Pb–Pb zircon ages of Archaean metasediments and gneisses from the Dharwar craton, southern India: Implications for the antiquity of the eastern Dharwar craton

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^{207}Pb–^{206}Pb ages of zircons in samples of metasediments as well as ortho- and para-gneisses from both the western and the eastern parts of the Dharwar craton have been determined using an ion microprobe. Detrital zircons in metasedimentary rocks from both yielded ages ranging from 3.2 to 3.5 Ga. Zircons from orthogneisses from the two parts also yielded similar ages. Imprints of younger events have been discerned in the ages of overgrowths on older zircon cores in samples collected throughout the craton. Our data show that the evolution of the southwestern part of eastern Dharwar craton involved a significant amount of older crust (>3.0 Ga). This would suggest that crust formation in both the western and eastern parts of the Dharwar craton took place over similar time interval starting in the Mesoarchaean at ca. 3.5 Ga and continuing until 2.5 Ga. Our data coupled with geological features and geodynamic setting of the Dharwar craton tend to suggest that the eastern Dharwar craton and the western Dharwar craton formed part of a single terrane.

1. Introduction

The evolution of Archaean cratons often span from several hundreds to almost a billion years and are characterized by polymetamorphic and magmatic events involving both recycling of old crust and the accretion of young crust. Supracrustal metasedimentary rocks, preserved within highly metamorphosed gneissic complexes can provide a distinct record of the evolution of the continental crust during the Archaean (e.g., Schiøtte *et al* 1992; Mueller *et al* 1998; Dunn *et al* 2005).

Archaean gneissic complexes interspersed with older tracts of metasediments are polycyclic in origin. Relicts of gneisses generated during early cycles rarely retain their identity because of polymetamorphism and anatexis leading to migmatization obliterating the early events. These rocks are strongly deformed granitoid packages in which individual intrusions are not always distinguishable in the field or from petrographic characteristics. It is important to date such intrusions of the igneous precursors and ion microprobe Pb–Pb dating of microscopic domains in individual

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zircons having distinct morphologies (shape, internal structure, overgrowth) helps in tracing the evolutionary history of such complex granite-greenstone and gneiss-granulite terranes. A few such studies have been carried out on the Archaean cratons of India (e.g., Wiedenback *et al* 1996; Mishra *et al* 1999; Mondal *et al* 2002).

Studies of detrital zircon from Archaean metasediments have provided useful insight into the local provenance and in establishing regional geological history of various litho units. In particular, age spectra of detrital zircons provide information on the distribution and age of the provenance. Such dataset can be used as a correlation tool, making the assumption that coeval sediments in a basin display similar distributions. Alternatively, it can be used to trace the origin of detrital populations and to infer their possible provenances. This in turn helps in evaluating crustal growth models and terrane distribution. Despite limitations, detrital zircon age distributions provide important information that may prove critical for constraining tectonic evolution models for Archaean metasediments.

In this paper, we present results of ion microprobe ^{207}Pb–^{206}Pb dating of zircons from ortho- and para-gneisses and metasedimentary rocks from the southern part of the granite gneiss-greenstone terrain of the Dharwar craton of southern India. These results, combined with available geological and geochronological knowledge of this terrane, allowed us to assess the antiquity of the eastern Dharwar craton *vis-à-vis* the western Dharwar craton and also examine the prevalent concepts on the tectonic evolution of the Dharwar craton.

2. Geological and geochronological setting

The Dharwar craton consists primarily of greenstone-granite gneiss terrain with gneiss-granulite terrain bordering it in the southern part (figure 1). The craton has been subdivided into two parts, namely the western Dharwar craton (WDC)

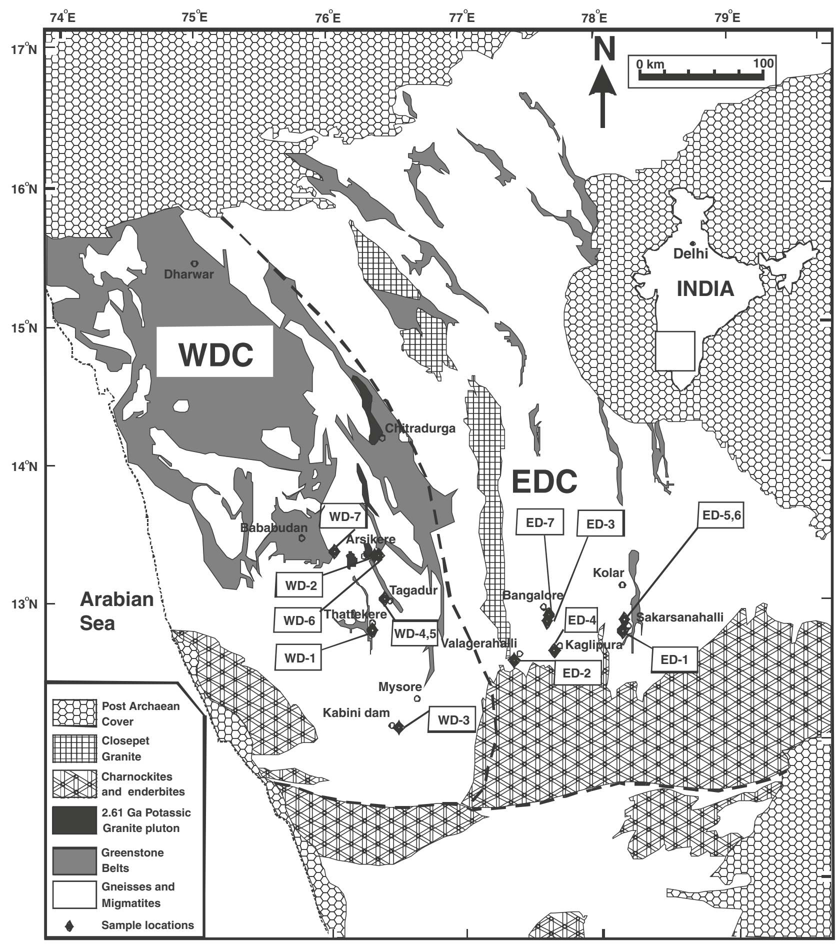

Figure 1. Geological map of the Dharwar craton (modified from Chardon *et al* 2008). Sampling sites are marked by filled diamonds. Location of some important cities, towns and sample locations are also shown (open circle).

and eastern Dharwar craton (EDC) based on the greenstone belts characteristics, degree of metamorphism and age and nature of the gneissic rocks (e.g., Swami Nath and Ramakrishnan 1981; Radhakrishna and Vaidyanathan 1997; Chadwick *et al* 2000; Jayananda *et al* 2000; Ramakrishnan and Vaidyanathan 2008). The greenstone-granite gneiss terrain consists of N–S to NNW–SSE trending supracrustal belts, known as the Dharwar schist belts, which are separated from each other by gneisses, designated as the Peninsular Gneiss. The supracrustal sequence occurring in the Dharwar schist belts, and also as small to large enclaves in Peninsular Gneiss, has been classified in to two lithostratigraphic divisions: the older Sargur Group and the younger Dharwar Supergroup (Swami Nath and Ramakrishnan 1981). The supracrustal rocks of the greenstone belts and the gneisses grade into a granulite complex in the southern part of the craton. According to Naha *et al* (1993) the Peninsular Gneiss is a polyphase migmatite-gneiss complex that evolved over a protracted period between 3.5 and 2.6 Ga. Ramakrishnan and Vaidyanathan (2008) state that the Peninsular Gneiss is a complex, which evolved in three distinct episodes: 3.4–3.3 Ga, 3.0–3.1 Ga and 2.5–2.6 Ga.

Based on Sm–Nd isotopic systematics, Jayananda *et al* (2008) suggested that the ultramafic melts for the Sargur komatiite volcanism were extracted from the mantle at ca. 3.352 Ga and based on the SHRIMP U–Pb zircon geochronological study, Peucat *et al* (1995) had reported contemporaneous 3.3 Ga felsic volcanic rocks in the area. Nutman *et al* (1992), in the first SHRIMP zircon geochronological study on the rocks of the Dharwar craton, found no detrital zircons younger than 3 Ga in the metapelite of the Sargur Group in the Holenarasipur schist belt and near Banavar in the WDC. They found preponderance of 3.3–3.4 Ga zircons and less than 5% zircons older than 3.5 Ga in these quartzites. From the foregoing it is inferred that the antiquity of the WDC goes beyond 3.5 Ga and the Sargur Group in the WDC accumulated prior to 3 Ga. Rb–Sr, Pb–Pb, Sm–Nd and SHRIMP U–Pb isotope dating led to identification orthogneisses with ages of 3.3 to 3.0 Ga in the WDC (Beckinsale *et al* 1980; Naha *et al* 1993; Peucat *et al* 1993).

The Dharwar Supergroup in the WDC has been subdivided into Bababudan Group and Chitradurga Group. The Bababudan Group consists of quartz pebble conglomerate-metabasalt-quartz arenite-rhyodacite-BIF sequence. Sm–Nd dating of mafic volcanic rocks shows that the Bababudan volcanism occurred between 2.91 and 2.85 Ga (Anil Kumar *et al* 1996). Zircons separated from volcanic tuffs interbedded with BIFs have yielded SHRIMP U–Pb age of 2.72 Ga (Trendall *et al* 1997). These observations constrain the age of the Bababudan Group between 2.91 and 2.72 Ga.

Chitradurga Group consists of quartz arenite-carbonate banded manganiferous iron formation assemblage at the base, and basalt-dacite-rhyodacite-greywacke-iron formation sequence at the top. The Sm–Nd isochron age for the volcanic rocks of the Chitradurga Group is 2.75 Ga (Anil Kumar *et al* 1996). The acid volcanics of Chitradurga Group have yielded SHRIMP U–Pb ages of 2.61 Ga (Nutman *et al* 1996; Trendall *et al* 1997).

The Sargur Group and the Dharwar Supergroup have been intruded by younger potassic granitoids between 2.6 and 2.5 Ga [e.g., Chitradurga Granite – 2.61 Ga, Arsikere–Banavar Granite – 2.62 Ga (Jayananada *et al* 2006) Uchchangidurga granite NW of Chitradurga – 2.65 Ga, Harapanhalli granite – 2.6 Ga, Turchihal Granite, Gadag schist belt – 2555 ± 22 Ma (Chadwick *et al* 2007)].

In the EDC, there are sericitic and fuchsitic quartzites, metapelites (andalusite, corundum bearing or cordierite-hypersthene-sillimanite bearing schists and gneisses), calc-silicate rocks and banded manganiferous iron formations occurring as enclaves in orthogneisses. These have been correlated with the Sargur Group of the WDC (Swami Nath and Ramakrishnan 1981). However, unlike in WDC, there are no geochronological data for EDC to verify if some of these rocks are older than 3 Ga and whether they record evidences for sources as old as 3.3–3.5 Ga. In addition to these enclaves, there are schist belts dominantly composed of ultramafic to mafic, and felsic volcanic rocks and banded iron formations. These include the well known Kolar, Ramagiri, Hutti, Sandur, Kadiri and Gadwal schist belts. Whole-rock Sm–Nd and Pb–Pb isochron age of the metatholeiites of the Kolar schist belt is 2.7 Ga (Balakrishnan *et al* 1990). U–Pb age of zircons from acid tuffs in the Kolar schist belt and pyroclastic rocks of Ramagiri schist belt is also 2.71 Ga (Balakrishnan *et al* 1999). Pb–Pb ages of acid volcanics from Ramagiri belt were reported as 2.75 Ga (Zacharia *et al* 1995). SHRIMP zircon U–Pb ages for the acid volcanics of Sandur schist belt is 2.66–2.69 Ga (Nutman *et al* 1996). Thus, the ages of metavolcanic rocks from the schist belts of EDC are *ca* 2.7 Ga, similar in age to the volcanic rocks of the Dharwar Supergroup of the WDC.

Isotope data indicate that portions of the gneissic terrain of EDC have old ages (∼3.0 Ga or older), similar to those in the WDC. A few zircons in the gneisses, occurring to the west side (within 1 km) of the Kolar schist belt have yielded Pb–Pb zircon ages of 3.1 Ga (Krogstad *et al* 1991;

Balakrishnan *et al* 1999). Friend and Nutman (1991) recorded 3.1 Ga ages in some zircons from gneisses in the Kabbaldurga area. The existence of ∼3.1 Ga gneisses is also documented further east near Bangalore (Jayananda *et al* 2000). Migmatitic orthogneiss of tonalitic composition immediately east of the shear zone bordering the Chitradurga schist belt are thought to be largely pre-2.9 Ga gneisses (Chadwick *et al* 2000; Friend and Nutman 1991). Isolated N–S bodies of juvenile tonalite with crystallization age of 2.56 Ga intrude the gneisses in the EDC (Chadwick *et al* 2000; Jayananda *et al* 2000). The granite gneiss east of the Sandur schist belt has also a relatively old age (2.72 Ga, Nutman *et al* 1996). Zircons from a granodiorite adjacent to the Hutti schist belt has a $^{207}Pb/^{206}Pb$ SHRIMP age of 2.58 (Vasudev *et al* 2000). Available geochronological data has led to the view that bulk of the granitoids and orthogneisses in EDC are younger and fall in the age range of 2.5–2.6 Ga (see Chadwick *et al* 2000; Jayananda *et al* 2000).

The WDC has been considered to be an Archaean nucleus to which Late Archaean to Early Proterozoic (2.7–2.5 Ga) terrane of EDC accreted (Radhakrishna and Naqvi 1986; Balakrishnan *et al* 1999). Chadwick *et al* (1992) suggested that the WDC and EDC are separated by a shear zone that can be traced along the eastern boundary of the Chitradurga schist belt. The gneisses of the WDC and the EDC have also been suggested to be distinct, with the gneisses of the WDC designated as Peninsular Gneiss, and the gneisses of the EDC as 'Dharwar batholith' (Chadwick *et al* 1996). A summary of the characteristic features of the WDC and EDC are presented in table 1.

A firm age for the protolith and subsequent evolution of EDC gneisses and metasediments has not been established because of the paucity of geochronological data. In this paper, we present results of ^{207}Pb–^{206}Pb dating of zircons from both WDC and EDC to address this issue as well as propose the idea that EDC and WDC formed part of a single terrane rather than late accretion of EDC to WDC.

3. Sample details

Fourteen samples, out of more than five dozen samples collected across the EDC and WDC, yielded reasonable number of zircons suitable for ion microprobe studies. Samples that might define the antiquity of EDC and WDC and shed light on the question of separate evolution of the two blocks followed by possible accretion of the EDC to the WDC, as suggested in some earlier studies (Radhakrishna and Naqvi 1986; Krogstad *et al* 1991; Balakrishnan *et al* 1999; Chadwick *et al* 2000), were specifically targeted based on available geological records. A brief description of the samples selected for analysis is provided in the following (sampling locations are shown in figure 1).

Table 1. *Comparative characteristics of WDC and EDC.*

Western Dharwar craton (WDC)	Eastern Dharwar craton (EDC)
Significant preservation of history older than 3.0 Ga (e.g., [1, 2, 3, 4])	Older components rare. Largely 2.55 Ga (e.g., [5, 6])
Extensive supracrustal belts (Dharwar Supergroup) – unconformity at the base preserved at several places [7]	Narrow linear Dharwar supracrustal belts – basal unconformity not documented [7]
Major metamorphic-magmatic episodes at ∼3.0 Ga and ∼2.55 Ga [8, 9]	Dominant metamorphic episode at 2.55 Ga. Vestiges of $\geq$ 3.0 Ga event [10, 6]
High-pressure metamorphic facies series [11]	Intermediate-pressure metamorphic facies series [11, 12]
Late-Archaean (2.55–2.6 Ga) granites subordinate [7, 13, 14, 15, 16, 17]	Late-Archaean granites prominent [5, 6]
DSS and wave-form modelling indicate thicker crust (40–52 km) [18]	Indicate thinner crust (33–36 km) [18]
Magnetotelluric studies show a low resistivity layer with 20 Ωm (G) at a depth of 40 km [19]	Low resistivity layer at a depth of 100 km [19]
Heat flow 29–32 mWm^2 [20]	Heat flow 23–50 mWm^2 [20]
Mantle heat flow 11–23 mWm^{-2} [21]	Mantle heat flow 11–16 mWm^2 [21]

[1] Beckinsale *et al* (1980); [2] Nutman *et al* (1992); [3, 4] Peucat *et al* (1993, 1995); [5] Balakrishnan *et al* (1999); [6] Jayananda *et al* (2000); [7] Jayananda *et al* (2006); [8] Bhaskar Rao *et al* (1983); [9] Bidyananda *et al* (2003); [11] Rollinson *et al* (1981); [12] Harris and Jayaram (1982); [13] Taylor *et al* (1984); [14] Rogers (1988); [15] Bhaskar Rao *et al* (1992); [16] Pandey *et al* (1994); [17] Chadwick *et al* (2007); [18] Gupta *et al* (2003); [19] Gokaran *et al* (2004); [20] Rao *et al* (2003); [21] Roy *et al* (2008).

3.1 *Samples from the western Dharwar craton (WDC)*

3.1.1 *Quartzite, quartz–mica–chlorite schist, and paragneiss from Sargur Group*

We sampled a quartzite representative of Sargur Group from a hillock near Thattekere village (WD-1; 12°48′16.4″N, 76°17′12.2″E) in the Holenarasipur schist belt. A quartz–mica–chlorite schist was sampled from the northern bank of the Arsikere irrigation tank (WD-2; 13°18′16.94″N, 76°15′51.17″E) in the northern part of the Nuggihalli schist belt, considered to be of Sargur Group. Kyanite bearing paragneiss was also collected from the Mullurbetta hillock near the Kabini Dam (WD-3; 11°58′39.7″N, 76°28′20.1″E) from the type area for the Sargur Group (Swami Nath and Ramakrishnan 1981) to look for presence of inherited older zircons in the Sargur supracrustal rocks.

3.1.2 *Orthogneiss adjacent to the Nuggihalli schist belt*

Samples of orthogneiss were collected from areas adjacent to the Nuggihalli schist belt. Gneisses of the area are reported to show syntectonic injection into the supracrustal schist belt (e.g., Swami Nath and Ramakrishnan 1981). Two gneiss (TTG) samples were collected from the area around Tagadur mines (WD-4; 13°02′00.73″N, 76°27′07.82″E) and (WD-5; 13°02′01.41″N, 76°27′08.67″E) and a third one from the Kodihalli village on the eastern bank of the Arsikere tank (WD-6; 13°17′58.59″N, 76°16′32.88″E). Gneisses from the Tagadur area are grey coloured with quartz and plagioclase as the dominant phases; K-feldspars occur as phenocrysts and biotite is the dominant ferromagnesian mineral. Accessory minerals include apatite and zircon. The primary phases in the granitic gneiss from the Kodihalli area are quartz and K-feldpsar; phenocryst plagioclase is partially altered. Biotite is present as secondary (minor) mineral, while apatite, zircon and magnetite occur as accessory minerals.

3.1.3 *Gneiss clasts from the conglomerate of the Dharwar Supergroup*

A gneissic clast from the polymictic Kaladurga conglomerates of the Dharwar Supergroup was sampled to constrain the age of the pre-Dharwar crust in the WDC. The sampling site was on the west side of the Shivpura railway station (WD-7; 13°25′32.2″N, 76°09′08.5″E) on the Kadur–Shimoga road. The conglomerate displays cobbles and boulders of tonalitic gneisses, migmatised amphibolites, metavolcanics, quartzites, marbles and BIF. The matrix is composed of fine-grained quartz, saussuritized plagioclase, biotite and muscovite.

3.2 *Samples from eastern Dharwar craton (EDC)*

3.2.1 *Metapelites and quartzites*

Metapelite and quartzite bodies, a few kilometers along strike and several tens to several hundred metres across, occur within the gneisses of the EDC. Three metapelite samples were collected from different parts of the EDC. A cordierite bearing metapelite was collected from an abandoned pit near the Dodderi village (ED-1) west of Kolar greenstone belt, another from the western slope of a hillock near the Valagerahalli village (ED-2; 12°35′48.7″N, 77°14′91.8″E) to the south of Bangalore, and the third sample from a location about 100 metres west of Honniganahatti village (ED-3; 12°58′34.0″N, 77°25′01.4″E). Samples' locations are shown in figure 1. The quartzites are fuchsite bearing and the metapelites include cordierite–hypersthene–sillimanite (±garnet) bearing gneisses (Harris and Jayaram 1982). These have been considered to be stratigraphic equivalents of Sargur Group in the WDC (Ramakrishnan and Viswanatha 1981). One quartzite sample was collected from a mound about two kilometers east of Kaglipura village (ED-4; 12°47′ 84.3″N, 77°32′07.7″E) and another from a small hillock near Sakarsanahalli (ED-5; 12°48′68.3″N, 78°12′44.5″E).

3.2.2 *Possible older gneisses*

There are reports of gneisses from the west of Kolar greenstone belt yielding inherited zircon ages of >3 Ga (Krogstad *et al* 1991). We have collected such a gneissic sample close to the Sakarsanahalli village (ED-6; 12°48′02.0″N, 78°13′03.8″E) to look for records of Archaean crustal components. The gneiss is grey with quartz and plagioclase as the dominant phases, K-feldspar and pyroxene occur as secondary phases.

3.2.3 *Migmatite bodies (enclaves) in gneisses with earliest structural fabric*

The Dharwar and Sargur supracrustal rocks show three phases of folding and the gneissic complex shows syntectonic evolution during these three episodes in both WDC and EDC (Naha *et al* 1986, 1990). Evidence for an additional phase of isoclinal folding and migmatization that predates the first folding event in the Dharwar and Sargur supracrustal sequences was also found in certain bodies present within the gneisses (Naha *et al* 1986, 1990). We have sampled such body from Hulimavu quarry in southern Bangalore in EDC (ED-7; 12°52′65.3″N, 77°36′03.8″E).

4. Analytical methods

All the samples were processed using a standard technique to obtain zircon grains (Wiedenback and Goswami 1994). Each sample was crushed into centimeter-sized chips and was thoroughly washed after eliminating weathered portions. The clean chips from each sample were then pulverized to <250 micron size in a clean environment using a stainless steel piston and cylinder. Non-magnetic, high-density mineral grains were concentrated by density separation using aqueous Na-polytungstate solution (density=3 g cm^{-3}) followed by magnetic separation using a Frantz isodynamic separator. Zircon grains were handpicked from this fraction using a binocular microscope. Individual clear, unfractured and least intensely coloured zircons were selected and mounted on a double-sided tape, cast in epoxy and sectioned by polishing. Transparent zircons with simple internal structure were documented in detail. Zircons from the metasediments are subrounded to subhedral, transparent and colourless to brown in transmitted light while those from the gneissic samples are generally transparent, colourless to pale brown, euhedral in shape and mostly inclusion free. A few zircons show fine zoning while a few others have distinct overgrowths. The zircon mounts were thoroughly cleaned in ethanol using an ultrasonic bath and coated with a 100 nm thick, high-purity gold film for isotopic measurement using an ion microprobe. Most of the zircon grains selected for analysis was colourless, equant to prismatic. A few were slightly rounded and were free of visible alteration, cracks and inclusions. Photomicrographs of some of the analysed grains are shown in figure 2.

We used a Cameca ims–4f ion microprobe at the Physical Research Laboratory for measuring Pb isotope ratios ($^{207}Pb/^{206}Pb$) in the zircons using procedures described previously (Wiedenback and Goswami 1994). The instrument was operated at a high-mass resolution (M/ΔM∼4600) that can resolve all the significant isobaric molecular interferences in the Pb isotope mass spectrum. A 7 nA focused primary beam of $^{16}O^-$ was used to sputter ∼20 micron domain of individual zircon grains. Each analysis consisted of 15 blocks of data and each block comprised of 5 scans through the mass sequence $^{204}(Zr_2O)$, ^{204}Pb, ^{206}Pb, ^{207}Pb, $^{208}(HfO_2)$ and ^{208}Pb in peak jumping mode. A typical analysis took about 90 minutes. The age for a given analysis was inferred from the weighted mean $^{207}Pb/^{206}Pb$ ratio obtained from the data of the 15 quasi-independent blocks that were corrected for common Pb following the method of Cumming and Richards (1975). The age of a sample was

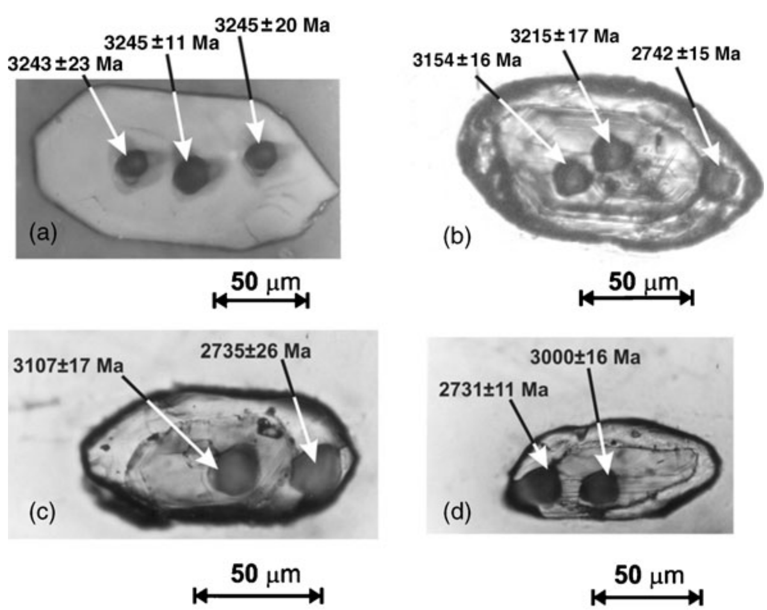

Figure 2. **(a)** Reflected light photomicrographs of homogeneous zircon from the Sakarsanahalli gneissic enclave; three analyses conducted on this zircon yielded concordant ages. **(b–d)** Transmitted light photomicrographs of heterogeneous zircons from the Sakarsanahalli metapelite showing core–overgrowth morphology. The $^{207}Pb–^{206}Pb$ ages for the core and overgrowth are also shown.

inferred from the data obtained from analysis of multiple zircons as well as multiple analyses of single zircons. The exclusion of uranium isotopes in our measurement routine, rules out the possibility of having specific information on Pb-loss, as well as, detecting the presence of multiple age components within such datasets. Several objective criteria (Wiedenback and Goswami 1994; Wiedenback *et al* 1996) were used for identifying analyses belonging to the magmatic component and the age of a sample was derived from the mean radiogenic $^{207}Pb/^{206}Pb$ ratio obtained by pooling the data (at block level) for all such analyses. The inferred age may be considered as the 'minimum' age of the sample. However, for samples that show a sharp cut-off in higher radiogenic $^{207}Pb/^{206}Pb$ ratios, the minimum age closely approximates the true age of the sample. Details of the procedure adopted for data acquisition and assessment were reported earlier (Wiedenback and Goswami 1994; Wiedenback *et al* 1996). Even though we have selected nearly 50 to 60 zircons in each sample for analysis, low count rates as well as presence of high common lead restricted the analyzed dataset to a relatively small subset of zircons in most cases.

5. Results

The ^{207}Pb–^{206}Pb isotope data for the analyzed zircons for metasediments and gneisses from the WDC and EDC are presented in table 2. Results from analyses, in which Pb-loss was clearly discerned, were not included in the table; the number of such analyses ranged from two to five in different samples. They included analyses that yielded ages much lower than those inferred from the magmatic population in a given sample and/or analyses characterized by high U content. Even though the errors (1σ) estimated for the various samples, based on multiple analyses, are typically 10 Ma, the error on individual analyses is generally a few tens of Ma and our analytical technique does not allow us to uniquely distinguish samples differing in ages by <20 Ma.

5.1 *Western Dharwar craton*

5.1.1 *Quartzites, quartz–mica–chlorite schist and paragneisses from Sargur Group*

Twelve analyses were conducted on nine zircons separated from the quartzite collected from the Thattekere area (WD-1). All of them have low common Pb (<7%) and the inferred zircon ages ranged between 3100 and 3480 Ma (table 2). Six analyses (3, 4A, 4B, 5B, 7, 9) yielded ages ranging between 3.35 and 3.40 Ga; ages for four other analyses (1A, 1B, 2, 8) lie between 3.1 and 3.2 Ga and two analyses (5A and 6) yielded ages greater than 3.4 Ga. Older relict zircons (>3.5 Ga) reported by Nutman *et al* (1992) from samples collected in this region were not found in our study and are inferred not to have widespread occurrence.

Eighteen analyses were conducted on nine zircons from the metasediment (quartz–mica–chlorite schist) sample from Arsikere (WD-2); the Pb-isotopic data of these analyses are presented in table 2. All the analyses have a low common Pb component (<10 %) and yielded ages in the range of ∼2.4 to 3.2 Ga. Two analyses conducted on a single zircon have concordant ages of 3184 ± 26 Ma (1A; 1σ error) and 3160 ± 34 Ma (1B). Three zircons with distinct core–overgrowth morphology (2, 4 and 9) were analyzed. The core region in one grain yielded an age of 3202 ± 25 Ma (2A) while the ages determined for the overgrowth were lower, 2845 ± 73 Ma (2B) and 2746 ± 44 Ma (2C). In the other two cases, the core regions yielded ages of ∼3.0 to 3.1 Ga (4A, 4B, 9A and 9C) while the ages of the overgrowths are much lower (2.67 to 2.43 Ga).

Seventeen analyses were conducted in eight zircon grains from the paragneiss collected near the Kabini Dam (WD-3). Four of the zircons have distinct core–overgrowth morphology (3, 4, 7 and 8). The core regions yielded ages of ∼3.25 (3A, 7B) and ∼3.12 Ga (8A, B), while the rim ages are distinctly younger (<3 Ga). Three analyses conducted in a single grain (#6A, B, C) yielded a reproducible age of ∼3.3 Ga (table 2).

5.1.2 *Orthogneiss adjoining Nuggihalli schist belt*

We have conducted eight analyses in four zircons from one TTG sample (Tag-1, WD-4) and nine analyses on eight zircons from another TTG sample (Tag-2, WD-5) collected from the Tagadur area. Some of these zircons have high U content and we cannot rule out possible Pb-loss due to their probable metamict nature. Five analyses conducted on four zircons in sample Tag-1 (WD-4) belong to one age group, while the other analyses yielded lower ages between 2.7 and 2.95 Ga. We consider the five analyses with higher ages as magmatic and this dataset yielded a weighted mean radiogenic $^{207}Pb/^{206}Pb$ value of 0.2357 ± 0.001 corresponding to an age of 3091 ± 8 Ma for this sample (table 2).

In Tag-2 (WD-5), we have considered data for eight analyses of zircon domains with U content <1300 ppm and obtained a mean radiogenic $^{207}Pb/^{206}Pb$ value of 0.2312 ± 0.0011 corresponding to an age of 3060 ± 8 Ma (table 2) for the sample. Two of the analyses conducted on a

Table 2. *Pb isotopic data of zircons from the Dharwar craton.*

Analysis no.[a]	Measured $^{204}Pb/^{206}Pb$	Measured $^{207}Pb/^{206}Pb$	Total ^{206}Pb (counts)	$^{206}Pb^b$ (ppm)	U^c (ppm)	$^{207}Pb/^{206}Pb^b$	Obs./Exp.[d]	Age[e] (Ma)
Western Dharwar Craton								
1. Quartzite, Thattekere area (WD-1; 12°48′16.4″N, 76°17′12.2″E)								
1A	0.0016	0.2669	59275	308	561	0.2496 ± 34	1.1	3182 ± 22
1B	0.0012	0.2681	27835	165	297	0.2547 ± 47	0.93	3214 ± 29
2	0.0017	0.2587	39490	174	325	0.2396 ± 39	0.92	3117 ± 26
3	0.0016	0.2964	41360	184	312	0.2798 ± 37	1.0	3362 ± 20
4A	0.0012	0.2898	30055	161	276	0.2772 ± 58	1.38	3347 ± 33
4B	0.0015	0.2936	15575	83	141	0.2775 ± 82	1.05	3349 ± 46
5A	0.001	0.3006	41730	240	399	0.2905 ± 34	1.06	3420 ± 18
5B	0.0016	0.2985	20715	125	211	0.2823 ± 63	1.03	3376 ± 34
6	0.0011	0.3135	25925	144	233	0.3025 ± 65	1.38	3483 ± 33
7	0.0017	0.296	38005	220	374	0.2786 ± 44	1.09	3355 ± 24
8	0.0016	0.2554	21045	130	244	0.2380 ± 67	1.1	3106 ± 45
9	0.0012	0.2992	11455	94	157	0.2864 ± 142	1.4	3398 ± 77
2. Quartz–mica–chlorite schist, Arsikere tank (WD-2; 13°18′16.94″N, 76°15′51.17″E)								
1A	0.00032	0.2535	42320	99	180	0.2500 ± 41	1.3	3184 ± 26
1B	0.00062	0.2531	25080	77	142	0.2462 ± 53	1.0	3160 ± 34
2A	0.00036	0.2568	44530	222	401	0.2528 ± 41	1.3	3202 ± 25
2B*	0.00179	0.2234	16820	99	202	0.2169 ± 91	1.2	2845 ± 73
2C*	0.00162	0.2100	25750	172	369	0.1906 ± 52	0.98	2746 ± 44
4A	0.00086	0.2522	42835	148	274	0.2426 ± 40	1.2	3137 ± 26
4B*	0.00057	0.2380	104980	703	1335	0.2314 ± 25	1.55	3062 ± 17
4C*	0.00180	0.2330	43430	234	464	0.2120 ± 42	1.10	2921 ± 32
5*	0.00103	0.2159	20080	131	271	0.2038 ± 72	1.12	2857 ± 57
6	0.00126	0.2449	14455	81	154	0.2305 ± 86	0.97	3055 ± 60
7A	0.00134	0.2597	10940	64	116	0.2446 ± 113	1.01	3150 ± 72
7B*	0.00027	0.2201	38110	204	406	0.2169 ± 37	1.04	2958 ± 28
8*	0.00025	0.2183	10745	72	145	0.2154 ± 81	1.05	2946 ± 61
9A	0.00123	0.2447	10210	88	167	0.2307 ± 125	1.05	3057 ± 86
9B*	0.00081	0.1672	20840	219	553	0.1571 ± 75	1.19	2425 ± 81
9C	0.00156	0.2378	8430	112	217	0.2198 ± 163	1.13	2979 ± 120
9D*	0.00117	0.1970	28610	280	623	0.1829 ± 55	1.17	2679 ± 49
10*	0.00091	0.2090	57100	488	1025	0.1983 ± 28	1.1	2812 ± 23
3. Kyanite-bearing paragneiss, Mullurbetta (Kabini Dam) (WD-3; 11°58′39.7″N, 76°28′20.1″E)								
1C*	0.0015	0.2269	23095	285	572	0.2095 ± 62	1.09	2901 ± 48
2A	0.0026	0.2504	20665	208	398	0.2201 ± 72	1.06	2981 ± 52
2B	0.0017	0.2442	35650	221	422	0.2249 ± 54	1.27	3016 ± 38
2C	0.0007	0.2293	22120	86	167	0.2214 ± 60	1.02	2991 ± 43
3A	0.0015	0.279	23380	140	243	0.2626 ± 55	0.97	3262 ± 32
3B*	0.0012	0.2137	36425	285	594	0.1992 ± 39	1.03	2820 ± 32
4A	0.0022	0.256	50715	401	746	0.2306 ± 50	1.26	3056 ± 34
4B*	0.0013	0.1939	38115	356	807	0.1773 ± 45	1.24	2628 ± 42
5	0.0003	0.2056	53270	377	789	0.2016 ± 33	1.29	2839 ± 27
6A	0.0005	0.2843	29435	241	408	0.2794 ± 55	1.29	3360 ± 31
6B	0.0006	0.2766	12465	163	280	0.2705 ± 92	1.1	3309 ± 53
6C	0.0009	0.2902	43240	533	894	0.2811 ± 49	1.5	3369 ± 27
7B	0.0008	0.2694	20665	171	301	0.2609 ± 65	1.08	3252 ± 39
7C*	0.0006	0.2239	69040	607	1202	0.2176 ± 22	1.0	2963 ± 16
8A	0.0004	0.2427	48820	163	305	0.2388 ± 42	1.47	3112 ± 28
8B	0.0001	0.2446	55500	194	360	0.2432 ± 27	1.13	3141 ± 17
8C*	0.0002	0.1857	41550	267	601	0.1829 ± 43	1.31	2680 ± 38

Table 2. *(Continued).*

Analysis no.[a]	Measured $^{204}Pb/^{206}Pb$	Measured $^{207}Pb/^{206}Pb$	Total ^{206}Pb (counts)	$^{206}Pb^b$ (ppm)	U^c (ppm)	$^{207}Pb/^{206}Pb^b$	Obs./Exp.[d]	Age[e] (Ma)
4. Tag-1, TTG, Tagadur (WD-4; 13°02′00.73″N, 76°27′07.82″E)								
1B	0.00113	0.2412	130245	604	1166	0.2283 ± 32	1.7	3040 ± 22
2A	0.0019	0.2529	76035	350	671	0.2310 ± 31	1.1	3059 ± 22
3B	0.00075	0.2458	183430	867	1633	0.2375 ± 14	1.0	3103 ± 09
4A	0.00063	0.2562	43215	188	343	0.2492 ± 48	1.5	3180 ± 30
4B	0.00040	0.2444	79720	322	602	0.2399 ± 29	1.5	3119 ± 19
5. Tag-2, TTG, Tagadur (WD-5; 13°02′01.41″N, 76°27′08.67″E)								
1A	0.0016	0.2408	74505	537	1054	0.2224 ± 30	1.1	2998 ± 22
2A*	0.00147	0.2381	52655	441	870	0.2211 ± 36	1.1	2989 ± 26
2C	0.00083	0.2490	41320	457	855	0.2398 ± 33	1.0	3118 ± 22
2D	0.00083	0.2503	35065	357	665	0.2410 ± 42	1.1	3127 ± 28
3A	0.00088	0.2362	49955	647	1257	0.2261 ± 43	1.6	3024 ± 31
3C	0.00044	0.2507	43595	498	917	0.2458 ± 38	1.2	3158 ± 24
5A	0.00070	0.2491	42860	687	1280	0.2413 ± 34	1.1	3128 ± 22
5C	0.00078	0.2393	80380	604	1159	0.2304 ± 32	1.6	3055 ± 22
6. Granitic gneiss, Kodihalli (WD-6; 13°17′58.59″N, 76°16′32.88″E)								
2A	0.00024	0.2482	222905	933	1719	0.2455 ± 15	1.5	3156 ± 09
4	0.00104	0.2484	243485	637	1201	0.2367 ± 29	2.1	3098 ± 19
5A	0.00062	0.2617	29675	90	163	0.2549 ± 44	1.0	3215 ± 27
5B	0.00034	0.2584	49135	98	176	0.2546 ± 28	1.0	3214 ± 17
5C*	0.00051	0.2468	51305	120	223	0.2411 ± 55	2.0	3127 ± 36
6	0.00122	0.2501	89020	601	1118	0.2364 ± 27	1.20	3096 ± 18
7	0.00152	0.2493	73870	478	896	0.2321 ± 33	1.21	3066 ± 23
10	0.00151	0.2715	19305	137	242	0.2548 ± 89	1.38	3215 ± 55
11	0.00034	0.2471	44200	173	320	0.2433 ± 32	1.00	3141 ± 20
7. Gneissic clast, Kaladurga conglomerate (WD-7; 13°25′32.2″N, 76°09′08.5″E)								
1A*	0.00064	0.2579	31915	125	227	0.2508 ± 41	1.13	3190 ± 26
1B*	0.00179	0.2669	38845	154	282	0.2471 ± 57	1.32	3166 ± 36
1C	0.00137	0.2777	20885	95	167	0.2630 ± 60	1.2	3265 ± 36
3A*	0.00034	0.2373	15265	50	95	0.2334 ± 71	1.29	3075 ± 48
3B*	0.00075	0.2605	6380	40	73	0.2523 ± 140	1.04	3199 ± 87
3C	0.00011	0.2628	25665	88	156	0.2616 ± 38	1.0	3257 ± 22
4A	0.00019	0.2399	12555	52	97	0.2377 ± 68	1.0	3105 ± 46
4B	0.00042	0.2468	6480	45	84	0.2421 ± 125	1.05	3134 ± 82
5	0.00026	0.2596	18400	104	186	0.2567 ± 62	0.96	3227 ± 38
6	0.00129	0.257	26315	152	283	0.2426 ± 69	1.0	3137 ± 45
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8. Metapelite, Dodderi village (ED-1)								
1A	0.0003	0.258	79575	312	562	0.2548 ± 20	1.42	3215 ± 17
1B*	n.d.	0.19	70935	404	887	0.1900 ± 15	1.25	2742 ± 15
1C	n.d.	0.245	54815	262	483	0.2453 ± 19	1.33	3154 ± 16
2A	0.0003	0.226	80460	284	558	0.2226 ± 19	1.23	3000 ± 16
2B*	n.d.	0.189	106935	493	1088	0.1887 ± 11	1.1	2731 ± 11
3A	0.0016	0.219	59280	470	996	0.1992 ± 32	1.07	2819 ± 29
3B*	0.0005	0.194	67365	424	940	0.1877 ± 22	1.11	2722 ± 21
4A	n.d.	0.277	64435	230	394	0.2773 ± 18	1.0	3348 ± 10
4C*	0.0004	0.194	84535	283	624	0.1888 ± 18	1.25	2731 ± 20
5A	n.d.	0.238	82255	214	402	0.2381 ± 15	1.7	3107 ± 17
5B*	n.d.	0.189	93045	590	1300	0.1892 ± 12	2.36	2735 ± 26
6	n.d.	0.236	104535	727	1376	0.2355 ± 13	2.25	3090 ± 18
7	0.00005	0.26	81955	753	1341	0.2591 ± 17	1.2	3241 ± 12

Table 2. *(Continued).*

Analysis no.[a]	Measured		Total ^{206}Pb (counts)	^{206}Pb[b] (ppm)	U[c] (ppm)	^{207}Pb/^{206}Pb[b]	Obs./Exp.[d]	Age[e] (Ma)
	^{204}Pb/^{206}Pb	^{207}Pb/^{206}Pb						
9. Cordierite-bearing metapelite, Valagerahalli village (ED-2; 12°35′48.7″N, 77°14′91.8″E)								
1C	0.00094	0.2578	59285	400	733	0.2470 ± 28	1.13	3168 ± 18
2	0.00144	0.2154	58710	502	1068	0.1980 ± 40	1.32	2812 ± 33
3A	0.0001	0.267	46455	333	583	0.2660 ± 30	1.2	3282 ± 18
3B	0.0001	0.2302	70375	470	905	0.2290 ± 32	1.69	3046 ± 22
3C	0.00018	0.242	54375	437	816	0.2400 ± 44	1.71	3120 ± 29
3D*	0.00038	0.1984	55645	408	882	0.1940 ± 37	1.41	2775 ± 31
3E	0.00031	0.2536	30780	367	667	0.2500 ± 42	1.04	3186 ± 27
4A	0.0001	0.2706	47685	293	510	0.2700 ± 32	1.29	3303 ± 18
4B	0.00013	0.2621	17175	260	461	0.2610 ± 49	1.0	3251 ± 29
4C	0.0002	0.2631	35960	236	419	0.2610 ± 34	1.0	3252 ± 20
5	0.00011	0.2455	44595	268	495	0.2440 ± 26	1.0	3148 ± 17
6A*	0.0001	0.1886	52915	354	785	0.1870 ± 24	1.05	2719 ± 21
6B	0.00011	0.2455	20375	156	288	0.2440 ± 43	0.96	3148 ± 28
7A	0.00016	0.2338	82765	468	895	0.2320 ± 19	1.0	3066 ± 13
7B	0.00019	0.2388	96960	549	1036	0.2370 ± 17	0.91	3097 ± 11
10. Cordierite-bearing metapelite, Honniganahatti (ED-3; 12°58′34.0″N, 77°25′01.4″E)								
1A	0.00106	0.2602	138005	830	1498	0.2485 ± 28	1.55	3175 ± 17
1B	0.00208	0.2781	65950	361	631	0.2554 ± 49	1.5	3219 ± 30
1D*	0.00117	0.2188	125105	807	1651	0.2050 ± 24	1.2	2867 ± 18
1E*	0.00114	0.2068	113020	880	1880	0.1930 ± 28	1.41	2768 ± 24
3A*	0.00077	0.2032	170045	641	1371	0.1939 ± 17	1.17	2776 ± 14
3B	0.00201	0.238	74190	296	580	0.2145 ± 44	1.38	2940 ± 33
3C	0.00121	0.2344	65705	352	686	0.2203 ± 61	2.2	2983 ± 44
3D*	0.00107	0.2075	119935	597	1269	0.1946 ± 20	1.06	2781 ± 17
6A	0.0002	0.2192	112305	617	1231	0.2169 ± 22	1.45	2958 ± 16
6B	0.00135	0.2369	91525	554	1074	0.2213 ± 29	1.24	2990 ± 21
6C*	0.00009	0.2082	83295	653	1346	0.2072 ± 43	2.54	2884 ± 33
6D	0.00004	0.2215	67305	544	1073	0.2211 ± 22	1.33	2989 ± 16
6E*	0.00016	0.1894	81610	673	1489	0.1874 ± 37	2.0	2719 ± 32
7A	0.00027	0.2281	92995	592	1151	0.225 ± 20	1.17	3017 ± 14
7B*	0.00025	0.2122	83170	637	1300	0.2093 ± 29	1.64	2900 ± 23
7C*	0.00017	0.2192	69520	512	1019	0.2173 ± 32	1.6	2961 ± 24
11. Quartzite, Kaglipura (ED-4; 12°47′84.3″N, 77°32′07.7″E)								
2	0.00184	0.2436	16165	133	255	0.2224 ± 83	1.05	2998 ± 60
4B*	0.00064	0.2316	33840	617	1196	0.2242 ± 47	1.18	3011 ± 33
4C	0.00027	0.2435	42215	740	1376	0.2404 ± 33	1.05	3123 ± 22
5A	0.00022	0.2426	114395	653	1217	0.2401 ± 28	1.8	3121 ± 18
5B*	0.00045	0.2232	48745	489	968	0.2180 ± 44	1.52	2966 ± 32
7	0.00087	0.2418	40385	223	422	0.2319 ± 39	1.17	3065 ± 27
8A	0.00067	0.2366	55550	341	651	0.2289 ± 26	1.0	3044 ± 18
8B	0.00067	0.2348	79655	759	1458	0.2272 ± 42	2.07	3032 ± 29
9A	0.00073	0.2409	64585	364	687	0.2326 ± 30	1.25	3070 ± 20
9B	0.00025	0.2321	74215	595	1143	0.2292 ± 37	1.79	3047 ± 25
9C	0.00004	0.239	62770	669	1255	0.2386 ± 23	1.25	3110 ± 15
12. Quartzite, Sakarsanahalli (ED-5; 12°48′68.3″N, 78°12′44.5″E)								
1A	n.d.	0.3122	52325	116	185	0.3122 ± 36	1.7	3532 ± 17
1B*	0.001	0.2933	41805	106	180	0.2785 ± 48	1.42	3354 ± 27
1C*	n.d.	0.1683	34885	202	487	0.1683 ± 41	1.67	2541 ± 40
2A	n.d.	0.3132	31695	95	151	0.3132 ± 42	1.4	3537 ± 21
2B	n.d.	0.3021	20710	58	95	0.3021 ± 47	1.2	3481 ± 24
3	n.d.	0.2816	67550	211	358	0.2816 ± 25	1.4	3372 ± 14

Table 2. *(Continued).*

Analysis no.[a]	Measured $^{204}Pb/^{206}Pb$	Measured $^{207}Pb/^{206}Pb$	Total ^{206}Pb (counts)	$^{206}Pb^{b}$ (ppm)	U^{c} (ppm)	$^{207}Pb/^{206}Pb^{b}$	Obs./Exp.[d]	Age[e] (Ma)
4	n.d.	0.2592	63825	274	488	0.2592 ± 20	1.09	3242 ± 12
5A*	n.d.	0.2316	45215	66	126	0.2316 ± 41	2.0	3063 ± 28
5B	n.d.	0.2816	29055	66	111	0.2816 ± 30	1.0	3372 ± 16
6	0.00004	0.2715	30680	67	117	0.2660 ± 51	1.21	3283 ± 29
7	0.000004	0.2168	126340	334	684	0.2092 ± 21	1.33	2900 ± 16
8	n.d.	0.2606	49165	72	127	0.2606 ± 29	1.31	3250 ± 17
9	0.000004	0.2131	118795	275	569	0.2063 ± 17	1.08	2877 ± 13
10	0.001	0.2453	69200	135	259	0.2292 ± 35	1.26	3046 ± 24
11	0.00004	0.2629	65770	70	124	0.2572 ± 30	1.29	3230 ± 18
12	0.0004	0.2358	120005	209	400	0.2313 ± 19	1.3	3061 ± 13
13	0.00005	0.2497	75365	114	209	0.2492 ± 28	1.8	3180 ± 18
14	n.d.	0.25	40940	57	104	0.2500 ± 49	2.14	3185 ± 30
13. Older gneissic enclave, Sakarsanahalli (ED-6; 12°48′02.0″N, 78°13′03.8″E)								
2	0.00089	0.1821	93800	424	1009	0.1710 ± 21	1.05	2568 ± 20
3A	0.00033	0.2622	85075	398	709	0.2587 ± 19	1.0	3239 ± 11
3B	n.d.	0.2595	58855	459	816	0.2595 ± 38	2.09	3243 ± 23
3C	n.d.	0.2597	32665	263	469	0.2597 ± 33	1.18	3245 ± 20
4	0.00109	0.2143	40970	198	417	0.2014 ± 40	1.14	2837 ± 32
5	n.d.	0.189	49735	356	783	0.1890 ± 26	1.38	2734 ± 22
6	0.00034	0.2014	18510	185	396	0.1973 ± 78	1.33	2804 ± 65
7B	0.00014	0.2352	145140	478	910	0.2336 ± 12	1.0	3077 ± 08
7C*	0.00031	0.1646	154520	448	1121	0.1606 ± 12	1.09	2462 ± 12
8A	n.d.	0.2573	97175	683	1221	0.2573 ± 17	1.25	3230 ± 10
8B*	0.00015	0.1731	90430	247	587	0.1712 ± 18	1.06	2570 ± 17
9A	0.00098	0.2697	83305	300	534	0.2591 ± 24	1.15	3241 ± 15
9B	0.00115	0.2666	102070	302	544	0.2541 ± 25	1.15	3210 ± 15
14. Migmatite enclave, Hulimavu quarry (ED-7; 12°52′65.3″N, 77°36′03.8″E)								
1	n.d.	0.1763	46265	156	363	0.1763 ± 19	0.89	2618 ± 18
2	0.00154	0.1867	66500	175	422	0.1675 ± 44	1.47	2533 ± 44
3A	0.00085	0.2781	111710	1001	1742	0.2691 ± 21	1.2	3301 ± 12
3B	0.00061	0.2821	69255	1298	2225	0.2757 ± 43	2.0	3339 ± 24
4A	0.00146	0.1926	42430	147	343	0.1745 ± 46	1.26	2601 ± 44
4B	n.d.	0.1747	30655	143	334	0.1747 ± 41	1.56	2604 ± 39

[a]The letters refer to multiple analyses of single zircons. [b]Radiogenic value corrected using model common Pb following Cumming and Richards (1975). ^{206}Pb content based on instrument sensitivity (counts/s/ppm ^{206}Pb) determined by using a standard (91500) of known composition (Wiedenback and Goswami 1994). [c]Calculated value based on the assumption that the sample has remained a closed system. [d]Ratio of the observed to the expected (ion counting based) precision estimates. [e]Errors are 1σ. n.d. – no ^{204}Pb counts were detected. * rim/overgrowth analysis.

single grain (#2C and D) yielded a nearly concordant age of ∼3.1 Ga.

Twelve analyses were conducted in 10 zircons isolated from the granitic gneiss from Kodihalli (WD-6). In two grains with clearly discernable core–overgrowth morphology, we obtained similar ages (∼3215 Ma) for three analyses conducted in the core region of two grains (5A, B and 10), while one analysis conducted in the overgrowth (5C) yielded an age of ∼3.12 Ma (table 2). The lower age of the overgrowth is similar to the ages inferred from analyses (2A, 4, 6, 7 and 11) of five additional zircons from this sample. Three more analyses yielded significantly lower ages that perhaps reflect Pb-loss in these cases. We identify seven analyses with ages close to 3.1 Ga as belonging to the magmatic group and obtain a mean radiogenic $^{207}Pb/^{206}Pb$ ratio of 0.2313 ± 0.0129 corresponding to an age of 3067 ± 9 Ma for this gneissic sample. The higher age of 3.21 Ga inferred for core regions in two grains (5 and 10) most probably represents an inherited component.

5.1.3 *Gneissic clast from Kaladurga conglomerate*

Ten analyses conducted in five zircons from four orthogneissic pebbles from the Kaladurga conglomerate (WD-7) are considered to reveal the probable age of the pre-Dharwar gneissic crust. All the analyses have low common Pb (<3%) and yielded ages ranging between 3.1 and 3.26 Ga (table 2). Two of these grains (1 and 3) show distinct core-rim overgrowth and yielded core ages of ∼3.26 Ga, while the ages of the overgrowths are <3.2 Ga. Three analyses conducted on two homogeneous zircons (4, 6) yielded an age of ∼3.1 Ga. If we combine the data for the homogeneous grains and the overgrowths with ages between 3.1 and 3.2 Ga, we obtain a mean radiogenic age $^{207}Pb/^{206}Pb$ ratio of 0.2497 ± 0.0014 corresponding to an age of 3183 ± 9 Ma. Relatively lower ages measured in a few additional zircons may represent imprints of younger events.

5.2 *Eastern Dharwar metapelite samples*

5.2.1 *Dodderi village*

Most of the zircon grains from the sillimanite bearing metapelite collected near Dodderi village (ED-1) west of Kolar schist belt show distinct core-rim morphology (figure 2). Results obtained from 13 analyses conducted in seven zircons are presented in table 2. The core of a heterogeneous grain yielded an age of 3348 ± 10 Ma (4A) while the age of the rim material is 2731 ± 20 Ma (4C). Overall, the results reflect multiple age components, with core ages ranging from 3.0 to 3.35 Ga, while the ages of the rims are much younger and range from ∼2.7 to 2.75 Ga.

5.2.2 *Valligerahalli village*

The majority of the zircons in the cordierite-bearing metapelite (ED-2) collected near the Valligerahalli village are subhedral along with a few euhedral grains. Seven zircon grains from this sample were analyzed. Three analyses in a single grain (4) yielded a reproducible age of ∼3.27 Ga. Most of the ages obtained for the other grains are higher than the radiometric ages of ∼3 Ga reported previously for samples from this region (Friend and Nutman 1991; Mahabaleshwar *et al* 1995; Mojzsis *et al* 2003). Three analyses conducted on rim material yielded younger ages ranging from 2.7 to 2.8 Ga.

5.2.3 *Honniganahatti village*

Zircons separated from the metapelite (ED-3) collected near Honniganahatti village also show distinct core-rim morphology. The relatively large size and elongate euhedral nature of the grains suggests that they may have experienced only limited transport and a possible proximal source. Sixteen analyses conducted on four zircons revealed a spectrum of ages ranging from 3.0 to 3.2 for core regions and 2.7–2.9 Ga for the rims.

5.3 *Eastern Dharwar craton quartzites*

5.3.1 *Kaglipura village*

Six zircons from the quartzite sample (ED-4) collected at Kaglipura village near Bangalore. The zircons from the Kaglipura quartzite are subhedral to rounded in shape. Analyses conducted on these zircons yielded ages that cluster between 3.0 and 3.1 Ga.

5.3.2 *Sakarsanahalli village*

The analyzed zircons from the Sakarsanahalli quartzite sample (ED-5) are euhedral to rounded, with a few grains having distinct core–overgrowth morphology. We have conducted eighteen analyses in fourteen zircons. A zircon with distinct core–overgrowth morphology yielded an age of 3532 ± 17 Ma (1A) for the core-region, while the ages of the overgrowths are lower, 3354 ± 27 Ma (1B) and 2541 ± 40 Ma (1C). Two more grains (2, 5) yielded ages of ∼3.5 and ∼3.4 Ga, respectively. The overall spread in zircon ages ranges from ∼2.9 to 3.54 Ga.

5.4 *Older migmatite*

5.4.1 *Sakarsanahalli village*

Two types of zircon population were found in the migmatite bodies (ED-6) from Sakarsanahalli; large zircon grains that are brownish, stubby and show distinct core-rim morphology, and elongate grains that are mostly homogeneous. Fifteen analyses were made in nine zircons. The age data show distinct clustering at 3.2 Ga and also a range of younger ages. Data for 13 of these analyses in eight grains are shown in table 2. Three analyses on a single grain (3A, B, C; figure 2b) and three analyses from core region of two grains (8A, 9A, B) yielded reproducible ages of ∼3.23 Ga. A weighted mean radiogenic $^{207}Pb–^{206}Pb$ values of 0.2592 ± 0.0010 (90 blocks of data) corresponding to an age of 3235 ± 9 Ma can be inferred from this dataset. On the other hand, data from three homogeneous grains (4, 5, 6) yielded a weighted mean radiogenic $^{207}Pb–^{206}Pb$ values of 0.2014 ± 0.0020 corresponding to an age of 2838±17 Ma. Lower ages (∼2.6 Ga) have also been determined in rim material.

5.4.2 *Hulimavu quarry*

Zircons from the coarse-grained tonalite layers (ED-7) in a migmatite within the medium grained grey gneisses from the Hulimavu quarry in the southern outskirts of Bangalore, show elongated euhedral morphology and are mostly homogeneous. The ages obtained show two distinct groupings. Two analyses made in a single grain (#3A, B) yielded nearly concordant ages of 3301±12 (3A) and 3339±24 Ma (3B), respectively. Four other analyses in three grains yielded ages ranging between 2.53 and 2.62 Ga similar to the reported granitoid ages from the Bangalore area (e.g., Jayananda *et al* 2000).

6. Discussion

6.1 *Zircon ages: Western Dharwar craton (WDC)*

The data obtained in this study confirm the predominance of the oldest rocks in the WDC. The two samples from Tagadur area (Tag-1 and Tag-2) and a granitic gneiss from Kodihalli yielded ages of 3060±8, 3091±8 and 3067±9 Ma, respectively. Although we cannot rule out possible Pb-loss in some zircons from these two TTG samples because of their high U content, we consider the age of 3.1 Ga to be close to the true age of the gneissic protolith. The lower ages recorded in several zircons in these samples appear to be an overprint of younger events at 2.8–2.9 Ga, whose signatures are also present in the zircon data for the studied metasediments.

Zircons from the three orthogneissic samples from the Nuggihalli schist belt area and the orthogneissic clast from the Kaladurga conglomerate yielded ages ranging from 3.0 to 3.26 Ga. Ages of 3.2 Ga for the core region in heterogeneous zircons in these samples are comparable to the reported ^{207}Pb–^{206}Pb zircon and Rb–Sr whole rock ages of 3.0 to 3.3 Ga for the gneisses from the Gorur–Hassan region in the WDC (Beckinsale *et al* 1980; Naha *et al* 1993; Peucat *et al* 1993). Concordant ages seen in both individual zircons and in multiple analyses within single zircons (table 2) and the well-preserved core–overgrowth age relationship validates the identification of the magmatic component in our dataset for these three gneissic samples and indicates that the inferred ages of 3.1 Ga is close to their formation age. Ages of ∼2.5–2.6, and ∼2.8–2.9 Ga obtained for a subset of zircons from these gneissic samples are suggestive of secondary overprints by younger events.

Analyses of the core region of a heterogeneous zircon from the Thattekere quartzite yielded an age of ∼3.5 Ga. Zircon ages of 3.3 Ga for Kabini Dam paragneiss and 3.2–3.5 Ga for Thattekere quartzite (table 2) confirm the presence of provenance as old as ∼3.3 Ga, reported earlier for the Gorur gneiss (Beckinsale *et al* 1980). However, the older detrital zircon ages (>3.4 Ga) obtained in the present study and reported earlier by Nutman *et al* (1992), may have been derived from different sources if we consider the lack of older exposed orthogneiss sequence in the WDC in this and previous studies (Beckinsale *et al* 1980). Although the younger ages (2.4 to 2.8 Ga) for the overgrowths in the metasedimentary zircons may represent secondary metamorphic events, it is not possible to uniquely characterize these events. We note that some of these ages are similar to the reported ages of 2.75–2.9 Ga for metavolcanics from the Bababudan group (Anil Kumar *et al* 1996) and probably might have resulted from the reported mixing of old continental component with juvenile mafic material (Jayananda *et al* 2006). Our data for the metasediment suggest the presence of sources with ages of 3.05 to 3.5 Ga and also the imprints of younger multiple deformation and metamorphic episodes.

The zircon ages of the WDC basement gneisses and the metasediments obtained in this study are consistent with those reported earlier for gneisses from Holenarasipur, Gorur–Hassan and Chikmagalur regions of the Dharwar craton (Beckinsale *et al* 1980; Taylor *et al* 1984; Meen *et al* 1992; Naha *et al* 1993; Peucat *et al* 1993). A span of crystallization ages ranging from 3.0 to 3.3 Ga for the orthogneiss protoliths are evident in the data presented here and those reported earlier suggests that episodic emplacement of the TTG suite in the WDC over a time span of few hundred million years.

6.2 *Zircon ages: Eastern Dharwar craton (EDC)*

U–Pb and Pb–Pb ages of zircons and titanites from the EDC volcanics, gneisses and granite units reported earlier, span the range from 2.5 to 2.8 Ga (e.g., Krogstad *et al* 1991; Balakrishnan *et al* 1999; Jayananda *et al* 2000). However, data obtained in this study for zircons in EDC orthogneissic bodies at Sakarsanahalli demonstrate presence of older age components ranging from 2.9 to 3.3 Ga along with younger overprints. The well defined ^{207}Pb–^{206}Pb age of 3.3 Ga for a zircon from the Hulimavu orthogneissic represents the oldest magmatic phase in the EDC reported so far. Clustering of zircon ages around 2.5 to 2.6 Ga in both these samples (table 2) appears to reflect the time of late Archaean granitoid magmatism reported for this block (see Balakrishnan *et al* 1999; Jayananda *et al* 2000). We also note that intermediate ages between 2.7 and 2.8 Ga obtained in a few zircons (table 2, Sakarsanahalli gneiss, #4–6) are similar to the metamorphic ages of rocks in the EDC reported earlier (Mojzsis *et al* 2003). The scatter in the age data most probably reflects the complex succession of geological events in the EDC. Despite the poor state of preservation of the older gneissic rocks in the EDC, our data provide evidence for an important period of magmatism in the south westernmost part of the EDC, west of the Kolar schist belt region between 3.1 and 3.3 Ga.

The metasedimentary rocks in the EDC are less widely distributed than in the WDC (figure 1). Zircon ages obtained in this study for metasedimentary samples from the EDC show a preponderance of ages >3.0 Ga. Age data for the quartzite sample from the Sakarsanahalli area, yielded detrital zircon ages ranging from ∼2.9 to 3.3 Ga along with a few older ages of >3.4 Ga indicating that the ages of the source areas for metasedimentary rocks of EDC overlaps with those from the WDC (see figure 3). Since the ancient sediments in the EDC occur as highly strained metamorphosed amphibolite–granulite facies rocks, primarily as thin inclusions and tectonic intercalations in terranes dominated by granitoid rocks and orthogneisses, it is difficult to interpret the age data in relation to the WDC. The spread of minimum ages of detrital zircons from the metasedimentary rocks is rather large (2.5–3.5 Ga; table 2) and suggests that the sediments have different provenance. A minimum age for the onset of deposition in this block may be inferred from the presence of 2.5 Ga zircons in granitoids and charnockites (Mojzsis *et al* 2003) that formed as a result of associated metamorphism presence of 2.5 Ga rims in our dataset (table 2, Sakarsanahalli quartzite data 1c). Nonetheless the ages of detrital zircons, obtained in this study, establish the presence of an epoch of crustal growth at ∼3.3 Ga prior to the voluminous emplacement of younger granitoids during 2.5–2.7 Ga. Analysis of well defined cores and rims in zircons from Sakarsanahalli quartzite (grain 5A, B) show the presence of 3.0 Ga overgrowths on 3.3 Ga or older cores. Although it is difficult to correlate the ages with specific thermal events, it appears that the 3.0 Ga event may be related to the initial stabilization of the WDC that preceded the deposition of the Dharwar Supergroup (Srinivasan and Ojakangas 1986; Naqvi and Rogers 1987) that migmatized pre-existing sediments and older gneisses. The younger ages of overgrowths may be correlated with Dharwar volcanism in the greenstone belts and the late Archaean cratonization event marked by large-scale granite emplacement.

6.3 *Evolution of the Dharwar craton*

The ages for detrital zircons from both the WDC and the southwestern part of the EDC indicate a widespread distribution of >3.0 Ga crustal components in the two blocks. Detrital zircon ages of ∼3.3 Ga for metasediments from the EDC obtained in this study and granitoid zircons of ∼3.1 Ga reported by Krogstard *et al* (1991) and Jayananda *et al* (2000) in their study of the EDC granitoids, provide evidence of early (pre-3.0 Ga old) Archaean crustal sources. The possibility of *in situ* older crustal component in the EDC is also supported by zircon ages ranging from 3.0 to 3.3 Ga (table 2) for orthogneiss bodies within the younger granitoids that may be considered equivalent to the 3.3 Ga old Gorur gneiss in the WDC. Presence of a few detrital zircons with ages of >3.4 Ga indicates that some of the EDC metasedimentary protoliths were probably in or close to the EDC at the time of deposition and provides evidence of early Archaean crustal sources. The distribution of older detrital zircons (>3.4 Ga) suggests that local as well as

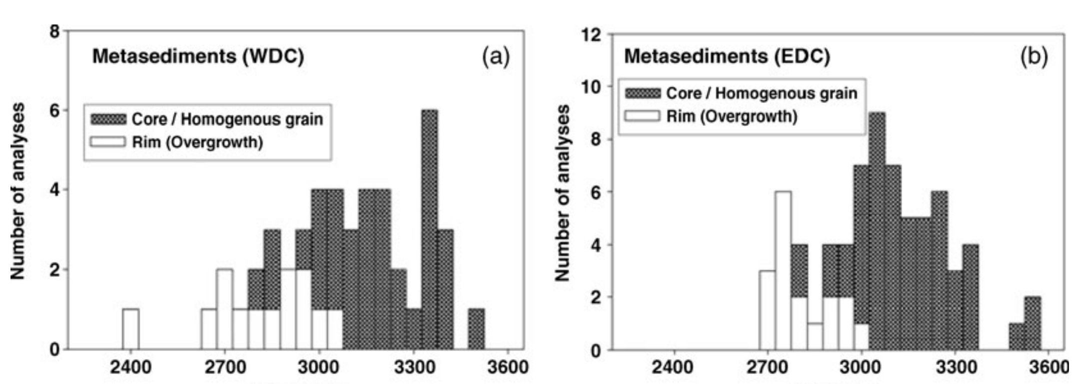

Figure 3. Histograms of age distributions of detrital zircons from the metasedimentary rocks of WDC and EDC.

regional variations controlled the distribution of zircons incorporated in these metasediments. If the distribution of these older zircons originated via recycling of grains derived from a separate, non-Dharwar terrane, it would likely be more widely distributed, as are the zircons belonging to the 3.0–3.3 Ga age group. The fact that the older zircons from EDC are confined to the quartzites suggests that their provenance was not a remotely sourced, widespread rock.

The zircon ages for samples from the WDC define two major events of magmatic activity, an older event (3.1 to 3.3 Ga) and a younger (2.5–2.6 Ga) episode. It has been proposed that amalgamation of the WDC with the EDC to form a single continental domain was achieved by accretion of the 2.7 Ga old schist belts of the EDC to the much older 3.1–3.4 Ga old western Dharwar nucleus (Balakrishnan *et al* 1999). In contrast, the zircon age data presented in this study indicate that evolution of the EDC and WDC of the Dharwar craton appears to be contemporaneous (see figures 3 and 4) and the magmatic activities in both the blocks persisted for close to a billion years. The oldest age of 3.5 Ga for detrital zircon from the Sakarsanahalli quartzite in the EDC has its counterpart in ∼3.5 Ga old analysed detrital zircon from the Thattekere quartzite and the reported 3.56 Ga detrital zircon from the Holenarasipur schist belt (Nutman *et al* 1992). Zircon ages for metasediments indicate that both the EDC and WDC were affected by subsequent younger events between 3.1 Ga and 2.5 Ga. In the EDC, the Neoarchaean magmatism is reflected mainly through the emplacement of voluminous, composite Closepet Granite at 2.5–2.6 Ga.

Krogstad *et al* (1991) and Jayananda *et al* (2000) have reported ages of 3140 Ma (zircon core) and 3127 Ma (single zircon) in granitoid samples from the EDC. However, the paucity of chronological data, particularly for the Archaean era in this block, has been a major hurdle for constructing a plausible evolutionary model of the Dharwar craton as a whole. The zircon ages of >3.0 Ga for metasediments and the orthogneissic bodies in the southwestern part of the EDC reported in this study show that the antiquity of source rocks in the EDC goes as far back as 3.5 Ga just as does the WDC. There was pre-existing sialic crust in the EDC and the largely granitic and gneissic EDC is interpreted here to be a result of reworking of >3.0 Ga old crust. This possibility was also suggested in some earlier studies (e.g., Krogstad *et al* 1991). The EDC was reworked further at ∼2.5–2.6 Ga during large scale granitic emplacement and subsequent metamorphism.

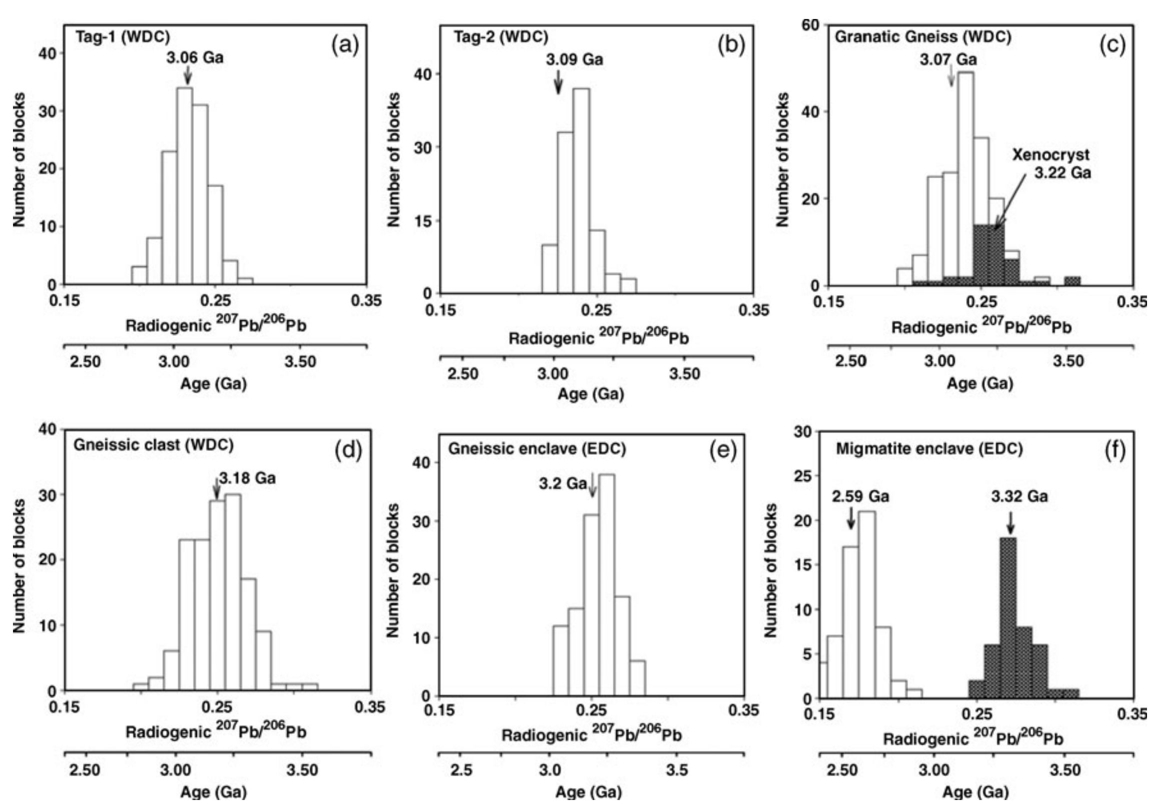

Figure 4. Histograms of data for radiogenic $^{207}Pb/^{206}Pb$ at block level for six orthogneissic samples from the Dharwar craton. The inferred ages are also indicated. **(a, b, c, d)** are for gneisses from the WDC and **(e, f)** for gneisses from the EDC.

If the antiquity of the EDC and WDC is one and the same as suggested by the data presented in this paper, the significance of the tectonic models that assume EDC and WDC as distinct terranes that have been sutured (cf. e.g., Naqvi 1985) needs reconsideration. The structural unity throughout the Dharwar craton, as had been proposed by Naha *et al* (1986, 1990) does not support suturing of two discrete terranes. The EDC and the WDC could be one and same terrane, with the EDC having been affected more by the granitic magmatism at 2.5–2.6 Ga. In such a case, the proposed suture could be one of the later thrusts that have been mapped along the margins of the greenstone belts in the Dharwar craton (see Drury *et al* 1984; Chadwick *et al* 1989, 1996). It may be noted that in contrast to EDC, only a subdued, record of granitic activity during the 2.5–2.6 Ga interval is present in the WDC (see e.g., Taylor *et al* 1984; Rogers 1988; Bhaskar Rao *et al* 1992; Pandey *et al* 1994; Jayananda *et al* 2006; Chadwick *et al* 2007).

6.4 *Geodynamic setting*

Similar antiquity of EDC and WDC indicated by the present geochronological study, coupled with the structural unity (similarity of style, sequence and orientation of structures) proposed by Naha *et al* (1986, 1996) and same plan of deformation applicable to both the EDC and WDC proposed by Chadwick *et al* (2000) together tend to suggest that these two bodies form part of a single terrane. The traceable history of this terrane, suggests that it was a sialic terrane, on which sedimentary-volcanic basins that served as repositories of the supracrustal rocks of the Sargur Group and Dharwar Supergroup evolved. Srinivasan and Naha (1993) and Chadwick *et al* (2000) have applied plate tectonic concepts for the Archaean crustal evolution in the Dharwar craton and suggested that the schist belts and granitoids in the EDC evolved in a magmatic arc environment with the WDC representing the adjoining foreland basin. Whether this foreland basin was a fore arc basin or a back-arc basin is an issue that needs further investigation.

It is well known from Phanerozoic plate tectonic settings, that the magmatic arc environments are characterized by intense granitic magmatism and low-pressure metamorphism (cf. Miyashiro 1961; Zwart 1967). Dominance of granitic magmatism in the EDC and development of assemblages like andalusite bearing and cordierite-hypersthene-sillimanite bearing metapelitic assemblages, are in conformity with the view that EDC is a magmatic arc terrane. Occurrence of volcanic rocks of intermediate composition (boninites, andesites, adakites and dacites) among the volcanic rocks of the schist belts of EDC (see Manikyamba and Khanna 2007; Manikyamba *et al* 2005, 2007, 2008), also indicate the evolution of these schist belts from intra-arc volcano-sedimentary associations. The subdued granitic activity, preponderance of intermediate pressure kyanite bearing mineral assemblages, dominance of sedimentary rocks and bimodal nature of volcanic rocks in the Dharwar basins in the WDC, suggest that the WDC evolved adjacent to the EDC magmatic arc, probably as a retro-arc foreland basin. While retro-arc basins are known to be characterized by the presence of bimodal volcanism, and a mix of continent as well as arc derived sediments as seen in the Dharwar schist belts of WDC, fore-arc basins are known to be devoid of volcanic rocks and derive their sediments from evolving magmatic arc (see e.g., Condie 1997).

Drury and Holt (1980), Drury *et al* (1984) and Chadwick *et al* (2000) have traced several N–S to NNW–SSE faults/shear zones along the margins of the Dharwar schist belts and within them both in the EDC and WDC, all of which, have been explained by a common deformation plan developed in a WNW directed oblique compression regime proposed by Chadwick *et al* (2000). The fault traced along the eastern margin of the Chitradurga schist belt (Chitradurga fault for simplicity) is one of them. In the light of the possibility that EDC and WDC are part of a single terrane, it may be suggested that the Chitradurga fault may not be a terrane boundary or suture between EDC and WDC, but an oblique slip fault between foreland basin region and the magmatic arc region in the Dharwar craton.

Based on our study and those reported previously as well as current geodynamical understanding of the Dharwar craton, the following explanations may be proposed for the differences in the characteristic of the WDC and EDC listed in table 1. Reworking or remobilization of the >3 Ga old crust in the EDC is a natural consequence of large-scale arc magmatism in the EDC region. The latter phenomenon has wiped out basement contacts and records of older events to a large extent in the EDC. In the retro-arc foreland region, the 2.7 to 2.6 Ga magmatism is subdued, although it is present. This has left the basement-cover relations for the Dharwar supracrustal belts preserved at several places. The low-pressure metamorphism in the EDC, as against intermediate pressure metamorphism in the WDC, is consistent with the former being in the arc region and latter outside it. Large-scale potassic granitic activity, expected in the EDC arc region, can account for radioisotope enrichment in granitoids of the EDC and therefore, higher heat flow in the EDC relative to the WDC, which is dominated by tonalitic crust. The thickening of the crust and lithosphere from east to west in the Dharwar craton is also consistent with the model with EDC being magmatic arc and WDC being back-arc regions.

7. Conclusions

^{207}Pb–^{206}Pb ages of zircons in metasediments, ortho- and paragneisses and granitoids from the WDC and EDC establish the widespread occurrence of Archaean crust (>3.0 Ga) in them. Even though data from EDC are sparse, zircon ages of metasediments and orthogneisses from both WDC and EDC range between 3.0 and 3.5 Ga. The ages of detrital zircons in the EDC reveals presence of widespread Archaean sources. The occurrence of 3.1–3.3 Ga bodies of orthogneiss in the EDC confirms the presence of Mesoarchaean units. Common age distributions of different type of rocks from the southwest part of EDC and WDC establish a geological link that requires large-scale tectonism and sedimentation to create a uniform detrital zircon population over a relatively large area. Both the terranes have been subsequently affected by later geological activities notably at 2.8 and 2.5 Ga. Geochronological data coupled with geological and geodynamical characteristics of WDC and EDC suggest them to be part of a single terrain. The hypothesis that accretion to an older WDC by a younger EDC led to the formation of the Dharwar craton as well as the status of suture accorded to the thrust along the eastern margin of the Chitradurga schist belt needs further scrutiny and reconsideration.

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