant grains yielding an age of 1184.7 $^{+22.2}/_{-19.7}$. (b) Discordia plot using fragmentary zircons from I5143 and the 6 concordant analyses in (a). Upper intercept age is 1212 $^{+20}/_{-21}$ and the lower intercept age is 506 $^{+18}/_{-19}$. Photo of zircon grain from plug 1 grains 1-3 (Appendix A).

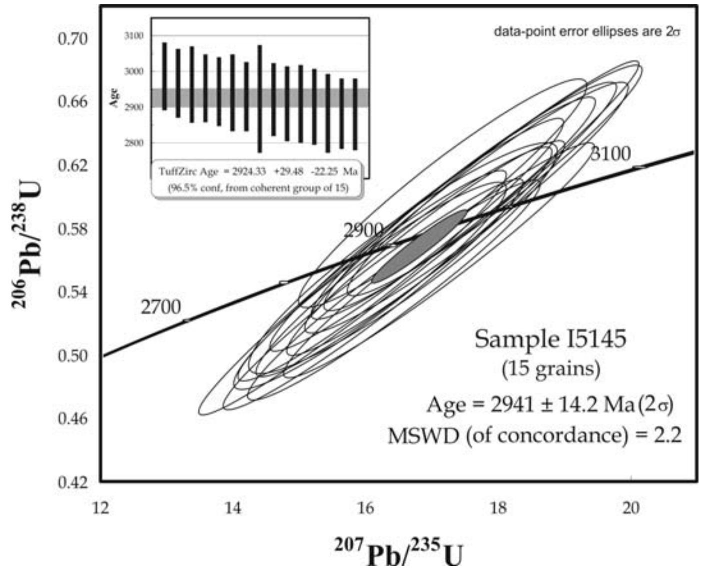

Figure 4: (a) U-Pb concordia diagram for concordant zircons from sample I5145. inset: '*tuffzirc*' analysis (Ludwig, 2003) for the concordant grains yielding an age of 2924.3 $^{+29.5}/_{-22.3}$.

The previous age estimates for the alkaline dykes at Harohalli are called into question by our current study. Although only 2 N-S trending dykes contained dateable material, neither of these alkaline dykes gave ages in the range from 800-900 Ma. The most concordant grains yielded an age of 1192±10 Ma which is far older than all previously published ages on the Harohalli and supposedly correlative dykes (Ikramuddin and Stueber, 1976); Anil-Kumar et al., 1989 and Devaraju et al., 1995).

The study by Ikramuddin and Stueber (1976) used only whole rock samples to derive their K-Ar and Rb-Sr ages. While whole-rock Rb-Sr and K-Ar ages may yield reasonable age estimates, the geochemical/geological requirements for whole-rock dating-especially for older mafic dykes, are strict and rarely met (Bernard-Griffiths, 1989).

The most detailed geochemical and geochronological study of related dykes was conducted by Devaraju et al., 1995). The study by Devaraju et al. (1995) on alkaline dykes from southern India considered equivalent to the N-S trending alkaline dykes at Harohalli yielded two distinct ages. According to that study, a regression on 6 whole rock samples yielded an isochron with an age of 1046±21 Ma (2σ) and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70476 ± 0.0001. Devaraju et al. (1995) rejected the data from one of the dykes and arrived at an isochron age of 832±40 Ma for the alkaline dykes.

We have re-analysed the data reported in the paper by Devaraju et al. (1995) using the ISOPLOT (Ludwig, 2003) programme and were unable to reproduce the ages based on the data reported in the paper. A robust regression (Ludwig, 2003) through all 6 whole rock data points yields an age of 883 $^{+130}/_{-220}$ Ma (MSWD=76; $(^{87}Sr/^{86}Sr)_i$=0.7065; Fig. 5a). According to their analysis a better fit was obtained by removing one sample from the group. We find a slightly poorer 'errorchron' is generated from a robust regression of these data at 806 $^{+160}/_{-320}$ Ma (($^{87}Sr/^{86}Sr)_i$ = 0.7079) Fig. 5b). Although both overlap with previously cited ages for the Harohalli dyke swarm neither is a particularly good fit.

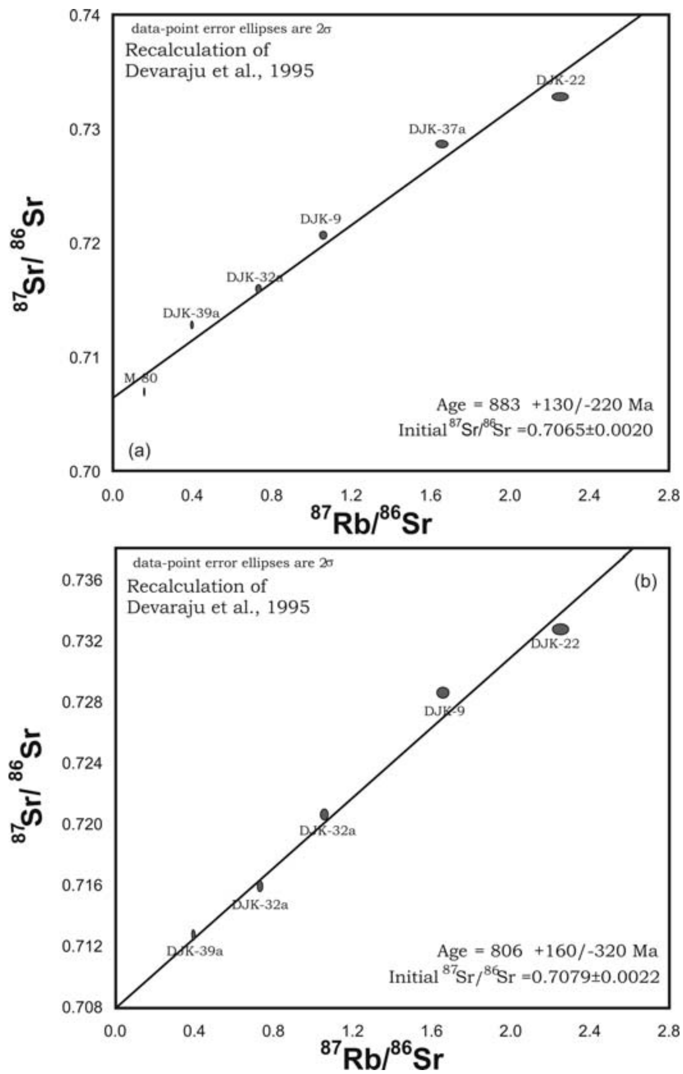

Figure 5: (a) Recalculated rubidium-strontium isochron analysis of data reported by Devaraju et al., 1995 for alkaline dikes in Karnataka using all data reported in that paper and (b) recalculated rubidium-strontium isochron analysis of data in the Devaraju et al. (1995) paper removing sample M-80. Both results differ from ages reported in the original paper.

Data from dyke I5145 (Fig. 1) yielded 15 concordant zircons with a concordant age of 2941 ± 14.2 Ma (MSWD=2.2; Fig. 4). There are no known dykes of this age in peninsular India, but the Peninsular gneisses are of this approximate age (Mojzsis et al., 2003). Our interpretation is that this dyke contains a suite of inherited zircons from the basement region. Paleomagnetic data from this dyke show only an northerly and shallow-up direction similar to the B-directions reported by Halls et al. (2007) and also the low-coercivity and high-temperature directions in dyke I5150 (Fig. 2e and Table 1). We interpret this as an overprint of ~Ediacaran age and it may correspond to the slightly discordant ~590 Ma ages observed in sample I5143 (Fig. 3b; Appendix A).

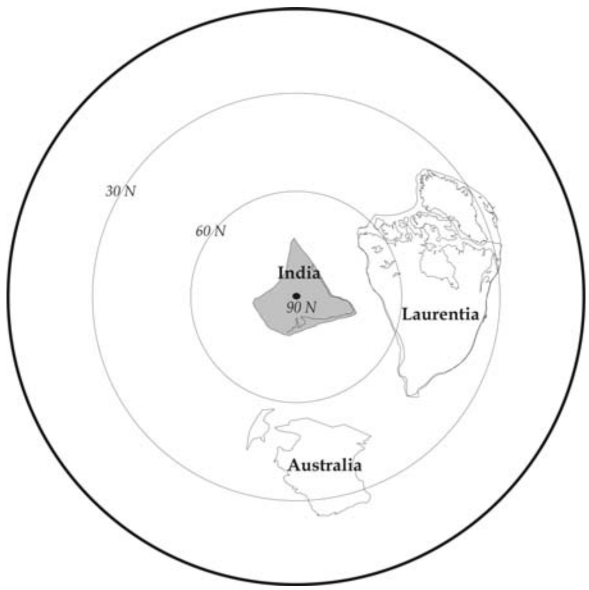

Figure 6: Reconstruction at ~1.15 Ga based on our new age and data reported in Pesonen et al. (2003).

Conclusion

The Harohalli alkaline dykes pole has been treated as a robust paleomagnetic pole for the Indian continent in spite of the poor age controls on the dyke. Previous estimates on the dykes resulted in broadly consistent Rb-Sr and K-Ar whole rock ages between 800-850 Ma. We report here the first attempt to date the dykes using the U-Pb method and have obtained a concordant age of 1192±10 Ma (2σ; MSWD=2.4) for one of the largest alkaline dykes in the area. A second dyke yielded 15 concordant zircons with an age of 2941±14.2 Ma (2σ; MSWD=2.2). This age is considered to reflect inheritance from the basement rocks in the region.

We treat our new age with some caution as it requires an almost 400 Ma revision in the age of the Harohalli alkaline dykes. We also note that the dyke which yielded the 1192 Ma age did not yield paleomagnetic directions and the dyke that yielded paleomagnetic directions did not yield any useful minerals for geochronology. Since the Harohalli dykes intrude the Peninsular gneiss (2.9 Ga) and the Closepet granite (2.5 Ga) these would be the most likely sources of inherited zircons. Inheritance of 1192 Ma zircons is considered an *ad-hoc* explanation for the age obtained here.

An interesting implication of our new age is that it would place India adjacent to both Australia and Laurentia in a ca. 1.2 Ga reconstruction (Fig. 6; Pesonen et al., 2003). Lastly, we note that several extreme geodynamic models (inertial interchange and true polar wander events) have been proposed based in part on presumed ~823 Ma age for the Harohalli alkaline dykes (Li et al., 2004; Maloof et al., 2006). If our new age data are indeed accurate, then those geodynamic models become less well-constrained.

We are continuing our work on the Harohalli alkaline dykes, but we urge caution in the uncritical use of the extant paleomagnetic and geochronologic results from these dykes.

Acknowledgements

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Appendix A-I5143

Grain	^{207}Pb/^{206}Pb	1σ error	^{206}Pb/^{238}U	1σ error	*^{207}Pb/^{235}U	1σ error	^{206}Pb/^{238}U	1σ	^{207}Pb/^{235}U	1σ	^{207}Pb/^{206}Pb	1σ	% Disc
Plug-1													
I5143_1	0.06345	0.00008	0.15998	0.00089	1.6473	0.098	1194	17.9	1206	12.3	1226	12	1
I5143_2	0.06273	0.00022	0.15849	0.0012	1.4725	0.089	1185	18.6	1191	12.9	1204	14	1
I5143_3	0.06201	0.0002	0.15489	0.00093	1.48487	0.09	1160	17.6	1167	12.4	1181	14	1
I5143_4	0.04810	0.00016	0.07357	0.00057	0.49256	0.0075	576	9.5	593	8.3	659	15	3
I5143_5	0.04927	0.00018	0.07477	0.00044	0.52290	0.0071	584	9.3	611	8.2	710	15	4
I5143_6	0.04828	0.00012	0.07429	0.00029	0.50903	0.013	581	8.9	599	7.8	667	14	3
I5143_7	0.05003	0.00022	0.07528	0.00064	0.52139	0.01	587	9.9	620	8.9	742	16	5
I5143_9	0.06004	0.00063	0.12643	0.0013	0.71417	0.26	957	17	1007	14	1117	24	5
I5143_10	0.05977	0.00073	0.12033	0.0023	0.96380	0.064	913	21	972	18	1108	27	6
Plug-2													
I5143_04	0.06352	0.00172	0.15217	0.00103	1.30551	0.15045	1207	14	1214	21	1227	54	1
I5143_05	0.06266	0.00182	0.14637	0.00193	0.81900	0.13793	1165	18	1177	23	1200	58	1
Plug-3													
I5143_24	0.06484	0.00018	0.16658	0.00320	1.60018	0.07300	1178	24	1180	18	1185	23	0

Appendix B-I5145

Grain	^{207}Pb/^{206}Pb	1σ error	^{206}Pb/^{238}U	1σ error	*^{207}Pb/^{235}U	1σ error	^{206}Pb/^{238}U	1σ	^{207}Pb/^{235}U	1σ	^{207}Pb/^{206}Pb	1σ	% Disc
Plug-1													
I5145_01	0.20139	0.00094	0.42412	0.01065	11.57250	0.73620	2859	126	2941	53.5	2998	23	3
I5145_03	0.19433	0.00330	0.42238	0.00966	10.67222	0.36281	2867	124	2910	54	2940	35	1
I5145_05	0.19540	0.00150	0.42128	0.00929	11.26985	0.29659	2856	123	2911	52	2949	25	2
I5145_06	0.19727	0.00110	0.41022	0.01147	10.87436	0.52806	2770	127	2884	55	2965	24	4
I5145_08	0.19254	0.00113	0.43914	0.00241	11.24917	0.28656	2996	115	2954	47	2925	24	-1
I5145_09	0.20006	0.00131	0.41286	0.00903	11.10058	0.56857	2781	122	2902	53	2987	24	4
I5145_10	0.19294	0.00147	0.42881	0.02725	11.29180	1.81756	2918	185	2924	75.3	2929	25	0
I5145_16	0.19276	0.00098	0.41524	0.00485	11.41154	0.39880	2819	114	2883	49	2927	23	2
I5145_17	0.18764	0.00198	0.44235	0.00401	11.47673	0.35060	3034	116	2944	48	2884	25	-3
I5145_18	0.19368	0.00105	0.44900	0.00312	11.85102	0.33358	3066	117	2987	47	2935	24	-3
I5145_22	0.19287	0.00121	0.44343	0.00448	12.53204	1.11569	3027	117	2968	48	2928	23	-2
I5145_23	0.19191	0.00098	0.42950	0.00866	12.65479	3.22206	2926	122	2923	51	2920	24	0
I5145_25	0.19459	0.00221	0.41241	0.00443	11.09926	0.31495	2793	113	2881	50	2942	25	3
I5145-26	0.19624	0.00087	0.42662	0.00344	11.56610	0.39893	2892	114	2930	48	2956	26	1
I5145-27	0.19455	0.00183	0.44014	0.01144	11.65435	0.66839	2997	130	2964	53	2942	24	-1

Italicized data were not used in concordia age determinations but were used in discordia fits.