Petrology, geochemistry and tectonic settings of the mafic dikes and sills associated with the evolution of the Proterozoic Cuddapah Basin of south India

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In this article we summarize the petrological, geochemical and tectonic processes involved in the evolution of the Proterozoic intracratonic Cuddapah basin. We use new and available ages of Cuddapah igneous rocks, together with field, stratigraphic, geophysical and other criteria, to arrive at a plausible model for the timing of these processes during basin evolution. We present petrological and geochronological evidence of dike emplacement along preferred lineament directions around the basin in response to stresses, which may have been responsible for the evolution of the basin itself. Basaltic dike intrusion started on the south Indian shield around 2400 Ma and continued throughout the Cuddapah basin evolution and sedimentation. A deep mantle perturbation, currently manifested by a lopolithic cupola-like intrusion under the southwestern part of the basin, may have occurred at the onset of basin evolution and played an important role in its development. Paleomagnetic, gravity and geochronological evidence indicates that it was a constant thermal source responsible for dike and sill emplacement between 1500 and 1200 Ma both inside and outside the basin. Lineament reactivation in the NW–SE and NE–SW directions, in response to the mantle perturbation, intensified between 1400 and 1200 Ma, leading to the emplacement of several cross cutting dikes.

Fe-Mg partition coefficients of olivine and augite and Ca-Na partition coefficient of plagioclase, calculated from the composition of these minerals and bulk composition of their host rocks, indicate that the dikes outside the Cuddapah basin are cumulates. The contemporary dikes may be related by fractional crystallization as indicated by a positive correlation between their plagioclase Ca# (atomic Ca/[Ca+Na]) and augite Mg# (atomic Mg/[Mg+Fe]). A few NW–SE and NE–SW cross cutting dikes of the period between 1400 and 1200 Ma, preserve petrographic evidence of episodic magmatic intrusive activity along preferred directions. Petrological reasoning indicates that a magmatic liquid reacted with a set of cross cutting dikes, intruding into one that was already solidified and altering the composition of the magma that produced the other dike.

The Cuddapah basin tholeiites may be related by fractional crystallization at 5 kb and 1019–1154° C, which occurred in the lopolithic cupola near the southwestern margin of the basin. Xenolith bearing picrites, which occur near the periphery of the cupola, originated by the accumulation of xenoliths in the tholeiites. This is indicated by the composition of the olivine in the xenoliths ($Fo_{78.7-81.9}$), which are closely similar to calculated olivine compositions ($Fo_{77.8-78.3}$) in equilibrium with the tholeiites under the same *P-T* conditions. 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.

Keywords. Cuddapah; proterozoic; basalt; geochemistry; mafic dike; mafic sill; petrology.

The tholeiites both inside and outside the basin are enriched in incompatible elements compared to mid oceanic ridge basalts. The Ba, Rb and K contents of the Cuddapah and other Proterozoic Gondwana tholeiites indicate that a widespread metasomatic enrichment of the mantle source may 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. Large-scale differences such as the low P_2O_5-TiO_2 and high P_2O_5-TiO_2 basaltic domains of the Jurassic Gondwana basalts, however, did not exist during the Proterozoic time period under consideration.

Although we are beginning to understand the tectono-magmatic processes involved in the evolution of the Cuddapah basin, much work remains to be done to obtain a complete picture. Future research in the Cuddapah basin should focus on obtaining accurate ages of the igneous rocks associated with the evolution of the basin.

1. Introduction

Igneous rocks associated with intracratonic Proterozoic basins play a vital role in establishing their evolutionary history. Dikes and dike swarms provide evidence of the state of stress of the lithosphere, nature of crustal extension and rifting during basin evolution. Ages of dikes, sills and flows help in stratigraphic correlation as well as in providing timing constraints on processes involved in basin evolution. The igneous rocks in and around the Cuddapah basin of south India present a unique opportunity to study their significance with respect to the evolution of the basin.

The Cuddapah basin is superposed on Archean gneisses and granites of the Dharwar Craton, and is the largest Proterozoic basin on the Indian peninsula covering an area of about 34,000 km^2 (figure 1). It is situated between 13° 15' N and 17° 00' N latitudes and 77° 45' E and 80° 15' E longitudes, convex westward and extends north to south over a crescent length of 440 km with a maximum width of 150 km east to west. The sediments in the basin consist of easterly low dipping (10°–15°) alternating sequences of arenaceous, argillaceous and carbonate assemblages. The total estimated thickness of the sedimentary formations is of the order of 6.5 km (Murty 1979). In many cases, the sediments are interlayered with sills, tuffs and lava flows at different stratigraphic horizons. They are marked by unconformities and post-depositional folding and faulting. The maximum depth near the center of the basin, obtained from deep seismic sounding (DSS) profiles is 8–8.5 km (Kaila and Tewari 1983).

One of the most striking features in the Archean crust surrounding the Cuddapah basin is the occurrence of a large number of dikes and dike swarms (figure 1). Some of these dikes and dike swarms are arranged radially around the western and southern margins of the basin, whereas, others are aligned along the major NE–SW and NW–SE lineaments of south India (Bhattacharji 1987; Murty *et al* 1987). Petrological and geochronological studies of several cross cutting dikes show that these dikes may be related to lineament reactivation during the evolution of the Cuddapah basin.

The Cuddapah basin area is interesting from a global tectonic perspective since, tholeiitic and high-Mg dikes similar in age and composition to the Cuddapah tholeiites are also found in a section of east Antarctica, which was adjacent to the Cuddapah area during Proterozoic. It has long been recognized that the Enderby Land coast of east Antarctica fits well with the eastern coast of India (Smith and Hallam 1970). Reconstruction of Gondwanaland and Laurentia has reaffirmed that the Indian and East Antarctic shields were juxtaposed (figure 2) during middle to late Proterozoic (Johnson and Veevers 1984; Piper 1987; Dalziel 1991; Hoffman 1991).

1.1 *Thermal events and stratigraphy*

Phases of igneous activity, tectonic events and changes in the depositional environment associated with the Cuddapah stratigraphy have been well documented by Bhattacharji (1987). The Precambrian shield of India consists of a high grade metamorphic belt of charnokite-khondalite and migmatites, the Dharwar system of schists, greenstone and granites, and the Purana group consisting of the Proterozoic Cuddapah, Kurnool, Srisailam and Palnad sedimentary systems, together with the enclosing Peninsular Gneissic basement complex. The evolution of the Cuddapah basin is marked by cyclic heating and upliftment of the crust and a break in sedimentation followed by subsidence, gravity faulting and sedimentary deposition (Bhattacharji 1987).

The Cuddapah region of the south Indian shield experienced extensive igneous activity in the form of dike intrusion between 2400 and 2000 Ma, which may be considered a precursor to the Cuddapah basin evolution. A funnel-shaped intrusion in

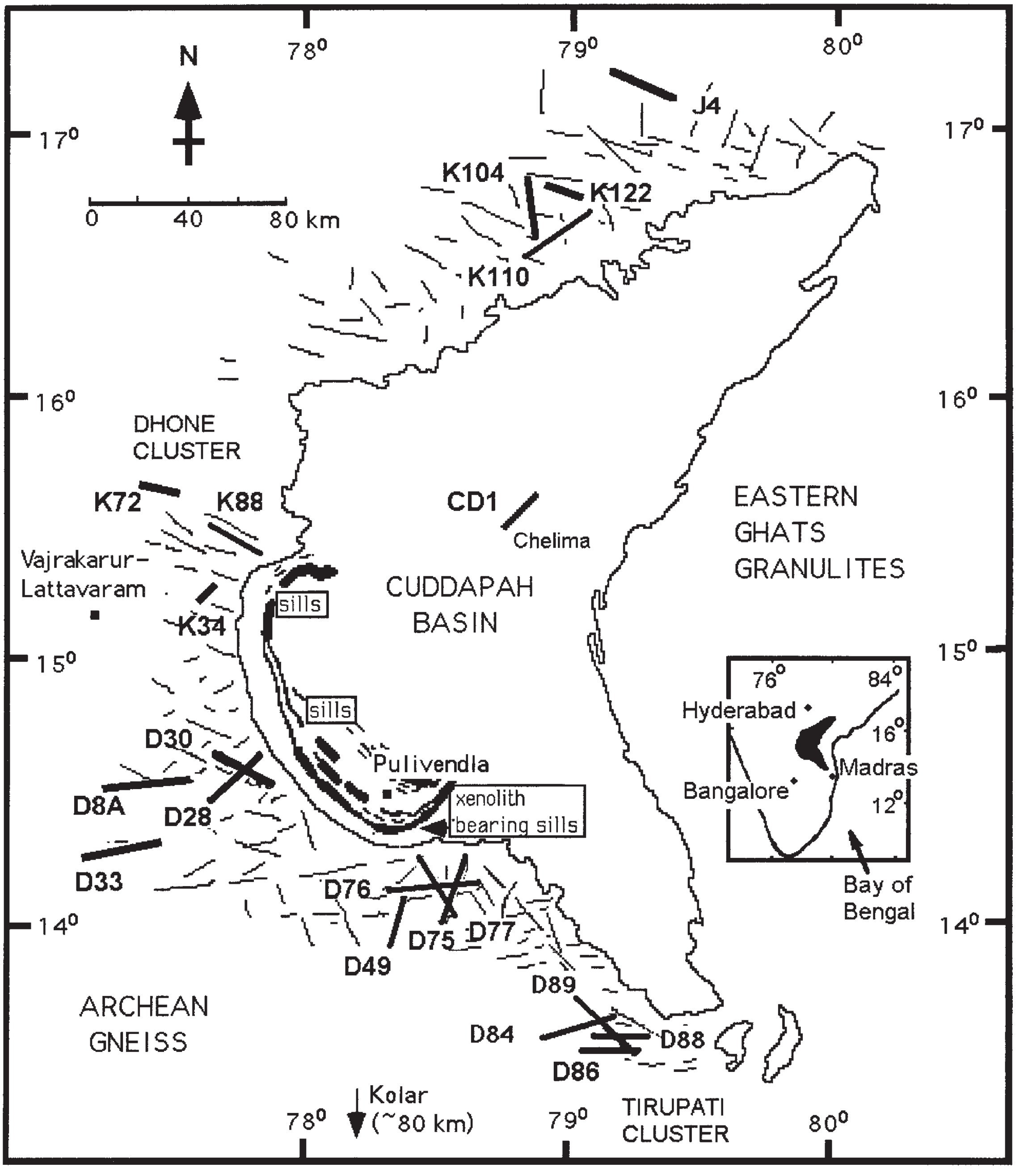

Figure 1. Map of Cuddapah basin showing location and orientation of mafic dikes around the basin. Important dikes studied in detail are shown in bold lines. Orientation of the dikes and dike swarms outside the basin (shown in thin lines) are from Murty *et al.* (1987). The inset shows the location of Cuddapah basin in the Indian subcontinent. Note the structural trends defined by the dikes.

the upper crust possibly occurred at the onset of basin evolution. This intrusion is manifested by a gravity-high in the southwestern region of the present day basin (Bhattacharji 1987). 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 Cuddapah sequence, known as the Papaghni Group, consists of the Gulcheru quartzites and conglomerates and the Vempalle dolomites and shales. The Vempalle dolomites and shales are interlayered with sills, tuffs and lava flows. The igneous activity produced crustal heating and upliftment, which led to a break in the depositional cycle. The overlying sequence, separated by a disconformity and known as the Chitravati (Cheyair) Group, consists of the Pulivendla quartzites, Tadpatri shales and dolomites and the Gondikota quartzites. The Tadpatri shales and dolomites contain many basaltic and picritic sills and lava flows. This extensive igneous activity again heated and uplifted the crust leading to another break in deposition. Subsidence,

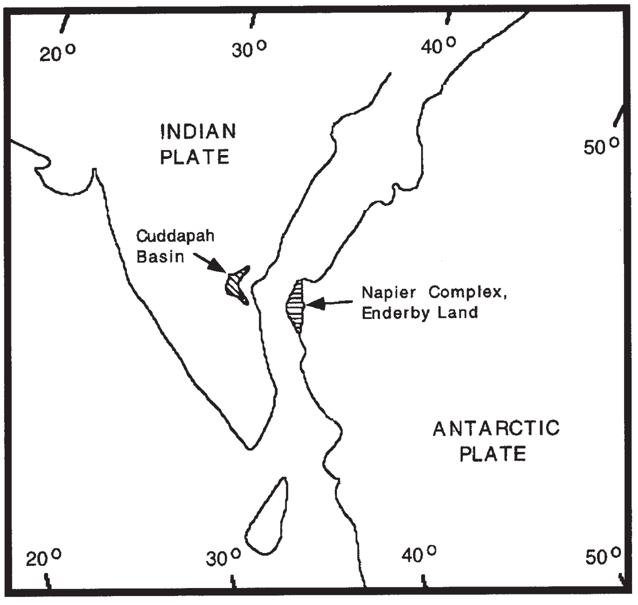

Figure 2. Schematic representation of a part of Gondwanaland showing locations of Napier Complex, Enderby Land (east Antarctica) and Cuddapah basin (south India) during late Proterozoic. This reconstruction, representing Gondwanaland more than 160 Ma ago, is from Johnson and Veevers (1984) and is based on the fit of the 4 km isobath of the Indian and Antarctic coasts. The paleolatitudes are from paleomagnetic determinations of Embleton (1984).

flexuring and gravity faulting resulted in an eastward tilting and shifting of the center of sedimentary deposition toward east.

The overlying Nallamallai Group is separated from the Chitravati (Cheyair) Group by an angular unconformity. This group contains the Bairenkonda (Nagri) quartzites and the Cumbum shales and phyllites. Deposition of the Nallamallai Group was accompanied by extensive alkaline and acidic volcanic activity. In addition to the emplacement of alkaline syenite and granites within the basin, the Chelima lamproite dike near the center of the basin, the Kotakonda kimberlite outside the northwestern margin of the basin, and later, the kimberlite dikes west of the basin in the granite-granulite terrain near Vajrakarur-Lattavaram intruded. This resulted in localized crustal heating, domal upwarps and break in deposition followed by subsidence. The depositional areas shifted as gravity induced block faulting occurred, producing the isolated sub-basins of Srisailam in the north and Palnad in the northeast.

An unconformity marks the upper boundary of the Nallamalai Group, above which sediments were deposited in the Srisailam sub-basin in the north, and Palnad sub-basin in the northeast of the main Cuddapah basin. The post-Kurnool period was marked by deformation at the eastern margin and late-stage igneous activity outside the western margin in the form of granophyre dike intrusion.

1.2 *Geophysical characteristics*

The Cuddapah basin and its surroundings have been extensively studied through gravity, magnetic, deep-seismic sounding, electrical resistivity, heat flow and telluric methods. These studies reveal the depth of the basin, crustal structure, areas of mantle upwelling, igneous intrusions, deep faults and lineaments in this region (Balakrishna 1979; Kaila *et al* 1979; Sankaranarayan *et al* 1979; Rao *et al* 1979; Balakrishna *et al* 1983; Kaila and Tewari 1983). Bouguer gravity anomalies (Balakrishna 1979) and DSS profiles (Kaila *et al* 1979) show the Moho boundary at an average depth of 38–40 km, with thinning of the crust toward the east. Two DSS profiles across the basin (Kaila and Tewari 1983) indicate that the basement depth is highly variable within the basin, with a maximum depth of 8.0 to 8.5 km in the central axial region. DSS profiles also show that the basement crust is faulted into several blocks underneath the basin. Some of these blocks are upthrown, and some are downthrown, more or less in a step-like fashion towards the east. Many of these deep-seated faults extend to the crust-mantle boundary (Kaila *et al* 1979), some to a depth of 40 km or more near the eastern margin. Interestingly, tectonic configurations and several igneous intrusives (e.g., Chelima lamproite dikes) occur close to the postulated deep faults in the east-central area of the basin, indicating a causal relationship between the basement configuration and the emplacement of deep mantle-derived igneous rocks within the basin.

A broad gravity low (approximately -23 mgals) with a few gravity highs occurs across the basin. The detailed gravity anomaly map of the Cuddapah basin and its surroundings (Balakrishna 1979; Grant 1983) shows an elongated closure of positive anomaly (+60 mgals) covering an area approximately 80×50 km in the southwestern part of the basin. This is also a terrain of extensive mafic and ultramafic sills and flows, and mafic and felsic tuffs within the basin. Extensive radial and some arc-concentric dolerite-gabbro dikes and dike swarms occur in the immediate vicinity outside the basin (figure 1). This positive gravity anomaly is situated almost concentrically within a very broad, almost circular gravity low. The shape of this anomaly indicates that it is caused by an oval-shaped, shallow crustal lopolithic intrusion with a system of thin feeder dikes (Grant 1983).

The estimated densities of this anomalous mass and the central feeder dike are 3.0–3.1 gm.cm^{-3} and 3.2 gm.cm^{-3} respectively. They correspond to olivine-gabbro or picrite in the main funnel and feldspathic peridotite or troctolite for the feeder zone. The origin of this anomalous high density body can be ascribed to the formation of a lopolithic or a funnel-shaped magma cupola in the upper crust due to an asthenospheric upwelling at the southwestern part of the basin (figure 1). The correspondence of this high density mantle mass with the picrite and olivine- gabbro-dolerite sills, and with some of the dike swarms of similar chemistry suggests a common source and a close genetic relationship among them (Murthy *et al* 1985). Paleomagnetic studies (Balakrishna *et al* 1972; Kumar and Bhalla 1983; Hargraves and Bhalla 1983) show three different intensities of magnetization and polarities for several dikes at the western margin, indicating three different episodes of dike activity. This may also indicate reactivation of preexisting planes of weakness and/or poorly healed fractures in the brittle crust during dike intrusive activities and crustal dilation.

1.3 *Tectonic evolution*

The variety of structural settings and tectonomagmatic events associated with intracratonic basins makes it difficult to arrive at a single satisfactory mechanism for sedimentary basin evolution (Haxby *et al* 1976; Bott 1978; McKenzie 1978; Steckler and Watts 1978; Artyushkov *et al* 1980; Sleep *et al* 1980, etc.). Some basins are associated with early igneous activity and normal faulting, while others are not. Some are accompanied by igneous activity prior to basin formation, while others exhibit no apparent igneous activity during the whole history of sedimentary accumulation or subsequent to formation, and still others appear to have been affected only by late-phase magmatism. The role of mantle upwelling and magmatism, lineament reactivation and crustal uplift in the evolution of the Cuddapah basin can be established with some degree of certainty (Bhattacharji and Singh 1984; Bhattacharji 1986, 1987; Murty *et al* 1987; Chatterjee and Bhattacharji 1998).

The Cuddapah basin has an extremely complex evolutionary history. It experienced several cycles of uplift and subsidence, episodic magmatism prior to and during the sedimentary accumulation, and syn- to post-depositional deformation. The sediment types, their structural and lithofacies changes indicate that the deposition of the basin sediments occurred at the margin of geosynclinal shelf, primarily on a platform which experienced marine transgressions and regressions as well as oscillations of the basin floor, and four cycles of basin upliftment and subsidence. Each cycle of upliftment was preceded by igneous activity and followed by erosion, and then slow to rapid subsidence of the basin (Bhattacharji 1981). Bhattacharji and Singh (1984) found that a mechanical (Airy type) subsidence model for the Cuddapah basin with only isostatic subsidence due to sedimentary accumulations alone does not adequately explain the depths of the basin floor. They presented a thermomechanical model, which includes both sedimentation and a thermal-driving load to account for the maximum depth and explain most realistically the geological and geophysical features of the Cuddapah basin.

Apart from simple sedimentary loading, isostatic subsidence of a basin can also occur by thermal cooling and contraction of the crust after igneous intrusive activity and the subsequent increase in density and sinking of the lithosphere (Beloussov 1960; Sheridan 1969). Watts and Ryan (1976) have shown that the 'driving load' for Atlantic-type continental margins is thermal contraction (cooling). Included in this type of 'driving load' for basin subsidence are also increases in the density of the lower crust by metamorphism or phase transformation (Falvey 1974; Haxby *et al* 1976; Artyushkov *et al* 1980). The computed isostatic subsidence of the basin floor by elastic flexuring of the basement crust is of the order of 6.5 to 6.7 km, which accounts for the estimated thickness of the total column of sedimentary formations and emplaced igneous materials still preserved in the basin. However, it is not commensurate with the maximum basin depth of 8 to 8.5 km at the center of the basin estimated from deep seismic sounding profiles by Kaila and Tewari (1983). This additional 1.5 to 2.0 km depression may be the result of isostatic subsidence produced by a thermal 'driving load' (Watts and Ryan 1976). The 'driving load' for the initial subsidence of the Cuddapah basin appears to underlie the platform of the granite gneiss-greenstone belt crust near the southwestern margin, an area of positive gravity anomaly attributed to an asthenospheric upwelling. Thermal cooling and contraction of the emplaced high-density mantle material in the upper crust may have produced the initial basin subsidence. Gravity faulting along lineaments in the basement crust at the basin's margin during thermal cooling of the emplaced mantle mass may have produced some subsidence of the basin floor (Bhattacharji and Singh 1984; Bhattacharji 1987).

1.4 *Lineaments around the Cuddapah basin*

Sundaram *et al* (1964) have argued that the major NW–SE structural trend and lineaments in the Dharwar belt controlled the epiorogenic adjustments and the development of sedimentary basins on the peninsular Indian shield. A careful examination of the relative positions and shapes of the Proterozoic basins on the south Indian shield shows that their development was controlled by reactivation of the NW–SE and NE–SW trending linea-

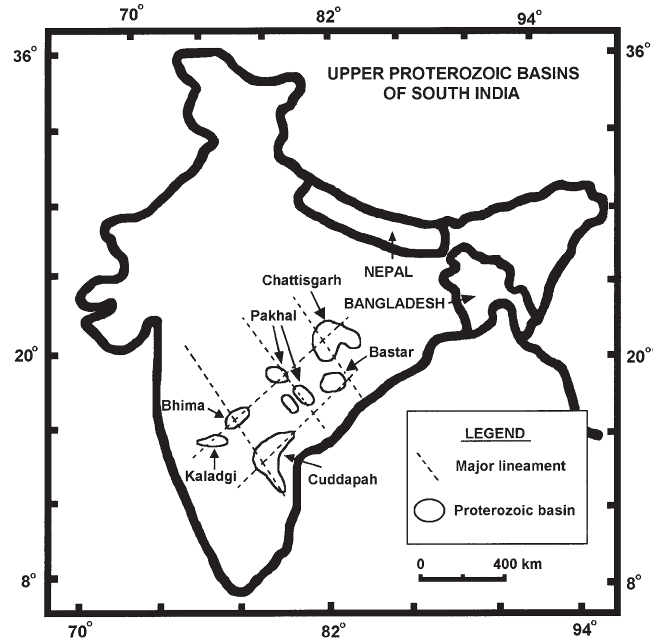

Figure 3. The orientation of two major lineaments (NW–SE and NE–SW) in the Precambrian crust of the south Indian shield and its apparent control of the development of Proterozoic basins (adopted from Bhattacharji 1987). Note the arcuate to crescent shape of the Cuddapah basin, which appears to be controlled by the superposition of narrow rectilinear to oval-shaped shallow sub-basins along the NE–SW lineament direction over the oval-shaped Proto-Cuddapah basin along NW-SE to N–S lineament direction. The crescent shape was accentuated by post-depositional E–W tectonic compression.

ments (figure 3). The prominent rhombic aeromagnetic linears along the same trends at the western margin of the Cuddapah basin reaffirm this conclusion and suggest a possible E–W tectonic compression and reactivation of these lineaments (Bhattacharji 1987; Murty *et al* 1987).

A lineament generally represents a prominent zone of weakness: a deep fracture or fault manifested as widely spaced and sharp linear planes with specific aerial trends. Field, aerial and landsat photographs, and aeromagnetic anomaly maps show that the major lineament trends on the peninsular Indian shield around the Cuddapah basin are NW–SE to WNW–ESE, NE–SW to ENE–WSW (Murty *et al* 1987). Some of these trends correspond to major faults, and others correspond to major dike systems. The major orientation of the extensive linear dikes and dike swarms around the Cuddapah basin are E–W, NW–SE to WNW–ESE, NE–SW to ENE–WSW, and N–S (Murty *et al* 1987 and figure 1). As the dike emplacements represent the dilation of the upper crust by magma intrusion with extensional fracturing or faulting, NW–SE to WNW–ESE and NE–SW to ENE–WSW dikes and dike swarms indicate the possible reactivation of lineaments or deep faults in the basement crust (Bhattacharji 1987).

Field evidence suggests that the ENE–WSW linear trend is a major tectonic break zone within the Archean crust, which traverses the Cuddapah basin and terminates at the thrust belt on its eastern margin. The NW–SE fracture zone also traverses the western margin of the Cuddapah basin and is a part of the basement beneath the basin itself. This is also the major structural trend of the Dharwar belt. A prominent WNW–ESE linear fault crosses the area near the kimberlite pipes at the southwestern part of the basin (between 14° and 15°N). The intersections of the WNW–ESE lineaments with the ENE–WSW lineaments or deep faults appear to be the sites for some igneous intrusive and effusive activities. These intersections are marked by ore-mineralization (e.g., barite) within the southwestern part of the basin and outside the basin at Vajrakarur-Lattavaram, where deep mantle derived kimberlites from a depth of approximately 120 to 180 km are found (Ganguly and Bhattacharya 1987; Bhattacharji 1987).

2. Basaltic igneous rocks

The dikes intruding the Archean crust around the Cuddapah basin are composed of tholeiites and alkali basalts and their differentiates. There are dikes of gabbro, amphibolite (metamorphosed gabbro), kimberlite, granophyre and syenite. But the majority of the dikes are basalt-dolerites. The largest concentration of mafic dikes occur as E–W clusters at the southern end of the basin and are known as the Tirupati dike swarm or cluster (figure 1). They extend westward over long distances across the greenstone-granite gneiss terrain. Many of the oldest dikes of this area precede the formation and evolution of the Cuddapah basin. But there are many younger E–W trending dikes in this region, which were emplaced during the formation and evolution of the basin (Murty *et al* 1987). These E–W trending dikes at the southern end of the basin were correlated with the E–W trending gravity high in this region by Balakrishna *et al* (1984). A few NW–SE trending dikes are also present which cut across some of these dikes (figure 1).

The second largest concentration of mafic dikes occurring as a dike swarm near Dhone is known as the Dhone cluster (Murty *et al* 1987, figure 1). The dikes in this dike swarm trend primarily NW–SE, paralleling the major NW–SE lineament trend of the Dharwar Archean crust. These dikes constitute a part of the radial dike system surrounding the Cuddapah basin (Bhattacharji 1986). A few NE–SW trending dikes are also present in this area which cut across some of the NW–SE trending dikes (figure 1).

At the western and southwestern margins of the Cuddapah basin, the Archean crust is intruded by numerous dikes and dike clusters. Many of these dikes occur as isolated dikes trending parallel to the NW–SE and NE–SW lineament trends for over 150 km or more. In general, a majority of the dikes are short and segmented and often occur in en echelon pattern. The width of the majority of the dikes range from 10 to 50 m, but there are a number of dikes as wide as 70 to 80 m.

Inside the basin, the lower Cuddapah Vempalle and Tadpatri formations contain many tholeiitic sills, lava flows and tuffs. Along the southwestern margin of the basin occurs a group of sills that are concentric with the arcuate margin of the basin. Near Pulivendla, some of the sills contain gabbroic xenoliths and accumulations of mafic xenocrysts. These xenolith bearing arc-concentric sills constitute a minor, but petrologically significant element of the Tadpatri formation near the southwestern margin of the basin (figure 1). Various workers (e.g., Murthy 1964; Rao and Rao 1964, Sinha and Krishna Rao 1968; Somayajulu and Singhal 1968; Dasgupta 1986) have described these sills as picritic. Dikes are absent inside the basin with the exception of the Chelima lamproites near the center of the basin (figure 1). The xenolith bearing area of the sills coincides with the gravity high attributed to the lopolithic intrusion beneath the southeastern part of the basin (Grant 1983, Murty *et al* 1987).

Counterparts of the Cuddapah basin tholeiites are found in east Antarctica (figure 2). A group of doleritic tholeiite dikes occurring in the Napier Complex of east Antarctica (the Amundsen dikes, Sheraton and Black 1981) are especially interesting since, they are of Mid-Proterozoic age and are similar in chemistry to the Cuddapah basin tholeiites.

3. Geochronology

In tables 1(A) and 1(B), we present radiometric ages of whole rock samples determined in this study and previously determined ages by other workers. In figure 4, we show apparent integrated ^{40}Ar-^{39}Ar ages of three dike samples plotted against fractions of released ^{39}Ar. These samples did not show well-defined plateau ages. The gas fractions were added over the imperfect plateau region to arrive at an integrated age of the whole rock sample. Uncertainties in these ages are estimated at the 1σ confidence level. For K-Ar whole rock age determination, all samples were crushed to $-80/+200$ mesh and treated with dilute HF and HNO_3 to remove alterations. For each dike, two whole rock samples were analyzed. The uncertainties for the K-Ar apparent ages are estimated at the 2σ confidence level.

Ages of important igneous bodies are shown in table 1(A). The oldest tholeiite dikes on the south Indian shield (Bidadi-Harohalli area, about 100 km SW of Kolar) are 2369 ± 246 Ma old (Rb-Sr age determined by Ikramuddin and Stueber 1976; recalculated by Collerson and Sheraton 1986) with an initial ^{87}Sr/^{86}Sr of 0.7012 ± 0.0010. However, the oldest dike that may be associated with the initiation of the Cuddapah basin is the 1879 ± 5 Ma old, E–W trending dike southwest of the basin, as dated by the ^{40}Ar-^{39}Ar method. A recent Rb–Sr isochron age of ~ 1900 Ma of gabbroic dike swarms has been determined by Kumar *et al* (1990) in the Dharwar craton intruding ~ 2100 Ma old Proterozoic granites. This supports a thermal event and crustal dilation with dike intrusive activity at the SW margin of the present day Cuddapah basin where early sedimentation in the basin occurred (Bhattacharji 1987; Bhattacharji and Singh 1984). The age of the oldest mafic flows inside the basin is debatable, but they are probably contemporary to the oldest E–W dike immediately outside the basin. Although a K-Ar age of 1841 ± 71 Ma of a Vempalle lava flow has been determined by Murty *et al* (1987), a recent Rb-Sr age of a Pulivendla sill in the Chitravati group by Bhaskar Rao *et al* (1995) yields an identical age of 1817 ± 24 Ma. The Tadpatri formation (Chitravati Group) consists of ~ 4600 m thick sediments and overlies an unconformity between the Vempalle and Tadpatri formations. Thus, it is likely that the Vempalle formation is older than 1841 ± 71 Ma. Crawford and Compston (1973) determined an Rb-Sr age of 1550 ± 147 Ma by with an initial ^{87}Sr/^{86}Sr of 0.7044 ± 0014 (recalculated by Collerson and Sheraton 1986) of a mafic flow from the lowermost Vempalle sedimentary sequence in the western side of the basin. This age is improbable, as the samples were poorly radiogenic and the isochron may have been poorly defined (Bhaskar Rao *et al* 1995). Crawford and Compston (1973), however, suggested that volcanism in the Cuddapah basin may have started as early as ~ 1700 Ma.

While dike emplacement started possibly before the initiation of basin formation, it continued intermittently throughout and after sedimentary deposition in the basin (Kumar *et al* 1988). The Chelima lamproite dikes, which intrude the Cumbum formation of the upper Nallamalai Group near the center of the basin, place an upper bound on the age of the Cuddapah sequence at approximately 1400 Ma. This is indicated by a ^{40}Ar-^{39}Ar plateau age determination of 1417.8 ± 8.2 Ma (Chalapathi Rao *et al* 1999, see table 1A) and supported by K-Ar ages of 1371 ± 45 Ma (Murty *et al* 1987) and 1363 ± 48 Ma (Chala-

Table 1(A). *Whole rock age of important igneous bodies in and around the Cuddapah basin, south India.*

	Location	Age	Method	Source
Mafic dike	Bidadi-Harholli, west of Kolar	2369 ± 246	Rb-Sr	Ikramuddin and Stueber 1976, Collerson and Sheraton 1986.
Mafic dike trending E–W	Southwest of basin	1879 ± 5	^{40}Ar- ^{39}Ar	This study.
Mafic flow	Lower part of lower Cuddapah, Vempalle formation, western part of basin	1841 ± 71	K-Ar	Murty *et al* 1987.
Mafic sill	Upper part of lower Cuddapah, Pulivendla formation, western part of basin	1817 ± 24	Rb-Sr	Bhaskar Rao *et al* 1995.
Mafic flow	Lower part of lower Cuddapah, Vempalle formation, westerm part of basin	1550 ± 147	Rb-Sr	Crawford and Compston 1973, Collerson and Sheraton 1986.
Lamproite dike trending NE–SW	Upper Cuddapah, Cumbum formation of Nallamalai group, center of basin near Chelima	1418 ± 8	^{40}Ar- ^{39}Ar	Chalapathi Rao *et al* 1999
Lamproite dike trending NE–SW	Upper Cuddapah, Cumbum formation of Nallamalai group, center of basin near Chelima	1371 ± 45	K-Ar	Murty *et al* 1987.
Arc-concentric, mafic sill	Upper part of lower Cuddapah, Tadpatri formation, western part of basin	958 ± 29	K-Ar	Murty *et al* 1987.
Arc-concentric, mafic sill	Upper part of lower Cuddapah, Tadpatri formation, western part of basin	809 ± 29	K-Ar	Murty *et al* 1987.
Granophyre dike trending NE–SW	Southwest of basin	646 ± 23	K-Ar	Dayal and Padmakumari 1987.

pathi Rao *et al* 1996). If these ages are true indications, the entire Cuddapah sequence was deposited between 1850 and 1400 Ma approximately, within the error limits of the age determinations.

Igneous intrusion continued both outside and inside the basin after sedimentation ceased. The youngest dike (granophyre) outside the basin dates back to 646 ± 23 Ma (K-Ar age, Dayal and Padmakumari 1985). Within the basin, some arc-concentric sills in the Tadpatri formation of the Chitravati group (upper part of the lower Cuddapah sequence) were emplaced between 958 ± 29 Ma and 809 ± 29 Ma as determined by the K-Ar method (Murty *et al* 1987, see table 1A). These sills are too young to be directly related to the mantle perturbation and must represent a different episode of magmatic activity. If these ages are correct, igneous activity in the basin must have continued intermittently over a period of 900–1000 Ma. However, in view of the contradictions in the ages of the lower Cuddapah igneous rocks as discussed above, further geochronological studies supported by paleomagnetic data are clearly required to determine the duration of thermal events and their tectonomagmatic significance in the evolution of the Cuddapah basin.

Interestingly, the high-Mg and tholeiitic dikes of Napier Complex, east Antarctica (Sheraton and Black 1981) show a temporal proximity and isotopic similarity to the Dharwar dikes. The high-Mg dikes of east Antarctica are 2350 ± 48 Ma old with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7020 ± 0.0008 (Sheraton and Black 1981), and comparable to the dikes of Bidadi-Harohalli area of south India (Ikramuddin and Stueber 1976). The tholeiitic Amundsen dikes of east Antarctica, which are 1190 ± 200 Ma old with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7041 ± 0.0005 (Sheraton and Black 1981) are also similar to the Cuddapah basin tholeiites (e.g., Crawford and Compston 1973). Igneous activity in the Cuddapah area was at least partly contemporaneous with the igneous activity in the Napier Complex of east Antarctica.

4. Bulk composition

The basaltic rocks inside and outside the basin contain a wide range of MgO (Murty *et al* 1987; Chatterjee and Bhattacharji 1998). Selected compositions are given in table 2. The xenolith and xenocryst bearing basalts inside the basin contain

Table 1(B). *Whole rock age of basaltic dikes around the Cuddapah basin, south India.*

	Location*	Trend	Age	Method	Source
K110	N	NE–SW	1335 ± 49	K-Ar	Murty *et al* (1987).
K34	W, Dhone	NE–SW	1157 ± 41	K-Ar	Murty *et al* (1987).
K72	W, Radial dike, Dhone	NW–SE	1454 ± 56	K-Ar	Murty *et al* (1987).
K88	W, Radial dike, Dhone	NW–SE	1489 ± 5	^{40}Ar-^{39}Ar	This study.
K122	N	WNW-ESE	1471 ± 54	K-Ar	Murty *et al* (1987).
K104	N	N–S	1384 ± 13	K-Ar	This study.
D75	SW	NE–SW	1414 ± 52	K-Ar	Murty *et al* (1987).
D28	SW	NE–SW	1367 ± 49	K-Ar	Murty *et al* (1987).
D110		NE–SW	1335 ± 49	K-Ar	Chatterjee and Bhattacharji (under preparation).
D49	SW	NE–SW	1349 ± 49	K-Ar	Chatterjee and Bhattacharji (under preparation).
D84	S, Tirupati	ENE-WNW	1333 ± 4	^{40}Ar-^{39}Ar	Chatterjee and Bhattacharji (under preparation).
D9		NW–SE	1203 ± 47	K-Ar	Chatterjee and Bhattacharji (under preparation).
D30	SW	NW–SE	1212 ± 4	^{40}Ar-^{39}Ar	Chatterjee and Bhattacharji (under preparation).
D89	S, Tirupati	NW–SE	1280 ± 47	K-Ar	Murty *et al* (1987).
D77	SW	NNW–SSE	1371 ± 4	^{40}Ar-^{39}Ar	This study.
D76	SW	E–W	1713 ± 65	K-Ar	Murty *et al* (1987).
D33	SW	E–W	1250 ± 38	K-Ar	Murty *et al* (1987)
D8A	SW	E–W	1879 ± 5	^{40}Ar-^{39}Ar	This study.
D11			1518 ± 37	K-Ar	This study.
D88	S, Tirupati	E–W	1349 ± 48	K-Ar	This study.
D86	S, Tirupati	E–W	1161 ± 45	K-Ar	Murty *et al* (1987).

* For location, see figure 1.

the highest Mg with MgO>20 wt%. Other high-MgO tholeiites outside the basin contain as high as 12 wt% MgO. A majority of the basalts are tholeiites with MgO<8 wt%. About half of the tholeiites outside the basin are olivine-normative. The rest are quartz-normative.

4.1 *Trace element composition*

Basalts from both inside and outside of the basin are enriched in large-ion-lithophile elements (LILE) K, Rb and Ba, whereas, they have similar or slightly depleted concentrations of other incompatible elements compared to MORB (Chatterjee and Bhattacharji 1998, and figure 5). The trace element patterns further indicate that the rocks outside the basin have a higher Rb content and higher Zr/P and Zr/Ti than the rocks inside the basin. In general, the rocks outside the basin have lower Ba/Rb, Ti/Zr and Ti/Y and higher Zr/Nb and Y/Nb than the Cuddapah basin rocks (figure 6). Hofmann and White (1983) have argued that the ratio of very highly incompatible elements such as Ba:Rb is constant in tholeiites and their differentiates and reflect the ratio of their mantle source. And Nesbitt and Sun (1976) noted that Ti/Zr, Ti/Y, Zr/Nb and Y/Nb are relatively constant in komatiites from western Australia, Canada and South Africa indicating their primary character and implying that they are not appreciably altered by metamorphism. It is likely that Ba and Rb were mobile during metamorphism. This is the reason we see scatter in the diagrams that involve Ba/Rb (figure 6). Despite alteration, Ba/Rb of our samples and the Amundsen tholeiites of east Antarctica falls into three broad groups corresponding to the three regions under consideration.

5. Petrogenesis

The bulk composition of samples, plotted on a clinopyroxene-plagioclase-olivine (cpx-plag-oliv) pseudoternary diagram according to the method of Grove (1993), shows considerable scatter especially for the samples outside the basin (figure 7). Harker-type variation diagrams with contents of different oxides as a function of the MgO content also show large scatter (figure 8). Thus, the bulk composition data does not seem to indicate any fractional crystallization relation among the basalts outside the basin. A different picture emerges, however, when the mineral compositions and their textural relationships are considered. Calculated values for the olivine-bulk and augite-bulk $\mathrm{K_D^{Fe-Mg}}$'s ($= [\mathrm{X_{Fe}^{mineral}.X_{Mg}^{bulk}}]/[X_{\mathrm{Mg}}^{\mathrm{mineral}}.\mathrm{X_{Fe}^{bulk}}]$)

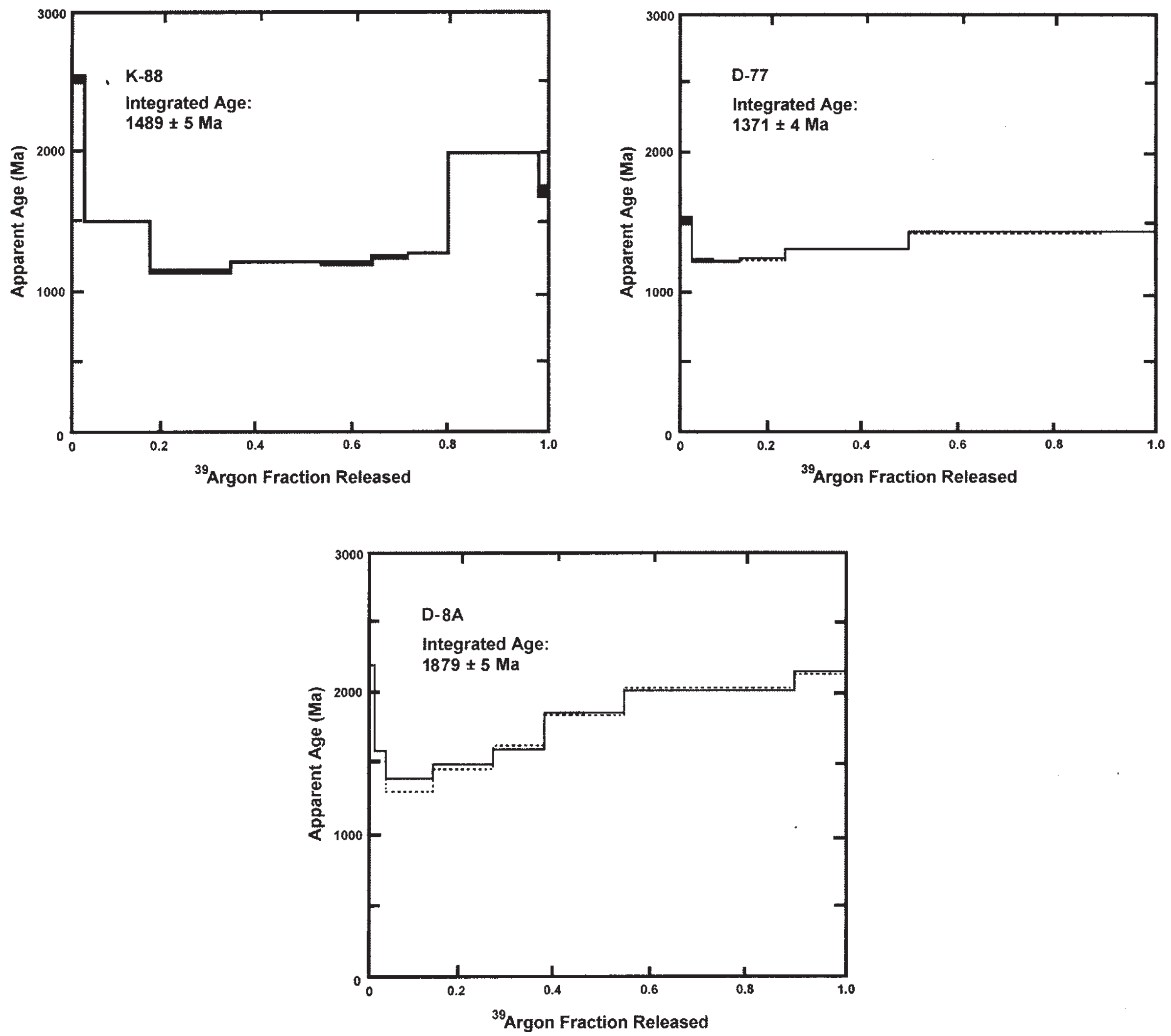

Figure 4. Integrated $^{40}Ar/^{39}Ar$ age of NW–SE trending dike K88 from the Dhone radial dike swarm, and NNW–SSE trending dike D77 and E–W trending dike D8A outside the southwest margin of the Cuddapah basin.

and the plagioclase-bulk K_D^{Ca-Na}($= [X_{Ca}^{plag}.X_{Na}^{bulk}]/[X_{Na}^{plag}.X_{Ca}^{bulk}]$) from bulk compositions and compositions of olivine, pyroxene and plagioclase (table 3) indicate that in most cases, these minerals are not in equilibrium with the bulk rock. For basalts, the equilibrium values of these partition coefficients are 0.3, 0.23 and about 1.5 respectively under low pressure and anhydrous conditions (Sisson and Grove 1993; Grove *et al* 1997). For the Cuddapah dikes, these values range 0.69–0.85, 0.18–0.54 and 0.54–2.1 respectively (Chatterjee and Bhattacharji, under preparation). Hence, most of these rocks are cumulates. These cumulates, however, show a positive correlation between their plagioclase-Ca# (atomic Ca/[Ca+Na] in plagioclase) and augite-Mg# (atomic Mg/[Mg+Fe] in augite). This indicates that the co-crystallization of plagioclase and augite was important in the formation of these rocks, and they may be related by fractional crystallization.

For the basaltic sills inside the basin, Chatterjee and Bhattacharji (1998) showed that they may be related by fractional crystallization at 5 kb by calculating a liquid line of descent for the B1 starting composition, according to the method of Grove *et al* (1992). The same authors also demonstrated that the xenolith-bearing basalts are related to B1 by addition of the xenolithic component to B1. They further observed that the olivines in the xenoliths are similar in composition to calculated olivine compositions in equilibrium with B1 ($Fo_{77.8}$) and B81 ($Fo_{78.4}$) at 5 kb and 1142–1154° C using Ford *et al*'s (1983) equations after corrections based on Parman *et al* (1995). A similar temperature range (1019–1148°C at 5 kb) was obtained for the equilibration of the xenoliths from two-pyroxene thermometry using the equation of Brey and Kohler (1990).

Periodic intrusion by magma along the same conduits and magma mixing is evident in some of the

Table 2. *Chemical composition of basaltic sills and dikes in and around Cuddapah Basin.*

Sample	B1	B81	B37	M3	J4	K104	D30A	D75A	D84A	D89A
Rock	thol	thol	thol	thol	thol	hi-Mg	hi-Mg	thol	hi-Mg	thol
Location	inside	inside	inside	inside	out	out	out	out	out	out
Dike/Sill	sill	sill	sill	sill	dike	dike	dike	dike	dike	dike
Weight per cent										
SiO_2	45.99	48.39	50.39	49.79	51.40	53.09	48.97	49.61	53.87	48.12
TiO_2	1.66	1.03	1.52	1.46	0.66	0.64	0.54	1.60	0.65	1.05
Al_2O_3	15.02	16.59	13.36	14.73	15.69	13.22	14.90	14.42	14.59	15.82
$Fe_2O_3^*$	7.65	5.04	9.10	15.59	3.12	4.99	3.59	7.00	1.55	5.94
FeO	10.27	9.40	7.50	n.d.	7.28	7.69	7.70	10.19	9.93	8.64
MnO	0.22	0.17	0.26	0.17	0.16	0.16	0.18	0.22	0.07	0.19
MgO	7.90	7.10	5.63	5.34	7.80	9.52	11.19	4.20	8.22	7.23
CaO	8.74	9.36	9.03	9.48	9.88	7.69	10.33	9.47	7.60	9.22
Na_2O	1.70	1.96	2.66	2.49	2.97	1.47	2.07	2.49	2.08	2.26
K_2O	0.61	0.76	0.32	1.36	0.88	1.32	0.49	0.62	1.35	1.41
P_2O_5	0.24	0.20	0.23	0.36	0.15	0.22	0.05	0.18	0.08	0.11
FeO^{**}	17.16	13.93	15.69	14.03	10.09	12.18	10.93	16.50	11.32	13.98
M′	45.06	47.59	39.00	40.42	57.95	58.23	64.60	31.20	56.42	47.95
Weight ppm										
Ba	212	181	81	148	n.d.	161	58	205	147	196
Rb	17	29	7	37	35	61	38	18	121	61
Nb	5	4	8	6	n.d.	n.d.	n.d.	n.d.	6	6
Sr	198	141	279	47	303	132	149	100	163	307
Zr	103	71	114	83	182	147	115	135	159	157
Y	22	17	25	17	27	34	29	27	30	37
Co	n.d.	n.d.	n.d.	n.d.	47	48	58	88	43	59
Cr	n.d.	n.d.	n.d.	n.d.	57	473	1036	69	496	296
Cu	206	65	199	91	19	115	103	138	99	200
Ni	163	155	57	104	48	171	313	70	184	203
V	n.d.	n.d.	n.d.	n.d.	n.d.	292	282	311	284	270
Zn	110	81	111	84	n.d.	105	45	200	41	114

- Concentrations are determined by XRF except Fe_2O_3 and FeO, which are determined by wet chemical techniques.
- The major oxide concentrations are normalized to a sum of 100; where FeO is not available, 50% of Fe_2O_3 is considered as FeO in normalization calculation.
- **thol**: tholeiite; **hi-Mg**: high-MgO tholeiites; **n.d.**: not determined; **M'** = atomic $100 \times Mg/(Mg + Fe)$. Location refers to inside or outside the basin; for precise locations, refer to figure 2.
- *reported as total Fe_2O_3 where FeO data are not available; ** total FeO.

cross cutting dikes outside the southwestern margin of the Cuddapah Basin (Chatterjee and Bhattacharji, under preparation). Dike intrusion into a pre-existing long fracture or lineament (deep-seated fault or plane of weakness in the crust) usually occurs at the time of reactivation of the lineament. Comparison of relative ages and compositional relationships of cross cutting dikes, therefore, reflects not only the petrogenesis of these dikes, but also the relative time of crustal extension with reactivation of major lineaments, especially if they intrude over a long distance paralleling the lineament trends.

At the southwestern margin of the basin, where the oldest sedimentary formation of the Cuddapah basin was deposited, there are two prominent cross-cutting tholeiitic dikes (D28 and D30) which trend parallel to the NE–SW and NW–SE lineaments of the Dharwar Archean crust respectively. The tholeiitic dike D28, dated at 1367 ± 49 Ma (table 1B), is a prominent geomorphic feature, occurring as prominent ridges and extending over 20 km in the NE–SW direction from the basin margin. This dike is segmented and the segments occur in an en echelon pattern. Cutting across this dike is another tholeiitic dike, D30, which is dated at 1212 ± 4 Ma (table 1B) and also occurs as segmented dike ridges paralleling the major NW–SE lineament. In the olivine-tholeiite dike D28, a vein of magma different in composition from the bulk is found to intrude the host dike. Dike D30, which cross cuts D28, contains Mg-poor resorbed orthopyroxenes surrounded by a higher-Mg overgrowth rim and rhythmically zoned plagioclase (figure 9) strongly indicating that magma mixing was important in its formation. The rationale behind selectively studying these two major dikes at the southwestern margin of the Cuddapah basin is that the time of intrusion or emplacement of these two cross cutting dikes should indicate the relative time of crustal extension associated with the initial development of the Cuddapah basin.

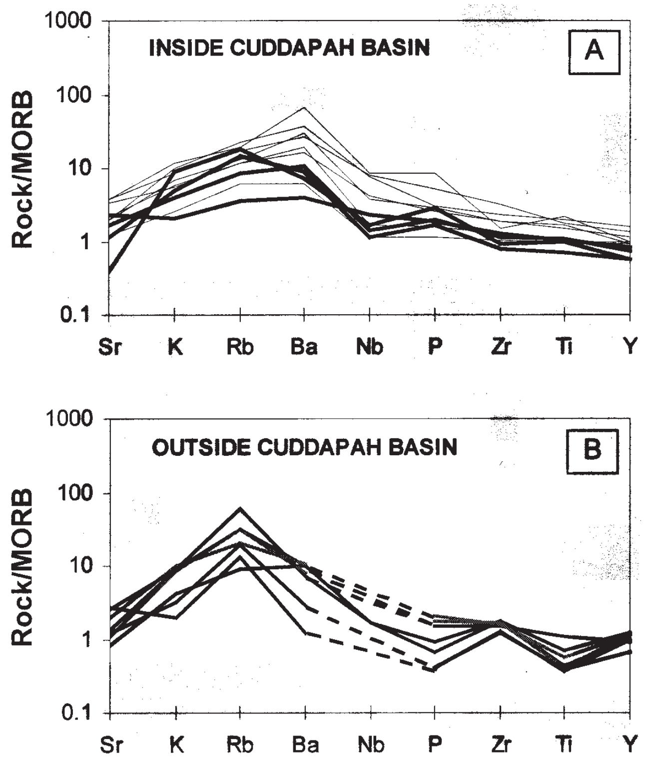

Figure 5. MORB normalized (according to Pearce 1983) incompatible trace element contents of tholeiite sills within Cuddapah basin **(A)** and outside the basin **(B)**. Amundsen tholeiites from Napier Complex, east Antarctica (Sheraton and Black 1981) are also shown in thin lines in (A).

6. Discussion

Bhattacharji (1987) noted an episodic igneous activity in the form of dike intrusions in the Dharwar Archean basement over a period between 2400 and 650 Ma on the basis of thirteen K-Ar age determinations (one by Balasubrahmanyan 1975) and two Rb-Sr ages determined by Ikramuddin and Stueber (1976). Available radiometric ages of mafic dikes around the margin of the Cuddapah basin and the eastern Dharwar craton suggest at least three major episodes of dike intrusive activity during 1900–1700 Ma, 1500–1300 Ma and 1200–640 Ma respectively (Padmakumari and Dayal 1987; Mallikharjuna Rao *et al* 1995; Sarkar and Mullik 1995). Paleomagnetic studies confirm these three separate periods of dike emplacement (Kumar and Bhalla 1983; Hargraves and Bhalla 1987). Ages of several mafic dikes along the NE–SW and NW–SE lineaments outside the basin (1500–1200 Ma, table 1B), the Dhone radial dike swarm west of the basin (1500–1400 Ma, table 1B) and the Chelima lamproite dikes near the center of the basin (1300–1400 Ma, table 1A) fall in the second of the three periods mentioned above. It is postulated that these dikes owe their origin to a deep mantle perturbation, which is manifested by the funnel shaped lopolithic intrusion in the southwestern part of the present day basin. Thus, it seems that the mantle perturbation, which is believed to have started at the onset of basin evolution, was a constant thermal source between 1500 and 1200 Ma, leading to crustal dilation, lineament reactivation and igneous intrusive activity.

It must be mentioned here that all available K-Ar and Rb-Sr age dates, including from this study, have large uncertainties. ^{40}Ar-^{39}Ar dates have lower uncertainties, but the ^{39}Ar release spectra do not show plateaus (figure 4). Both K-Ar and ^{40}Ar-^{39}Ar dates are susceptible to errors due to the problems of Ar loss. Rb-Sr systems have also been known to reset during metamorphism. The ^{39}Ar release spectrum of K88 shows a prominent saddle (figure 4). Saddles can occur in a spectrum in different ways. The initial high ^{39}Ar release is normally attributed to degassing of altered/weathered minerals in the initial heating step. The large release of ^{39}Ar in one of the last steps may be due to trapped Ar in anionic sites of feldspars, which require high temperatures to be released (Professor Kip Hodges, MIT, personal communication, 2000). D8A shows a step-like increase in ^{39}Ar production with temperature (figure 4). This can happen either by post-crystallization Ar loss due to metamorphism, or by very slow cooling of the rock, whereby, Ar remains near the cores of minerals, but diffuses out from grain boundaries (Hodges, personal communication, 2000). If the higher temperatures reflect the actual age of formation, the age of D8A will be pushed back slightly. Indeed, an initial K-Ar age determination of D8A yielded 1938 Ma. Keeping in mind the large uncertainties in the age dates, we are presenting a plausible model for the evolution of the Cuddapah basin.

The radiometric ages of the NW–SE and NE–SW trending dikes in the southern and southwestern regions outside the Cuddapah basin (figure 1, table 1B) indicate that the lineaments along these directions were intensely reactivated between 1400 and 1200 Ma during the evolution of the Cuddapah basin. Petrographic evidence of lineament reactivation is preserved in some of the cross-cutting dikes of this region. These reactivations were in the form of dilation along the NW–SE and NE–SW directions leading to channeling of magma in these preferred directions. The later intrusions gave rise to cross cutting relationships between these dikes and the dikes from the earlier intrusions. Dike D28, which is cross-cut by the younger dike D30, preserves interesting petrographic evidence of renewed magmatic activity along the directions of the two major lineaments.

Mass balance calculations in the reaction zone surrounding the vein in D28 indicate that 38% of the vein reacted with 62% of the host dike. If the

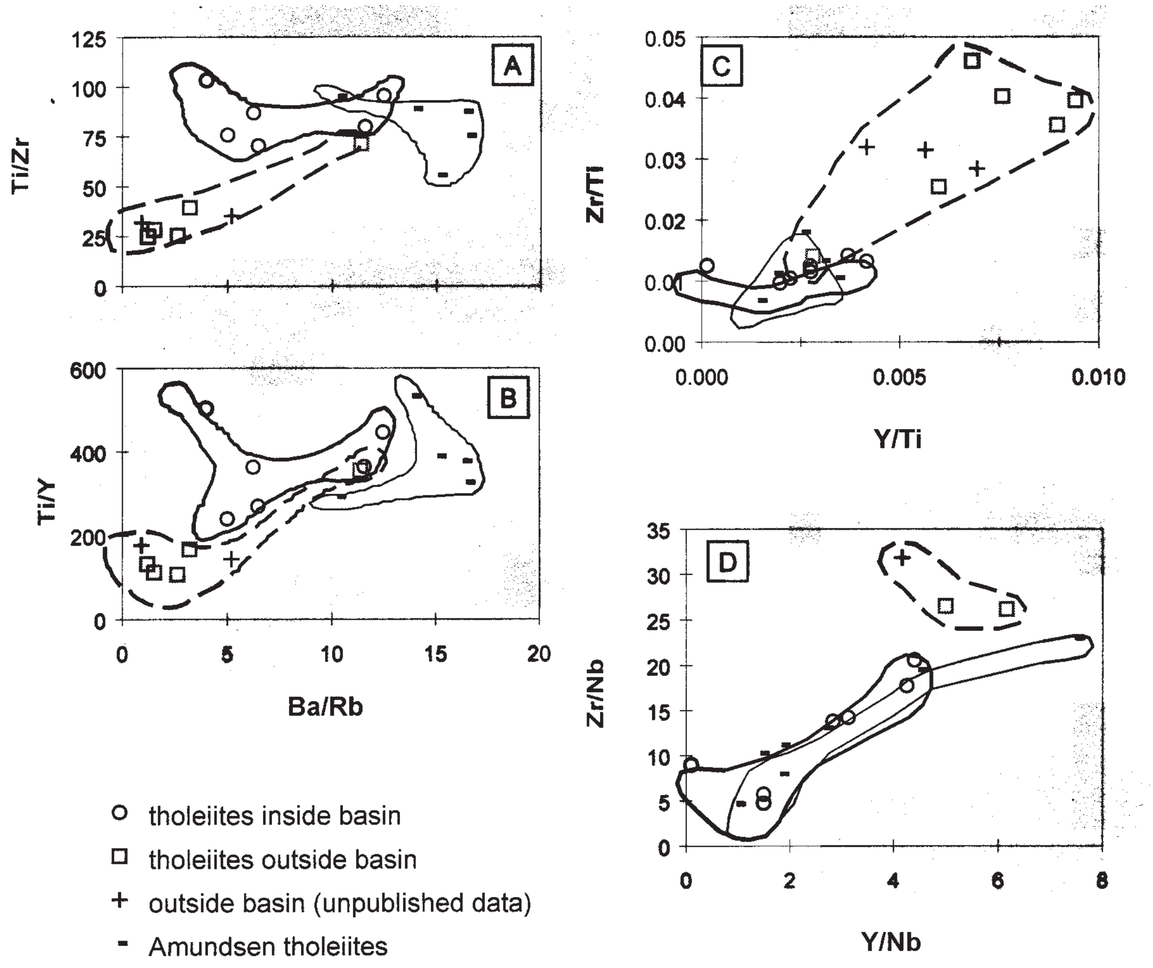

Figure 6. Variation of **(A)** Ti/Zr and **(B)** Ti/Y with Ba/Rb; **(C)** Zr/Ti with Y/Ti; and **(D)** Zr/Nb with Y/Nb. Symbols are as follows: **open circles**: Cuddapah basin basalts, **squares and plusses**: basalts outside the basin, and **dashes**: Amundsen tholeiites from east Antarctica (Sheraton & Black 1981). The boundary around the Cuddapah basin basalts is in bold line; around the basalts outside the basin, in dashed line; and around the Amundsen tholeiites, in thin line.

liquid in equilibrium with the core of the relict orthopyroxenes in D30 is mixed in a 0.65:0.35 proportion with the vein material of D28, the resulting liquid will be in equilibrium with the Mg-rich overgrowth rim of the orthopyroxenes of D30 (Chatterjee and Bhattacharji, under preparation). This indicates that chemically similar liquids interacted with an older solidified rock (D28), which was intruded, and a younger magma undergoing crystallization (D30), whose compostion was altered by the process of magma-mixing.

The dense lopolithic intrusion beneath the southwest region of the basin is indicated by the seismic profiles of Kaila *et al* (1979), gravity anomaly maps of Balakrishna (1979) and Grant (1983), and magnetic anomaly data of Murty *et al* (1987). Bhattacharji (1987) postulated that an asthenospheric upwelling and diapiric rise of magma with excess magma pressure gave rise to the cupola or funnel shaped intrusion into the upper levels of the crust (figure 3 of Bhattacharji 1987). The magma cupola was postulated as the proximal source for emplacement of sills, dikes and lava flows around and within the basin. Bulk composition of the sills and composition of the minerals in the xenoliths indicate that the tholeiites in the cupola originated at a temperature of 1019–1154°C and a depth of about 18 km (Chatterjee and Bhattacharji 1998). The cupola may have served as a site for fractional crystallization. Fractionated melts possibly rose to the surface to form concentric sill intrusions along the periphery of the lopolithic cupola. Crystal fractionation products possibly settled along the wall of the cupola. Sills containing fractionated crystals (the xenolith bearing sills) are thus located at the outermost periphery.

6.1 *Trace element implications*

Basalts both inside and outside the basin are enriched in Ba, Rb and K compared to MORB (figure 5). Sheraton and Black (1981) found evidence of a Ba-Rb-K-Th-rich fluid that enriched the source of some of the Amundsen tholeiites. A similar metasomatic enrichment may have occurred

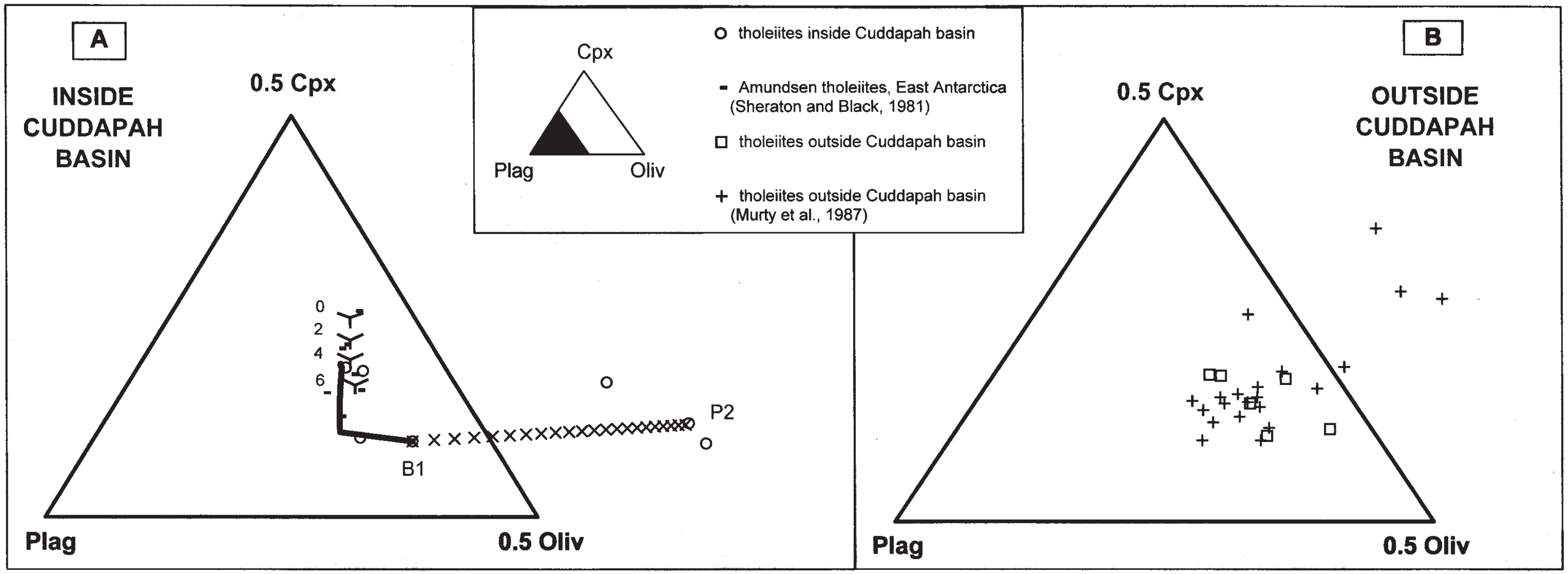

Figure 7. Clinopyroxene-plagioclase-olivine (cpx-plag-oliv) pseudoternary diagrams plotted according to the method of Grove (1993) showing phase relations for **(A)** Cuddapah basin basalts and Amundsen tholeiites of Napier Complex, and **(B)** tholeiites outside Cuddapah basin. Symbols are as in figure 6, and plusses: basalts outside the basin from Murty *et al* (1987). Also shown in (A) are cpx-plag-oliv invariant points for the B1 composition at different pressures (in kb), 0 corresponding to 1 bar; and fractional crystallization (bold line) and crystal-accumulation (crosses) paths for B1 (see text for details).

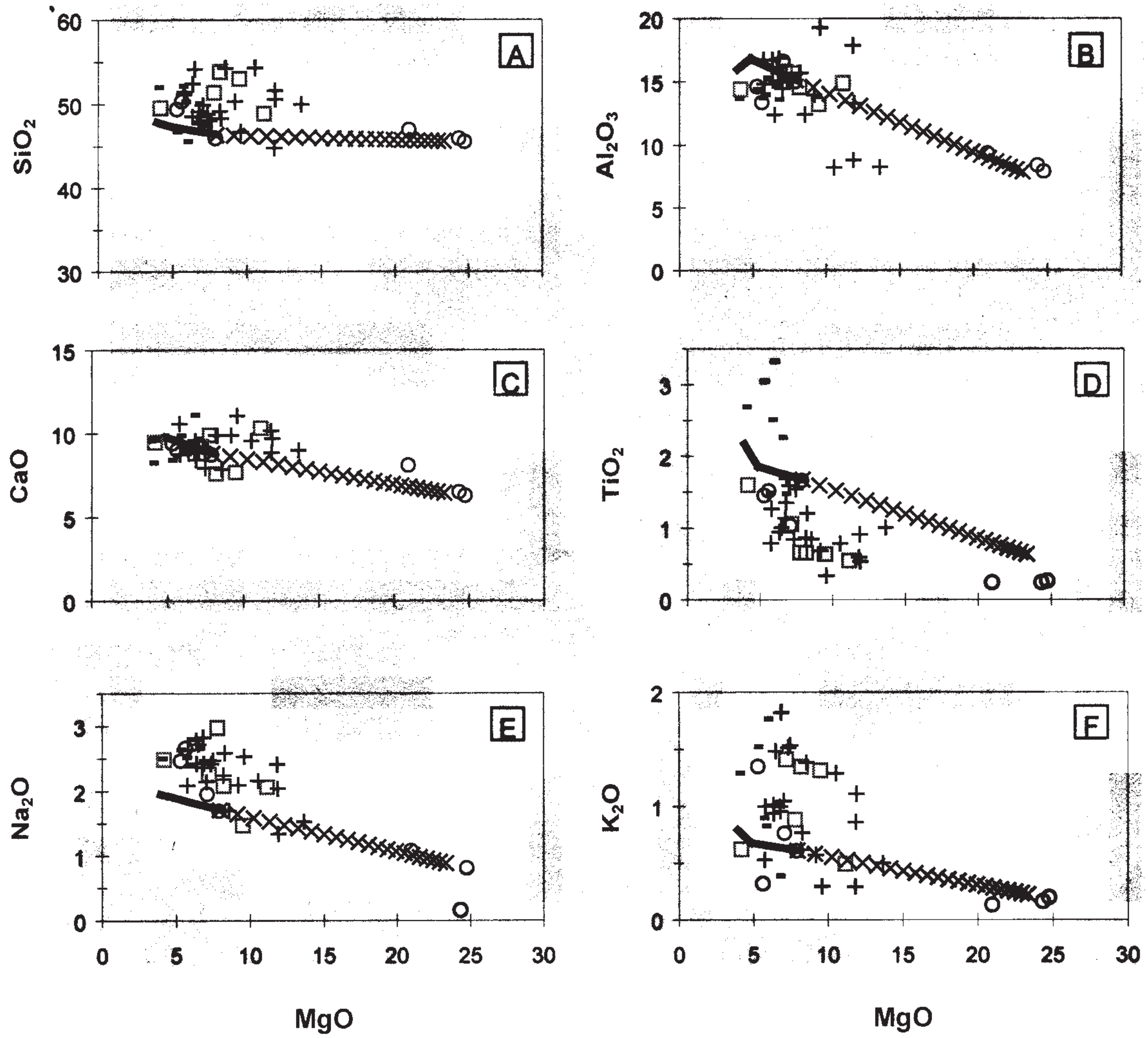

Figure 8. Variation of different oxides with MgO. Symbols, and fractionation and accumulation paths are as in figure 7.

in the Cuddapah area. Higher $^{87}Sr/^{86}Sr$ in the younger tholeiites (0.7041–0.7044) than the older ones (0.7012–0.7020) in south India and east Antarctica (Crawford and Comspton 1973; Ikramuddin and Stueber 1976; Sheraton and Black 1981) may reflect contributions from Rb to the ^{87}Sr content in a Rb-enriched mantle as time progressed. This metasomatic enrichment of the mantle may have been widespread on a global scale. In addition to east Antarctica, Marsh *et al* (1992) found evidence of metasomatic enrichment in the Proterozoic Klipriviersberg tholeiites ($\sim$ 2.7 Ga) of the Kaapvaal craton of South Africa, which was a part of the Proterozoic Gondwanaland. These tholeiites contain similar amounts of Ba, Rb and K to the Cuddapah tholeiites. In figure 10, the MORB-normalized incompatible trace elements of Proterozoic basalts are plotted. The 2.7 Ga and younger basalts include the Cuddapah tholeiites (both inside and outside the basin), the Napier Complex tholeiites and high-Mg basalts, and the Klipriviersberg tholeiites. The Kolar basalts (about 80 km south of Cuddapah basin, see figure 2), which are about 2.9 Ga (Bhalla *et al* 1978, as in Rajamani *et al* 1985), show lower contents of Ba, Rb and K. We can thus conclude that the metasomatic event may have occurred between $\sim$ 2.9 and 2.7 Ga.

There is local heterogeneity in the mantle as indicated by different Zr/Ti, Y/Ti, Zr/Nb and Y/Nb inside and outside the Cuddapah basin (figure 6). We also see different ranges of values for Ba/Rb in the regions outside Cuddapah basin, inside Cuddapah basin and the Napier Complex area (figure 6). There is also evidence of major element heterogeneity in the mantle in the region outside Cuddapah basin. Rajamani *et al* (1985) concluded that the mantle source for the Kolar komatiitic amphibolites have a higher Fe content than pyrolite (proposed by Ringwood 1975). On the other hand, mantle composition at Vajrakarur-Lattavaram (west of Cuddapah basin, figure 1), calculated from mineral compositions (Ganguly and Bhattacharya 1987) and modes in garnet

Table 3. *Sample mineral compositions of the dikes around Cuddapah basin measured by electron microprobe.*

	D84 plag core	D30 plag core	D84 aug core	D30 aug core	D30 opx relict	D30 opx overgrowth
SiO_2	53.00	49.77	52.38	53.03	54.12	54.67
TiO_2	-	-	0.44	0.13	0.22	0.11
Al_2O_3	29.48	31.57	2.23	2.14	1.62	1.86
Cr_2O_3	-	-	0.12	1.18	0.49	0.68
FeO	0.95	0.51	12.55	5.56	12.70	9.82
MnO	-	-	0.30	0.20	0.28	0.25
MgO	0.16	0.21	16.63	19.99	28.44	30.27
CaO	12.70	13.86	16.17	18.08	2.29	2.49
Na_2O	4.27	3.25	0.23	0.21	0.03	0.01
K_2O	0.16	0.14	-	-	-	-
Total	100.71	99.31	101.06	100.53	100.19	100.18
Si	2.396	2.286	1.933	1.921	1.936	1.931
Ti	-	-	0.012	0.004	0.006	0.003
Al	1.571	1.709	0.097	0.092	0.069	0.078
Cr	-	-	0.004	0.034	0.014	0.019
Fe	0.036	0.020	0.387	0.169	0.380	0.290
Mn	-	-	0.009	0.006	0.009	0.008
Mg	0.011	0.015	0.915	1.079	1.516	1.594
Ca	0.615	0.682	0.639	0.702	0.088	0.094
Na	0.374	0.290	0.017	0.015	0.002	0.001
K	0.009	0.008	-	-	-	-
Oxygen	8	8	6	6	6	6
Cations	5.011	5.009	4.013	4.02	4.018	4.018
En or An	0.62	0.70	0.47	0.55	0.76	0.81
Fs or Ab	0.37	0.30	0.33	0.09	0.19	0.15
Mg# or Ca#	0.62	0.70	0.70	0.86	0.80	0.85
Bulk Rock Mg# or Ca#	0.67	0.73-0.71	0.56-0.48	0.65-0.53		
K_D^{Fe-Mg} or K_D^{Ca-Na}	1.24	1.13-1.03	0.54-0.39	0.29-0.18		

- Mg# =atomic Mg/(Mg + Fe), Ca#=atomic Ca/(Ca+Na).
- aug = augite, plag = plagioclase, opx = orthopyroxene.
- Mg# applies to augite and orthopyroxene, Ca# applies to plagioclase.
- K_D^{Fe-Mg} calculated for augite-bulk, K_D^{Ca-Na} calculated for plag-bulk (see text for explanation).

lherzolite xenoliths (worldwide average, suggested by Maaloe and Aoki 1977) shows a higher MgO (43.95 wt%) and lower FeO (6.69 wt%) content than pyrolite.

Although the mantle under the Proterozoic Gondwanaland was locally heterogeneous, there is no evidence of large-scale differences as found during the Jurassic period. Geochemical studies on Jurassic Gondwana flood basalts in Parana (Bellieni *et al* 1984, 1986; Mantovani *et al* 1985; Fodor 1987), Karoo (Cox *et al* 1967) and Etendeka (Duncan 1987; Marsh 1987) have revealed a northern high P_2O_5-TiO_2 (HPT) region and a southern low P_2O_5-TiO_2 (LPT) region. The boundary between the two regions may be stretched to the Ferrar province of southeast Australia-Antarctica (Hergt *et al* 1991). The differences between the two regions have been attributed to different mantle source compositions and crustal contamination. The Cuddapah tholeiites are all LPT basalts. The older Kolar basalts (Rajamani *et al* 1985) are also low TiO_2 basalts (P_2O_5 data unavailable). The Klipriviersberg tholeiites (Marsh *et al* 1992) are also LPT basalts. On the other hand, both LPT and HPT basalts are present in east Antarctica (Sheraton and Black 1981). Thus, it appears that the Jurassic LPT-HPT regimes did not exist during the Proterozoic time period under consideration.

7. Conclusion

Precursors to the evolution of the Cuddapah basin may be traced back to about 2400 Ma when the first basaltic dikes were emplaced in the south Indian shield. E–W trending dikes were emplaced in the west of the present-day basin beginning at about 1900 Ma. The first igneous activity began inside the basin in the form of lava flows seems to have begun at about 1850 Ma, although the actual age remains uncertain. Mantle upwelling resulting in the emplacement of a lopolithic magma cupola in the present day southwestern region of the Cuddapah basin, evident from a positive gravity anomaly, may have happened at the onset of the Cuddapah basin evolution. This deep mantle pertur-

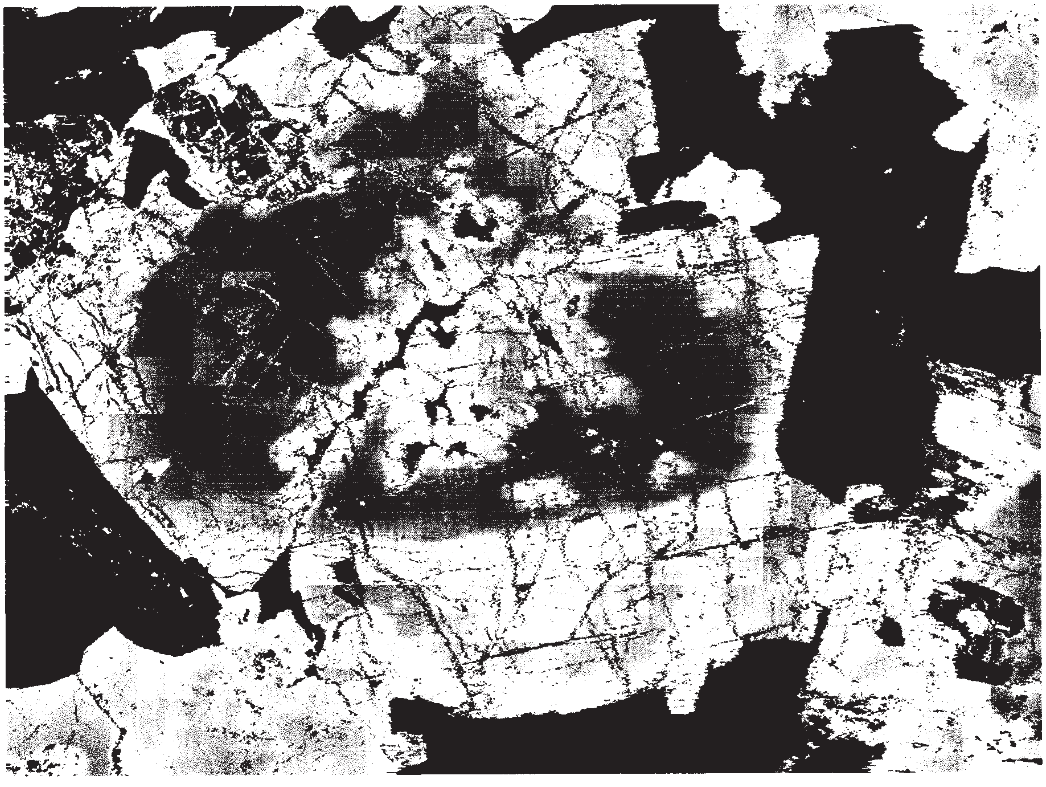

Figure 9. Backscattered electron images of a cross-section of a large grain of orthopyroxene surrounded by grains of plagioclase in dike D30. The width of the image is 4 mm. The orthopyroxene contains a relict grain at the center and a thick overgrowth showing Fe-Mg zoning with Fe increasing toward the periphery. The relict is richer in Fe than the overgrowth in the immediate vicinity.

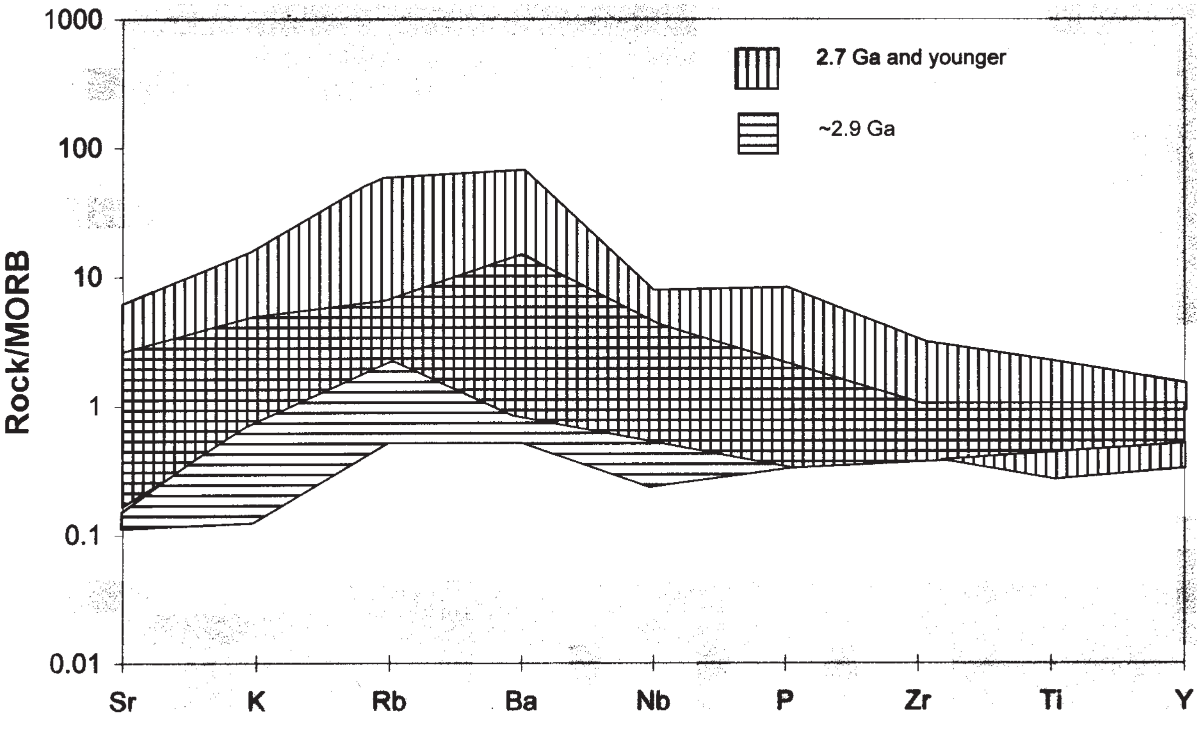

Figure 10. MORB normalized (according to Pearce 1983) concentration ranges of incompatible trace elements of 2.7 Ga and younger (vertically lined-area), and ∼ 2.9 Ga (horizontally lined-area) Proterozoic Gondwana tholeiites and high-MgO basalts. Data for 2.7 Ga and younger basalts are from this study, Sheraton & Black (1981, for Napier complex tholeiites and high-MgO basalts) and Marsh *et al* (1992, for Klipriviersberg tholeiites); and for ∼ 2.9 Ga, from Rajamani *et al* (1985, for Kolar basalts).

bation played an important role in the development of the basin, as it was a constant thermal source responsible for dike and sill emplacement between 1500 and 1200 Ma both inside and outside the basin. Lineament reactivation in the NW–SE and NE–SW directions intensified between 1400 and 1200 Ma, leading to the emplacement of several cross cutting dikes.

Fe-Mg and Ca-Na partition coefficients of olivine, augite and plagioclase, calculated from the composition of these minerals and the bulk composition of their host rocks indicate that the dikes outside the Cuddapah basin are cumulates. The contemporary dikes may be related by fractional crystallization as indicated by a positive correlation between their plagioclase Ca# and augite Mg#. NW–SE and NE–SW cross cutting dikes of this period preserve petrographic evidence of episodic magmatic intrusive activity along preferred directions possibly in response to lineament reactivation that led to the evolution of the Cuddapah basin. Petrological reasoning indicates that similar magmatic liquids reacted with a set of cross cutting dikes, intruding into one that was already solidified and altering the composition of the magma that produced the other dike.

Igneous activity continued intermittently throughout and possibly after the deposition of the Cuddapah sediments inside and outside the basin. This included the emplacement of alkali syenite and granite bodies and the Chelima lamproite dikes within the Nallamalai sediments near the center of the basin, younger sills in the Tadpatri formation, and granophyre dikes outside the basin. The Chelima lamproite dikes, which are dated at about 1400 Ma, place an upper bound on the age of the Cuddapah sequence. If these ages are true indications, the entire Cuddapah sequence was laid down between approximately 1850 and 1400 Ma. Intrusive activity, however, continued after sedimentation ceased until about 800 Ma. The Lower Cuddapah tholeiites may be related by fractional crystallization at 5 kb and 1019–1154°C. The xenolith bearing picrites originated by the accumulation of xenoliths in the other tholeiites as indicated by the composition of the olivine in the xenoliths of the picritic sills ($Fo_{78.7-81.9}$), which are closely similar to calculated olivine compositions ($Fo_{77.8-78.3}$) in equilibrium with the tholeiites under the same *P-T* conditions. Fractionation of the tholeiites thus occurred at a depth of about 18 km in the lopolithic cupola. The fractionated crystals may have settled on the walls of the cupola. As a result the xenolith-bearing sills occur at the periphery of the lopolithic body.

Compared to MORB, the tholeiites both inside and outside the basin are enriched in K, Ba and Rb and similar in P, Zr, Ti and Y. The Ba, Rb and K contents of $\sim$ 2.4 Ga Bidadi-Harohalli tholeiites (south India) and high-Mg east Antarctic tholeiites, $\sim$ 2.9 Ga Kolar tholeiites (south India) and $\sim$ 2.7 Ga Klipriviersberg tholeiites of South Africa indicate that a widespread metasomatic enrichment of the mantle source may have occurred in Proterozoic Gondwana between $\sim$ 2.9 and $\sim$ 2.7 Ga. The basalts inside the Cuddapah basin have a different trace element signature than the basalts outside the basin, which may be attributed to small-scale local mantle heterogeneity. The Cuddapah basin tholeiites have higher Ba/Rb, Ti/Zr, Ti/Y and lower Zr/Nb and Y/Nb than the tholeiites outside the basin. Large-scale differences such as the low P_2O_5-TiO_2 and high P_2O_5-TiO_2 basaltic domains of the Jurassic Gondwana basalts, however, did not exist during the Proterozoic time period under consideration.

7.1 *Future research*

In establishing the tectonomagmatic history in the evolution of the Cuddapah basin, several intriguing and puzzling questions remain to be answered. Why did such intense magmatic activities occur within and around a prototype Proterozoic basin on the south Indian lithosphere, while such magmatic activities were limited and negligible in other adjacent basins during the same period? Further tectonic and geophysical study is required to find out if magmatism has indeed been negligible in the other basins. A more puzzling question is, how can such a prolonged period of magmatic activities, though episodic, be sustained over a period of almost a billion years? Even if one invokes a stationary or shifting mantle plume underneath the south Indian lithosphere, what could be the thermomechanical condition of the mantle and the south Indian lithosphere in late Archean-Proterozoic time which allowed deep mantle rejuvenation and mantle perturbation to produce episodic magmatic activities? Without much needed precise geochronological and paleomagnetic data, answer to such fundamental questions would remain conjectural and speculative.

Proterozoic rocks may suffer repeated thermal metamorphism and alteration during their long history, which may affect their radioactive systems commonly used in age dating. Both the K-Ar and ^{40}Ar-^{39}Ar methods may yield uncertain ages due to Ar loss. The Rb-Sr method is also known to reset during thermal metamorphism. The U-Pb zircon method is promising. This method, along with borehole stratigraphy, has been successfully applied to determine the age of the Klipriviersberg tholeiites of South Africa (references within Marsh *et al* 1992). Initial scans of dike samples by the first author of this study yielded very small grains of baddeleyite and zircon (5–10 microns) in the Cuddapah rocks. It is a daunting task to isolate these grains from the samples for mass spectrometry. But future research should focus in this direction.

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