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Synplutonic Mafic Dykes from Late Archaean Granitoids in the Eastern Dharwar Craton, Southern India

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Abstract: We present a first overview of the synplutonic mafic dykes (mafic injections) from the 2.56 – 2.52 Ga calc-alkaline to potassic plutons in the Eastern Dharwar Craton (EDC). The host plutons comprise voluminous intrusive facies (dark grey clinopyroxene-amphibole rich monzodiorite and quartz monzonite, pinkish grey porphyritic monzogranite and grey granodiorite) located in the central part of individual pluton, whilst subordinate anatectic facies (light grey and pink granite) confined to the periphery. The enclaves found in the plutons include highly angular screens of xenoliths of the basement, rounded to pillowed mafic magmatic enclaves (MME) and most spectacular synplutonic mafic dykes. The similar textures of MME and adjoining synplutonic mafic dykes together with their spatial association and occasional transition of MME to dismembered synplutonic mafic dykes imply a genetic link between them. The synplutonic dykes occur in varying dimension ranging from a few centimeter width upto 200 meters width and are generally dismembered or disrupted and rarely continuous. Necking of dyke along its length and back veining of more leucocratic variant of the host is common feature. They show lobate as well as sharp contacts with chilled margins suggesting their injection during different stages of crystallization of host plutons in magma chamber. Local interaction, mixing and mingling processes are documented in all the studied crustal corridors in the EDC. The observed mixing, mingling, partial hybridization, MME and emplacement of synplutonic mafic dykes can be explained by four stage processes: (1) Mafic magma injected during very early stage of crystallization of host felsic magma, mixing of mafic and felsic host magma results in hybridization with occasional MME; (2) Mafic magma introduced slightly later, the viscosities of two magmas may be different and permit only mingling where by each component retain their identity; (3) When mafic magma injected into crystallizing granitic host magma with significant crystal content, the mafic magma is channeled into early fractures and form dismembered synplutonic mafic dykes and (4) Mafic injections enter into largely crystallized (>80% crystals) granitic host results in continuous dykes with sharp contacts. The origin of mafic magmas may be related to development of fractures to mantle depth during crystallization of host magmas which results in the decompression melting of mantle source. The resultant hot mafic melts with low viscosity rise rapidly into the crystallizing host magma chamber where they interact depending upon the crystallinity and viscosity of the host. These hot mafic injections locally cause reversal of crystallization of the felsic host and induce melting and resultant melts in turn penetrate the crystallizing mafic body as back veining. Field chronology indicates injection of mafic magmas is synchronous with emplacement of anatectic melts and slightly predates the 2.5 Ga metamorphic event which affected the whole Archaean crust. The injection of mafic magmas into the crystallizing host plutons forms the terminal Archaean magmatic event and spatially associated with reworking and cratonization of Archaean crust in the EDC.

Keywords: Synplutonic mafic dykes, Granite plutons, Mafic Magmatic Enclaves, Magma chamber, Eastern Dharwar craton.

INTRODUCTION

The synplutonic dykes are mafic injections into crystallizing magma chambers which are spatially associated with calc-alkaline to potassic plutons ranging in age from Archaean to Phanerozoic. They are key to our understanding of magma chamber dynamics including interaction, mixing and mingling of felsic and mafic magmas, late thermal rejuvenation of magma chambers, chemical diversity of igneous rocks, geodynamic processes and evolving mantle compositions (Wiebe et al. 2004; Barnes et al. 2002; Barbarin, 2005). They interact in different ways depending on the crystallinity/rheology of the host magma chambers

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and the volume of injected mafic magma. They are mainly mafic in composition and are spatially associated with calc-alkaline to potassic plutons formed both in plate margin and intracontinental tectonic settings (Reid and Hamilton, 1987; Neves and Vauchez, 1995; Bedard, 1990; Pitcher, 1991; Stern and Hanson, 1991; Tate et al. 1997; Wiebe et al. 2004). In many cases these synplutonic mafic dykes acted as potential heat and fluid sources for remelting of crystallizing host plutons and generation of anatectic partial melts (Huppert and Spark, 1988). Several studies indicate their derivation from mantle source (e.g. Stern and Hanson, 1991; De Paolo et al. 1992). On a global geodynamic context these mafic dykes have been ascribed to melting of mantle in the arc environments (Wiebe et al. 2004; Stern and Hanson, 1991) and also considered to be significant in understanding supercontinent history (Heaman, 1997).

Calc-alkaline to potassic granite plutons constitute about 20% of the exposed continental crust and provide complimentary record of magma chamber processes. Several studies have shown injections of high temperature mafic synplutonic dykes into crystallizing granite plutons (Pitcher, 1991, 1997; Castro et al. 1990; Wiebe et al 2004 for review). Study of the mechanisms of injection of synplutonic mafic dykes into crystallizing felsic magma chambers and their interaction and mixing with the host magma provide much important information to our understanding of the evolution of calc-alkaline series. Composite plutonic sequences are manifestations of magmas with contrasting compositions emplaced contemporaneously and in spatial relationships. During magma intrusion and emplacement the original geochemical characteristics of magmas may be extensively modified by injection of mafic magma pulse. In recent years several studies have focused on the calc-alkaline to potassic plutons and associated synplutonic mafic dykes (Frost and Mahood, 1987; Castro et al. 1990; Pitcher, 1991; Blichert-Toft et al. 1992; Foster and Hyndman, 1990; Stern and Hanson, 1991). However, most of the studies focused on the synplutonic mafic dykes from Phanerozoic calc-alkaline plutonic complexes in arc settings. On contrary only a few studies focused on the synplutonic mafic dykes from Archaean plutons (Stern and Hanson, 1991) as these dykes are disrupted and frequently recrystallized, as the emplacement of most of the late Archaean plutons are spatially associated with regional deformation and metamorphism. In this context study of synplutonic mafic dykes found in the Late Archaean plutons are crucial to our understanding of magma chamber processes, interaction of felsic and mafic magmas, chemical diversity of granitoids, geodynamic settings of magmatism, reworking and cratonization of Archaean crust.

Calc-alkaline to potassic plutons constitute major proportion of exposed Archaean crust in the Eastern Dharwar Craton (EDC). Published geochronologic data indicate 2.56-2.52 Ga for magmatic emplacement of the plutons (Friend and Nutman, 1991; Krogstad et al. 1991; Peucat et al. 1993; Nutman et al. 1996; Balakrishanan et al. 1999; Jayananda et al. 1995, 2000; Chardon et al. 2002). Recent studies focus on field, structural, whole rock geochemical and isotope work on the plutons and discuss mechanisms of their emplacement, petrogenetic processes as well as geodynamic context of magma generation (Chadwick et al. 2000; Jayananda et al. 2000; Moyen et al. 2003; Chardon and Jayananda, 2008). However, so far no attempt has been made on the study of synplutonic mafic dykes found in calc-alkaline to potassic plutons in the EDC. Clearly a detailed field, petrographic, geochemical and isotopic study of these dykes through much insight into magma chamber processes including the crystallization history of plutons, petrogenesis and geodynamic context of magmatic accretion. This paper is a first attempt to document an overview of synplutonic mafic dykes in late Archaean granitoid plutons in the EDC corresponding to deep to higher crustal levels (Fig.1).

The major objectives of the paper are:

1. To present a first overview of the synplutonic dykes in the different granitoid plutons of EDC and discuss magma chamber processes including interaction of mafic injections with crystallizing felsic magmas, thermal rejuvenation magma chamber and
2. To discuss origin of mafic magmas and their time relationship with respect to terminal Archaean evolution in EDC including widespread juvenile magmatism, crustal reworking, metamorphism and cratonization.

GEOLOGICAL SETTING

Regional Geology

The Dharwar craton expose a large tilted section of Archaean continental crust and not affected by any major post-Archaean thermal events and unique for its preservation of protracted geologic record and geodynamic settings since ‘at least 3.6 Ga’. The preserved Archaean crust comprises 3.32-2.56 Ga TTG-type peninsular gneisses, two distinct volcano-sedimentary greenstone sequences (3.35-3.2 Ga Sargur Group and 2.9-2.65 Ga Dharwar Supergroup) and 2.62-2.52 Ga calc-alkaline to potassic plutons (Peucat et al. 1993, 1995; Chadwick et al. 2000; Jayananda et al. 2000, 2006, 2008; Naqvi, 2005; Ramakrishnan and Vaidynadhan, 2008). The craton is commonly divided into two sub-blocks (western and

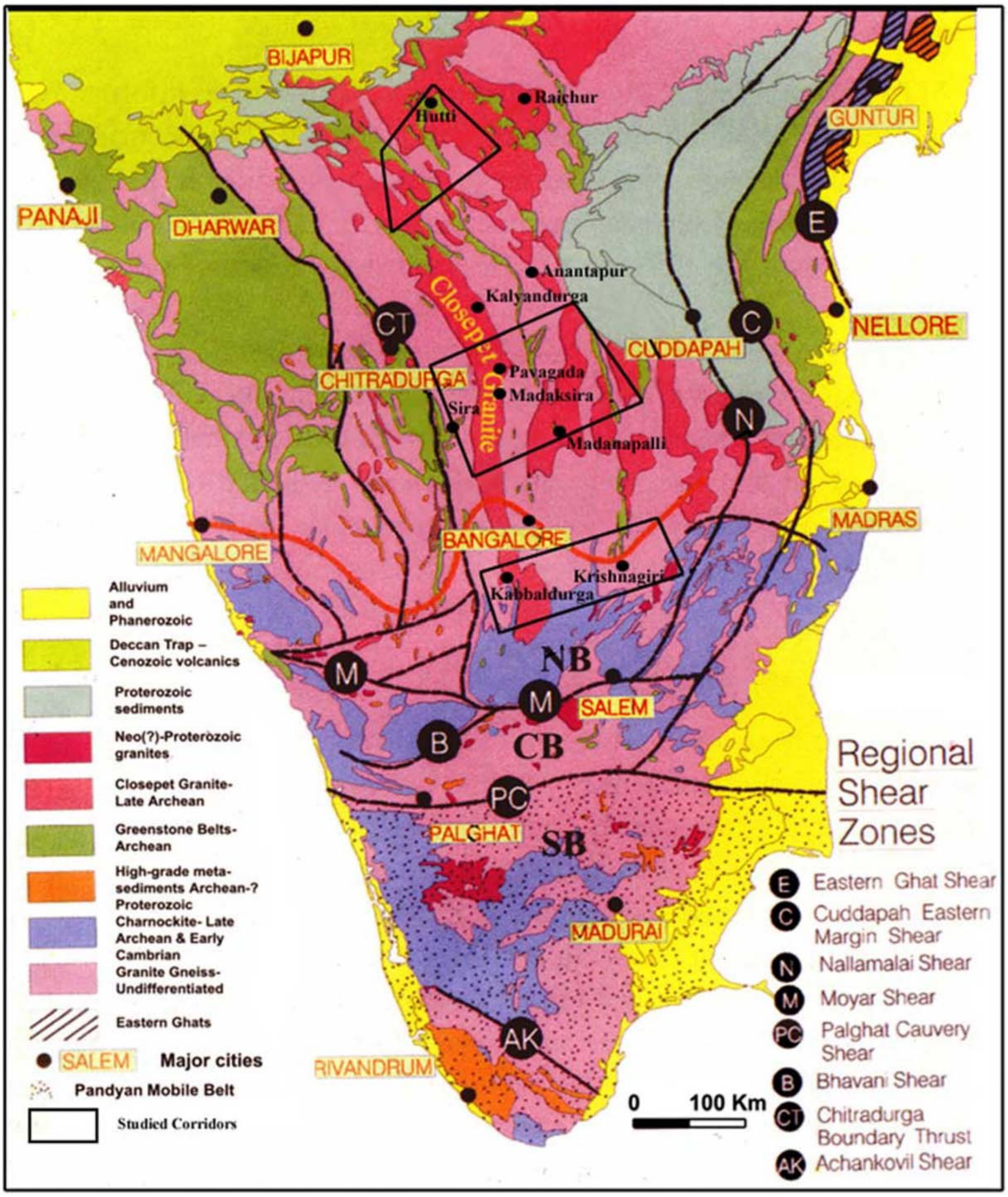

Fig.1. Geological sketch map of southern India showing the studied crustal corridors (Map after Geological Survey of India project Vasundara).

eastern Dharwar) based on the nature and abundance of granite-greenstones as well as nature and age of surrounding basement, crustal thickness, degree of metamorphism and melting (Swami Nath et al. 1976; Gupta et al. 2003). The steep mylonitic zone along the eastern boundary of the Chitradurga greenstone belt is generally considered as the dividing line between these two crustal blocks. The western Dharwar craton (WDC) dominated by old (>3.0 Ga) peninsular gneisses with broad sediment-rich greenstone basins, whilst the EDC comprises of younger TTG basement (2.7-2.56 Ga) with small remnants of older (>3.0 Ga) TTGs and volcanic- rich thin, elongated greenstone belts. On cratonal scale LANDSAT-TM data together with field based fabrics mapping reveal dome and basin patterns, north trending steep foliations, flat foliations and regional strike-slip shear zones (Chardon et al. 2008). The whole craton was affected by 2.5 Ga Archaean shear deformation and greenschist to granulite facies metamorphism that affected the whole Archaean crust (Bouhallier, 1995; Jayananda and Peucat, 1996). This event was immediately preceded by a major 2.56-2.52 Ga juvenile magmatic accretion event leading to emplacement of the several N-S trending granitoid plutons in the EDC including the most spectacular 400 km long Closepet granite (Chardon and Jayananda, 2008; Chardon et al. 2008). Cratonization of Archaean crust in the Dharwar craton was marked by crustal reworking, metamorphic cooling and injection of mafic dyke swarm during 2.51-2.43 (Ikramuddin and Steuber, 1976; Peucat et al. 1993; Jayananda and Peucat, 1996; Halls et al. 2007).

2.56-2.52 Ga Host Granitoid Plutons

2.56-2.52 Ga granitoid plutons are the most abundant lithologies and regionally distributed in the EDC (see Fig.1) which traverse in north-south direction from amphibolite-granulite transition zone in the south up to Proterozoic sedimentary basins and Deccan traps in the north. They are composite plutons containing two distinct magmatic suites including the most voluminous mantle derived juvenile facies with minor anatectic components (Peucat et al. 1993; Jayananda et al. 1995, 2000; Moyen et al. 2003). The juvenile facies are SiO_2 - poor dark grey quartz diorite, quartz monzonite, and monzodiorite, grey to pink porphyritic monzogranite and grey granodiorite, whilst anatectic components comprise light grey to pink granite (Balakrishnan and Rajamani, 1987; Jayananda et al. 1995, 2000, 2003; Chadwick et al. 2000; Moyen et al. 2001, 2003). Both mantle and crustal derived facies show interaction and mixing features (Jayananda et al. 1994). Recently Moyen et al. (2003) have documented four major types of granitoids in the EDC: (1) Na-rich TTG melts derived by slab melting, (2) Mg and K-rich sanukitoids formed by interactions of slab melts with mantle wedge, (3) highly enriched Closepet-type derived from enriched juvenile source in hot spot environments associated with plume and (4) Mg-poor anatectic granites formed by reworking of newly formed juvenile TTG crust. These plutons affected by late Archaean shear deformation and metamorphism (Jayananda et al. 2003)

Enclaves

Based on field observations two main types of enclaves can be distinguished which include xenoliths (pre-existing metaigneous and metasedimentary basement rocks) and mafic magmatic enclaves (MME) as disrupted materials of mafic injections into crystal poor host magma. They are found in plutons of all three studied corridors but generally more abundant in the exposed deeper levels.

Xenoliths

Xenoliths are metamorphic screens of country rocks found in plutons. They are readily distinguished from MME by their angular shape and strong pre-magmatic fabrics which are often rotated and fragmented as a result of felsic veining. Xenoliths of ultramafic, mafic and intermediate composition including metasedimentary rocks and TTG found in the plutons of EDC in all exposed crustal levels. They are particularly abundant along the periphery of the plutons or along major shear zones in the southern and central corridor. Several kinds of xenoliths with metamorphic mineralogy and strong pre-magmatic fabrics are found in the plutons (Fig.2). They are highly angular and fragmented or rotated which often partially digested or mechanically mixed with host granite (Fig.3).

Mafic Magmatic Enclaves (MME)

Mafic magmatic enclaves (MME) or igneous enclaves are identified according their rounded or pillow shape with igneous textures and more mafic than their enclosing host as defined by Barbarin (2005). MME consists of blobs of mafic to intermediate materials with rounded to pillow or ovoid shape with igneous texture and usually surrounded by a chilled margin. They are invariably darker and fine grained compared to their host. Numerous MME are found in different facies of plutons in all the three studied crustal corridors of EDC. They are mafic to intermediate generally rounded or pillow shaped and exhibit textures similar to their host pluton (Fig. 4). Clusters of rounded to rarely irregular shaped MME formed from a dismembered synplutonic mafic dyke (Fig.5) implying a close spatial and genetic relationship between them. In some instances clusters of oriented MME also show transition to disrupted synplutonic mafic dyke.

Synplutonic Mafic Dykes

Synplutonic mafic dykes are the mafic injections into the crystallizing host plutons. These synplutonic dykes found in the late Archaean (2.56-2.52 Ga) plutons of the EDC in all exposed crustal levels. In field synplutonic dykes are identified based on the characteristics features defined by Pitcher (1997) such as necking of dyke along its length, back-veining into the dyke frequently leucocratic veins and some times actual host, dismemberment of the dyke into trains of angular almost amoeboid enclaves and finally cuspate margins convex towards the host. We have studied the synplutonic mafic dykes from calc-alkaline to potassic plutons along three defined crustal corridors corresponding to three crustal levels.


Fig. 2


Fig. 3


Fig. 4

Figs.2-4. (**2**) Rotated mafic xenolith with strong Pre-magmatic fabric found in granodiorite about 6 km ‘E’ of Bargur in Krishnagiri – Chennai highway. (**3**) Xenolith of TTG basement rock in pink granite at about 5km north of Kambadur in Pavagada – Kalyandurga road. (**4**) Mafic magmatic enclave (MME) in grey granodiorite (location same as Fig.2).

Southern Corridor (Kabbaldurga-Krishnagiri-Peranumpatti Crustal Corridor)

The Kabbaldurga-Krishnagiri-Peranumpatti corridor corresponds to amphibole-granulite facies transitional domains in the Eastern Dharwar craton (see Fig. 1). This section exposes root zone of the plutons where migmatitic gneisses are the dominant lithologies (Moyen et al. 2003). Patchy arrested charnockite development on migmatitic gneisses, granulites is a common feature.

Numerous melt filled NE (12-30°) trending dextral shear bands traverse the migmatitic gneisses. These plutons are thin (2-5 km width) and are bounded by thick zone of migmatitic gneisses.

The studied plutons comprise dominant intrusive dark grey quartz monzonites, pink to grey porphyritic monzogranites, grey granodiorite and minor anatectic light grey to pink granite facies. They contain innumerable rounded to pillowed enclaves, angular xenoliths and most spectacular synplutonic mafic dykes. The synplutonic mafic dykes are discontinuous (Fig.6) and frequently disrupted or dismembered with back-veining of leucocratic variants of the host (Fig.7). Dismemberment of dyke into angular or amoeboid enclaves is most common phenomenon (Fig.8). They are generally fine grained and rarely medium grained and commonly show sharp and occasionally lobate contacts with host pluton. In the Kabbaldurga and Krishnagiri-Kaveripattinam area the synplutonic dykes show total recrystallization and affected by metamorphism as evidenced by incipient charnockite development on synplutonic dykes (see Fig.7).

These synplutonic mafic dykes are synchronous with crustal anatexis and are frequently dismembered by the interaction of anatectic melts where local mingling can be observed (Fig.9).

Central Corridor (Sira-Pavagada-Anantapur Crustal Corridor)

This crustal corridor forms mid-crustal levels and corresponds to magma accumulation zone (Moyen et al. 2003). The plutons are thickest and show relatively sharp contacts with the surrounding basement. The widest part of Closepet granite is exposed and bounded by thin zone of anatectic granites and diatexites. East of Closepet granite a few N-S trending granite massifs are found up to Cuddapah Basin. The prominent magmatic massifs are exposed in the areas of Penukonda-Bukkapatnam-Gorantla, Dharmavarm-Anantapur, Kadri-Rayachoti.

The Closepet granite comprise most abundant porphyritic monzogranite in the centre with minor dark grey amphibole rich quartz monzonite and bounded by pink granite or diatexite in the east and grey granite or diatexite in the west. Plutons occurring to the east of Closepet comprise mainly of grey granodioritic to light grey granite with sub-ordinate porphyritic facies.

The most spectacular synplutonic dykes are confined to


Fig. 5


Fig. 6

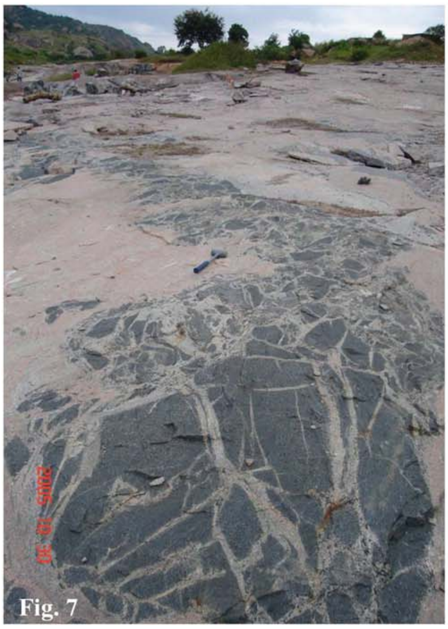
Fig. 7


Fig. 8

Figs.5-8. (**5**) Clusters of oriented MME form trains giving an appearance of dismembered synplutonic mafic dyke from a quarry about 25 km north of Hospet in NH13. (**6**) Discontinuous synplutonic mafic dyke in the Kabbaldurga quarry overprinted by incipient charnockite. (**7**) Boudinaged synplutonic mafic dyke with back veining of slightly pink granite in the southern end of the Closepet granite (from a large quarry at about 1 km north of Jakkegoudanadoddi in Kanakapura – Satnur road). (**8**) Dismemberment of mafic dyke into amoeboid enclaves (location same as Fig.7).

this crustal corridor particularly in the Closepet granite. The synplutonic mafic dykes show varying mineralogy and texture. They are fine grained but are occasionally medium to coarse grained.

Few thick mafic dykes (3 m width) are even showing fine grained to porphyritic texture across the dykes (Fig.10). In the central part of the granite massifs, the synplutonic mafic dykes occur as dismembered rounded to pillowed bodies with back veining of aplitic facies. They are bordered by coarse leucocratic to fine aplitic veins which disrupted the synplutonic mafic dykes. The dismembered dykes show sharp to lobate contacts. At several exposures interaction and mingling between synplutonic mafic dyke and the host granite can be observed.

Figs. 9-10. (**9**) Synplutonic mafic dyke disrupted by rising synchronous anatectic melts at Kabbaldurga quarry. (**10**) Synplutonic mafic dyke sharing coarse grained porphyritic texture along the boundary at a quarry in NE outskirts of Pavagada town.

Along the boundary of the plutons the synplutonic mafic dykes are spatially associated with the emplacement of anatectic pink to grey facies and diatexites. Here synplutonic mafic dykes are more continuous and necking of dyke is common (Fig.11). These mafic dykes together with anatectic facies define spectacular magmatic flow structures. Trains of dismembered dyke show convex shape towards host with pillow to rounded or occasional angular shapes indicating their coeval nature (Fig.12).

In the Sira-Pavagada-Anantapur crustal corridor the host plutons also contain rounded to ellipsoid MME (Fig.13) in the magma flow zone where different stages of mingling and partial hybridization can be observed. This corridor needs to be studied in more detail to understand hybridization processes, different types of MME and their spatial relationship with synplutonic dykes.

Northern Corridor (Kustigi- Hutti -Raichur Corridor)

The northern crustal corridor corresponds to upper crustal levels where typical high level plutons are exposed. The exposed crust is mainly affected by green schist facies metamorphism and locally amphibolite facies assemblages are found along major interfering shear zones. The plutons are comprised mainly of equigranular pink to grey granites with sub-ordinate porphyritic monzogranites and dark grey quartz-monzonite. Xenoliths are generally rare, which are mainly angular mafic fragments with strong rotated pre-magmatic fabrics. Occasionally medium to coarse grained rounded to pillow shaped MME having lobate to sharp contacts can be found in the host plutons.

Synplutonic dykes are less abundant as compared to southern and central crustal corridors. However, the observed synplutonic dykes are most spectacular which are mafic to intermediate in composition. They are often dismembered and show sharp contact with the host granite (Fig.14). About 3 km north of Gurgunta village, a wide (300 m), continuous (~5 km length) and highly coarse grained to porphyritic mafic synplutonic dyke is found within the granite pluton. Here the synplutonic mafic dyke comprise three facies including coarse grained hornblendite with remnants pyroxene, subordinate coarse grained gabbroic facies containing tiny plagioclase phenocrysts and most abundant highly coarse grained dark grey intermediate to mafic porphyritic facies. Occurrence of different facies with mineralogical variation implies that the magma of synplutonic mafic dyke evolved by internal differentiation. Small rounded clots (possibly olivine and now completely altered) with a reaction rim giving an appearance of augen shaped structure, which are possibly ocilli. The synplutonic mafic dyke shows diffused contacts with the host pluton. Frequent closely spaced rounded to sub-rounded MME as parts of disrupted mafic dyke found in pluton along the contact and at places some felsic veins are also penetrated into the synplutonic mafic


Fig. 11


Fig. 12


Fig. 13

Figs. 11-13. Continuous synplutonic mafic dyke together with diatexitic pink granite define magma flow at about 7 km 'N' of Madakasira in Pavagada road. (**12**) Trains of dismembered synplutonic dyke show convex shape towards host anatectic granite indicating comagmatic nature (location same as Fig.11). (**13**) MME in magma flow zone between injecting gabbroic dyke and pink granite host (about 5 km 'N' of Kokkanti cross in Madanapalli – Anantapur road).

dyke implying magma mingling between them (see Fig.15). Along the contact zone between pluton and synplutonic mafic dyke records various stages of interaction, mingling and local hybridization (see Fig.15).


Fig. 14


Fig. 15

Figs.14-15. (**14**) Disrupted fragments of dioritic synplutonic dyke containing host granite fragments suggesting their coeval nature. Exposure at about 30 km NW of Gangavathi town (in Tawargeri – Koppal road). (**15**) Synplutonic mafic dyke showing magma mixing and hybridization with the host granite, near Gollapalli (about 3 km north of Gurgunta in Gulbarga road).

DISCUSSION

Late Archaean Magmatism in the EDC

Granitoids may be spatially associated in time with synplutonic mafic dykes in different volumes of arc related igneous complexes in the plate margin settings. Spectacular synplutonic mafic dykes which show progressive transition to mafic enclaves described in the Sierra Nevada batholiths (Barbarin, 2005). In the EDC major calc-alkaline magmatic accretion occurred during 2.56-2.52 in the form of north-south trending plutons (for review Moyen et al. 2003; Chardon and Jayananda, 2008). Mafic magma injections in the form of MME and synplutonic mafic dykes in both intrusive and anatectic facies of plutons exposed at different crustal levels suggest a time relationship between magma chamber processes, emplacement and origin of mafic magmas within the geological frame work of host plutons.

Implications for Magma Chamber Processes

Coeval Felsic and Mafic Magmas

Our observed important field characteristics of synplutonic mafic dykes such as necking of the dyke along its length, dismemberment into trains of angular or amoeboid enclaves before complete crystallization of host clearly provide evidence for mafic magma injected into an unconsolidated, yet relatively cooler granitic host. Their coeval nature with host granitoid plutons is further evidenced by back-veining of leucocratic veins – where the crystallizing granitic host was likely to kept mobile by the superheating of injecting mafic magma so that leucocratic melts locally generated by reversal of crystallization or actual host back-vein into the synplutonic dyke (Pitcher, 1997). Latent heat of crystallization of invading mafic magma may also partly induce generation of leucocratic melt around the MME (Kumar et al. 2004).

Mixing, Mingling and Partial Hybridization

In the evolving granitoid magma chambers several factors control the degree of interaction between coeval felsic and mafic magmas, three main processes can be distinguished which include mixing, mingling and chemical exchanges (Barbarin, 1989). Viscosity play an important role on the dynamics of magma hybridization (Huppert et al. 1984); low viscosity contrasts between mafic and felsic magmas favour mixing and hybridization, whilst large viscosity contrasts do not permit mixing but only permit mingling.

The factors that control the interaction between mafic injections and crystallizing host granitic magma include the relative volumes of mafic magma and crystallizing host. Mixing cannot be achieved between crystallizing host (crystal mush) and mafic injections unless crystallization processes reversed by superheat of mafic injection (Pitcher, 1997). In the EDC the interaction of mafic injection with crystallizing host has been frequently observed on an outcrop scale. The similar texture and mineralogy of dismembered synplutonic mafic dyke and pillowed MME in the same outcrop imply that they were the parts of same mafic magma. Pillowed to ovoid MME were formed when host magma was sufficiently liquidus to allow mixing and mingling although they may have more complex history than their derivation from synplutonic dyke.

Mingling is a dominant process observed in all the three crustal corridors. MME with chilled margins found within the host granite show similar textures. At many exposures synplutonic mafic dyke can be traced to progressive mingling with host granite resulting in numerous medium to fine grained MME having similar textures often with chilled margins (Fig.16). However, because of large viscosity contrast limited exchange occurred as revealed by their sharp contacts.

Figs.16-17. (**16**) Synplutonic mafic dyke showing transition to ovoid to angular mafic magmatic enclaves (about 0.5 km from Mangalavada in Pavagada road). (**17**) Transitional contacts and flow structures between disrupted synplutonic mafic dyke and host granite (quarry exposure about 8 km north of Madakasira in Pavagada road).

Mesocratic medium to coarse grained highly heterogeneous hybrid zones are observed in all the crustal corridors corresponding to the three crustal levels. They form large masses with evident flow structures and transitional contacts between host granitoid and pillowed to dismembered synplutonic mafic dyke (Fig.17). The upward transfer of heat from mafic magma might have caused remelting of crystal mush by convective heat transport which would have mixed magmas resulting in mafic hybrid facies. The hybrid zones are further characterized by large textural heterogeneity and an increase of biotite/hornblende ratio towards the host. The processes of mixing and mingling occurred due intermittent injections of mafic magmas during different stages of crystallization of host granitoid magma.

Mafic magma can be injected as dyke along fractures into a cooling viscous but still mobile and crystallizing felsic host. Much of the independent evidence for such fracturing during crystallizing of viscous host granite magmas are documented by Berger and Pitcher (1970) and Hibbard and Watters (1985). They attribute that quasi-magmas deform by fracture or flow depends on the rate of stress in the active tectonic zones. Because of relatively small volume of the injected mafic magma, cooling will be rapid enough (Wiebe, 1991) to form synplutonic mafic dykes and MME with chilled margins. Field relationships in the three corridors indicate that the mafic magma pulses were injected into crystallizing host granitic magma chamber throughout the crystallization. When mafic magma pulse inject into early stage of crystallization of host magma or magma flow zone, where the viscosity difference would be low which leads to hybridization. On the otherhand when mafic magma injects into crystallizing host (ca. 50% crystals) viscosity contrast would be higher and mafic injections may occur in the form of dismembered synplutonic mafic dykes (see Fig.12). The latent heat of injecting synplutonic mafic dykes probably caused reversal of crystallization of host magma mush and locally induce remelting. The resultant melts can penetrate the crystallizing mafic magma as back-veining observed at several exposures (see Fig.7). A wide variety of intermediate stages exist between partially dismembered synplutonic mafic dykes and MME with arrested hybrid zones, imply injection of mafic magmas during early to late stage crystallization of host magma. Such relationships further suggest that the observed pillowed to ovoid mafic enclaves are derived from the same mafic magma but at different stages of viscosity contrasts.

Emplacement of Synplutonic Dykes

Field relationships suggest that emplacement of synplutonic mafic dykes and MME occurred during different stages of crystallization of host in magma chamber forming the plutons of EDC, which can be explained by four fold model (Fig.18) as proposed by Barbarin and Didier (1992)

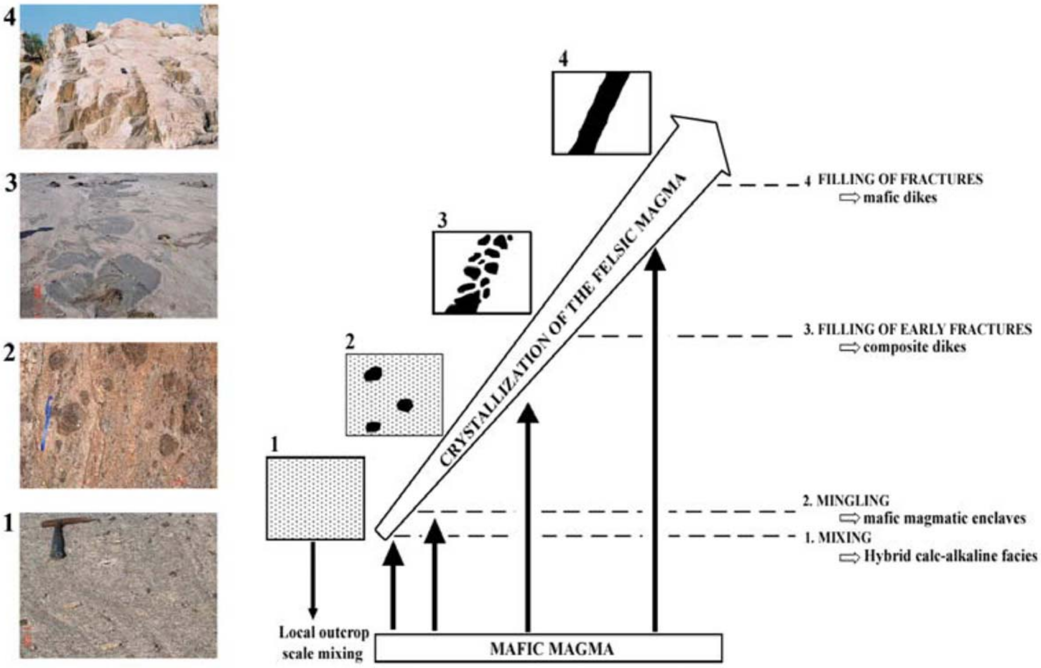

Fig.18. Four fold model (*after* Barbarin and Didier, 1992; Barbarin, 2005) for formation of MME, synplutonic mafic dykes, mixing and hybridization in the Eastern Dharwar Craton.

and Barbarin (2005). The four stages of processes during the crystallization and injection of mafic magmas are as follows:

1. Mafic magma when introduced during very early stage of crystallization of host felsic magma, on a local outcrop scale mixing of mafic and host felsic magma results in hybrid magmas leading to formation of slightly mafic calc-alkaline granitoids.
2. If the mafic magma is introduced slightly later, the viscosities of two magmas may be different and permit only mingling where by each component retain their identity. MME probably formed during this stage.
3. If the mafic magma is injected into crystallizing granitic host magma with higher proportions of crystals (ca.50%), the mafic magma is channeled into early fractures of crystallizing host and interacts with the remaining magmatic liquids and form dismembered synplutonic mafic dykes.
4. Finally when mafic magmas are injected into essentially crystallized (>80% crystals) granitic host, results in continuous dykes with sharp contacts. No interaction or exchange can be observed as rheology of the host and mafic injection are completely different.

Origin of Mafic Magmas

The origin of syn-magmatic mafic injections in to granitoid plutons is an important topic of discussion (e.g. Barbarin, 2005; Wiebe et al. 2004). The study of mafic microgranular enclaves and synplutonic mafic dykes should provide important information on the origin of mafic magmas. In EDC field evidence suggests that mafic magmas injected during different stages of crystallization of host plutons at different emplacement levels. However, field evidence alone does not provide precise information on the origin of magmas including nature and source. Recent geochemical and isotope studies on 2.55-2.52 Ga granitoids from EDC reveal a major juvenile mafic source (Short lived oceanic crust or mantle) but no information available on the origin and source of mafic magmas.

2.55-2.52 Ga calc-alkaline to potassic-rich magmatism in the EDC has been explained by lateral accretion in arc environment (Krogstad et al. 1995; Chadwick et al. 2000, 2007; Moyen et al. 2003) or by plume setting (Peucat et al 1993; Choukroune et al 1995; Jayananda et al. 1995, 2000; Chardon et al. 2002). In both the settings large quantities of juvenile magmas are derived by melting of mantle source. Those juvenile magmas moved upwards into the magma chamber in the crust where they started crystallization. As crystallization begin to progress, transformation of liquid to crystal-liquid mush probably results in contraction due to decreasing volume which results in development of fractures. These fractures might have caused the decompression melting of deeper source (mantle) resulting in the generation of small quantities of mafic magmas. The low viscosity newly generated hot mafic magmas rise rapidly along the fractures into crystallizing more viscous felsic magmas. The advective heat transfer by mafic magmas caused local remelting of crystallizing host resulted in more leucocratic melts which in turn injected into the mafic magmas as back veining.

Spatial Link between Mafic Magma Injection, Reworking and Cratonization of Archaean Crust

Recent geochronologic and geochemical data including Nd-Sr isotopic data suggest that large part of EDC accreted during 2.7-2.5 Ga (Friend and Nutman, 1991; Krogstad et al. 1991, 1995; Peucat et al. 1993; Nutman et al. 1996; Balakrishanan et al., 1999; Jayananda et al. 1995, 2000; Chardon et al. 2002). Further U-Pb zircon ages and Nd-Sr isotope data show widespread juvenile calc-alkaline magmatism during 2.56-2.52 Ga in the form of several north-south trending calc-alkaline to potassic plutons (Peucat et al. 1993; Krogstad et al. 1991; Balakrishnan et al. 1999; Jayananda et al. 1995, 2000; Chardon et al. 2002) whilst crustal reworking and formation of anatectic granites during 2528 - 2513 Ma (Friend and Nutman, 1991). On the other hand granulite facies event have been dated by U-Pb monazite at 2517-2509 Ma (Peucat et al. 1993; Mahabaleswar et al. 1995). The above geochronologic data suggest that Late Archaean events in the Eastern Dharwar craton characterized by wide spread juvenile magmatism, crustal reworking, hot metamorphism and cratonization of Archaean crust.

Geochemical and isotope data of the host plutons indicate a major juvenile input with a minor anatectic component derived from reworking of old crust (Jayananda et al. 2000). Based on field data and isotopic evidence Jayananda et al. (1995, 2000) have argued that intrusion of large quantities of mantle derived hot magmas caused the remelting of >3.0 Ga as well as 2.7 Ga TTG gneisses in the deeper levels and formed the anatectic granites. In the present study field evidence show synchronous nature of synplutonic mafic dykes and anatectic magmas as both together define magmatic flow structures. The present work also shows that late mafic magmas (synplutonic mafic magmas) are significant and widespread during different stages of crystallization at all crustal levels. These mafic magma injections forms MME, as dismembered synplutonic dykes in the intrusive facies indicating their injection during relatively early stage crystallization of host magma. In these late mafic injections could be potential source of additional heat and fluids for crustal reworking (anatexis) as revealed by back-veining and also numerous leucocratic veins around them.

In precise the synplutonic mafic dykes are synchronous with emplacement of crustal anatectic granite whilst slightly later with respect to emplacement of juvenile magmas. On the other hand synplutonic mafic dykes slightly pre-date the granulite facies event as they have been overprinted by incipient charnockite in Kabbaldurga-Krishnagiri area. They probably provided additional heat and fluids required for the granulite facies event. Consequently the synplutonic mafic dykes forms terminal event in the Late Archaean magmatism and spatially associated with crustal reworking, metamorphism and cratonization of Archaean crust. More detailed geochemical and Sr-Nd isotopic work is in progress to address their petrogenesis, mantle evolution and geodynamic processes.

CONCLUSIONS

The conclusions of the present study are summarized as follows:

1. This study for the first time document widespread mafic injections into the crystallizing 2.56-2.52 Ga calc-alkaline to potassic plutons in all exposed crustal levels in the EDC.
2. They injected during different stages of crystallization of host magmas; the early injections resulted in MME, local hybridization whilst slightly later injections lead to the formation of synplutonic mafic dykes.
3. Locally the mafic magma injections are caused reversal of crystallization of host and supplied additional heat required for crustal reworking processes.
4. These mafic injections forms terminal event in the 2.56-2.52 Ga magmatism and spatially linked to crustal reworking and cratonization of Archaean crust.

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