U-Pb baddeleyite ages from mafic dyke swarms in Dharwar craton, India – links to an ancient supercontinent

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Abstract: The Dharwar craton of India is an Archaean craton intruded by several different generations of mainly Palaeoproterozoic dykes. Recent studies have defined precise dyke emplacement ages for some of these swarms, such as the ca. 2370 Ma Bangalore dykes, the 2212-2220 Ma Kandlamadugu dykes, the ca. 2206 Ma Somala dyke and the ca. 2180 Ma Northern Dharwar dykes. In this thesis, precise U-Pb ID-TIMS baddeleyite ages of 14 dykes from swarms of varying trends are presented. The results reveal three hitherto undated swarms whereas the remaining U-Pb data are in agreement with the age of previously dated swarms with improved constraints on the timing of emplacement (duration) and regional distribution. Four N-S trending dykes located to the north and south of the Cuddapah basin are dated at ca. 2255 Ma, for three of them the name Ippaguda dyke swarm is suggested. Three dykes radiating around the Cuddapah basin are dated to ca. 2081 Ma defining a new swarm called the Devarabanda swarm. Another NW-SE trending dyke near the Cuddapah basin yielded an age of 1788±12 Ma. Besides these previously unidentified events an age of 2206±2 Ma, indistinguishable from the NW-SE trending Somala dyke already dated, was obtained and the name Anantapur dyke swarm is proposed for these dykes. Four dykes yielded identical ages (ca. 2365 Ma) with the previously defined Bangalore dykes reinforcing the dates and the areal extent of this prominent radiating swarm. Preliminary ages 2199-2215 Ma were obtained for two dykes with a trend similar to the ca. 2180 Ma Northern Dharwar dykes.

The new ages provide close age matches with coeval swarms in both the North Atlantic Craton (NAC) and Superior craton and indicate that Dharwar, Superior and NAC were most likely closest neighbours before the rifting of the supercraton "Superia". In the here preferred palaeoreconstruction the Superior craton is placed to the south of the Dharwar craton whereas NAC is placed to the east of the Dharwar craton.

Keywords: U-Pb TIMS, baddeleyite, mafic dykes, Dharwar, craton, palaeoreconstructions, Superia.

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U-Pb-baddeleyitåldrar från mafiska gångsvärmar i Dharwarkratonen, Indien: länkar till en förhistorisk superkontinent

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Sammanfattning: Dharwar i södra Indien, är ett arkeisk krustalt block (kraton) som har intruderats av ett flertal generationer gångbergarter (diabaser) huvudsakligen av palaeoproterozoisk ålder. Bildningsåldrar för vissa av dessa gångsvärmar har nyligen definierats; t.ex. för Bangaloresvärmen (~2370 Ma; Ma = miljoner år), Kandlamadugusvärmen (2212-2220 Ma), Somalasvärmen (2206 Ma) samt Norra Dharwarsvärmen (2180 Ma). Precisa bildningsåldrar genom U-Pb ID-TIMS på mineralet baddeleyit för 14 diabasgångar med varierande gångriktningar presenteras i denna masteruppsats. Resultat inkluderar tre hittills odaterade och okända gångsvärmar medan resten av U-Pb-åldrarna reproducerar tidigare publicerade åldrar men med förbättrad kännedom avseende magmatismens varaktighet samt regionala utbredning. Såväl söder som norr om Cuddapahbassängen har fyra gångar med N-S riktning daterats till 2255 Ma, för vilka namnet ”Ippaguda dyke swarm” (Ippagudagångsvärmen) föreslås. Tre gångar som radierar kring Cuddapahbassänge har daterats till ~2081 Ma. Dessa definierar en ny gångsvärm, ”the Devarabanda swarm” (Devarabandagångsvärmen). En annan NV-SO-strykande gång i närheten av Cuddapahbassängen gav en ålder på 1788±12 Ma. Förutom dessa tidigare oidentifierade händelser, erhölls en ålder på 2206±2 Ma (oskiljaktligen från den NV-SO-strykande Somalasvärmen). Dessa gångar föreslås namnet”Anatapur dyke swarm” (Anatapurgångsvärmen). Fyra av de daterade gångarna gav åldrar på ca 2365 Ma och är identiska med den tidigare väldefinierade åldern för Bangaloresvärmen. Preliminära åldrar på 2199-2215 Ma erhölls för två gångar vars riktning sammanfaller med den s.k. Norra Dharwarsvärmen (daterat till ca. 2180 Ma).

De från denna uppsats nya åldrarna kan till viss del korreleras med samtida gångsvärmar i såval Nordatlantiska kratonen (NAC) som Superiorkratonen, vilket indikerar att Dharwarcratonen, Superiorkratonen och NAC med hög sannolikhet var i kontakt med varandra före uppspricknigen av superkratonen Superia. I den rekonstruktion som föredras är Superiorkratonen lokaliserad söder om Dharwarkratonen, medan NAC är lokaliserad öster om densamma.

Nyckelord: U-Pb TIMS, baddeleyit, mafiska gångar, Dharwar, kraton, palaeorekonstruktion, Superia

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1 Introduction

The Archaean crustal record is represented within ca. 35 cratonic fragments that today are widely dispersed around the globe (Bleeker, 2003). It is debated whether all continental crust existed as a single large landmass by the late Arcahean (i.e. a "Kenorland" supercontinent), or was represented by a few large blocks (i.e. Vaalbara, Superia and Sclavia supercratons). Regardless, there are various lines of evidence that accretion and break-up of supercontinents may take place in cycles of approximately 400 Myr (e.g. Hawkesworth et al., 2009). The Archaean supercontinent (or Vaalbara, Superia and Sclavia supercratons) was followed by the assembly of 1.9 Ga Nuna (or Columbia) (Evans and Mitchell, 2011), the 0.9 Ga Rodinia (Li et al., 2008), and latest, the late Palaeozoic to Mesozoic Pangaea supercontinent. Mantle plumes represent the upwelling of abnormally hot rocks through the Earth's mantle and most likely originate from a thermal boundary layer deep in the mantle (Ernst and Buchan, 2001b). The occurrences of large volumes of short-lived dyke swarms emanating out from a magmatic centre (focal point) suggest that such mantle plumes probably play a critical role in initializing break-up events, or attempted break-ups, of supercontinents. The break-ups of these supercontinents are often accompanied by extensive volcanism with magma fed through mafic dykes, which should occur on both sides of the rift margins in settings break-up was successful (e.g. Bleeker, 2008; Bleeker and Ernst 2006) such as the Central Atlantic Magmatic Province (Marzoli et al., 1999).

Traces of brief, pulsed, mafic magmatic events are frequently preserved within Archaean cratons, especially as Large Igneous Provinces including mafic dyke swarms (Bryan and Ernst, 2008), and as such can be used as solid piercing points, with resembling chemical properties, palaeomagnetic poles and precise ages, to reconstruct ancient supercontinents, i.e. which cratonic blocks were once nearest neighbours (e.g. Bleeker and Ernst, 2006). Mafic dyke swarms are typically subvertical intrusive sheets that often reach deep into the interior of continental blocks, making them less susceptible to erosion. They also carry a memory of the Earth's magnetic field so that the latitudinal information at the time of crystallization of the dyke can be calculated. Precise ages for mafic dyke swarms for a craton can be arranged into a so-called barcode, with each line representing the crystallisation age of a precisely dated magmatic event. The counterparts for these events can then be compared with corresponding barcodes for other cratons. Once a number of matching events has been identified, it can be argued that the continents were adjacent relative to each other during the time interval over which matches are attained.

Baddeleyite (ZrO_2) is an accessory mineral ubiquitous in slowly cooled mafic units such as Si-unsaturated gabbroic plutonic rocks and in the centres of thick basic dykes and sills, and the ages of such rocks can be calculated by measuring the trace elements U and Pb and their isotopic compositions in representative baddeleyite crystals (Heaman and LeCheminant, 1993). A limiting step in obtaining a robust emplacement age from a mafic rock has for long been the difficulty in recovering baddeleyite from it. This is now largely eliminated owing to recent advances in mineral separation techniques (e.g. Söderlund and Johansson, 2002).

The Dharwar craton in southern India is a large Archaean cratonic fragment having numerous well exposed dykes of different trends dispersed throughout the craton. Robust ages for various Dharwar dyke swarms have been published recently by a number of authors (Halls et al., 2007; French and Heaman, 2010; Srivastava et al., 2011; Kumar et al., 2012). Emplacement ages for fourteen additional mafic dykes, with various trends, are presented in this thesis. The principle goal has been to establish a comprehensive barcode of extension-driven magmatic events in the Dharwar craton to be compared with other corresponding barcode records from other cratons. Ideally, the results will shed light on which cratons were possible nearest neighbours to Dharwar from the late Archaean into the Proterozoic.

2 Geological Setting

The Dharwar craton comprises most of the southern part of peninsular India (Fig. 1) with a size of approximately 900 km in N-S and 750 km in E-W directions. The craton is divided into the Eastern Dharwar craton (EDC) and the Western Dharwar craton (WDC) by the Chitradurga fault, which is an arcuate N-S fault (Mahadevan, 2008). The accretion between the two sub-cratons hase been proposed to have occurred at ~2.5 Ga (Chadwick et al., 2000). The dominant bedrock lithologies in the Dharwar craton include: (1) Archaean Tonalite-Trondhjemite-Granodiorite (TTG) gneisses, also known as Peninsular Gneisses with reported ages of 3.3-2.9 Ga, (2) Archaean greenstones and schists including both the 2.9-2.6 Ga Dharwar supergroup and a Neoarchaean greenstone-schist belt in Eastern Dharwar craton, (3) intrusive rocks, which consist of the Closepet granite, undifferentiated 2.9-2.6 Ga granites and mafic dykes (mainly Proterozoic in age), and (4) Phanerozoic sedimentary cover (Peucat et al., 1993; Chadwick et al., 1997; 2000; Meert et al., 2010). The ~2.5 Ga, K-rich Closepet granite batholith appears to have been formed by water-saturated anatexis of TTG gneisses induced by a basaltic liquid from an enriched mantle source (Friend and Nutman, 1991; Moyen et al., 2001). The Cuddapah basin in the east is an autochthonous Proterozoic intracratonic basin succession that mainly consists of clastic and chemical sedimentary rocks with occasional inter-

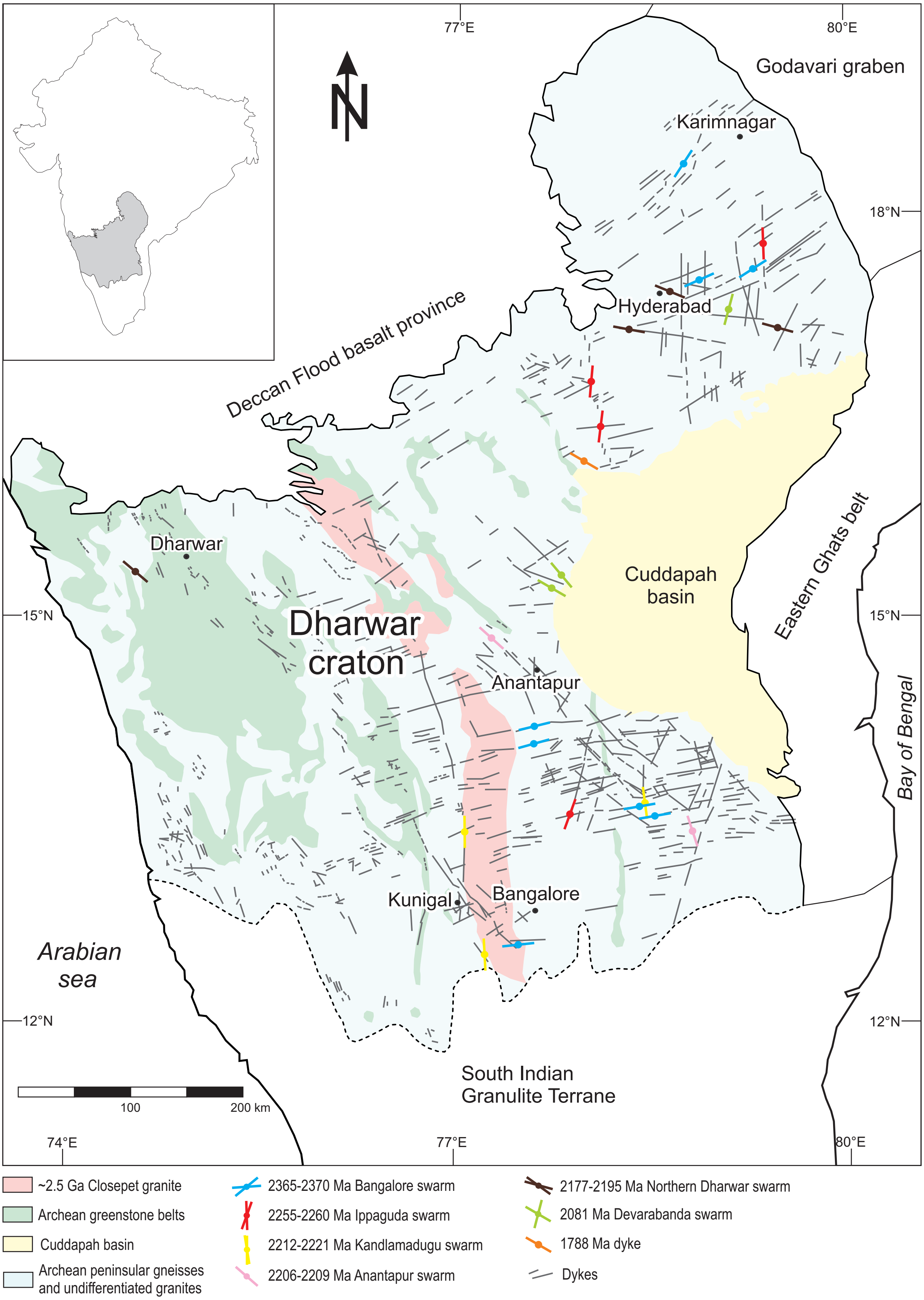

Fig. 1. Simplified geological map of the Dharwar craton showing mafic dyke occurrences and basement geology (modified after French and Heaman, 2010). Coloured symbols indicate distinct dykes that have been dated by the U-Pb method (Halls et al., 2007; French and Heaman, 2010; Srivastava et al., 2011; Kumar et al., 2012; this study).

calations of basaltic flows, mafic sills and tuffs in the lower part, non-conformably overlying the eastern part of the craton. A U-Pb baddeleyite age of ~1.9 Ga has been published for the Pulivendla sill in Cuddapah basin, and it is interpreted to represent a minimum age for the onset of deposition (French et al., 2008). In the north, the craton is concealed by the ~66 Ma Deccan Flood basalts and bordered by Godavari graben in the northeast (French and Heaman, 2010). The Eastern Ghats belt, which exemplifies a classic Precambrian deep crustal section, is an orogenic belt that underwent several continental growth processes through orogenesis (Dasgupta et al., 2012) and it was thrust onto the Cuddapah basin from the east (French et al., 2008). Towards the south, the Dharwar craton is successively transformed to metamorphic rocks of the South Indian Granulite Terrane, a series of high-grade metamorphic blocks (transitional boundary is depicted with dashed lines in Fig. 1). It is bounded by a ~63 Ma break-up margin in the west and rifted fragments of the western part of the craton are left behind as Madagascar and the Seychelles archipelago (Collier et al., 2008).

In the Dharwar craton numerous, mainly Proterozoic, dyke swarms with varying trends occur (Fig. 1; Halls et al., 2007; French and Heaman, 2010; Srivastava et al., 2011; Kumar et al., 2012). E-W and ENE-WSW trending dykes are especially widespread throughout the craton, whereas the N-S, NW-SE and NE-SW trending dykes are more subordinate and localized. The occurrence of dykes diminishes towards the South Indian Granulite Terrane and only a few dykes cut the Cuddapah basin (Murthy, 1987) suggesting that most dykes are older than ~1.9 Ga. The dominant E-W and NE-SW trending dykes belonging to Bangalore dyke swarm (light-blue dykes in Fig. 1) are abundant from Karimnagar in the north to Bangalore in the south. Previously reported ages of the Bangalore dykes fall within the range 2365 - 2370 Ma, indicating a short duration of peak magmatism for this event (e.g. Halls et al., 2007; French and Heaman, 2010; Kumar et al., 2012). The N-S to NNW-SSE trending dykes of the Kandlamadugu dyke swarm in the southern part of the craton (yellow dykes in Fig. 1) have ages ranging between 2212 Ma and 2221 Ma (French and Heaman, 2010; Srivastava et al., 2011). French and Heaman (2010) also reported a U-Pb age of 2209 ± 3 Ma for a NNW-SSE trending dyke near Somala (pink dyke in Fig. 1) and 2181 Ma and 2177 Ma for two dykes with NW-SE and WNW-ESE trends that they referred to as the Northern Dharwar dyke swarm (dark-brown dykes in Fig. 1). Besides these swarms, there are distinct N-S trending dykes in the northern part of the EDC as well as a large number of dykes with varying trends, especially nearby Cuddapah basin.

3 Methodology

Samples for geochronology were collected by Wouter Bleeker (Geological Survey of Canada, Ottawa) and Rajesh K. Srivastava (Banaras Hindu University, Varanasi, India) in 2009-2010. In general, samples were taken from the centres of dykes, i.e. the coarsest-grained rocks, as enrichment of incompatible elements, including Zr and U, is enhanced by slow cooling and an extended crystallization interval. The samples were processed at the Department of Geology at Lund University, Sweden. These were sawed into 2-3 cm-thick slices, broken up with a sledgehammer to cm-sized pieces and powdered using a small mill tray. The powder was carefully suspended in water and a small amount of detergent was added to reduce cohesive forces between grains. Portions corresponding to ~50 g of powder were loaded onto a Wilfley® water-shaking table following the procedures of Söderlund and Johansson (2002). After ~100 s, the finest material was washed off successively from the table deck using a squirt bottle and collected in a plastic beaker. After 2-3 loadings the collected heavy mineral concentrate was transferred to a petri dish. Fe-Mg minerals (oxides and silicates) were removed using a strong pencil-magnet and baddeleyite grains of best optical quality were handpicked under a binocular microscope. For samples dated in this study, approximately 30-80 baddeleyite grains were recovered from each sample. For isotopic measurements, typically 1-5 grains were combined into a fraction and the grains were transferred into a Teflon dissolution capsule using a handmade micropipette. The grains were washed in several steps, including a wash in ~3 N HNO_3 on hotplate for ~15 minutes. The liquid from the last washing step was removed before the sample was spiked with a $^{233-236}U$- ^{205}Pb isotopic tracer solution. The grains were dissolved in a 10:1 mixture of HF:HNO_3 acid at 190°C for 3 days and then the acid was evaporated on a hot plate at 100°C.

Baddeleyite fractions were then dissolved in 10 drops of 6 N HCl and dried down with 1 drop of 0.25 N H_3PO_4 acid on a hot plate at 90°C. Further purification of Pb and U solutions via ion exchange resins was not carried out. Instead, samples were re-dissolved in 1.8 µl of silica gel and loaded on outgassed Re (rhenium) single filaments using a small pipette. The sample was loaded in portions at a filament current set to 1 A. The current was subsequently increased step-wise in 0.1 A steps until the phosphoric acid had burnt off (at ~2.4 A), observed by emission of a white smoke at constant filament temperature. A further small temperature raise was performed until a weak glowing of the filament was observed, then the filament current was immediately turned down to 0 A.

All mass spectrometer analyses were made

Table 1.
U-Pb TIMS data

Sample name[1]	U/ Th	Pbc/ Pbtot[2]	$^{206}Pb/^{204}Pb$ raw[3]	$^{207}Pb/^{235}U$ corr[4]	± 2s % err	$^{206}Pb/^{238}U$	± 2s % err	$^{207}Pb/^{235}U$ (age, Ma)	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	± 2s	Concord-ance
EDD09-13, Horsley Hills dyke												
a (1)	10.3	0.024	2505.3	9.1637	0.36	0.43749	0.35	2354.5	2339.4	2367.6	1.8	0.988
b (3)	12.5	0.057	1055.2	8.9808	0.72	0.42971	0.68	2336.1	2304.4	2363.8	4.5	0.975
BNB10-021, Bhongir dyke												
a (3)	4.0	0.054	1075.9	9.0272	0.62	0.43179	0.59	2340.8	2313.8	2364.4	3.8	0.979
BNB10-003B, Madanapalle dyke												
a (5)	9.7	0.032	1755.0	8.9203	0.62	0.42754	0.59	2329.9	2294.6	2360.9	2.9	0.972
BNB10-031, Yenugonda dyke												
a (3)	5.6	0.167	300.0	8.0195	0.76	0.41087	0.66	2233.2	2218.9	2246.4	6.0	0.988
b (1)	10.1	0.203	290.9	8.0370	2.07	0.41000	2.07	2235.2	2214.9	2253.8	9.7	0.983
c (6)	7.4	0.098	566.5	7.8980	0.62	0.40340	0.59	2219.5	2184.7	2251.7	4.5	0.970
d (3)	5.3	0.323	137.8	8.0990	0.95	0.41202	0.84	2242.1	2224.1	2258.6	7.5	0.985
BNB10-029, Chennur dyke												
a (3)	3.7	0.013	4189.8	7.5174	0.33	0.38585	0.28	2175.1	2103.6	2243.2	3.2	0.938
b (4)	12.1	0.018	3419.6	7.9493	0.46	0.40665	0.40	2225.3	2199.6	2249.0	4.0	0.978
c (2)	7.6	0.172	301.4	7.9891	0.71	0.40748	0.69	2229.8	2203.4	2254.1	4.0	0.977
BNB10-001B, Dhiburahalli dyke												
a (2)	8.0	0.021	2805.8	8.0429	0.33	0.40984	0.32	2235.9	2214.2	2255.8	1.7	0.982
b (2)	8.4	0.068	829.3	8.1101	0.44	0.41343	0.42	2243.4	2230.6	2255.0	2.6	0.989
c (3)	11.0	0.056	1027.9	8.0826	0.42	0.41243	0.40	2240.3	2226.0	2253.4	2.4	0.988
BNB10-024, Ippaguda dyke												
a (3)	6.4	0.534	134.7	8.2472	8.44	0.42198	8.45	2258.5	2269.5	2248.7	21.9	1.009
b (3)	N.A[5]	N.A.	340.7	8.0182	0.83	0.41019	0.81	2233.1	2215.8	2249.0	3.7	0.985
c (4)	9.3	0.133	403.1	7.9579	0.71	0.40389	0.69	2226.3	2186.9	2262.7	3.3	0.967
d (3)	18.7	0.045	1351.4	7.8540	0.60	0.40262	0.60	2214.4	2181.1	2245.4	2.2	0.971
BNB10-026, Kandukur dyke												
a (2)	8.6	0.346	200.5	7.7726	5.38	0.40795	5.34	2205.0	2205.6	2204.6	11.7	1.000
b (4)	8.0	0.060	924.9	7.9395	0.36	0.40904	0.33	2224.2	2210.5	2236.8	2.7	0.988
c (4)	10.6	0.052	1083.4	7.7038	0.31	0.40272	0.22	2197.0	2181.6	2211.5	3.4	0.986

Table 1. continued

Sample name[1]	U/ Th	Pbc/ Pbtot[2]	$^{206}Pb/^{204}Pb$ raw[3]	$^{207}Pb/^{235}U$ corr[4]	± 2s % err	$^{206}Pb/^{238}U$	± 2s % err	$^{207}Pb/^{235}U$ (age, Ma)	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	± 2s	Concord-ance
BNB10-015A, Konapuram dyke												
a (2)	6.8	0.028	2222.7	7.5944	0.49	0.39824	0.49	2184.2	2160.9	2206.6	3.4	0.979
b (1)	14.7	0.051	1232.6	7.7031	0.74	0.40384	0.73	2197.0	2186.7	2206.1	2.3	0.991
EDD09-26, Narapally dyke												
a (2)	9.2	0.157	351.5	6.6168	1.22	0.35113	1.02	2061.6	1940.0	2185.5	11.1	0.888
b (2)	15.9	0.026	2299.9	7.1041	0.48	0.37531	0.46	2124.6	2054.3	2193.2	2.1	0.937
c (3)	9.7	0.052	1204.1	7.1967	0.36	0.38026	0.34	2136.1	2077.5	2192.9	2.2	0.947
d (4)	9.3	0.025	2535.5	7.0036	0.28	0.37050	0.25	2111.9	2031.7	2190.9	2.0	0.927
BNB10-020, Pyapili dyke												
a (3)	4.6	0.011	5152.0	6.6513	0.30	0.37486	0.27	2066.2	2052.2	2080.1	2.0	0.987
b (2)	4.3	0.090	601.3	6.6437	0.41	0.37412	0.38	2065.2	2048.8	2081.6	2.9	0.984
c (2)	15.7	0.381	122.6	6.3636	1.52	0.35786	1.42	2027.3	1972.0	2084.0	11.3	0.946
EDD09-023, Ramannapeta dyke												
a (3)	10.9	0.098	622.6	6.7492	1.10	0.38019	1.08	2079.1	2077.2	2081.0	5.8	0.998
b (2)	5.7	0.059	985.5	6.7015	0.59	0.37753	0.58	2072.8	2064.7	2080.9	3.0	0.992
BNB10-011, Devarabanda dyke												
a (4)	11.5	0.126	447.3	6.2354	1.17	0.35367	0.81	2009.4	1952.1	2068.9	13.6	0.944
b (5)	13.6	0.086	718.4	6.3786	1.05	0.36159	1.00	2029.3	1989.7	2069.8	6.6	0.961
c (6)	18.5	0.095	636.4	6.4837	0.98	0.36690	0.91	2043.7	2014.8	2073.0	6.7	0.972
BNB10-030, Pebbair dyke												
a (2)	2.1	0.674	74.3	4.1536	7.57	0.27544	7.53	1664.9	1568.3	1788.9	43.7	0.877
b (5)	3.5	0.324	156.7	4.6631	2.01	0.30971	1.95	1760.6	1739.3	1786.1	12.8	0.974
c (3)	1.6	0.373	131.0	3.8079	3.11	0.25196	3.05	1594.4	1448.6	1792.9	18.7	0.808

[1] Fraction, (x)=number of grains in each analysis.

[2] Pbc = common Pb; Pbtot = total Pb (radiogenic + blank + initial).

[3] Measured ratio, corrected for fractionation and spike.

[4] Isotopic ratios corrected for fractionation (0.1% per amu for Pb), spike contribution, blank (1 pg Pb and <1 pg U), and initial common Pb. Initial common Pb corrected with isotopic compositions from the model of Stacey and Kramers (1975) at the age of the sample.

[5] The value is not analyzed.

using a Finnigan Triton thermal ionization mass spectrometer (TIMS) at the Museum of National History in Stockholm, Sweden. The U and Pb isotopic compositions for most of the samples were analysed using a Secondary Electron Multiplier (SEM) equipped with a high abundance sensitivity filter (RPQ) in peak-switching mode. For larger samples, i.e. those with $^{206}Pb/^{205}Pb$ ratios exceeding ~5, Pb isotopic ratios were measured in static mode with ^{204}Pb measured on the SEM. Pb and U isotopic data were collected over temperature intervals of 1170-1200°C and 1240-1300°C, respectively. The total procedural total blank was estimated at 2 pg for Pb and 0.2 pg for U. Decay constants used are those of Jaffey et al. (1971) and the initial common lead composition was based on the terrestrial model of Stacey and Kramers (1975) at the age of the sample. All age errors in Table 1 and quoted in the text are given at the 95 % confidence level. U-Pb concordia plots and age calculations were made using ISOPLOT version 3.50 of Ludwig (2003).

4 Results

Generally, baddeleyite grains separated from the Dharwar dykes are well-crystallized with no, or only very minor, frosted surfaces. Typically, the grains are distinctly brown with a size ranging between 30 and 60 µm in longest dimension. U-Pb isotopic measurements are listed in Table 1 and concordia diagrams are shown in Figure 3. A summary of dyke emplacement ages, trends, coordinates and thicknesses are given in Table 2. All ages reported are given at 95% confidence, or at 2 sigma level. The choice of preferred lower intercept age in the regressions is discussed in section 5.1.

4.1 Horsley Hills dyke, EDD09-13

This dyke is located north of the town Madanapalle (Fig. 3C). It trends ~075º and has a width of about 25 m. A total of 35 baddeleyite grains were recovered from this sample. Two fractions comprising 1 and 3 grains were analysed, yielding model $^{207}Pb/^{206}Pb$ dates of 2368±2 Ma and 2364±5 Ma, respectively (Fig. 2A). The weighted average $^{207}Pb/^{206}Pb$ date for these two analyses is 2367±2 Ma.

4.2 Bhongir dyke, BNB10-021

This dyke is exposed just west of the town Bhongir (Fig. 3A), immediately south of highway 202. Its trend is ~050º and it has a width about 50 m. A total of 22 baddeleyite grains were separated and a single fraction of 3 grains plots 2.1% discordant below the concordia curve (Fig. 2A). The $^{207}Pb/^{206}Pb$ date of this single analysis is 2364±4 Ma, which is taken as a preliminary, though minimum, age of this dyke.

4.3 Madanapalle dyke, BNB10-003B

This major dyke is located 10 km northwest of the town Madanapalle (Fig. 3C). It trends ~080º and its width is about 75 m. Approximately 50 baddeleyite grains were recovered and selected from this sample. A single fraction comprising 5 grains is 2.8% discordant, and has a $^{207}Pb/^{206}Pb$ age of 2361±3 Ma (Fig. 2A). This is taken to represent a minimum age for this dyke.

4.4 Yenugonda dyke, BNB10-031

The location of this dyke is 5 km west of the town Mahbubnagar (Fig. 3A). The trend is ~005º and the width is about 50 m. Approximately 25 baddeleyite grains were recovered from this sample. Four fractions of 1 to 6 grains each were analysed. The analyses plot close to concordia (1.5 to 3.0% discordant) with $^{207}Pb/^{206}Pb$ ages ranging from 2246 Ma to 2259 Ma (Fig. 2B). Linear regression, using a forced lower intercept of 400±100 Ma, yields an upper intercept age of 2257±4 Ma (Mean Standard Weighted Deviation (MSWD)=2.6).

4.5 Chennur dyke, BNB10-029

This dyke is located ~35 km south of Mahbubnagar (Fig. 3A). The trend is ~007º and the width is about 30 m. Approximately 45 baddeleyite grains were obtained from this sample. Three fractions of 3, 4 and 2 grains, respectively, were analysed. Two analyses plot discordant by 2.2 and 2.3%, whereas the third analysis is 6.2% discordant. The $^{207}Pb/^{206}Pb$ ages range from 2243 Ma to 2254 Ma. Free regression of all three fractions gives an upper intercept age of 2256±5 Ma with a lower intercept of 317±140 Ma (MSWD=2.8; Fig. 2C).

4.6 Dhiburahalli dyke, BNB10-001B

This dyke is located 5 km north of Dhiburahalli, Karnataka, in the southwestern Dharwar craton (Fig. 3C). The trend is ~020-030º and its width is about 80 m. A total of 20 baddeleyite grains was recovered from this sample. Three fractions of 2, 2 and 3 grains were dated. All analyses plot close to concordia (1.1 to 1.8% discordant) with $^{207}Pb/^{206}Pb$ ages ranging narrowly from 2253 Ma to 2256 Ma. Regression using a forced lower intercept age of 400±100 Ma yields an upper intercept age of 2259±2 Ma but with a relatively high MSWD value of 3.0. If a forced lower intercept of 0±100 Ma is used, the upper intercept becomes 2255±1 Ma with an acceptable MSWD value of 1.3 (Fig. 2D). The improved MSWD using a recent Pb-loss model suggests that 2255±1 Ma likely represents the best age estimate of this sample.

4.7 Ippaguda dyke, BNB10-024

This dyke is located east of Hyderabad, ~35 km southwest of Warangal (Fig. 3A). The trend is ~355º and the width of the dyke is 60 m. Approximately 40 grains were extracted from this sample. Four fractions comprising between 3-4 small grains each were analysed. Two analyses plot close to concordia with -0.9 and 1.5%

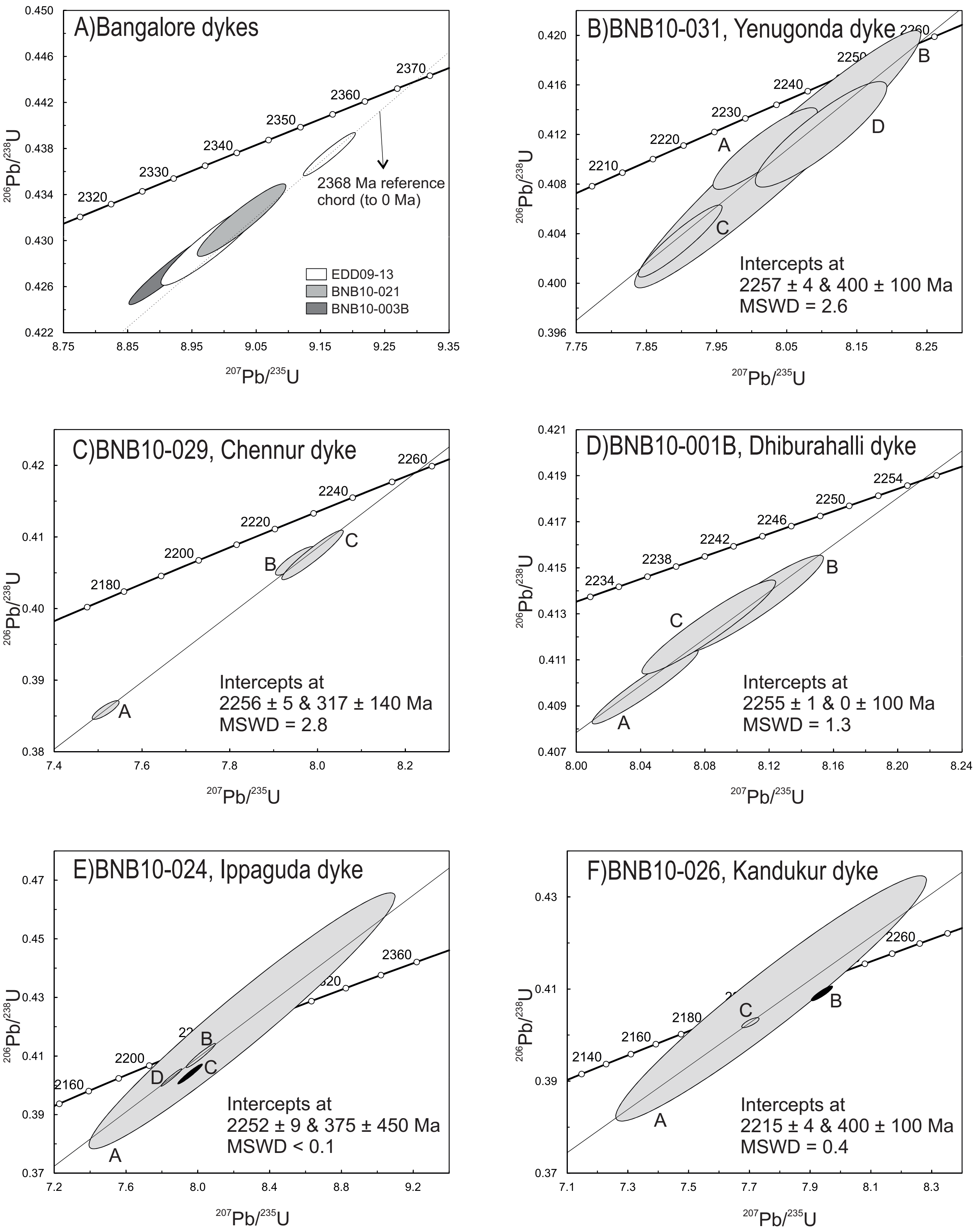

Fig. 2. U-Pb concordia diagrams of our new dating results on mafic dykes from the Dharwar craton. Black dots represent outliers and are not accounted in regression.

discordance. The other two analyses are 2.9 and 3.3% discordant. The $^{207}Pb/^{206}Pb$ ages of fractions A, B and D range from 2245 Ma to 2249 Ma. The $^{207}Pb/^{206}Pb$ age of fraction C is significantly older (2263±3 Ma) and is considered as an outlier (black ellipse), but there is no obvious explanation for the slightly older age. Free regression of the remaining fractions (A, B and D) yields an upper intercept age of 2252±9 Ma and a lower intercept age of 375±450 Ma (MSWD=0.07; Fig. 2E).

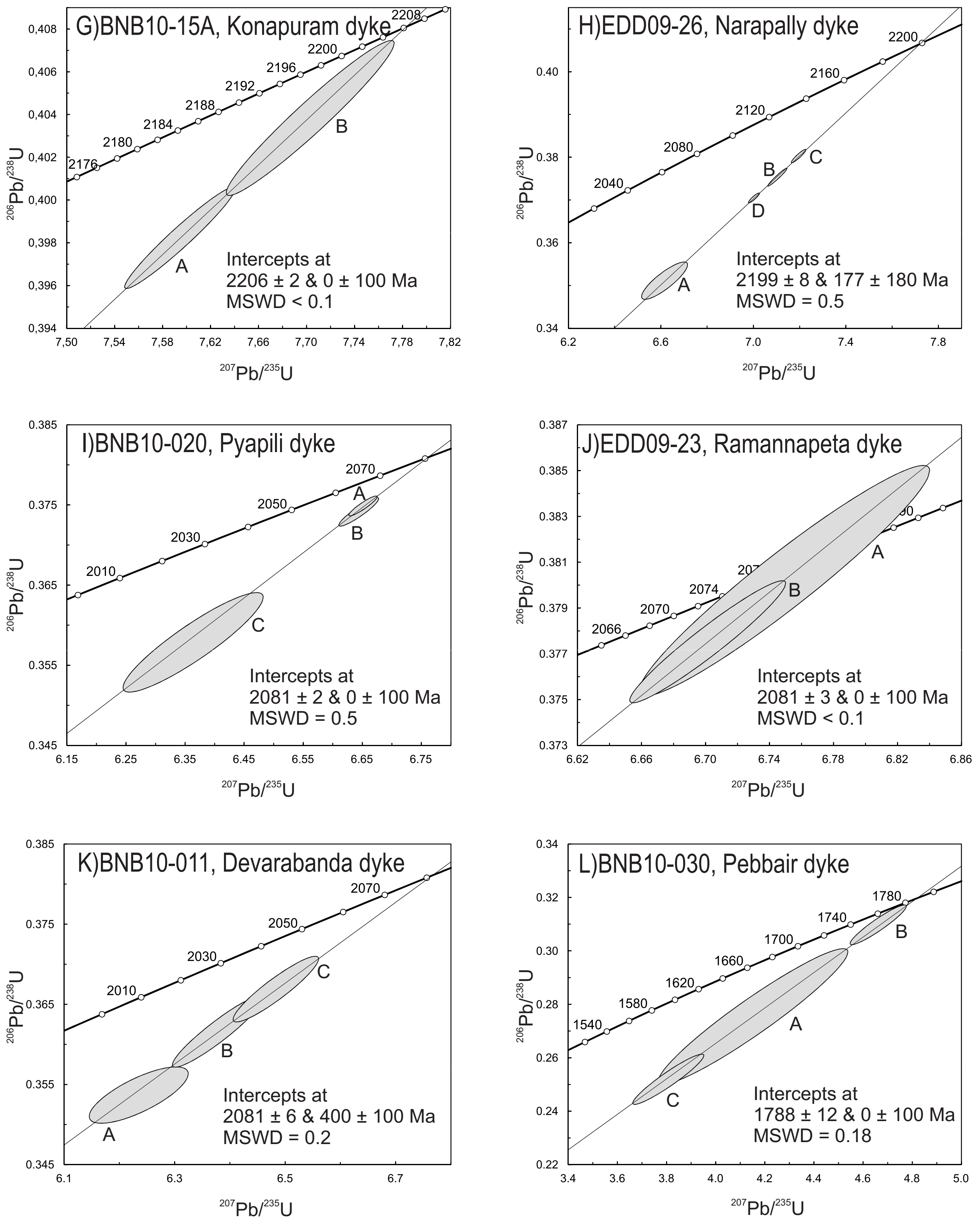

Fig. 2. Continued.

4.8 Kandukur dyke, BNB10-026

This dyke is located ca. 35 km south of Hyderabad (Fig. 3A). The trend of the dyke is ~280º and the width is 80 m. A total of 40 grains was recovered from this sample. Three fractions, comprising between 2-4 medium-sized grains each, were dated. Fraction A is concordant, but is relatively imprecise, while the other two fractions (B, C) plot close to concordia (1.2 and 1.4% discordant; Fig. 2F). The ^{207}Pb/^{206}Pb dates of the fractions are 2205±12 Ma, 2237±3 Ma and 2212±3 Ma, respectively. The ^{207}Pb/^{206}Pb age of fraction B is considerably higher than the others, therefore only fractions A and C have

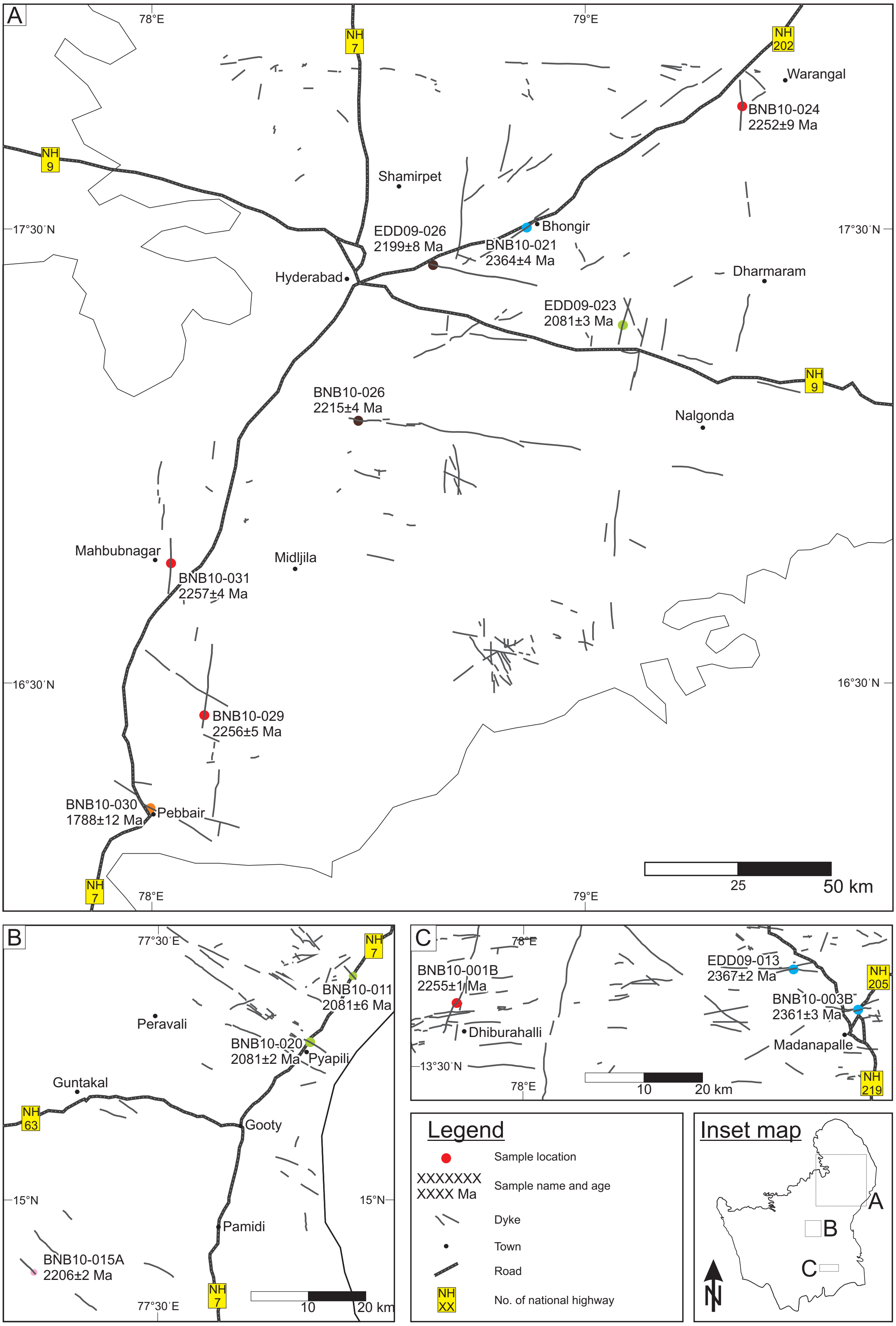

Fig. 3. Maps showing the dyke occurrences (traced from Google Earth images) focused on sampling sites. Coloured dots on dykes depict the sampling location and the representative dyke swarms shown in Fig. 1.

Table 2.

Descriptive data of U-Pb geochronology samples

Sample name	Name	Latitude	Longitude	Dyke trend	Dyke width	Age, error (2s)
Bangalore Dyke Swarm						
EDD09-013	Horsley Hills	13°38'56.08"N	78°25'15.41"E	~075°	~25 m	2367 ± 2 Ma
BNB10-021	Bhongir	17°30'12.06"N	78°52'03.82"E	~050°	~50 m	2364 ± 4 Ma
BNB10-003B	Madanapalle	13°35'19.26"N	78°31'23.46"E	~080°	~75 m	2361 ± 3 Ma
Ippaguda Dyke Swarm						
BNB10-031	Yenugonda	16°45'08.74"N	78°02'34.18"E	~005°	~50 m	2257 ± 4 Ma
BNB10-029	Chennur	16°25'29.58"N	78°06'53.80"E	~007°	~30 m	2256 ± 5 Ma
BNB10-024	Ippaguda	17°46'18.63"N	79°22'02.27"E	~355°	~60 m	2252 ± 9 Ma
BNB10-001B	Dhiburahalli	13°35'60.00"N	77°53'32.87"E	~020-030°	~80 m	2255 ± 1 Ma
Anantapur Dyke Swarm						
BNB10-015A	Konapuram	14°53'13.07"N	77°18'01.61"E	~310°	~80 m	2207 ± 6 Ma
BNB10-026	Kandukur	17°04'22.97"N	78°28'35.81"E	~280°	~80 m	2215 ± 4 Ma
EDD09-026	Narapally	17°25'18.15"N	78°38'26.21"E	~290°	~20 m	2199 ± 8 Ma
Devarabanda Dyke Swarm						
BNB10-020	Pyapili	15°14'42.20"N	77°44'50.35"E	~300°	~250 m	2081 ± 2 Ma
EDD09-023	Ramannapeta	17°17'26.84"N	79°05'18.11"E	~015°	~15 m	2081 ± 3 Ma
BNB10-011	Devarabanda	15°20'53.41"N	77°48'57.07"E	~320°	~90 m	2081 ± 6 Ma
BNB10-030	Pebbair	16°12'58.11"N	77°59'45.63"E	~300°	~60 m	1788 ± 12 Ma

been included in the regression. Linear regression, using a forced lower intercept of 400±100 Ma, yields an upper intercept age of 2215±4 Ma (MSWD=0.4), which is within error of the weighted average of the $^{206}Pb/^{207}Pb$ age of 2211±3 Ma for fractions A & C.

4.9 Konapuram dyke, BNB10-015A

The Konapuram dyke is located approximately 40 km northwest of Anantapur (Fig. 3B). Its trend is ~310º and its width is 80 m. A total of 60 grains was recovered from this sample. Two fractions, consisting of 1-2 grains only, were dated. Both fractions plot close to the concordia curve (0.9 and 2.1% discordant) with model $^{207}Pb/^{206}Pb$ ages of 2207±3 Ma and 2206±2 Ma (Fig. 2G). Free regression yields an upper intercept age of 2207±6 Ma with a lower intercept age of 65±630 Ma. Linear regression with a forced lower intercept age of 0±100 Ma yields an upper intercept age of 2206±2 Ma (MSWD=0.04). The latter one is interpreted as the best age estimate for this dyke, since the upper intercept age is more precise.

4.10 Narapally dyke, EDD09-26

The location of this dyke is 18 km east of Hyderabad (Fig. 3A). The trend is ~290º and the width is 20 m. About 40 grains were recovered from this sample. Four fractions with 2-4 grains each were dated. All fractions are relatively discordant (Fig. 2H). Fractions B, C and D plot 6.3, 5.3 and 7.3% discordant, respectively. Fraction A plots far below the concordia curve, being discordant by as much as 21.2%. Individual $^{207}Pb/^{206}Pb$ ages range from 2186 Ma to 2193 Ma. Free regression yields an upper intercept age of 2199±8 Ma and a lower intercept age of 177±188 Ma (MSWD=0.5).

4.11 Pyapili dyke, BNB10-020

The Pyapili dyke is located roughly 40 km east of Guntakal (Fig. 3B). The trend is ~300º and the dyke is as much as 250 m thick. A total of 40 baddeleyite grains was extracted. Three fractions, comprising between 2-3 grains each, were dated. Fractions A and B plot close to the concordia curve (2.3 and 2.6% discordant) whereas fraction C is 5.4% discordant (Fig. 2I). $^{207}Pb/^{206}Pb$ ages range from 2080 Ma to 2084 Ma. A linear regression, using a forced lower intercept of 0±100 Ma, yields an upper intercept age of 2081±2 Ma (MSWD=0.53), interpreted to represent the age of emplacement of this dyke.

4.12 Ramannapeta dyke, EDD09-23

This dyke cuts across the village of Ramannapeta, which is 70 km northwest of town Nalgonda (Fig. 3A). The trend is ~015º and the width of the dyke is 15 m. Approximately 30 high quality baddeleyite grains were recovered from this sample. Two fractions, with 3 and 2 grains each, were dated. Both fractions plot very close to concordia (0.8 and 0.2% discordant; Fig. 2J). The $^{207}Pb/^{206}Pb$ dates are almost identical: 2081±6 Ma and 2081±3 Ma. The weighted mean $^{207}Pb/^{206}Pb$ age is 2081±3 Ma (MSWD=0.01).

4.13 Devarabanda dyke, BNB10-011

The location of this dyke is roughly 50 km northwest of Guntakal (Fig. 3B). Its trend is ~320º and its width is 90 m. A total of 40 baddeleyite grains was obtained from this sample. Three fractions of 4-6 grains each, which were relatively small, plot somewhat discordantly (5.6, 3.9 and 2.8%; Fig. 2K). The $^{207}Pb/^{206}Pb$ ages range from 2069 Ma to 2073 Ma. Linear regression using a forced lower intercept age of 400±100 Ma yields an upper intercept age of 2081±6 Ma (MSWD=0.15).

4.14 Pebbair dyke, BNB10-030

This dyke is located 1 km north of the small town Pebbair, in Andra Pradesh (Fig. 3A). The trend of the dyke is ~300º and its width is 60 m. Approximately 50 grains were recovered from this sample. Three fractions, containing between 2-5 grains each, were dated. Two fractions (A and C) plot far below the concordia curve (12.3 and 19.2% discordant), whereas fraction B plots 2.6% discordant (Fig. 2L). Model $^{207}Pb/^{206}Pb$ ages range from 1789 Ma to 1793 Ma. Since the free regression yields a slightly negative lower intercept age, a forced lower intercept of 0±100 Ma was used. This yields an upper intercept age of 1788±12 Ma (MSWD=0.18). When a lower intercept is forced through 400±100 Ma, the upper intercept age becomes 1818±100 Ma but the degree of fit becomes unacceptably worse (MSWD=12). Hence, a lower intercept of 0±100 Ma is chosen to anchor the regression of this sample.

5 Discussion

5.1 U-Pb geochronology

In regressions of U-Pb data that plot below the concordia curve (i.e. data that are normally discordant), the lower intercept is generally interpreted as the time that discordance developed, either by loss of lead or by formation (overgrowth or replacement) of a younger component. Provided data are essentially collinear, the upper intercept should robustly record the age of initial crystallization of the sample. This is especially true when the lower intercept age can be temporally linked to a thermal event or another process (e.g. a tectonic or hydrothermal event) previously documented in the sample area. More complex situations arise when all fractions form a tight cluster just below the concordia and are only moderately discordantly (1-2%). When such data is clustered, regression of these data sets will result in upper intercept ages that are associated with “unrealistically” large errors, sometimes with negative lower intercept ages. To circumvent this dilemma, a typical approach is to anchor a lower intercept for the regressions, which inevitably leads to a significant decrease in error of the upper intercept age. However, the choice of lower intercept age is not always clear, especially for new samples from regions with no documentation of post-magmatic events. A few samples in the study of Indian diabase dykes by French and Heaman (2010) required such anchored lower intercepts. These authors opted to force data through a 600 Ma lower intercept, implying that Pb-loss was linked to a widespread Pan-African event, i.e. at the time Dharwar was positioned adjacent to the Tanzania block of present Africa before rifting away (Miller et al., 1996). However, there may be some ambiguity in this approach. Free regressions of their data, collectively with regressions of samples of this study, also permits an interpretation in which discordance developed closer to ca. 400 Ma. Second, it is debatable whether the Pan-African overprint was equally strong throughout the entire Dharwar block. Finally, the approach of French and Heaman (2010) to use a forced lower intercept at 600 Ma was constrained from regression of data that included a mixture of zircon and baddeleyite fractions (e.g. samples JEF00-1, JEF00-43). This approach assumes discordance in zircon and baddeleyite developed simultaneously and is due to similar processes. However, a number of studies indicate that discordance in baddeleyite may at times be intimately linked to baddeleyite-to-zircon reactions in the presence of free silica (Davidson and van Breemen, 1988; Söderlund et al., 2008), whereas a corresponding process is lacking for the U-Pb systematics in zircon. Although we have a limited knowledge of the mechanisms that cause discordance, these observations indicate different controls, and by inference, discordance should not be assumed to develope at the same time in different U-bearing minerals.

In regressions of samples BNB10-031, BNB10-001B, BNB10-011, BNB10-020, BNB10-026 and BNB10-030, a 400±100 Ma age was applied as a forced lower intercept. All these samples are distinguished by data that cluster tightly and are only moderately discordant. A 400 Ma lower intercept was calculated as a mean age, weighted by internal errors of unforced lower intercepts of samples from studies by Halls et al. (2007), French and Heaman (2010), Srivastava et al. (2011), Kumar et al. (2012) together with samples investigated in this study (see Table 3). Selected samples are those with at least one fraction plotting more than 1.5% discordant, including those giving negative lower intercept ages but within the error of 0 Ma. The approach taken here to obtain a lower intercept age to be used in anchored regressions is to some degree subjective, but is considered to represent a preferred proxy value. Notably, a few samples yielded significantly higher MSWD values and larger errors when applying a forced 400±100 Ma lower intercept (Dhiburahalli, Pyapili and Pebbair dykes). The baddeleyite grains in these samples appear to record discordance that developed more recently and accordingly a lower intercept of 0±100 Ma was used in the regressions.

5.2 Regional dyke swarms in the Dharwar craton

5.2.1 2368 Ma Bangalore dyke swarm

Precise U-Pb ages of dykes for the Bangalore swarm have been reported previously in a number of studies

Table 3.

Data used for calculation of lower intercept age

Sample Name	Lower Intercept (Ma)	Error (±)	Upper Intercept (Ma)	Error (±)	Number of fractions
EDD-09-13 [1]	392	540	2370	6	2
KB-2 [4]	-122	850	2366	4	4
JEF-99-1 [2]	20	21	2365	1	6
JEF-99-7 [2]	129	180	2369	1	3
KA-5 [3]	813	32	2369	3	4
HY-67 [3]	752	62	2368	1	4
BNB-10-015A [1]	65	630	2206	2	2
JEF-99-11 [2]	423	8	2208	0	3
BNB-10-024 [1]	375	450	2252	9	3
BNB-10-029 [1]	320	140	2256	5	1
BNB-10-031 [1]	399	3000	2257	47	4
BNB-10-001B [1]	-498	870	2252	5	3
JEF-00-1 [2]	286	65	2181	1	4
JEF-00-43 [2]	294	37	2169	1	2
BNB-10-020 [1]	-193	560	2079	4	3
BNB-10-011 [1]	225	530	2076	16	3
BNB-10-030 [1]	-57	190	1785	14	3

[1] This study
[2] French & Heaman, 2010
[3] Kumar et al., 2012
[4] Halls et al., 2007

(Halls et al., 2007; French and Heaman, 2010; Kumar et al., 2012). The dykes investigated near Horsley Hills and Hyderabad reinforce the observation that the Bangalore dykes, referred to as the Dharwar Giant dyke swarm by Kumar et al. (2012), comprise one of the most prominent mafic dyke swarms in the Dharwar craton. Collectively, the baddeleyite fractions of EDD09-13, BNB10-021 and BNB10-003B plot along a 2368 Ma reference chord (Fig. 3), in agreement with a short duration of magmatism (~2365-2370 Ma) for the Bangalore event (Halls et al., 2007, French and Heaman, 2010, Kumar et al., 2012). The trends of the dykes dated here also support a radiating pattern with a magmatic centre some 300 km west of the current west coast of Peninsular India (French and Heaman, 2010; Kumar et al., 2012).

5.2.2 2255 Ma Ippaguda dyke swarm

The Ippaguda swarm extends from the Ippaguda village to the town Mahbubnagar. It covers an area of ~170 km in the N-S direction and ~150 km in the E-W direction. The U-Pb ages determined from three N-S trending dykes define a new dyke swarm in the Dharwar craton; the 2257±4 Ma Yenugonda dyke (BNB10-031), the 2256±5 Ma Chennur dyke (BNB10-029), and the 2253±3 Ma Ippaguda dyke (BNB10-024). This newly dated set of dykes is here named as Ippaguda swarm, referring to the dyke near Ippaguda being the most prominent dyke considered here. The results suggest a relatively short duration of emplacement of only a few Myr, similar to the Bangalore event. In retrospect, BNB10-029 and BNB10-031 likely represent the same dyke, which had stepped over to the east ("left-stepping") towards south. The agreement in age lends support to this possibility.

5.2.3 2255 Ma Dhiburahalli dyke

The U-Pb age of 2255±1 Ma is presented for NNE-SSW trending Dhiburahalli dyke (BNB10-001B) in the southwest of the Cuddapah basin. Although the age of Dhiburahalli dyke is indistinguishable from those of N-S trending Ippaguda dykes to the north, these are recognized as two different swarms on the basis of differences in magnetic susceptibility, thickness and abundance of dykes, lack of an apparent gradual shift in trends and other characteristics (W. Bleeker, 2012, personal communication). Future geochronology, geochemistry and field observations are needed to consolidate the relation between Ippaguda dyke swarm and Dhiburahalli dyke.

5.2.4 2206 Ma Anantapur dyke swarm

The U-Pb age of 2206±2 Ma for the Konapuram dyke (BNB10-015A) is identical in age (within error) with the 2209±3 Ma Somala dyke (French and Heaman, 2010) located ca. 200 km southwest of the Konapuram dyke but nearly along the strike. Thus, together these dykes seem to belong to a separate swarm, herein named the Anantapur swarm. The ~10 Myr age difference between the Anantapur (~2206 Ma) and the Kandlamadugu (2212-2220 Ma) swarms may indicate a connection, though the difference in trend (~15º) and age (10-15 Myr) suggest two separate events of dyke intrusion.

5.2.5 2215 Ma Kandukur dyke

The U-Pb age of 2215±4 Ma for the E-W trending Kandukur dyke is preliminary since one fraction seems to be an outlier (fraction B) and another of the remaining fractions (A) has relatively poor precision.The U-Pb age of ca. 2215 Ma is controlled to some extent by the 400±100 Ma forced lower intercept age which additionally adds some uncertainty in the interpretation of its emplacement age. A 2215 Ma age would match perfectly with the 2212-2220 Ma Kandlamadugu dykes (French and Heaman, 2010) to the south of the Dharwar craton but the orthogonality between the trends (N-S versus E-W) is problematic for such a connection. The similarity in trend between the Kandukur dyke (BNB10-026) and the Narapally dyke (EDD09-26) (see Fig. 3A) offers a more direct connection, as discussed below.

5.2.6 2199 Ma Narapally dyke

The U-Pb age of 2199±8 Ma is obtained for the nearly E-W trending Narapally dyke (EDD09-26) near the town Hyderabad. Notably, four fractions are well-aligned along a discordia line,while three fractions (B, C and D) are fairly clustered (Fig. 3H). When the lower intercept ages of 0±100 Ma and 400±100 Ma are used in the regressions, the upper intercept ages become 2192 Ma and 2210 Ma, with MSWD values of 1.5 and 2.5, respectively. Nevertheless, the reasonable MSWD value of 0.5 obtained from the free regression suggests 2199±8 Ma as the best estimate for the crystallization age of Narapally dyke. The similarity in trends (E-W) of the Narapally and Kandukur dykes investigated here and the Bandepalem (2177 Ma) and Dandeli (2181 Ma) dykes investigated by French and Heaman (2010) indicates a possible connection. The Bandepalem and Dandeli dykes are proposed to be a part of a giant dyke swarm named the Northern Dharwar dyke swarm (~2.18 Ga), with a focal point west of the current Deccan basalt province (French and Heaman, 2010). Better age constraints are needed to confirm whether the Narapally and Kandukur dykes indeed belong to this swarm, or if several generations of dykes are intermixed.

5.2.7 2081 Ma Devarabanda dyke swarm

The three dated NW-SE to NNE-SSW trending dykes immediately west and north of the Cuddapah basin yield ages of 2081±2 Ma for the Pyapili dyke (BNB10-020), 2081±3 Ma for the Ramannapeta dyke (EDD09-23) and 2081±6 Ma for the Devarabanda dyke (BNB10-011). In Murty et al. (1987), a NW-SE trending mafic dyke to the southwest of the Cuddapah basin gave a K-Ar age of 2068±79 Ma, which suggests this dyke may also be a member of this swarm. This dyke swarm, here referred to as the Devarabanda swarm, extends ~250 km in the N-S direction with a width of ~100 km. However, the areal extent of this swarm is most likely larger as many dykes around the Cuddapah basin have NW-SE to NE-SW trends. The precise and identical U-Pb ages of 2081 Ma for three dykes dated indicates a very short duration of dyking. The significant difference between the thicknesses of Pyapili and Devarabanda dykes (250 and 90 m) and Ramannapeta dyke (15 m) may suggest different sub-swarms and the difference between their trends supports that suggestion. However, further geochemistry and field studies should be performed to test the relation between these dykes. Therefore, the variation of trends of Ramannapeta, Pyapili and Devarabanda dykes is interpreted in favour of a radiating pattern with a magmatic centre emerging from beneath Cuddapah basin.

5.2.8 1788 Ma Pebbair dyke

Dating of this NW-SE trending dyke, located to the northwest of Cuddapah basin, indicates an age of 1788±12 Ma. This dyke is here referred to as the Pebbair dyke (BNB10-030). Poorchandra Rao (2005) reported a compilation of Ar-Ar and K-Ar ages ranging from 1850 Ma to 650 Ma for dykes around the Cuddapah basin and hypothesised several pulses of dyke emplacement. However, there is no direct age match with the Pebbair dyke in their data set. Peng et al. (2006) have described mafic dykes of similar age from the North China craton, and related them to plume-related breakup of that craton from other block. Thus, the relative positions and a possible break-up at 1.79 Ga of Dharwar and North China cratons could be considered. The new dyke, with the age of 1788±12 Ma is a newly recognized event in the Dharwar craton, but additional investigations are required to better understand its regional importance and global implications.

5.3 Palaeoproterozoic rotation of the Dharwar craton?

The emplacement of the Closepet granite at ~2.5 Ga is believed to mark the final age of amalgamation and cratonization of the Dharwar craton (Bleeker, 2003). It is also argued that the Closepet granite marks the suture between lithologically different EDC and WDC (Chadwick et al., 1997; Meert et al., 2010). However, Mahadevan (2008) states that the boundary is marked with an arcuate N-S fault. Kumar et al. (2012) point out the possibility of counter-clockwise rotation of the northern part of the Dharwar craton with respect to the southern part and base the argument on the curvature in the trends of greenstone, plutonic belts and a 350 km long mafic dyke following the trend of the Closepet granite (see Fig. 1), as well as palaeomagnetic data. The rotation indeed would be feasible provided the primary patterns of the Bangalore (~2.37 Ga) and Ippaguda (~2.25 Ga) dyke swarms were originally more linear. If so, this relative rotation of parts of the Dharwar would be younger than 2215 Ma. Alternatively, the apparent curvature of the basement geology trend is a late Archaean feature and the N-S trending of dykes simply followed the structural grain of the basement. Furthermore, rotation of the northern part of the craton relative to the southern part would require extensive fracturing and extension of eastern Dharwar crust, but no pervasive E-W trending dykes linked to such attempted break-up seem to exist. Also paleomagnetic data provided by Kumar et al. (2012) are inconclusive. Lastly, the proposed 35º change in the trend of the dykes would require excessive crustal addition to the craton, which would be hard to explain by simple geologic processes. Presently, the proposed rotation of the Dharwar craton is very speculative and more work on the definitions of the lithologies within the craton and additional palaeomagnetic data on well-dated dykes are needed.

5.4 Palaeoreconstructions

Previously, possible reconstructions have been made for the Dharwar craton based on the similarity of the lithologies, exact age matches for volcanic events, and palaeomagnetic data (Bleeker, 2003; Zhao et al., 2003; French and Heaman, 2010; Mohanty, 2011; Nilsson et al., in press). Detailed matching of magmatic event barcodes (Fig. 4) can be used to identify cratons or crustal blocks that were likely nearest neighbours with the Dharwar craton (Bleeker and Ernst, 2006). Moreover, if age matches involve two or more events and are spread across an interval of time, the chance of a successful correlation significantly increases ("rule of multiple independent matches") (Bleeker, 2008). Therefore, the mafic dykes dated in this study and any associated age matches are used as pivotal points for reconstructions herein. The barcodes for Dharwar, North Atlantic craton (NAC), Superior, East Antarctica and Slave cratons are shown in Fig. 4 and other important age matches for individual events are discussed below.

Occurrences of the ca. 2367 Ma magmatism around the globe are scarce, with the Bangalore dyke swarm in the Dharwar craton constituting the largest known principal occurrence. However, Nilsson et al. (in press) obtained precise ages of 2374±4 Ma and 2365±2 Ma for dykes in West Greenland, also in agreement with a preliminary age of ca. 2375 Ma for a Scourie dyke in the Lewisian complex of west Scotland (Davies et al., 2010). Together, therefore, the occurrence of similar-aged mafic dykes in the North Atlantic craton (S. Greenland, Nain and Scotland) represents a potentially valid barcode match for the Bangalore swarm. Other possible matches exist from the Napier complex in Antarctica, specifically a Rb-Sr 2350±48 Ma age for a tholeiitic dyke from the Napier complex in Enderby land (Sheraton and Black, 1981) and a Sm-Nd internal isochron age of 2349±61 Ma for a dolerite dyke from Aker peaks (Belyatsky et al., 2007).

Global magmatic activity, including emplacement of dated mafic dykes, was widespread at ca. 2.2

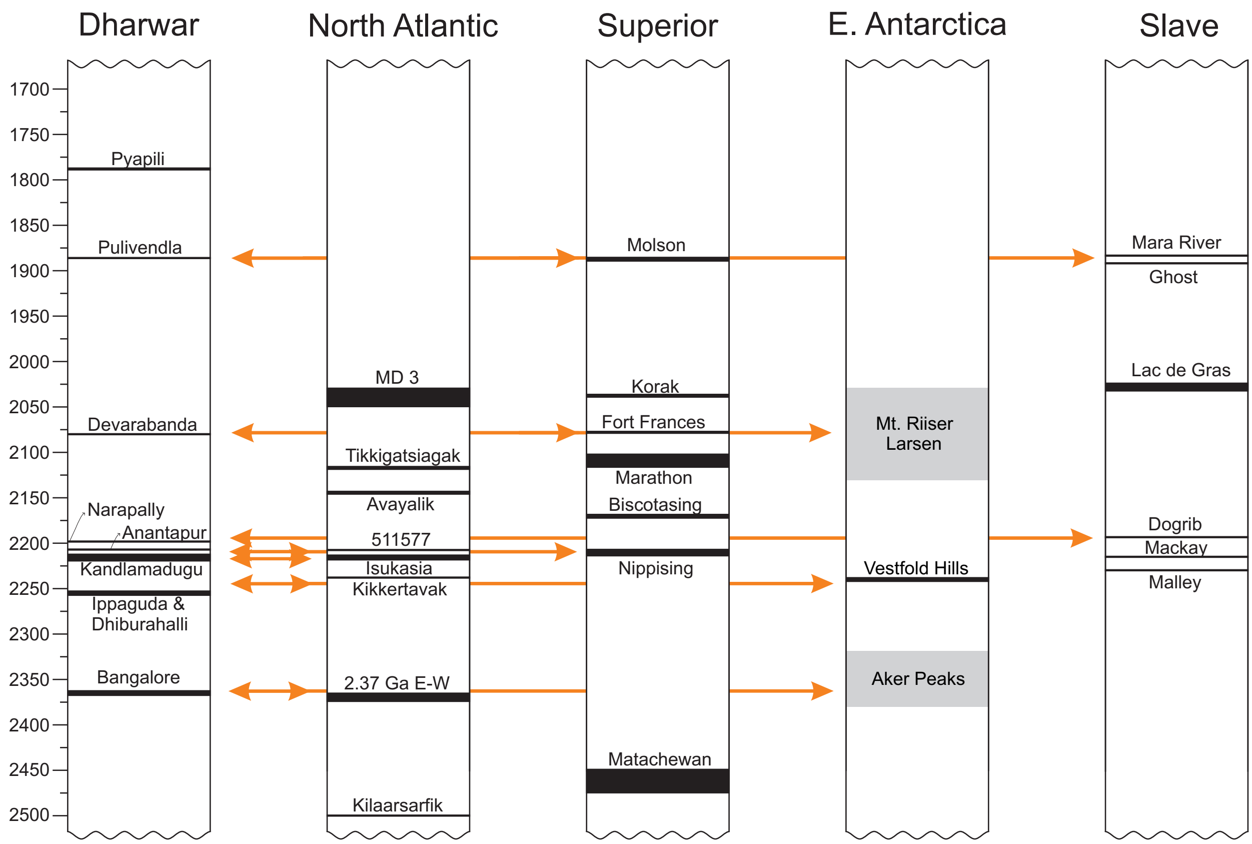

Fig. 4. Diagrammatic representation of magmatic event histories on vertical timelines (magmatic "barcodes"), for selected Archaean cratons. The thicknesses of the bars indicate the errors in isotopic ages. The grey bars indicate ages obtained from Rb-Sr and Sm-Nd systems, usually with larger errors than those for U-Pb (Pulivendla Sill: French et al., 2008; Kandlamadugu dykes: French and Heaman, 2010; 2.37 Ga E-W dykes, 511577 dykes, MD 3 dykes, and Kilaarsfik dykes: Nilsson et al., in press; Kikkertavak dyke: Cadman et al., 1993; Isukasia dyke: Nutman et al., 1995; Tikkigatsiagak dyke: Hamilton et al., 1998; Avayalik dyke: Connely, 2001; Nippising sills: Buchan et al., 1998; Matachewan dykes, Marathon dykes, Biscotasing dykes, Mackay dykes, Molson dykes: Ernst and Buchan, 2001a; Fort Frances dykes: Buchan et al. 1996; Korak sill: Machado et al., 1993; Aker Peaks dyke: Belyatsky, 2007; Vestfold Hills dykes: Lanyon et al., 1993; Mt. Riiser-Larsen dykes: Suzuki et al., 2008; Malley dykes: Buchan et al., 2012; Lac de Gras dykes, Mara River sills, and Ghost dykes: Bleeker and Ernst, 2006; the others: this study).

Ga, yet there are no direct matches at present for the 2255 Ma Ippaguda dyke swarm. The closest matches include the 2235±2 Ma Kikkertavak mafic dyke in NAC (Cadman et al., 1993), the 2241±4 and 2238±7 Ma Vestfold Hills noritic dykes in East Antarctica (Lanyon et al., 1993), the 2262±2 Ma Chimbadzi Hill intrusion in Zimbabwe (Manyeruke et al., 2004) and the 2231±2 Ma Malley diabase dyke in Slave craton, North America (Buchan et al., 2012). Due to the inadequacy distinguishing Ippaguda dykes and Dhiburahalli dyke and lack of exact age matches, these dykes are described together in following palaeoreconstructions.

The Anantapur dyke swarm can be related to the 2209±1 Klotz dykes (Buchan et al., 1998) and 2210±4 Ma Nippising sills (Noble and Lightfoot, 1992) from Superior craton, 2209±1 Ma dykes from Greenland, NAC (Nilsson et al., in press) and ~2208 Ma mafic sills and dolerite dykes from Hammersley Hill, Australia (Müller et al., 2005).

There are two possible global connections to the ca 2080 Ma magmatic activity in the Dharwar craton. First is the 2076±5 Ma Fort Frances dyke swarm in the Superior province of North America (Buchan et al., 1996), and second is the Rb-Sr age of 2078±104 Ma of dykes in Mt. Riiser-Larsen, Napier complex (Suzuki et al., 2008).

The 1788±12 Ma Pebbair dyke has an age match with extensive mafic dyke swarms in North China craton dated to 1.8–1.75 Ga (Peng et al., 2006).

Considering the ages above, two exact age matches at (1) ~2370 Ma, and (2) ~2210 Ma and another close age match between the Ippaguda dyke swarm (~2.255 Ga) and the Kikkertavak dykes of Labrador (~2.24 Ga) suggest that the Dharwar craton was in close proximity over this time interval with the NAC. Moreover, the NAC is postulated to have been an original crustal element in the eastern part of supercraton Superia (Nilsson et al., 2010). If the North Atlantic and Superior cratons indeed were neighbours, then the 2081 Ma Devarabanda dykes and 2076 Ma Fort Frances dykes could be proposed as a third exact age match. One thing to note is that even though mafic dykes older than 2.4 Ga are identified on both Superior craton and NAC, they are yet to be found on the Dharwar craton. Therefore, the NE-SW trending dyke cross-cut by one of the Bangalore dykes to the southwest of Cuddapah basin mentioned in French and Heaman (2010) may provide another crucial match in such linkage.

A connection of the Eastern Block of the North China craton with the Dharwar craton is also proposed, based on the similarities of both the magmatic and sedimentary records (Zhao et al., 2003). Specifically, 1788 Ma magmatic activity in the Dharwar craton can be matched with 1.8 – 1.75 Ga dyke emplacement in North China craton (Peng et al., 2006).

A connection with the Dharwar craton and Napier complex in Antarctica is rather speculative due to the lack of precise ages on dykes of the Napier complex. However, published Rb-Sr and Sm-Nd ages support such kinship. Notably, the U-Pb age of ~2.24 Ga obtained from the Vestfold Hills (Lanyon et al., 1993), another cratonic block in East Antarctica, is close to the age of Ippaguda dyke swarm.

5.5 Possible reconstructions between Dharwar, North Atlantic and Superior cratons

In previous studies, a possible link between the Dharwar and Slave cratons was favoured (Bleeker, 2003; French and Heaman, 2010), based on similar basement geology and contemporaneous mafic dykes. The reconstruction in French and Heaman (2010) was based on the 2176-2181 Ma Northern Dharwar dykes, the 2209 Ma Somala dyke and the 2212-2220 Ma Kandlamadugu dykes. However, newly identified ages from the Dharwar cra-

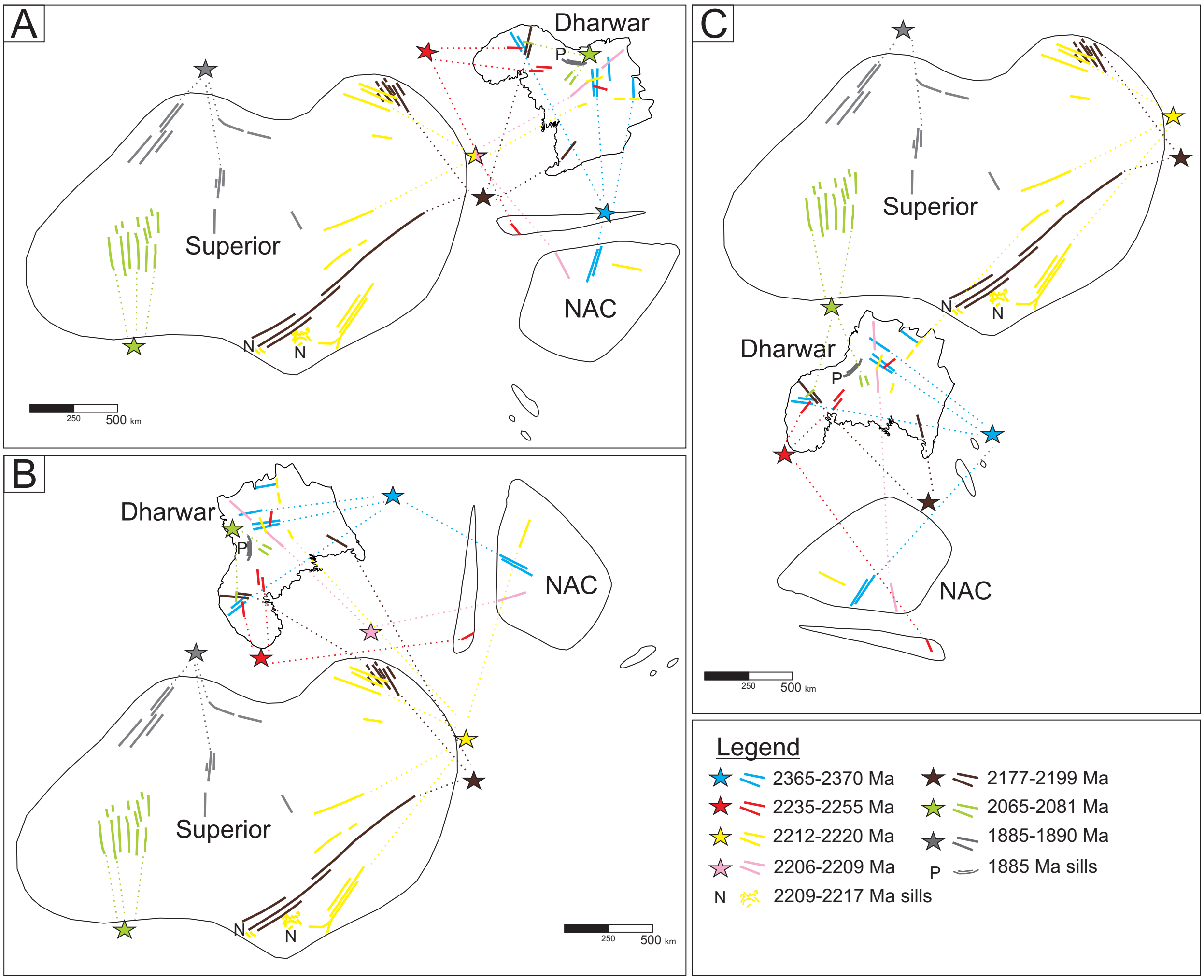

Fig. 5. Three possible reconstructions for Dharwar, North Atlantic and Superior cratons. Stars indicate the proposed plume centres, lines indicate dated dykes, dashed lines trace the dykes to the plume centres. The two-coloured star illustrates that two events with nearly similar ages are considered as one. Age and maps from: Superior (Ernst and Buchan, 2001a; Bleeker and Ernst, 2006), North Atlantic (Nilsson et al., 2010; Nilsson et al., in press), Dharwar (Halls et al., 2007; French and Heaman, 2010; Srivastava et al., 2011; Kumar et al., 2012; this study).

ton in this thesis raise the possibility of an ancestral connection with Superior and North Atlantic cratons, supported by three exact age matches.

Three possible configurations for Dharwar, North Atlantic and Superior cratons are shown in Fig. 5. It needs to be noted that these reconstructions are solely based on the precise ages from these three cratons, without accounting for corresponding data from other cratons or previous suggested palaeoreconstructions. Also dykes with ages older than 2.37 Ga such as the 2.47-2.49 Ga Matachewan dykes in Superior or the 2.5 Ga Kilaarsarfik dykes in North Atlantic craton are not accounted for, since no dykes from Dharwar older than 2368 Ma have been dated yet.

In Fig. 5A, the Dharwar craton is placed north of the NAC and northeast of the Superior. The 2.37 Ga Bangalore dykes (light-blue) fit well in this configuration, but the magmatic centre is then located on Labrador and no 2.37 Ga dykes are identified there yet. Ernst and Buchan (2001b) argued that dyke abundance usually increases towards the plume centre, whereas 2.37 Ga dykes are much more abundant in the Dharwar craton compared to the NAC. Also the Ippaguda dykes (red) fit well in this configuration, matching the 2235 Ma Kikkertavak dykes in NAC. The slight change in the trend of Dhiburahalli dyke and Kikkertavak dykes could be due to the long distance from the plume centre. Ernst and Buchan (2001b) indicate that the dyke trends, which are more than 1000 km away from the plume centre, likely swing to the direction of regional stress field. In this configuration a common plume centre for the 2206 Ma Anantapur swarm (pink) and the 2212-2220 Ma Kandlamadugu (yellow) dykes might be feasible when considering an age difference of ca. 13 Myr between the dyke swarms. The 2.18 Ga Northern Dharwar dykes (dark-brown) (French and Heaman, 2010), including the Narapally and Kandukur dykes from this study, fit well with the 2.17 Ga Biscotasing swarm. A proposed match for 2.07 Ga Fort Frances dyke swarm and 2.08 Ga Devarabanda swarm (green) appears to be coincidental in this reconstruction, given the large separation distances involved.

Fig. 5B shows a configuration, where the Dharwar craton is located to the north of the Superior craton whereas NAC is placed to the northeast of the Superior. A proposed plume centre for 2.37 Ga Bangalore dykes fits better according to the abundance of the dykes in each respective craton. Also the proposed plume centre for ca. 2.255 Ga Ippaguda dyke swarm is plausible considering the paucity of these dykes in NAC. However, the lack of 2.255 Ga dykes in Superior craton is a major shortcoming for this configuration. For 2212-2220 Ma Kandlamadugu dykes and 2206 Ma Anantapur dykes, two different plume centres are proposed. Since the continental drift rates were arguably higher in Palaeoproterozoic (Moyen and van Hunen, 2012 and references therein), the ~1000 km drift of the plates with respect to a stationary long-lived mantle plume is conceivable. Also the proposed plume centre of 1885 Ma Molson event (Ernst and Buchan, 2001a) is located conveniently close to the 1890 Ma plume centre on the east side of the Dharwar craton (Ernst and Srivastava, 2008), which is defined by the convergence of the NW-trending 1891-1883 Ma swarm of the Bastar craton (French et al., 2008) with the 1894 Ma E-W trending dyke of the Dharwar craton (Halls et al., 2007). This assumes attachment of the Bastar craton to the Dharwar craton prior to ~1.9 Ga.

In Fig. 5C, the Dharwar and North Atlantic cratons are positioned to the south of the Superior, even though the location is occupied by Hearne and Karelia cratons in a previous reconstruction made by Bleeker and Ernst (2006). The 2.37 Ga, 2.255 Ga and 2.08 Ga dykes fit well in this configuration, except that the 2.255 Ga dykes that supposedly transect the entire NAC have not been identified yet. The 2206 Ma dykes in both Dharwar and NAC seem to trend linearly, but have a different trend than the 2212-2220 Ma Kandlamadugu dykes, which fit to the radiating pattern of Ungava event despite the ~2000 km distance from the magmatic centre. It is also important to note that the Pulivendla sills near the Cuddapah basin are nearly 2500 km far away from the plume centre of Molson event. Moreover, the plume centre for 2.18 Ga Northern Dharwar dykes is located near the North Atlantic craton, where precise U-Pb ages in that range are absent.

Among those three possible reconstructions, the one demonstrated in Fig. 5B is favoured in this study. This is due to the coherence of fit of the more precisely dated dykes such as 2370 Ma and 2206 Ma. All in all, these reconstructions are rough estimations which require testing with further paleomagnetic and geochronological studies.

6 Conclusions

- The regional extent and age constraints of the previously identified Bangalore dyke swarm (~2.37 Ga) have been reinforced. The apparent radiating pattern, relies on no post-2.37 Ga rotation having taken place between the northern and southern portions of the craton.

- A globally unrecognized episode of dyke emplacement affected the eastern Dharwar craton at 2.255 Ga. The trend of this swarm is N-S and is named here as the Ippaguda dyke swarm. Also a NNE-SSW trending dyke is presented with a similar age, but with distinct characteristics.

- The age for the Konapuram dyke (BNB10-015A) at

2206 Ma is identical to the similarly trending Somala dyke (French and Heaman, 2010). Together these dykes are considered as a new swarm called the Anantapur dyke swarm.

• Three mafic dykes located in the vicinity of Cuddapah basin yield consistent ages of 2081 Ma. The dykes indicate a radiating pattern with a possible magmatic centre ca. 100 km southeast of the sampling sites of Pyapili and Devarabanda dykes. The name Devarabanda swarm is proposed for dykes belonging to this event. The emplacement mechanism may relate to the opening of the Cuddapah basin.

• One of the many undated dykes around the Cuddapah basin is now dated at 1788 Ma (Pebbair dyke), which represents a new precise age for mafic dykes in the Dharwar craton.

• During the early Palaeoproterozoic, the Dharwar craton is postulated to have been a nearest neighbour to the NAC and Superior craton, which are proposed to have omprised parts of the older supercraton Superia (Nilsson et al., 2010 and references therein). Such an ancestral linkage is now strongly supported by three exact and independent age matches between the cratons. Several palaeoreconstructions are suggested; palaeomagnetic work on the dated dykes is essential to further test these.

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