Anatomy of 2.57 - 2.52 Ga granitoid plutons in the eastern Dharwar craton, southern India: Implications for magma chamber processes and crustal evolution

We present results of field studies for magmatic processes of 2.57-2.52 Ga calc-alkaline plutonic bodies from three corridors in the eastern Dharwar craton (EDC) corresponding to different crustal levels. At deeper levels plutons are bounded by thick zone of migmatites with numerous melt filled shear bands which often overprinted by incipient charnockite. On the other hand in the mid-to-upper crustal levels plutons show relatively sharp contacts and truncates the adjoining basement. The plutons are composite which comprises voluminous intrusive monzodiorite, quartz-monzonite and porphyritic monzogranite in the central part and minor anatectic granites or diatexite at periphery. Numerous xenoliths, Mafic Magmatic Enclaves (MME), disrupted trains of synplutonic mafic dykes are found in both intrusive and anatectic facies. The plutons show magmatic as well as solid-state plastic fabrics defined by magmatic flow banding and C-S fabrics respectively. Crustal scale shear zone network comprising early melt filled NE trending hot ductile dextral shear bands and slightly later colder NW trending sinistral shear bands defined by rotation of mafic boudins, phenocrysts and C-S fabrics. The internal architecture of plutons is attributed to the crustal scale magma chamber processes where voluminous intrusive magmas emplaced into the crust caused reworking of surrounding basement resulting in production of anatectic magmas. Crystallization of voluminous intrusive magmas in the deep crust probably caused development of fractures to mantle depth causing decompression melting of mantle and resultant mafic magmas penetrated the crystallizing host in magma chambers. Field evidences together with published ages and Nd isotope data reveal a spatial link between late Archaean magmatic accretion, reworking and cratonization.

Introduction

In recent years, tremendous progress has been made in understanding the dynamics of magma chamber processes and pluton emplacement mechanisms by study of granitoid batholiths from different tectonic settings (Barbarin, 2005; Barnes et al., 2002; Castro, 1987; Frost and Mahood, 1987; Paterson et al., 1996, 2004; Santosh Kumar, 2010; Tobisch et al., 1997; Turnbull et al., 2010). A good synthesis on origin and geodynamic environments of different granitoid types has also been documented by Barbarin (1999). On the contrary only few studies have been focused on the internal structure and magma chamber processes of Archean and Proterozoic granitoid plutons (Chardon and Jayananda, 2008; Moyen et al., 2003a; Neves and Vauchez, 1995; Ramsay, 1989), while numerous contributions have presented a wealth of elemental and isotopic data (Halla, 2005; Heilimo et al., 2010; Jayananda et al., 2000, 2006; Martin et al., 2005; Moyen et al., 2003b, 2010; Sylvester, 1994 and references therein). Granitoid plutons are important constituents of Archaean cratons and occupy over 20 percent area of exposed felsic rocks. Study of their anatomy including relationship with surrounding TTG and greenstone belt is key to our understanding of fundamental architecture of Archaean cratons. Further, study of Archean granitoid plutons is crucial to address host of other issues such as magmatic accretion processes including dynamics of felsic magma chambers, interaction of coeval felsic and mafic magmas, crustal reworking together with their spatial link to regional deformation patterns and cratonization of Archaean crust. Most of the field studies on Archaean granite plutons generally dealt with structural patterns and thermo-mechanical aspects of their emplacement, their role in greenstone tectonics and cratonization (Brun, 1983; Chardon and Jayananda, 2008; Chardon et al., 2002, 2008; Chown et al., 2002; Cruden and Launeau, 1994). However, anatomy of these Archean granitoid plutons including relationship between different facies of plutons, enclaves, xenoliths, synplutonic mafic dykes and interaction of coeval felsic and mafic magmas is poorly documented. The Eastern Dharwar Craton (EDC) in southern India (Fig.1) exposes a tilted cross-section of crust with several N-S trending 2.57-2.52 Ga granitoid plutons (Chadwick et
relationships with regional shear deformation. However, no major attempt has been made to study the anatomy of plutons, dynamics of magma chamber processes and time relationships of different facies with respect to crustal reworking, regional deformation patterns and cratonization of Archaean crust in the Dharwar craton. This contribution presents an overview of anatomy of the granitoid plutons at different crustal levels with particular emphasis to characterize magma chamber processes including interaction of coeval felsic and mafic magmas, their spatial relationship, regional deformation and metamorphic patterns within the geological framework of the EDC. Finally by integrating our field data with published isotopic data we discuss tectonic context of Neoarchaean calc-alkaline magmatic accretion and its spatial link to crustal reworking and cratonization.

Regional Geology

The Dharwar craton, southern India corresponds to a large oblique section of Archaean continental crust with protracted crustal history from 3.6 to 2.5 Ga and forms a major wide hot orogen during end Neoarchaean (Chardon et al., 2011). The craton comprises vast areas of polyphase TTG-type gneisses regionally known as peninsular gneisses, two generations of volcanic-sedimentary greenstone sequences (older Sargur Group and younger Dharwar Supergroup) and 3.0 Ga, 2.62 Ga and 2.57-2.50 Ga calc-alkaline to high-K granitoid plutons. The craton is generally divided into two crustal blocks viz., western Dharwar craton (WDC) and eastern Dharwar craton (EDC) based on crustal thickness, abundance of TTG-greenstones-granites, structure and metamorphic patterns (Chadwick et al., 2000; Chardon et al., 2008, 2011; Drury, 1983; Jayananda et al., 2006; Swaminath et al., 1976). The steep mylonitic shear zone along the eastern boundary of the Chitradurga belt is considered as the dividing line between the two crustal blocks (Drury, 1983; Jayananda et al., 2006; Chardon et al., 2011).

The basement in the western Dharwar craton comprises abundant TTG gneisses with interlayered Sargur Group greenstone basins. Published geochronologic and Nd isotope data of TTG indicate 3.4-3.2 Ga for the emplacement of their magmatic protoliths (Bhaskar Rao et al., 2008; Meen et al., 1992; Peucat et al., 1993a). The Sargur Group comprises 3.38-3.0 Ga komatiite-basalt-felsic volcanic rocks with interlayered quartzite-pelite-carbonate-BIF association (Bhaskar Rao et al., 2000; Jayananda et al., 2008; Peucat et al., 1995). Detrital zircons from the sediments indicate 3.63 – 3.23 Ga for their provenance (Nutman et al., 1992; Bhaskar Rao et al., 2008). The TTG-Sargur Group greenstones are unconformably overlain by the younger (2.91-2.67 Ga) Dharwar Supergroup greenstone basins which begins with basal conglomerate/quartzite followed by basalt-intermediate to felsic volcanic flows with carbonate-argillite-greywacke sequences and thick banded iron formations forms the summit (Anil Kumar et al., 1996; Jayananda et al., 2011; Nutman et al., 1996; Trendall et al., 1997a). Largely mylonitic high potassic 3.0 Ga Bukkapatna granite plution found along the eastern boundary of Chitradurga belt within the boundary shear zone (Chardon et al., 2011) whilst several 2.62 Ga high-K plutons intrude either TTG-Sargur Group basement or Dharwar Supergroup greenstone basins in the western Dharwar craton (Jayananda et al., 2006; Chadwick et al., 2007). Metamorphic mineral assemblages (kyanite-garnet-staurolite-chloritoid) from south central part of WDC indicate pressures close to 6-8 Kb and 550-700°C (Bouhallier, 1995). Dome-basin patterns, sagduting greenstone ridges with broadly spaced regional shear zones are the dominant structures documented in the
Figure 1. Geological sketch map of Dharwar craton (modified after Geological Survey of India, project Vasundara)

Legend

- Late Archaean granitoids
- EDC greenstones
- Greenstones (Dharwar Supergroup)
- Greenstones (Sargur Group)
- TTG Gneisses
- Cenozoic sediments
- Deccan traps
- Proterozoic cover
- Eastern ghat
- Granulites

CSZ - Chitradurga Shear Zone
WDC - Western Dharwar Craton
EDC - Eastern Dharwar Craton

1. Raichur greenstone belt
2. Hutti-Muski greenstone belt
3. Kushtagi-Hungund greenstone belt
4. Ramagiri greenstone belt
5. Kadiri greenstone belt
6. Velligalu greenstone belt
7. Kolar greenstone belt

(a) Southern corridor
(b) Central corridor
(c) Northern corridor
The Archaean basement in the EDC comprises mainly 2.7 Ga tonalitic to granodioritic gneisses with large remnants of 3.0-3.38 Ga TTG with interlayered Sargur-type greenstones (mostly occur as discontinuous 4-6 km long bands confined to the southwestern part of EDC, 2.7 – 2.54 Ga volcanic-dominated greenstone belts and 2.57-2.52 Ga most voluminous N-S trending calc-alkaline plutonic belts (Balakrishnan et al., 1990, 1999; Chadwick et al., 1999, 2000; Chardon et al., 2008; Dey et al., 2012; Jayananda et al., 2000, 2012; Friend and Nutman 1992; Nutman et al., 1996). The most spectacular of these plutonic belts is the 400 km N-S trending Closepet granite which traverses large part of the EDC. The basement TTG was involved in reworking event close to 2.52 Ga which is spatially linked to major juvenile magmatic accretion and regional shear deformation (Chardon et al., 2008; Jayananda et al., 1995, 2000; Krogstad et al., 1995). The EDC is affected by low pressure and high-T metamorphism with preserved assemblages corresponding to a progressive transition amphibolite facies to granulite facies (Janardhan et al., 1982) which was dated at ca. 2.5 Ga (Mahabaleswar et al., 1995; Peucat et al., 1993a; Mozis et al., 2003). More recently an earlier 2.62 Ga granulite facies close UHT conditions has been documented from the central part of EDC (Jayananda et al., 2011). The EDC traversed by closely spaced regional shear zones which trends NNE in the south and NNW in the north (Chardon et al., 2008). Spectacular flat fabrics in the 2.56 Ga tonalitic gneisses in the central part of EDC attributed to longitudinal flow of hot juvenile crust during end Archaean accretion in a wide hot orogen (Chardon et al., 2011). The plutons are composite and contain two major magmatic suites including voluminous intrusive facies and the anatectic granite as well as diatexitic facies surrounding them. The intrusive facies comprises of clinopyroxene-amphibole bearing dark grey monzodiorite to quartz-monzonite, porphyritic monzogranite and grey granodioritic rocks whilst the anatectic facies include pink to light grey granites. In the deepest level the intrusive facies found as sheets or dykes traversing the basement gneisses. The volume of intrusive facies progressively increases to the northern part of southern corridor in Magadi – Madanapalli area where inselburgs are mainly composed of porphyritic monzogranites and quartz-monzonites. Diatexites are abundant which show progressive evolution to inhomogeneous granite with abundant biotite schlieren and eventually to homogeneous granite. Diatexites frequently contain boudins/enclaves of intrusive facies (Fig. 2). The intrusive facies contain recrystallized areas with large crystals of amphibole and clinopyroxene close to the veins of anatectic granite which could be attributed to the interaction of fluid associated with anatectic granite (Fig. 3). The whole southern corridor contain anatizing network of shear zones which include an earlier N10-25° E trending syn-melt dextral shear bands (Fig. 4) and a later N10-20° W trending sinistral shear bands containing numerous mafic enclaves and rotated angular mafic to ultramafic xenoliths with strong fabrics (Fig. 5). The intrusive facies of the plutons show magmatic as well as tectonic fabrics. Magmatic foliation is characterized by magmatic flow banding and alignment of feldspars (Fig. 6). The anatectic facies show magmatic flow fabrics with oriented small biotite schlieren and alignment of fragments of intrusive quartz-monzonite defining flow direction (Fig. 7). The intrusive and anatectic facies often show diffused contact or sharp contact with reaction rim indicating short time gap or emplacement of anatectic facies when the intrusive facies were in advanced stage of crystallization. Major sinistral shear zones are confined to the boundary of the plutons which contain numerous mafic to ultramafic and also traverse the plutons. Numerous sub-rounded mafic magmatic enclaves (MME) are found in the intrusive facies whilst anatectic facies contain disrupted boudins or fragments of symplutonic mafic dykes (Fig. 8 and 9). Frequently mafic enclaves and xenoliths are broken where recrystallization of mafic enclaves and xenoliths lead to the formation of large concentration amphiboles with occasional clinopyroxene rimmed with amphibole.

Arrested charnockite development with prograde reaction producing orthopyroxene on the migmatic gneisses, anatectic as well as intrusive facies is the most striking features of the southern corridor (Fig. 10). Charnockite development is mainly confined to steep fabrics along the conjugate shear bands that traverse the migmatises, intrusive as well anatectic facies (Chardon and Jayananda, 2008). Such arrested charnockite formation has been explained by CO₂-rich fluid streaming causing dehydration in the hotter deep crust (Janardhan et al., 1982). U-Pb monazite dating of charnockite formation indicate 2507±5 Ma in the Kabbaldurga area (Mahabaleswar et al., 1995) whilst 2517±5 Ma in Krishnagiri area (Peucat et al., 1993a).
Figs (2-7). 2 – Diatexites contain the boudins of porphyritic monzogranite from a large quarry about 5 km north of Madanapalli in Anantapur road. 3 – Quartz-monzonite contains large crystals of amphibole and/or clinopyroxene along the anatectic veins. 4 – Melt filled N20°E trending dextral shear bands from a large quarry exposure about 6 km east of Krishnagiri in Chennai road. 5 – N18° W trending sinistral shear containing rotated mafic boudins at quarry exposure near Kailashgiri in Vaniyambadi - Peranampattu road. 6 – Dark grey quartz-monzonite and porphyritic monzogranite together define magmatic flow banding at a quarry NE of Lakshmipura in Ramanagaram-Magadi road. 7 – Anatectic facies define magmatic flow fabrics with fragments of intrusive quartz-monzonite at quarry near 27 km from Mudivedu in Gollapalli road.
To summarize, the southern corridor expose the deepest crustal levels with relatively thin granitoid bodies with large screens migmatized basement gneisses, fragmented synplutonic mafic dykes and numerous melt filled shear zones.

Central corridor

The central corridor corresponds to zone of accumulation of granitoid magmas and plutons are voluminous and widest. This corridor covers granitoid plutons of the Closepet granite, Lepakshi-Bukkapatnam, Anantapur-Gooty and Kadiri-Rayachoti areas (Fig. 1b). The plutons are widest in this corridor which shows relatively sharp contacts with the adjoining basement. This corridor also includes three prominent greenstone belts including Ramagiri-Penakacherla, Kadiri and Veligallu belt. The basement mainly forms low-lying areas with ground level exposures whilst plutons generally form inselberg topography with tors or flat tops. The basement comprises two major types of lithologies viz. minor screens of migmatitic TTG which mainly occur in the western part of the corridor and rare or absent in the eastern part. Few small discontinuous exposures of high grade pelitic assemblages corresponding to granulite facies or close ultra-high temperature conditions (850°C and 5 kb) found in a NE trending shear zone along the eastern boundary of Closepet granite (Jayananda et al., 2011). On the other hand strongly banded tonalitic to granodioritic gneisses are abundant. Zircon U-Pb SHRIMP dating of these migmatitic gneisses from western boundary of the Closepet granite indicate ages in the range of 3222-3255 Ma, 3301-3360 Ma (Jayananda unpub. data). The banded tonalitic to granodioritic gneisses in the vicinity Ramagiri schist belt indicates U-Pb zircon age of 2650 ±7 Ma (Balakrishnan et al., 1999). The narrow thin N-S trending greenstone belts are dominated by volcanic rocks with basalts in the lower levels and felsic volcanics flows or pyroclastics in the higher stratigraphic levels. U-Pb zircon dating of zircon from pyroclastic rocks in the central part of the Ramagiri granite indicate ages in the range of 3222-3255 Ma, 3301-3360 Ma (Jayananda unpub. data). The banded tonalitic to granodioritic gneisses in the vicinity Ramagiri schist belt indicates U-Pb zircon age of 2650 ±7 Ma (Balakrishnan et al., 1999). The narrow thin N-S trending greenstone belts are dominated by volcanic rocks with basalts in the lower levels and felsic volcanics flows or pyroclastics in the higher stratigraphic levels. U-Pb zircon dating of zircon from pyroclastic rocks in the central part of the Ramagiri granite indicate ages in the range of 3222-3255 Ma, 3301-3360 Ma (Jayananda unpub. data). The banded tonalitic to granodioritic gneisses in the vicinity Ramagiri schist belt indicates U-Pb zircon age of 2650 ±7 Ma (Balakrishnan et al., 1999). The narrow thin N-S trending greenstone belts are dominated by volcanic rocks with basalts in the lower levels and felsic volcanics flows or pyroclastics in the higher stratigraphic levels. U-Pb zircon dating of zircon from pyroclastic rocks in the central part of the Ramagiri granite indicate ages in the range of 3222-3255 Ma, 3301-3360 Ma (Jayananda unpub. data).
Plutons are composite which comprise two magmatic suites viz. most voluminous intrusive facies and minor anatectic facies with numerous mafic xenoliths, MME and fragmented / boudinaged synplutonic mafic dykes. The intrusive facies include most abundant porphyritic monzogranite with sub-ordinate amphibole-rich dark grey quartz-monzonite. Occasionally large fragments or sub-rounded enclaves of dark grey monzodiorite occurs in association with porphyritic facies (e.g. Pavagada quarry). Both porphyritic monzogranite and quartz-monzonite appears to be coeval as they are interlayered and often show diffusive contacts (Fig. 11). In some instances, the intrusive facies is traversed by anatectic facies particularly close to the periphery of the plutons. The intrusive facies occasionally show magmatic banding and flow structures defined by alignment of feldspar phenocrysts or amphibole crystals but generally show plastic fabrics defined by stretched phenocrysts (Fig. 12). Cream to light pink colored phenocrysts constitutes 40-50% and at places their accumulation indicates possible filter pressing processes during emplacement (Fig. 13). Frequently phenocrysts show crude zoning and also in some instances exhibit rapakivi texture or orbicular structure (Fig. 14a and 14b). Rounded to elliptical MME are found mainly in porphyritic monzogranite where phenocrysts developed within MME indicating their co-magmatic stage (Fig. 15). In general, intrusive facies show good solid-state crystal-plastic structures such as S-C fabrics which indicate mainly sinistral sense or occasional

Figures 11-14. 11 – Anatectic and intrusive facies show diffuse contacts at a large quarry near V.E.S School in Pavagada town. 12 – Stretched and rotated phenocrysts indicating right lateral sense of displacement at about 1 km S of Billuru near Bagepalli. 13 – Phenocrysts accumulation in porphyritic monzogranite about 3 km N of Kumbaragipalli cross in Puttaparthi road. 14a – K-feldspar phenocrysts show crude zoning 1 km before Reddicheruvukatta in Kadri-Gorantla road. 14b - Phenocryst showing crude rapakivi texture ~3 km north of Kodikonda cross.
dextral sense of displacement (Fig. 16). The quartz-monzonite often interlayered with porphyritic facies where biotite-rich reaction rim indicate contrasting temperature of magmas (Fig. 17). They also occur as large angular enclaves in anatectic granites (Fig. 18). Coarse grained amphibole-rich dark grey quartz-monzonite found as continuous sheets of over 20 km along the western boundary of the Kadiri greenstone belt.

In the central corridor, anatectic facies evolve into more homogeneous granite with occasional biotite schlieren or thin partially disintegrated remnants of basement (Fig. 19). The anatectic facies include coarse grained pink to light grey granites confined to periphery of individual plutons. They often found along the foliation of intrusive facies and also occasionally magmatic flow boudinage the intrusive facies. Numerous mafic enclaves, migmatitic TTG and angular blocks

Figures 15-20. 15 – K-feldspar phenocrysts in MME at ~3 km N of Kumbaragipalli cross in Puttaparthi road. 16 – S-C fabric in porphyritic monzogranite near V.E.S School in Pavagada town. 17 – Diffuse contact between porphyritic monzogranite and quartz-monzonite at a quarry near V.E.S School in Pavagada town. 18 – Large enclaves of dark grey quartz-monzonite in anatectic pink granite from a quarry 5 km from Kalyandurga in Bellary road. 19 – Remnant of basement in anatectic pink granite at large quarry 5 km north of Kalyandurga in Bellary road. 20 – Anatectic pink granite and synplutonic mafic dyke define magmatic flow fabrics about 7 km north of Madakasira in Pavagada road.
of rotated xenoliths are common. In the eastern boundary of the Closepet granite, pink anatectic granite together with spectacular synplutonic mafic dykes define magmatic flow structure (Fig. 20). Frequently volatile-rich anatectic veins inject as anatomizing network of coarse grained veins into huge basement mafic enclaves causing disruption where reaction leads to growth of huge amphibole as well as fluorite crystals in granite veins (Fig. 21). Numerous enclaves including MME, basement gneisses and xenoliths of varying shapes and dimensions are found in both intrusive and anatectic facies, particularly abundant along the periphery of the plutons. Several spectacular fragmented or rarely continuous synplutonic mafic dykes found mainly along the periphery of the plutons. A progressive transition from oriented MME to fragmented synplutonic mafic dykes or even to nearly continuous dyke can be seen (Fig. 22). Numerous fine grained to porphyritic synplutonic mafic dykes often fragmented also traverse the intrusive facies which show sharp to diffuse contacts with host. Back-veining of leucocratic melts are common in synplutonic mafic dykes. This phenomenon can be attributed to reversal of crystallization of host granitoid magma caused by heat advection of mafic magma pulse and resultant leucocratic melts in turn penetrates the crystallizing mafic magma. South east of Kadi near Tanakallu village numerous rounded to pillowed MME with pink granite found along the boundary between large synplutonic gabbroic dyke and the pink granite indicate magma mingling process (Fig. 23). MME and the host granite show similar fabrics with diffusive contacts with progressive mingling and hybridization. In hybrid zones fine grained darkest grey MME appears to be more primitive corresponding to original melt composition compared to coarse grained dark grey MME which evolved and contain amphibole and feldspars.

In summary granitoid magmas accumulate and emplace into larger homogeneous plutonic bodies displaying different stages of magmatic flow to solid-state structures. The host granitoid magmas and mafic injections show interactions including mingling, mixing and hybridization.

Northern corridor

This corridor (Fig. 1c) corresponds to the higher crustal levels (Moyen et al., 2003a) that contain elongated NNW trending greenstone belts, minor TTG and most voluminous granite intrusions with synplutonic mafic dykes (Anand and Balakrishnan, 2010; Chadwick et al., 2000; Jayananda et al., 2009; Prabhakar et al., 2009a).

The greenstone belts include Kustagi-Hungund, Hutti-Maski, Raichur, Gadwal and Narayanapet comprising dominantly of basalts with minor boninitic to intermediate volcanic rocks and adakites (Manikyamba et al., 2009 and references therein; Naqvi et al., 2006). Whole rock Pb-Pb isochron of metabasalts define an isochron age of...
2706±130 Ma (Anand and Balakrishnan, 2010) whilst SHRIMP U-Pb zircon dating of felsic volcanic from Hutti greenstone belt indicate 2586±59 Ma (Jayananda et al., 2012; Rogers et al., 2007) suggesting bimodal age distribution of the greenstone succession. Basement gneisses are confined to the low lying areas in between plutonic belts. Two types of gneisses occur in this crustal domain which includes viz. highly migmatitic TTG with mafic layers and boudinaged leucocratic veins generally occur as large enclaves in the high strain zones close to the periphery of the plutons (Fig. 24) and strongly banded dark grey tonalitic facies cut by anatectic granites widespread throughout the northern corridor (Fig. 25). Isotopic age data on gneisses is poor and preliminary U-Pb zircon data indicate ages around 2.7 Ga (Jayananda unpub. data). The plutons generally found as low lying bouldary exposures in the western part whilst frequently as stocks in the eastern part showing sharp contact with the surrounding basement. SHRIMP U-Pb zircon data of Kavital porphyritic granodiorite from Hutti indicate 2543±39 Ma (Rogers et al., 2007). On the other hand, zircons from clasts of granodiorites in the Palakanmardi conglomerate from the Hutti schist belt define SHRIMP U-Pb age of 2576±12 Ma which has been interpreted as magmatic stage of erosional provenance (Vasudev et al., 2000). These granitoid plutons are generally bounded by major NNW trending shear zones along their periphery (Chardon et al., 2008) or high strain zones (Chadwick et al., 2000) characterized by progressive increase in strain to the periphery of plutons leading to development of mylonitic fabrics. The important feature is that the anatectic facies are homogeneous as well as abundant. They comprise dominant pink to light grey granite facies. On the other hand the intrusive facies comprise voluminous granodiorite with minor quartz monzonite and porphyritic monzogranite. The anatectic facies and intrusive facies are often interlayered with diffuse contacts indicating their co-magmatic nature. Discrete bodies of diorites or fine grained intermediate rocks emplaced in sub-volcanic environments are found at Kallur and Kalmal village which contain numerous round dark spots containing aggregates of olivine and clinopyroxene. Numerous highly coarse pegmatites with huge feldspar crystals cut across all the granite facies. The different facies of plutons are more homogeneous compared to central and southern corridor. Xenoliths are rare whilst rounded to pillow shaped MME are common which rarely show a transition to disrupted syngrowth mafic dyke. These MME are generally medium to fine grained and exhibit magmatic textures similar to their host and also show lobate contact with host pluton. Syngrowth dykes are not common but few fragmented intermediate to mafic dykes are found. North of Gurgunta village a huge spectacular syngrowth mafic dyke traverse the pluton which show various stages of interaction of mafic magmas with crystallizing host pluton involving magma mixing, mingling and hybridization processes (Fig. 26).

Discussion

Granitoid plutons constitute significant part of preserved continental crust and study of their anatomy and emplacement modes provide useful information on the fundamental architecture, thermal as well as rheological state of continental lithosphere. The emplacement mechanism of plutons is a function of interplay of magma buoyancy and ambient tectonic force. The tectonic control of pluton emplacement is characterized by the study of deformation patterns of plutons and surrounding basement. Globally during the
last three decades multidisciplinary studies have made an impressive progress in our understanding of granite petrogenesis including pluton emplacement processes, magma chamber dynamics involving interaction of coeval felsic and mafic magmas, thermal rejuvenation of magma chambers (Bonin, 2004; Chardon and Jayananda, 2008; Hutton, 1988; Moyen et al., 2003b). The granitoid plutons covers large part of the EDC and their actual surface area is much more than shown in the published maps. Here we discuss magma chamber processes, spatial link between granitoids magmatism, crustal reworking and regional deformation patterns and tectonic environment of magma generation and emplacement within the regional geological framework of the Dharwar craton.

Anatomy of the plutons at different crustal levels

The anatomy of plutons and their relationships with surrounding basement reflects the emplacement mechanisms and depth of emplacement in the crust. In the EDC, field data such as contact relationships, strain patterns and documented metamorphic gradient indicate that the exposed plutons correspond to a large crustal panel from lower to upper crust. The volume of plutons progressively increases from deeper to upper crustal levels. The plutons show diffuse contacts in the deepest levels and bounded by 5-10 km thick migmatite zone whilst contacts becomes relatively sharp in the higher levels reflecting the rheological behavior of the surrounding crust. All the studied plutons contain two major components viz. voluminous intrusive facies and minor anatectic granites (Jayananda et al., 2000).

In the lower crustal levels, plutons are volumetrically minor which are heterogeneous and mixed with basement undergoing partial melting. Abundant diatexites indicate hot ductile nature of the crust. Numerous melt filled ductile shear bands imply a spatial link between shear deformation and lower crustal melting. The mantle derived hot juvenile magmas (monzodiorite, quartz-monzonite and monzogranite) introduced probably as pulses into lower crust which provided heat and fluids required for melting of already hot basement. Numerous disrupted synplutonic mafic dykes in plutons and surrounding diatexites (see Figs. 8 and 9) show that injection of mafic magmas into crystallizing host magmas are contemporaneous with crustal melting leading generation of anatectic granite. The juvenile magmatism and crustal reworking culminated with a major granulite event as attested by incipient granulite overprint on diatexites, intrusive and anatectic facies, and synplutonic mafic dykes.

In the mid-crustal levels plutons becomes voluminous, homogeneous and boundaries become sharper suggesting accumulation of differentiated magmas. A progressive transition from diatexite through inhomogeneous to homogenous granite can be attributed to accumulation and emplacement anatectic magmas. The observed magmatic flow fabrics of anatectic granites and synplutonic mafic bodies (see Fig. 20 and 22) suggest contemporaneous emplacement of anatectic melt and synplutonic mafic dykes. On the other hand solid-state plastic fabrics such as strong alignment as well as stretched feldspar phenocrysts, C-S fabrics are common in intrusive facies implying substantial crystallinity in intrusive facies at the time of initiation of shear deformation. Major shear zones confined to periphery of plutons transported numerous basement enclaves, mafic to ultramafic xenoliths from lower crust. The close association of anatectic granite sheets and boudins of intrusive facies with N10-25°E trending dextral shear zones suggest regional shear zone development during ascent of anatectic magmas that coincides with cooling of intrusive granitoids (see Fig. 2 and 4). Chadwick et al (2000) and Chardon et al (2008) documented sinistral shear zones with thick mylonites in basement intervening plutons. These NS-14°W trending sinistral shear zones probably developed during the late stage cooling of plutons as they traverse the plutons and contain chlorite-epidote with rotated boudins of intrusive facies. The strong fabrics (often constrictional) in tonalitic gneisses found in between plutonic belts could be related longitudinal constrictional flow of hot orogenic crust during pluton emplacement as documented west of the Closepet granite (Chardon et al., 2011). The most voluminous porphyritic facies often show diffused margins with dark grey quartz-monzonite suggesting their co-magmatic nature. On the other hand, the anatectic facies show cross-cutting relationships with intrusive facies and occasionally show diffuse contacts suggesting short time gap between them. Close to the periphery of the plutons progressive disruption of dark grey quartz-monzonite or dioritic facies with light colored anatectic granite or diatexites during magmatic flow led much of the observed diffuse banding and also biotite schlieren (Fig. 27). Late stage injection of mafic magmas into host plutons caused reversal of crystallization of host leading to back-veining, mingling and hybridization (Fig. 28).

Plutons in the upper crustal levels form homogeneous intrusions with occasional enclaves and synplutonic mafic rocks. In northern

Figure 27 – Anatectic granite with disrupted quartz-monzonite define diffusive banding at 6 km from Pavagada in Sira road. 28 – Back-veining of leucocratic veins in disrupted synplutonic mafic dyke 32 km west of Bangalore in Magadi road.
part of EDC, occurrence of diorite (extremely fine grained rocks with plagioclase and clinopyroxene crystals) intrusions in sub-volcanic environments imply shallow crustal levels. Trains of dismantled synplutonic mafic dykes in pink granites and also dark grey dioritic to quartz-monzonite facies co-mingled with light grey facies also suggest coeval felsic and mafic magmas in sub-volcanic environment. The plutons show intrusive relationships with greenstone belts (Hutti-Muski, Deodurg and Hungund) but on an outcrop scale pink or light grey veins are found along foliation of amphibolites.

**Magma chamber processes (Magma Chamber processes, coeval felsic and mafic magmas, mixing and hybridization)**

Interaction of felsic and mafic magmas with mixing or mingling and progressive hybridization processes have been widely documented from plutons in the arc environments of Phanerozoic plate margin settings (Bateman, 1995; Barnes et al., 2002; Foster and Hyndman, 1990; Frost and Mahood, 1987; Reid and Hamilton, 1987; Santosh Kumar, 2010; Turnbull et al., 2010). The interaction of mafic injections with host felsic magmas is poorly known in the Archaean granitoid plutons as they are often affected by deformation and metamorphism. Although several studies focused on the structure and emplacement of late Archaean granitoid plutons in the EDC (Chadwick et al., 2000; Chardon and Jayananda, 2008; Moyen et al., 2003a), magma chamber processes particularly coeval felsic and mafic magmas, mixing, mingling and hybridization processes is poorly documented (Jayananda et al., 2009; Prabhakar et al., 2009a).

In the EDC the plutons exhibit field evidences for magma chamber processes particularly for coeval mafic and host felsic magmas, their interaction, mixing, mingling and hybridization processes. A number of features such as cuspate contacts between mafic injections and felsic host, similar magmatic fabrics and presence of large k-feldspar phenocrysts with rapakivi/orbicular textures (Fig. 29) and dismembered synplutonic mafic dykes indicate coeval nature of felsic and mafic magmas. Figures 30a-c shows demonstrate for coeval mafic and felsic magmas in all the three studied corridors corresponding to different crustal levels in EDC. The presence of several rounded to pillowed mafic enclaves and dismembered synplutonic mafic dykes with chilled margins also indicate injection of mafic magmas into crystallizing host magma. The mafic magmas appears to be entered into crust at the time anatectic melts begin to move upwards as revealed by magmatic flow structures defined by mafic magmas and anatectic melts. The synplutonic mafic dykes are generally disrupted but occasionally continuous implying their injection into host felsic magma with different crystallinity. They

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**Figure 29.** K-feldspar phenocryst showing crude orbicular texture, ~3 km north of Gurganta.

**Figure 30.** (a) Boudins of synplutonic dyke showing interaction with felsic host ~ 8 km east of Kabbaldurga. (b) Exposure showing magma mingling process ~ 10 km from Penukonda in Madakasira road. (c) Exposure showing mixing, mingling and hybridization process at ~ 3 km north of Gurgunta in Gulbarga road.
display sharp to crenulated contacts with the felsic host indicating solidified margins and liquidus interiors (see Fig. 30b). Interaction, mixing of coeval mafic and felsic host leading to hybridization can be observed in several stages. Injection of mafic magma into felsic crystallizing host or anatectic zone cause thermal disequilibrium as mafic magma cause local increase in temperature thus melt content may further increased in felsic host. The heat and volatiles of the mafic magma also cause reversal of crystallization of felsic host causing local interaction and back veining.

**Spatial link between 2.7-2.5 Ga juvenile magmatism, crustal reworking and regional deformation patterns**

Geochronologic and Nd isotopic data reveal that EDC was built in two major episodes of crust accretion during 2.7-2.65 Ga and 2.57-2.52 Ga (Jayananda et al., 2012) with large 3.35-3.0 Ga remnants of old crust found in the western boundary of the Closepet granite (Chardon et al., 2011; Friend and Nutman, 1991; Mahabaleswar et al., 1995). The 2.7-2.65 Ga crust accreted in the form of mafic greenstone volcanism and tonalitic to granodioritic plutonism contributing to large scale continental growth (Balakrishnan et al., 1990, 1999; Anand and Balakrishnan, 2010; Jayananda et al., 2012). This major episode of crust accretion outlasted with the reworking of ancient crust and granulite metamorphism close to UHT conditions and emplacement of potassic plutons along western fringe of EDC close to 2.62 Ga (Jayananda et al., 2006, 2011). The 2.57-2.52 Ga corresponds to period of intense geological activity in the EDC. During this period large quantities of juvenile magmatic materials accreted to the EDC (Krogstad et al., 1991, 1995; Jayananda et al., 2000, 2012; Pencat et al., 1993b; Dey et al., 2012). Besides the Closepet granite, all other north-south trending magmatic intrusion in the east (see Fig.1) emplaced during this event. More recently Jayananda et al (2009) document widespread occurrence of MME and synplutonic mafic dykes in 2.57-2.52 Ga plutons. This juvenile magmatic accretion spatially associated with the reworking of ancient crust as revealed by field data and U-Pb zircon ages of 2.57 -2.53 Ga intrusive and 2.53 -2.52 Ga anatetic facies (Friend and Nutman, 1992; Jayananda et al., 1995, 2000). Innumerable synplutonic mafic dykes traverse the host crystallizing granitoids probably supplied additional heat and volatiles for crustal reworking. These hot mafic magmas show interactions, mixing and mingling with crystallizing host granitoid magmas. The 2.57-2.52 Ga accretion culminated with granulite to greenschist facies regional metamorphism at 2.5 Ga that affected whole Archaean crust which followed slow cooling and final cratonization close to 2.45 Ga (Jayananda et al., 2000). The above lines of arguments suggest that the two major episodes of accretion (2.7-2.65 Ga and 2.57 -2.5 Ga) contributed to the large scale continental growth in the EDC which are spatially associated with reworking and cratonization at the end of Archaean.

**Tectonic context of magma generation and emplacement**

Any model proposed on the Neoarchean evolution of EDC should explain the observed bimodal age distribution of greenstone sequences and TTG - granitoids of 2.7-2.65 and 2.57-2.52 Ga. More recently based on elemental characteristics of EDC greenstone sequences, Manikyamba and Kerrich (2012) proposed a two stage accretion of 2.7-2.65 Ga continental lithosphere in EDC wherein komatiite and high-Mg basalts attributed to plume melting whilst associated tholeiite to calc-alkaline basalts explained by subduction of young hot oceanic lithosphere. On the other hand Jayananda et al (2012) explained 2.7-2.67 Ga mafic greenstone volcanism and surrounding TTG by a combined plume-arc setting. In this model melting of plume below oceanic lithosphere generate Mg-rich mafic magmas forming oceanic plateaus and shallow angle subduction of intervening hot oceanic crust generated TTG magmas. In the present contribution we briefly discuss about 2.57-2.52 Ga magmatic accretion and associated crustal reworking and high-T and low-P regional metamorphism. Based on our field data from three corridors in EDC together with published ages and Nd-Sr isotopic data, and metamorphic P-T paths we discuss a combined model involving lateral accretion in arc setting for generation of granitoid magmas followed by a plume impact to account reworking, granulite metamorphism and cratonization. Field observations in the three studied corridors show emplacement of huge quantities of granitoid magmas with subordinate coeval mafic magma injections. Published age data (Jayananda et al., 2012 and references therein) together with our unpublished ages show that granitoid magmas (intrusive and anatectic) and mafic injections are coeval emplaced during 2.57-2.52 Ga. Nd-Sr isotope data reveal major juvenile source for granitoids with minor crustal input. Consequently the granitoid magmas must be derived either by direct melting of mantle or melting of down going oceanic slab in arc setting. In this study with the field data alone we are unable to constrain role of mantle and slab in granitoid magma generation. However, several recent studies (e.g. Martin et al., 2010; Moyen et al., 2010) show that decrease in geothermal gradients during the end of Archaean, smaller degree of slab melting occurred at greater depths. In such conditions the slab melts strongly contaminated with overlying mantle during their passage to crust. The proposed model involves westward subduction oceanic slab and melting of down going slab at greater depth (50-60 km) generated felsic to intermediate magmas. The resultant magmas rise through thick colon of overlying mantle causing interaction of slab melts with the mantle gaining compatible elements (Moyen et al., 2003b). Accumulation and differentiation of calc-alkaline magmas in the deep crust leads to development of shrinkage cracks to the mantle depth causing the decompression melting of mantle. The resultant mafic magmas injected into crystallizing magma chambers in the crust where they show varying degree of interaction with the host depending on the crystallinity. The heat and fluids associated with slab derived magmas cause partial melting of surrounding TTG crust resulting in anatectic melts. Closure of arcs during ca. 2.52 Ga and catastrophic collapse of down-going slabs at 660 km depth triggered plume production (Condie, 1998) which rise below continental crust causing the reworking of old as well as newly formed juvenile crust and regional metamorphism. Such mechanisms explain the observed field, petrological characteristics of the composite granitoids plutons including synplutonic mafic dykes, reworking, 2.5 Ga hot metamorphism and final cratonization of Archaean crust with slow cooling rates upto 2.4 Ga (Jayananda and Peucat, 1996; Peucat et al., 1993b).

**Conclusions**

The conclusions of the present study can be summarized as follows:

1. The late Archaean granitoid plutons in the EDC are composite
containing dominant intrusive as well as minor anatetic facies and form windows to magma chamber processes at different crustal levels
2. The granitoid plutons contain significant amount of coeval magmas represented by MME and symplutonic mafic dykes.
3. Mafic magmas inject into crystallizing host with varying degree of crystallinity and show different stages of interaction, mixing, mingling and hybridization
4. Field data show 2.57-2.52 Ga magmatism is spatially associated with crustal reworking, regional metamorphism and cratonization of Archaean crust and
5. 2.57-2.5 Ga magmatism and reworking processes can be attributed to two stage model involving slab melting in arc setting followed by a plume impact.

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