CHAPTER-V

TECTONICS AND CRUSTAL EVOLUTION
In this chapter, an attempt is made to review and discuss the evolutionary models on the origin of Mafic Dyke swarms (MDS) suggested by various workers. The author has also suggested the possible evolutionary model for the emplacement of MDS in the study area. Crustal ponding of magmas and episodic magmatic activity were also continued after cratonisation and played a major role in different stages of crust formation processes and evolution of Eastern Dharwar Craton initially in abortive rift tectonic environment and later influenced by hot-spot activity. There is no genetic link basement MDS and Cuddapah basin flows and sills. The REE data of Mallikharjuna Rao et al., (2007) and Anand et al., (2003) on Cuddapah flows and sills are not in agreement with each other. But they signify negligible role of plagioclase fraction (no or mild -ve Eu anomaly) or plagioclase accumulation (strong +ve anomaly). The REE, trace elements and major oxides data of these rocks are quite contrasting when compared to basement MDS.

Two tectonic models are frequently indicated for the origin of MDS viz either by plume model (hot-spot) or plate-tectonic model (subsurface intracrustal/crust-mantle subduction or underplating at crust-mantle interface inducing crustal delamination and thinning followed by rifting and volcanism). Relationship between rifting and formation of MDS is universally suggested (Halls and Fahrig; Parker et al, 1990). Fahrig (1987) has summarised such data and advanced a model for development of continental MDS amply supported by Canadian examples. Plate tectonic models for origin of MDS in Canadian shield are supported by geometric and age relationships between the great MDS, rifting and volcanism.

The MDS are supposed to form due to decompression melting of thermally anomalous hot-spot peridotite rising below rapidly stretched and thinned (rifed) continental crust (Meckenzie and Bickle, 1988). Fitton and Dunlop (1985) state that MORB does originate within convecting upper mantle and so by implication must have common source with OIB and continental rift basalts. The occurrence of oceanic type tholeiites in continental setting has been discussed by Gill (1981).
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The MDS from united data available is shown to be of Palaeo to mesoproterozoic in age. The intrusion of tholeiitic MDS during mesoproterozoic has been impressive in earth’s history (Windley, 1984), and is assumed to represent a new type of tectono-magmatic evolution which is quite different from the Archaean. Such swarms supposedly indicate a major change in the crustal conditions and formation of extensive rigid or semi-rigid plates. Escher et al., (1975) has even correlated the MDS across continental plates to account for plate movements.

Anderson’s (1951) postulations for conditions necessary for the emplacement of MDS is. Ideally a wedge of magma is visualized below the crust which induces tension and if the magmatic pressure was to exceed the lithostatic pressure, the fracture is propagated upwards, providing channel ways for magma emplacement. This will be along planes perpendicular to minimum horizontal stress, compressive or tensile. Carey (1958) (quoted in Frankel, 1967) suggests that the type of emplacement as flow or dyke is controlled by presence or absence of cover sediments over folded terrains. Presence of such sediments favors, depending on thickness of cover, sill or dyke intrusions. Distinct periods of dyke intrusion may characterize a craton during its evolution (Fahrig, 1963; Clifford, 1968).

Among the Proterozoic MDS, two main conditions of emplacement are recognized (Windley, 1984). One type intruded at depth while the crust was still hot and the other at shallower in colder conditions. The earlier type includes (e.g. Scotland) synkinematic dykes intruding country rocks undergoing ductile deformation as well as some of which were emplaced in later stages of granulite metamorphism. Another type of MDS is typically intruded in more brittle conditions and at shallower levels. The Tirupati cluster dykes can be included in this type. The dextral and sinistral shifts in en echelon pre-dyke fractures discussed in an earlier section indicate that apart from tension, shearing deformation too was probably a mechanism for the emplacement of MDS.

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Harris and Bailey (1974) have reviewed certain aspects of the mechanisms of magmatism which can also be applied for generation of MDS. They indicate mantle upwelling as a convection plume or wedge on to shallower pressure (e.g. Oxburgh and Turcotte, 1968) which on differentiation forms tholeiitic magma, especially at oceanic ridges. Similar mechanism in a continental plate should result in alkaline magmatism as up-welling will be sluggish and the plume cannot reach shallower depths.

It is generally believed that an early to mid Proterozoic MDS intruded in association with stress systems that formed during early abortive attempts to break up the continental plates (Windley, 1984). Such argument have been advanced, though for Mesozoic MDS in India by Raza and Akhunji (1981) and for Cretaceous MDS by Sinha Roy (1983) and S. Roy and Radhakrishna (1983); and by implication for Proterozoic MDS in Tamil Nadu and Karnataka (Sugavanam and Vidyadharan, 1988) and in Kerala (Radhakrishna et al., 1986). Fitton and Dunlop (1985) stated that MORB does originate within connecting upper mantle and so by implication must share a common source with the OTT and continental rift basalts. Glikson (1982) has also commented upon occurrence of oceanic type tholeiitic in continental situations. The spread of theta (θ) values in MDS, their overlapping OTT, IAT, MORB and possibly HAB characters, as perceived from plots in various diagrams could reflect above reasoning.

While studying Matachewan dyke swarm (2450 Ma) of Canada H.C. Halls & B. Zhang (1995) proposed a theory that clouding in feldspars is a consequence of Fe-exsolution (submicroscopic inclusions of magnetite in feldspars) during slow cooling from sub-solidus temperatures of about 500°C at deeper crustal levels (>10Km). A positive correlation of the intensity of feldspar clouding is observed with published estimates of dyke crystallisation depth using an amphibole geobarometer. The variation in clouding intensity across a major dyke swarm may therefore be used especially to study broad scale crustal tilting and warping in shields after intrusion of the swarm. The method may be useful in the study of post-cratonisation deformation in Archaean shields because the clouding phenomenon is especially common in early
Proterozoic dyke swarms particularly where they cut high grade (granulite) terrains (Pitchamuthu, 1959). Archaean cratons have been deformed by Proterozoic collisional orogens occurring around craton margins. Less often Mesoproterozoic dykes show the same clouding phenomenon where they have been up-thrust along major fault zones. Clouding of feldspars is a magmatic feature rather than metamorphic feature. Clouded feldspars have high Fe content than clear feldspars. The clouded feldspar bearing dykes intrude into moderate to deep crustal levels. Clouded feldspars are generally calcium rich. The NE-SW trending Karimnagar MDS, lying across the trend of Godavari rift valley, cuts granulites at NE end where granulites bound Godavari Graben and transect Archaean granite-greenstone terrane at SW end. The dykes intruding granulate show clouding of feldspars. All along length of the swarm the intensity and variation of clouding has been observed. This phenomenon indicates that the Karimnagar MDS was tilted to the SW in response to movement along the margin of the major SW boundary fault of the Godavari Graben.

The transition between Archaic and modern petrogenetic mechanisms took place at Archaean-Proterozoic transition (APT) about 2500 Ma ago. The typical Archaean tonalite- trondhjemite- granodiorite (TTG) gneiss (juvenile crust) was continued to form up to 2700 Ma whereas high-Mg plutonism took place in all Archaean cratons between 2600 and 2500 Ma. These plutons generally referred to a late granodioritic or granitic plutons were recently termed as 'sanukitoids' by Stern and Hanson (1991). When they carried out work on late Archaean granites of the superior province of Canada special characteristics of these rocks (calc-alkaline differentiation trends, strong enrichment in LREE and LILE, TTG like REE patterns and generally high Mg#, Ni, Cr) were described by them and proposed the term 'sanukitoids'. They interpreted formation of sanukitoids by partial melting of an enriched mantle in a subduction zone context. In eastern Finland, Querre (1985) described late Archaean phenocrystic granodiorites and interpreted them as the reworking of the older basement with the interference of komatiitic flows. They are similar to Canadian and Indian sanukitoids. Several geodynamic models have been proposed to explain late Archaean magmatism, metamorphism and structural patterns.
of the Dharwar Craton. In short two main groups of models are deserved to be mentioned.

1). Active margin models have been proposed by Chadwick et al., (1997), Krogstad et al., (1989, 1995), and Hansen et al., (1995) to explain structural and petrological features of the eastern Dharwar craton in terms of subduction, magmatic arcs and back arc basins.

2). A plume model has been proposed by Peucat et al., (1993), Choukroune et al., (1995) and Jayananda et al., (1995) and interpreted diapiric structures, late Archaean Juvenile magmatism and hot metamorphism in Dharwar craton in terms of rising mega-plume beneath a mature Archaean lithosphere. Jayananda attributed highly enriched mantle and ancient TTG crust is the source for the 400 Km long linear Closepet Granite batholith; enriched mantle and TTG crust for the Bangalore granites, c.a. chondritic mantle source for the granitoids of Hoskote-Kolar and the quartz-monzonites for the granitoids of western Kolar schist belt (KSB) and slightly depleted mantle for granodiorites of the eastern margin of the KSB. In terms of plume model he interpreted all these variations. The centre of the plume would be an enriched ‘hot spot’ in the mantle that lies below the present exposure level of the Closepet batholith. Melting of such an enriched mantle hot spot produces high temperature magmas (Closepet Granite) that penetrate overlying ancient crust where they strongly interact and induce partial melting of the surrounding crust. These magmas cool very slowly as the hot-spot maintains high temperatures for a long time thus they appear younger (2518 Ma) on the contrary to the east, the plume induces melting of c.a. chondritic or slightly depleted mantle that produces relatively colder and less enriched magmas which show less or no interactions with the surrounding crust and cool rapidly and appear slightly older (2552-2534 Ma). This plume model can also account for late Archaean geodynamic evolution, including juvenile magmatism, heat source for reworking, inverse diapirism and granulite metamorphism in the Dharwar craton. The heterogeneity as well as other features of the late Archaean domain of southern India can be interpreted in terms of a rising of mega-plume.
Ramachandra et al., (1995) studied Bhanupratappur-Keskal mafic dyke swarm (BK-MDS) of Bastar craton and opined that they are similar to Labrador swarm and characterized by high Mg or Fe quartz tholeiites. The dykes show moderate Fe-enrichment and evolved character and their fractionation was controlled by cpx. Gravity data indicated possible presence of sub-crustal magma reservoir along fractures induced by a least compressive stress acting perpendicular to the dyke plane. Thinning of crust and generation of magma from decompression melting of sub-continental lithosphere or a similar mechanism during dyke emplacement is indicated by the LKT and transitional continental –oceanic tholeiite character. They may be responsible for the evolution of Abujihmar volcanic-sedimentary belts and represent failed arm dykes.

Rajesh K. Srivastava et al., (1996) indicated presence of earlier amphibolites and later dolerite dykes in Bastar craton. Amphibolites were derived from an earlier relatively high MG, low Ti and olivine tholeiite magma. The latter dykes are derived from low-Mg and high Ti-quartz tholeiitic magma. There has been a genetic relationship between amphibolites and dolerites. Older dykes are low in incompatible trace elements while the younger dolerites are rich in incompatible trace elements and show negative Sr anomaly (more evolved). Two sets of dykes are not related to normal fractional crystallization processes. They were derived from slightly different parental magma types. There is a clear temporal development in the nature of mafic magmatism.

It may thus be concluded that MDS shows characters typical of Proterozoic MDS in India and in other parts of the earth’s crust. The MDS were probably emplaced more commonly into cold country rocks at shallow levels in brittle conditions, mainly in tensional and to a lesser extent shear controlled deformational environment. MDS less commonly were emplaced synkinematically at greater depths under waning granulite metamorphic conditions. Thus MDS indicate major crustal disturbances (eg. Intraplate rifting, basin formation, etc.) at the time of their emplacement.
Basaltic volcanism is a common manifestation of extensional tectonics and intraplate magmatism. Dykes represent the most important avenues for transfer of basaltic magma from mantle to upper crust, and often are interpreted as feeders to flood basalts as well as relict zone of extensional fractures, particularly in continental areas (Pearce et al. 1975). The numerous dykes and dyke swarms in the south Indian shield indicate periodic crustal dilation during early-proterozoic to late-proterozoic period. Based on regional scale LANDSAT imagery studies, Halls (1982) has highlighted the importance of mafic dykes and dyke swarms to geodynamic processes. Drury (1984) presented a LANDSAT photo imagery study of the dyke swarms of the southern part of the Cuddapah Basin and speculated that the origin of the E-W trending dykes was related to crustal upwarp at the southern part of the basin. Some aspects relating to tectonics and magmatism of the Cuddapah basin were discussed earlier by Narayanaswami (1966), Bhattachari and Sing (1984) and Meijernk et al. (1984).

Deep seismic studies (Kaila et al. 1979) indicate a thick crust for the South Indian Lithosphere (of the order of 40-50 km) in areas of the Cuddapah Basin. The Thermo-mechanical structure of the South Indian shield, based on heat flow and rheological studies of the Precambrian shield (Bhattacharji and Singh, 1984), also indicates similar crustal thickness of the Indian lithosphere during Proterozoic times.

The dyke swarms in study area form mainly an E-W trending (oldest) swarm with subordinate NW-SE, NE-SW and N-S (youngest) trends criss-crossing granite-greenstone terrain. Dominantly the dykes are dolerites and gabbros. A few pyroxenite and lherzolite dykes are found. The dykes extend up to 50 km with ranging up to 30 m width. Emplacement of the dykes has been controlled by deep-seated fractures as they are parallel to joint trends. Most of the dykes are tholeiitic in composition and fall in oceanic tholeiite field. The Sugimura Index (>38) indicates emplacement of dykes at deeper levels in thinner crust (<30 km) with minimum crustal contamination (K2O=0.34 to 3.74; Av-0.94 %).Mg nos.(29 to 64; Av.49) suggest different degrees of evolution of magma from a common source. Dykes show LREE enrichment and HREE depletion and the total REE is highest in dolerites. A
positive relationship between total REE and LREE enrichment is observed. The strongly fractionated nature of magma generated by low degree of partial melting of probably LREE enriched sub-crustal garnet rich source (Sarma, 1996). Some negative Eu anomaly indicates plagioclase fractionation prior to intrusion.

According to Murthy et al. (1987), five sequences of dykes identified in mafic dyke swarms located around Cuddapah Basin. Dyke swarms are predominantly of dolerite-gabbro although amphibolite, pyroxenite / peridotite and alkaline dykes are present. It was suggested that these emplacements have occurred during a time span of Ma 2100 to 600 Ma in at least three major epochs viz., 1700 Ma (tholeiitic), between 1000 to 1700 Ma (both tholeiitic and alkaline) and 1000 Ma. According to them, some of the dyke swarms may have contemporaneous with the igneous activity in the adjoining Cuddapah Basin. The overlapping ages of the mafic rocks within and outside the basin suggest that the igneous activity in the adjoining crystallines has a bearing on the origin and development of Cuddapah Basin.

According to Murthy et al. (1987 and 1995), mafic dykes of southern Peninsular Shield are grouped into five swarms and characterised by five episodes of magmatism. They are:-

**Swarm 1** : (a) 2420-2068 Ma, (b) 1938-1700 Ma, (c) 1470-1250 Ma and (d) 650 Ma.

**Swarm 2 & 3** : 2270-2065 (Swarm 1 is found located in southern part of A.P. while two and three are located in central and north to NNE part of A.P.)

**Swarm 4** : (a) 2193-1900 Ma, (b) 1600-1400 Ma and (c) 1535-1018 Ma.

**Swarm 5** : (a) 2200-1600 Ma and (b) 476-75 Ma (swarm 4 is confined to central Dharwar craton while Swarm 5 is confined to west coast of Kerala).

Mafic dykes are seen in E-W and NNW to NW trending swarms. They are tholeiitic basalts with local alkali-olivine basalt association. The dense swarms on the western margin of mid-Proterozoic Cuddapah basin seem to have been formed in the
distended crust by mantle plume activity around hot-spots. The basic flows and sills in
the Cuddapah basin are tholeiites comparable to Deccan basalts and newer dolerites.
The dykes which formed feeders to the metabasalts and basic traps in the greenstone
belts culminated as dykes traversing them.

They are also localised along dilatations in the domal up-warps in the
PGC terrain and the fractures in the Western Ghats region forming several clusters. The
ages of 2420 Ma to 70 Ma obtained for these dykes suggest that they are largely the
result of Proterozoic magmatism and at places associated with dykes of Deccan flood
basalt activity. The evolution of the South Indian shield was marked by continued
mantle activity in the form of basic and acid magmatism along rifts and tectonic
lineaments. Sedimentation is tectonically controlled. The alkaline magmatism
including kimberlite activity culminating with Proterozoic event related to the break
up of the Gondwana Land and dispersal of the continents. The dykes of Tirupati
magnetic dyke swarm are high-potash tholeiites and are similar to rift volcanics
(Anjanappa, 1972). It is tentatively concluded that the intrusion of dyke swarms was
an unsuccessful attempt to break the already cratonised Peninsular Indian Shield.

The western and south western margins of crescent shaped intra-cratonic
Cuddapah basin is occupied by Papaghni and Chitravati Groups of sediments. Arcuate
shaped mafic sills and flows extending for tens of kilometres profusely emplaced into
Vempalle dolomite and Tadpatri shale Formations. They are classified into picrite,
dolerite, porphyritic dolerite, gabbro and basalt. Picrite sill located between
Pulivendula and Vemula is a composite sill having intruded by a dolerite at central
part. This is dated at 1800 Ma (Sm-Nd method) by NGRI. Petrographically the sills
are classified into melagabbro-norite, picrodolerite, olivine gabbro/dolerite, norite and
dolerite. A total of seven basalt flows (vesicular-amygdular) overlying the Vempalle
dolomite near Kuppalapalle. Some of the sills in Tadipatri Formation contain pillows
at basal parts. Some of the sills in the middle and upper parts contain minor segregates
and veins of andesite, dacite and rhyolite. Dolerite is tholeiitic in character and show
enrichment in SiO₂ and alkalies indicating late-stage crystallisation- differentiation
series. The Mg numbers (0.77-0.57) indicate that the pre-Cuddapah mafic dykes

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forming the basement are less fractionated when compared to the mafic sills (Mg numbers – 0.5 to 0.32) of Cuddapah Basin.

Nilanjan Chatterjee and Somdev Bhattacharjee (2001) related evolution of Cuddapah basin to the subsurface lopolithic magma cupola like (funnel shaped) intrusion under the southwestern part of the Cuddapah basin. It was a constant thermal source responsible for the dyke and sill emplacement between 1500 and 1200 Ma both inside and outside the basin. Lineament reactivation in NW-SE and NE-SW directions in response to mantle perturbations were intensified between 1400 and 1200 Ma leading to the emplacement of the several cross-cutting dykes. MDS emplacement started around 2400 Ma both inside and outside the basin. Outside the Cuddapah basin, dykes are considered as cumulates and the contemporary dykes may be related to fractional crystallization. A few NW-SE and NE-SW cross-cutting dykes of the period between 1400 and 1200 Ma (petrography evidence) of episodic magmatic intrusive activity were confined along preferred orientations. Petrological reasoning indicates that a magmatic liquid reacted with a set of cross-cutting dykes intruding into one that was already solidified and altering the composition of the magma that produced the other dyke.

The Cuddapah basin tholeiitic may be related by fractional crystallization at 5 Kb and 1019°C – 1154°C which occurred in the lopolithic cupola near the southwestern margin of the basin. Mantle xenolith-bearing picrites, which occur near the periphery of the cupola, were formed by the accumulation of xenoliths in the tholeiites. It is inferred that fractionation in the cupola resulted in crystals settling on its walls. Hence, the xenolith bearing sills occur at the periphery of the lopolithic body. The tholeiites both inside and outside the basin are enriched in incompatible elements compared to MORB. The Ba, Rb and K contents of the Cuddapah and other Proterozoic tholeiites indicate that a widespread metasomatic enrichment of the mantle source might have occurred between ~2.9 and ~2.7 Ga. There may be local heterogeneity in the source of the Cuddapah tholeiites as indicated by different Ba/Rb, Ti/Zr, Ti/Y, Zr/Nb and Y/Nb in samples inside and outside the basin. The evolution of Cuddapah Basin is marked by a cyclic heating and upliftment of the crust and a break
in sedimentation followed by subsidence, gravity faulting and sedimentary deposition (Bhattacharjee, 1987). The Cuddapah region of south Indian shield experienced extensive igneous activity in the form of dyke intrusion between 2400 and 2000 Ma which may be considered a precursor to the Cuddapah basin evolution. A funnel shaped intrusion in the upper crust possibly occurred at the outset of basin evolution. The resultant heating and upliftment of the crust was followed by cooling, subsidence and gravity faulting in the southwestern margin of the proto-basin, which created ideal conditions for the deposition of the lower Cuddapah sediments. The lower Cuddapahs are interlayered with sills, tuffs and flows.

While describing the Narsampalli mafic dykes traversing Ramagiri Schist Belt of Anantapur district, Hanumanthu and Babaiah (1999) indicate the presence of olivine bearing, quartz bearing and MGP bearing continental tholeiites emplaced in to the crust of 30 Km thick.

Rao. V. Panganamamula and John F. Puffer (1996) identified LFTP and HFTP domains of mafic dyke swarms in A.P. The E-W trending dykes near SW margin of Cuddapah basin plot along a continuous tholeitic fractionation trend and are characterized by low concentrations of FeO(t), TiO₂ and P₂O₅ (an LFTP group) averaging 11.5, 0.85 and 0.15 wt% respectively. The dyke clusters trending NW-SE and ENE-WSW and located to the north and northwest of Cuddapah basin margin comprises dominantly LFTP group but also contain a HFTP group having high FeO(t), TiO₂ and P₂O₅ (averaging 15, 2.2 and 0.45 wt%). The HFTP is nearly enriched in HFSE elements and heavy rare earth elements compared to LFTP group suggesting independent magma sources. The HFTP is chemically typical of continental flood basalt (CFB) magmatism such as the Deccan Basalts and in interpreted as magma derived from a plume source that had assimilated source lithosphere rock. The LFTP dyke population is chemically unlike any plume or island related magmatism and differs from most continental rift related within-plate tholeiites. It is however similar to the Mesozoic rift related olivine normative dolerite dyke population of Eastern North American Province and its low (LTQ) counterpart.
Anand et al (2003) pointed out plate-tectonic model for the evolution of mafic sills of Cuddapah Basin. They have indicated initial phase of extension and volcanism in the Cuddapah basin at 1900 Ma based on Ar$^{40}$-Ar$^{39}$ dating of Tadipatri layered mafic-ultramafic sill (picrite-olivine gabbro-quartz dolerite) complex which have undergone varying degrees of accumulation or crystal fractionation from the melts generated at ~9 kbar i.e. base of the continental crust. Forward modelling of major and trace elements and inverse modelling of REE suggest that the primary Cuddapah melts were generated by ~10-15% partial melting of a lherzolitic mantle source. This corresponds to a mantle potential temperature of ~1500 °C. The thickness of mechanical boundary layer predicted by the the geochemical modelling is 70 km with a maximum initial lithospheric thickness of 120 km. This corresponds to a stretching factor of 1.6-1.8. Richter's (1988) secular cooling model for the Earth predicts that at 1900 Ma, the ambient mantle had a potential temperature of ~1500 °C. 

If the cooling model is correct then Proterozoic lithospheric stretching and mantle melting beneath the intracratonic basin could have been by passive rather than active rifting. The intra-cratonic basins of Peninsular India believed to have developed in a rift setting but none of these resulted in continental break-up, although links to an open seaway are evident from the recent occurrence of deposits representing tidal and storm influence (Chaudhuri et al., 2002).

Mallikarjuna Rao et al. (2007) carried out K-Ar ages and geochemical characters of lava flows and sills of Cuddapah basin and concluded that the evolution of Cuddapah basin was due to mantle upwelling (causing funnel shaped intrusion/magma cupola/ lopolith beneath the SW margin of Cuddapah basin), lineament reactivation and crustal uplift. Igneous activity commenced around 1800 Ma and continued for along period i.e. up to 1550 Ma. Mantle normalized incompatible trace elements show +ve peaks of Ba, K, Sm and Nd and -ve peaks of Sr, P, Ta, Nb and Th. Sr trough is due low pressure plagioclase fractionation of source magma. Negative Nb anomaly is due to crustal contamination while strong -ve Sr anomaly is due to derivation from Sr depleted source or as a consequence of plagioclase fractionation or mixture of both. LREE enrichment and flat HREE trends are characteristic. Positive Eu anomaly suggests plagioclase accumulation during their
crystallisation from the parent magma. They suggested evolution of flows and sills from MgO rich primary magma (picrites). Plagioclase and clinopyroxene, ± phenocrysts and Sr anomaly in spider diagram suggest that MgO rich magma underwent relatively low pressure crystal fractionation.

The study area MDS show comparable major trace element variation as other Precambrian MDS from India and other parts of the world. The definite but imperfect fractionation trends in several variation diagrams reflect mineralogical complexity noticed in field and petrographic studies. Some of the dykes show presence of sub-calcic augite and probable pigeonite and alkalic nature could be due to selective elemental migration associated with deuteritic alteration. The evolved nature of dykes indicate fractionation prior to emplacement, and episodic in nature. Ambiguous tectonic environments are indicated from chemical features of MDS, i.e. both continental and oceanic tholeiitic basaltic affinities. It is possible that MDS are of truly transitional nature in this regard.

Most of the dykes are quartz normative tholeiites with minor olivine normative tholeiites. Interference of magmas similar to sanukitoid magmas suggest the formation of large scale crustal disturbances after stabilization of the crust and triggering the LILE and LREE enriched primary mantle. REE patterns do indicate the dominance of older and younger groups of dykes showing moderate Eu (-ve) anomaly suggesting plagioclase fractionation. A positive correlation exists between LREE and total REE, which indicates a fractional crystallisation differentiation trend from LILE, and LREE enriched primary mantle source. Presence of youngest alkaline dykes indicates the extensional signatures and their derivation from altogether a different magma source.

Around Cuddapah basin the clouding phenomenon of feldspars in dyke swarms has been established from the present work. Dominantly the preponderance of the clouded feldspar bearing older dykes occur much away from the Cuddapah Basin while clear feldspar bearing younger dykes are abundant around the basin margin. The presence of TTG gneiss and occurrence of enclavial to small pluton like
enderbite-mangerite suite of rocks (charnockitic affinity) points to existence of lower crustal assemblages amidst younger granitoid suite- Chandragiri granite (2500 Ma).

The present work clearly indicates the source regions i.e. subcrustal lithosphere and mantle. Two sets of data and range in composition suggest that the partial melting of mantle and cumulates as well fractionates are present. Youngest alkali tholeiites represent a high-temperature fraction i.e., deep mantle source and variable degree of partial melting resulting into presence of both quartz and olivine normative tholeiites. Sub-crustal lithospheric source interfered with the mantle derived melts in an episodic manner is characteristic. Presence of quartz normative and olivine normative tholeiites suggest two different source regions as described above. In general, older dykes are dominantly quartz-normative tholeiites and younger dykes are dominantly olivine normative tholeiites. Interference of both is also observed. The presence of metasomatised enriched mantle source region has been indicated which probably was also responsible for the formation of late Archaean calcalkaline subduction related high- Mg granitoid suite.

Though mention of alkaline magmatism is not relevant in the present context along with the tholeiites of MDS the episodic protracted mantle derived magmatic activity is stressed upon in the present context for the evolution of Eastern Dharwar Craton. The triggering of mantle upwelling below the Cuddapah Basin (CB) could be due to the juxtaposition of transcratonic palaeo- Preterozoic Nellore Schist Belt at the eastern Dharwar craton margin. The thrusting of Eastern Ghat Mobile Belt (EGMB) on to the Dharwar craton (DC) triggered re-activation of mantle upwelling thus the successive episodic emplacements and zonal arrangement of alkaline rocks at the junction of DC and EGMB; lamproites in the craton margins (~1400 Ma) and in the centre of Cuddapah basin (Nallamalai fold belt); and kimberliite (~1100 Ma) in the interior of Dharwar Craton at different time intervals.

From the various lines of discussion the preferred model for the formation of MDS in the SW margin of the Cuddaph basin is due to ponding of mafic magmas in lopolithic sub-crustal magma chamber (Kaila et al 1979; Mishra et al 1987; Teware
et al 1987 and Murthy et al 1987) due to rising plume had caused episodic emplacement of MDC made-up of fractionates and cumulates which rapidly emplaced into the overlying crust. These main emplacement events of MDS viz at 2400 to 2200 Ma, 2200-2000 Ma and 2000-1800 Ma (compiled from the available geochronological data) took place indifferent crustal conditions. In addition to the above three pre-Cuddapah episodic activity of tholeiitic mafic magmatism (MDS) and alkaline magmatism, the last episode of minor mafic magmatism and alkaline magmatism (lamproites and picbeckite syenites) (Madhavan et al 1994) occurred during post-Nallamalai period ~ around 1400 Ma. This observation is also substantiated by the recent work of Mall et al (2008) who have clearly identified a strong gravity high anomaly (55 M Gal) a 100 km wide high conductivity anomaly extending up to 50 km in the mantle lithosphere and large scale intrusive activity and these features below the southwest4rn part of the Cuddapah basin is associated with a deep-seated late-Proterozoic mantle thermal anomaly possibly resulting from a plume. The Proterozoic thermal events could have only induced crustal attenuation and dyke intrusions in contrast to the extensive Continental Flood Basalt (CFB) volcanism and continental rifting in the Phanerozoic period.

In contrast to Phanerozoic plumes which have risen from deeper levels at core/mantle boundary and developed heads of large diameter (>1000 km) the Proterozoic plumes may have originated at shallower depths and developed heads of smaller diameter (~300 km). Consequently, the plumes could not produce sufficient thermal energy for the erosion of the lithosphere attention, associated crustal fractures and smaller volumes of mantle melts and the melts have occupied the crustal fractures manifesting as dyke swarms. Such a possible scenario has the potential to explain Proterozoic dyke swarms and may require further evaluation to understand proterozoic dynamic history of the Indian and other Precambrian shield areas.

The present study provides the complimentary geochemical evidence for the gravity and magnetic interpretations of a sub surface Mg-rich, Fe-poor magma under plating beneath the Papaghni sub-basin in the southern western Cuddapah Basin. On the basis of the it is concluded that there was an episodic mafic dyke
activity interspersed or alternated by alkaline magmatism and dykes were originated from different source regions for the dykes of basement and sills and flows of Cuddapah Basin. The pre-Cuddapah mafic dyke activity was solely responsible for the formation of Proterozoic Cuddaph basin.

Thus it is concluded that the MDS was emplaced (after an imperfect fractionation process) from differentiation of a tholeiitic parental magma, probably in response to abortive continental rifting processes, under brittle condition at shallow levels, during Palaeoproterozoic period. The MDS thus represents a major crustal forming process in the evolution of the Dharwar craton.

From the aforementioned petrological and geochemical interpretations, it may be inferred that initially the partial melting of moderate Mg rich and metasomatized mantle yielded mafic magmas at the onset of crustal thickening and cratonisation in an abortive rift environment. The ponding of magmas in sub-crustal chamber is evident due to the presence of fractionates and cumulates in older Group of MDS. This was later followed by mantle upwelling (hot-spot activity) in the form of subcrustal lopolith, formed by initiation of thrusting of EGMB on to the NSB. The partial melting of high Mg rich parental magma from deeper levels of mantle seems to be responsible for the generation of mafic magmas which were accumulated in the lopolithic subcrustal magma chamber. The episodic release of mafic magmas was responsible for the generation of younger group of Mafic Dyke Swarms of Tirupati cluster initially along E-W and N-S fractures and later on emplaced along NW and NE trending conjugate set of fractures of extensional nature in the vicinity of southern part of Cuddapah Basin.

The present work has substantially enhanced the available knowledge about the petrological petrogenetic and geochemical characters of the different types of mafic dykes surrounding the extreme south western margin of the Cuddapah basin. It has also helped to understand the probable thermotectonic evolution of this part of the Cuddapah basin and as well as the Eastern Dharwar Craton. The major conclusions and summary of the geological, petrological and geochemical investigations are given below.
• Five major types of mafic dykes (including synplutonic variety) were identified in these dyke cluster and they show lithological, petrological, mineralogical and compositional variation.

• The Tirupati cluster dykes are overwhelmingly east-west trending; only a very few dykes are NW-SE trending. The density of E-W trending dykes diminishes progressively northward.

• These dykes are not cutting across the lower Cuddapah formations inspite of the contemporaneous relationship with the basic-ultrabasic magmatism within the basin.

• A rare older set of synplutonic basic dykes and rare younger set of later stage mafic dykes and as well as ultramafic variety (olivine tholeiites/dolerites and high MgO basaltic dykes) were identified in addition to commonly occurring dolerites/gabbroic dykes of the extreme southern margin of Cuddapah basin.

• The mafic dykes are predominantly dolerites and they vary from basaltic types at chilled margins to gabbroic types at the central parts of the dykes. They range from fresh unaltered variety to partly altered types and show ophiitic to subophitic, acicular, radial, porphyritic and equigranular textures. The essential mineral are plagioclase, clinopyroxene, opaque and rarely contain orthopyroxene and olivine in varying proportions. The secondary altered minerals includes chlorite, calcite, hornblende, mica and sulphide minerals. Most of the dykes have similar over lapping petrological characteristics and suggests variable emplacement and crystallizing histories. The available age data and paragenetical histories are useful for grouping of these dykes and geodynamic structure of the crustal basement and its episodic nature.
• Geochemically, these dykes are sub-alkalic, tholeiitic basalt in composition and are mostly quartz normative in nature, however a few dykes exhibit olivine normative mineralogy.

• Overall the Tirupati mafic dykes show strong compositional similarity and also exhibit consistent and complementary REE and HFSE distribution patterns and a common mantle source and tectonic-magmatic model is applicable for the mafic dyke swarms.

• The compositional characteristics of the different dyke swarms of Tirupati region indicate the role played by depleted/enriched mantle source and the superimposition of different geological processes such as crustal contamination and post-magmatic metasomatic alterations in the derivation of these dyke suites.

• The data presented above indicate that the subalkaline tholeiitic basalt magmatism surrounding the lower stratigraphic horizons of Cuddapah basin is a characteristic feature of the Paleoproterozoic period.

• A mantle perturbation (mantle plume) currently manifested by a lopolithic cupola-like intrusion and as well as large radiating dyke swarms around the Cuddapah basin and particularly the SW margin of the Cuddapah basin may have occurred at the onset of basin evolution and played an important role in its development.

However, in order to substantiate the above models, detailed petrochemical and isotopic work should be taken up on a) mafic flows and sills of (inside Cuddaph) basin b) NW-SE and NE-SW trending mafic dyke swarms of outside Cuddapah basin in order to establish correlations between the within basin magmatism and the dyke magmatism around the basin. It is also clearly seen that individual dykes which are better dated around the basin are quite limited and not sufficient to ascertain the ages for the dykes based on their field orientation. It is
evident that this Proterozoic terrain being highly reactivated, Pb-Pb and U-Pb dating is extremely necessary to precise dating of magmatic events. Paleomagnetic and ground geophysical and geochronological studies are warranted in this part of the Eastern Dharwar Craton for a better understanding the Proterozoic thermal history of the Southern Indian shield.