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Paleoproterozoic magmatism in the Cuddapah basin, India

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ABSTRACT
The Proterozoic Cuddapah basin of Southern India, with an aerial extent of 44,500 km^2, is one of the largest sedimentary basins in the world that witnessed significant events of magmatism during its evolution. Initiated around 2.1 – 2.0 Ga, the basin preserves a protracted history of sedimentation, magmatism and tectonism from Paleo to Neoproterozoic. Through this paper we explicate the Paleoproterozoic ultramafic-mafic-felsic magmatic events that are contemporaneous with the sedimentation of Cuddapah Supergroup. The ~ 1.9 Ga ultramafic-mafic sills, along with basic and felsic volcanics and the interbedded tuffaceous rocks are stratigraphically confined to the Cuddapah Supergroup; that hosts substantial sedimentary sequence in the Cuddapah basin of Eastern Dharwar Craton. We provide a chronological illustration of Paleoproterozoic ultramafic-mafic-felsic magmatic events with details of available geochronological ages; their location and position in the stratigraphic succession constituting the Cuddapah Supergroup (see Table 1). Confinement of the Paleoproterozoic ultramafic-mafic sills within the clastic to shallow marine non-clastic sequences of Papaghni and Chitravathi sub basins, their configuration parallel to the basins arcuate western margin, associated Paleoproterozoic felsic volcanic, disposition of this geological domain along the eastern margin of the stabilised Dharwar craton, indicate a continental arc extensional setting for the evolution Paleoproterozoic segment of Cuddapah basin, India.

Key words: Proterozoic magmatism, extensional tectonics, Cuddapah basin, eastern Dharwar craton, India

INTRODUCTION

The Proterozoic Era in peninsular India is characterised by the deposition of thick sequences of clastic / non-clastic sedimentary rocks in platform-type continental margin shallow marine basins (Eriksson et al., 1998; Sharma et al., 2014; Kale, 2016). The Proterozoic Cuddapah basin of peninsular India (Figure 1) is one of the largest sedimentary basins in the world that preserves a thick sequence of clastic and non-clastic rocks, and associated magmatic rocks (King, 1872; Nagaraja Rao et al., 1987; Bhasker Rao et al., 1995; Mazumder and Eriksson, 2015). Petrological and geochronological studies of the magmatic rocks in the Cuddapah Supergroup have provided significant insights into the nature of tectono-magmatic processes that emerged during the basin evolution (e.g., Chatterjee and Bhattacharji, 2001; Anand et al., 2003; French et al., 2008; Chalapathi Rao et al., 2004; Sheppard et al., 2017).

Keeping in view of the broad interest of the readers in this globally significant sedimentary basin, we provide a chronological illustration of the Paleoproterozoic magmatic events, with details of geographical locations, nature of occurrence in various stratigraphic horizons in the Cuddapah Supergroup (see Table 1 & Figure 4). This Geology review signifies the role of a short lived Paleoproterozoic magmatic regime in the initiation and early evolution of Cuddapah basin in a continental arc extensional setting along the eastern margin of the stabilised Dharwar craton, India.

Regional Geology

The crescent shaped Proterozoic Cuddapah basin has an aerial extent of 44,500 km^{2}and it is considered to be one of the most important Purana basins in Southern India (Nagaraja Rao et al., 1987; Basu and Bickford, 2015). The basin is bounded by Archaean greenstone belts and Peninsular Gneissic Complex (Figure 1). The basin extends over a length of 440 km, with a maximum width of 145 km in the central part. The Nallamalai sub basin (Figure 1), occupies the eastern half of the Cuddapah Basin. The basin has gained prominence in the context of regional tectono-stratigraphy related to the evolution of Precambrian basins of India (Holland, 1909; Radhakrishna, 1987), and its role in the global configuration of supercontinent assembly (Sharma et al., 2014; Saha and Deb, 2014; Mazumder and Eriksson, 2015; Kale, 2016). King (1872) established the stratigraphy of the Cuddapah basin. GSI (1981); Nagaraja Rao et al., (1987); Lakshminarayana et al., (2001); Chakrabarthi et al., (2013), contributed on aspects related to sedimentation and stratigraphy.

Specular haematite mineralisation along the Veldurti - Gani Fault was reported by Krishnan and Balasundaram (1944). The structural and tectonic aspects of the Cuddapah

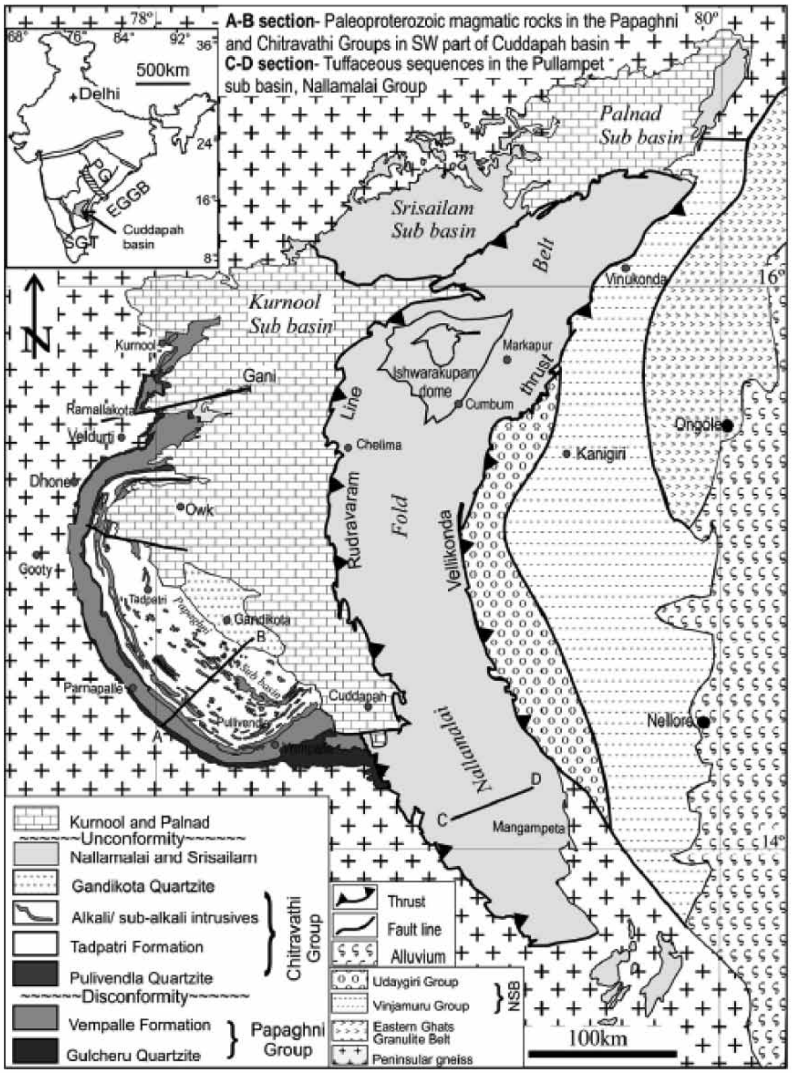

Figure 1. Geological map of the Cuddapah basin (after GSI 1981; Nagaraja Rao et al., 1987) showing the Paleoproterozoic magmatic domains in the Cuddapah Supergroup.

basin were studied by Narayanswami (1966); Nagaraja Rao et al., (1987); Chetty (2011); Tripathy and Saha (2015). The Proterozoic Cuddapah basin consists of: (i) The Cuddapah Supergroup and (ii) The Kurnool Group. The Papaghni sub-basin (western part of the Cuddapah basin) hosts undeformed rocks of Papaghni and Chitravathi groups, whereas, the Nallamalai sub-basin (eastern part) hosts deformed rocks of the Nallamalai group. The ~ 1.9 Ga ultramafic-mafic sills, along with basic and felsic volcanics and the interbedded tuffaceous sequence in the Cuddapah Supergroup are contemporaneous with the sedimentation and hence form part of the magmato-stratigraphy in the undeformed western part of the Cuddapah basin. The objective of this paper is to outline the key events of Paleoproterozoic ultramafic-mafic-felsic magmatic events that are contemporaneous with the evolution of Papaghni sub-basin (Ramakrishnan and Vaidyanathan, 2008).

Paleoproterozoic magmatism in the Cuddapah Supergroup

The Cuddapah domain represents one of the major Paleoproterozoic terranes in Peninsular India (Santosh, 2012). The Cuddapah basin during its early evolution witnessed significant events of Paleoproterozoic magmatism. The detailed discussion related to the ultramafic, mafic, and felsic magmatic events and interbedded tuffaceous sequence (Table 1) contemporary to the sedimentation in the Papaghni, Chitravathi and Nallamalai groups of the Cuddapah Supergroup is as follows.

Papaghni Group

King (1872) has observed that the basic flows, along with some igneous rocks remarkably follow bedding plane (sills) in the lower Cuddapah (Figure 2). Vesicular tholeiitic basalt

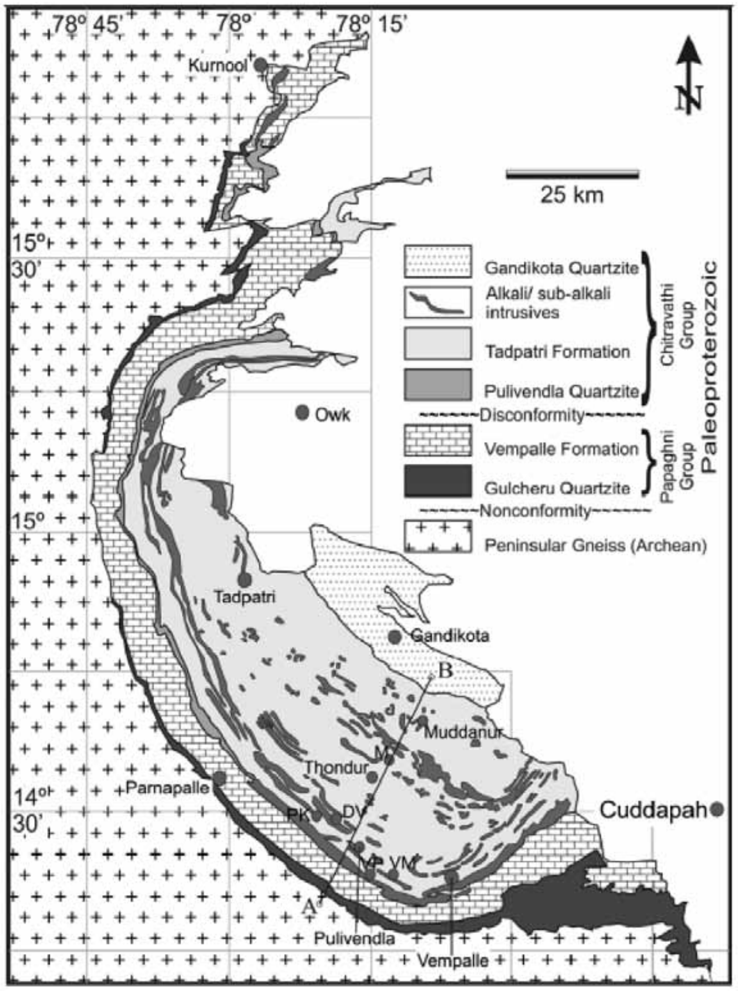

Figure 2. Geological map of SW part of the Proterozoic Cuddapah basin. Note the mafic-ultramafic sills disposed parallel to the basin configuration along its western margin. Section A-B from western margin of the basin- Pulivendela-Tonduru-Muddanuru-Gandikota transcets through Papaghni and Chitravathi Groups. Abbreviations: DV- Dondlavagu; M-Mallela; PK- Peddakudala; VM- Vemula; VP- Velpula

flows (Figure 3a, b) and basic sills represent prominent mafic magmatism associated with the Vempalle formation within the Papaghni sub-basin (Figure 1 and 2; Murthy, 1964; Jhanwar, 1964; Sen and Narasimha Rao, 1967; Srikantia, 1984; Nagaraja Rao et al., 1987; Chatterjee and Bhattacharji, 2001; Chakraborty et al., 2016). Crawford and Compston, (1973) provided an Rb-Sr age of 1583 ± 147 Ma for the basic lavas from Vemula area in south-west part of the Cuddapah basin. A Pb-Pb radiometric age of 1756 ± 29 Ma has been interpreted as the timing of uranium mineralisation in the Vempalle formation with predominantly carbonate sequence (Zachariah et al., 1999). Pyroclastic volcanism in the Papaghni sub-basin (Figure 4) has been reported from the south-west part of the Cuddapah basin (Sesha Sai, 2014). Geochemical studies (Chakraborty et al., 2016) suggested that basic flows in the Vempalle formation resulted due to low degree of partial melting of a mantle peridotite source.

Chitravati Group

Widespread Proterozoic magmatic events were recorded in the Tadpatri formation of the Chitravathi Group (Nagaraja Rao et al., 1987; Bhasker Rao et al., 1995; Anand et al., 2003; French et al., 2008; Chakraborty et al., 2016; Sheppard et al., 2017). Disposed parallel to the basin configuration in its southwestern part, the NNW-SSE to NW-SE trending ultramafic-mafic sills (Sesha Sai, 2011) and interbedded felsic magmatic rocks are contemporaneous with the sedimentation, and form part of the magmato-stratigraphy in the Tadpatri Formation (Figure 2).

The ultramafic sill (Figure 3d) is confined to lower part of Tadpatri Formation. The middle and upper part of the Tadpatri Formation are characterized by dolerite (porphyritic at places), mafic sill with elongated clinopyroxene phenocryst (Chakraborty et al., 2016) and olivine gabbro sill (Sesha Sai, 2011) along with rhyolite and fine-grained albite rich rock (vesicular on surface) that are interbedded

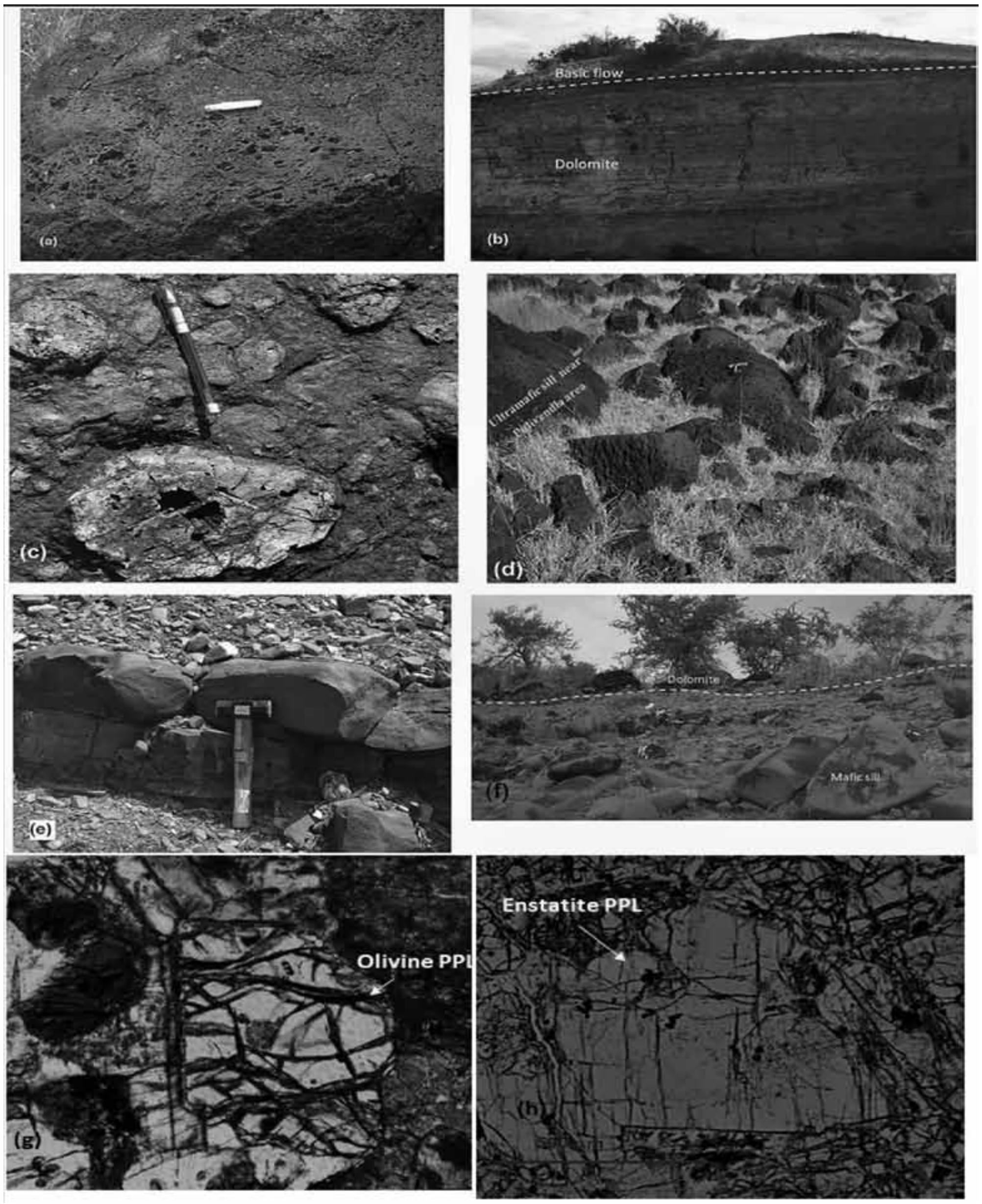

Figure 3. (a) Vesicular basic flow in Vempalle Formation, east of Motnutalapalle, SW part of the Cuddapah basin. (b) Basic flow over Vempalle dolomite, Vanambayi section, SW part of the Cuddapah basin. (c) Pillowed basalt fragments in mafic agglomerate Vanambayi section, SW part of Cuddapah basin. (d) Ultramafic sill in Tadpatri Formation, Loyala College section, Pulivendula, SW part of Cuddapah basin. (e) Rhyolite band within the dolomite-shale sequence of Tadpatri Formation, Mallela section, Cuddapah basin. (f) Mafic sill within the dolomite, Mallela section, SW part of the Cuddapah basin (g) Photomicrograph in PPL showing olivine in ultramafic sill. (h) Photomicrograph in PPL showing enstatite in ultramafic sill.

with dolomite-shale sequence (Figure 3e, f). During the course of cut-off trench excavation near Simhadripuram, large sized spindle shaped bodies resembling pyroclastic (5mm to 500mm diameter) were observed in Tadpatri formation (Babu and Satyanarayana, 2007 a). The basalt flows of Vempalle Formation (e.g., Srikantia, 1984; Murthy et al, 1987; Chatterjee and Bhattacharji, 2001; Chakraborty, et al., 2016) represent the early stage of volcanism in the Cuddapah basin. Incidentally, the basic volcanic flows are not seen in the stratigraphic horizons above the Papaghni group. However, felsic volcanics and fine-grained albite rich rocks are reported in Tadpatri and Nallamalai groups (Sesha Sai et al., 2016b; Das and Chakraborty, 2017; Figure 4). In a recent geochronologic study, Sheppard et al., (2017), indicated an age of 1862 ± 9 Ma for the felsic tuff in upper part of Tadpatri sequence in Chitravathi Group. A concealed body of olivine gabbro has been intersected in borehole during drilling at exit portal of Gandikota Tunnel,

Table 1. Paleoproterozoic magmatic events along with their geographical locations, ages and nature of occurrence at various stratigraphic horizons in the Cuddapah Supergroup (by Sesha Sai et al., present work; modified after Nagaraja Rao et al., 1987).

SUPER GROUP / GROUP	AGE	STRATIGRAPHIC SUCCESSION		MAGMATIC ROCKS IN CUDDAPAH SUPERGROUP	LOCATION IN CUDDAPAH BASIN	AVAILABLE AGE DATA
Kurnool Group (Kurnool and Palnad sub basins)						
~~Unconformity~~~~~~~~~~~~~~~~~~~~						
CUDDAPAH SUPERGROUP	PALEOPROTEROZOIC		**Srisailam Quartzite** Conglomerate, arenite, siltstone sequence	No Igneous rocks are reported within Srisailam Quartzite		
		NALLAMALAI GROUP	**Cumbum / Pullampet Formation** Shale, dolomite and arenite sequence	Tuffaceous sequences / associated (lapilli rosette) baryte (Karunakaran, 1976; Neelakantam, 1987; Deb and Bheemalingeswara, 2008) ultrapotassic rocks (Reddy, 1999) Mafic sills and felsic volcanics (Das and Chakraborty, (2017)	Mangampeta area in Pullampet sub basin. (Southern part of the NFB) Rajampet areas in Pullampet sub basin. (Southern part of the NFB)	No age data available
			Bairenkonda / Nagari Quartzite Conglomerate and arenite sequence		Southern part of NFB Rajampet area	No age data available
		~~Unconformity~~~~~~~~~~~~~~~~~~~~				
		CHITRAVATI GROUP	**Gandikota Quartzite** Shale and arenite	Olivine gabbro (Babu and Satyanarayana, 2007 b)		No age data available
			Tadpatri Formation Shale, dolomite, chert, jasper, shale and arenite sequence	Olivine Gabbro Rhyolite / Felsic tuff / Albite rich volcanic Ultramafic-mafic sills (contemporaneous with basin evolution)	Velupucherla section Mallela section Peddakudala-Pulivendla-Velpula section in SW part of Cuddapah basin	No age data available Felsic tuff - 1862 ± 9 Ma (Sheppard et al., 2017) Ultramafic sill 1817±24 Ma Rb-Sr Bhasker Rao et al. (1995) 1.9 Ga ^{40}Ar-^{39}Ar, (Anand et al., 2003) 1885.4±3.1 Ma U-Pb (French et al., 2008)
			Pulivendla Quartzite Conglomerate and arenite sequence	No Igneous rocks reported in Pulivendla Quartzite		
		~~Disconformity~~~~~~~~~~~~~~~~~~~~				
		PAPAGHANI GROUP	**Vempalle Formation** Dolomite, chert and siltstone sequence	Basic flows, felsic tuff, Mafic pyroclastics and mafic sills Rai, et al., (2015) Pb-Pb age of 1900-2000 Mafor dolomitisation and uranium mineralisation Zachariah et al., (1999) 1756 ± 29 Ma, uranium mineralisation in Vempalle Formation	Kuppalapalle-Vemula-Lingala-Lopatnutala section in SW part of basin	1841±71 Ma K-Ar (Murty et al., 1987) 1583±143 Ma Rb-Sr (Crawford and Compston, 1973)
			Gulcheru Quartzite Conglomerate and arenite sequence	Initiation of sedimentation ~ 2.1 Ga Gulcheru Red beds (Sesha Sai et al., 2016 a)	Western margin of Cuddapah basin	-
		~~Nonconformity~~~~~~~~~~~~~~~~~~~~				
Archaean granite-greenstone basement of eastern Dharwar craton						

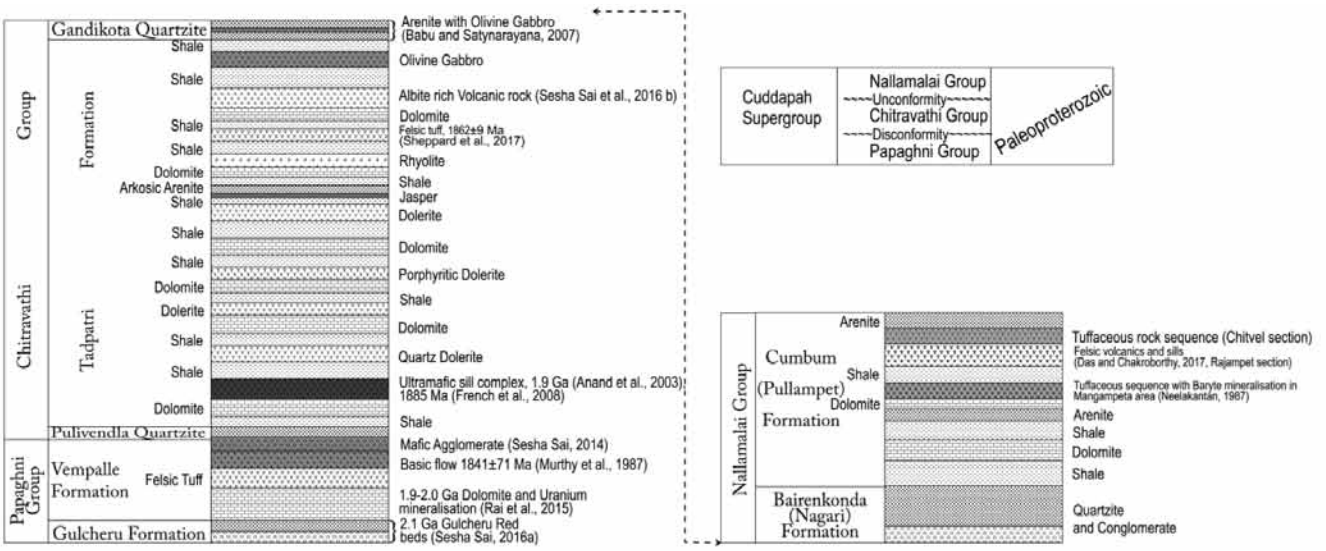

Figure 4. Chronostratigraphic illustration of the Paleoproterozoic magmatic rocks in various stratigraphic horizons in the Cuddapah Supergroup. Litholog not to scale, (modified after Nagaraja Rao at al., 1987).

upstream of Gandikota Dam, (Babu and Satyanarayana, 2007 b; Figure 4).

Pulivendla sill, IUGS nomenclature and its position in Cuddapah stratigraphy

Pulivendla Formation, with rudaceous and arenaceous succession is overlain conformably by the Tadpatri Formation of Chitravathi Group (see GSI, 1981; Nagaraja Rao et al., 1987). Most importantly, Pulivendla Formation is devoid of any igneous activity. Geographically, the 'Pulivendla' ultramafic sill occurs over a stretch of 12 km (Sesha Sai, 2011) from Peddakudala in NW to Velpula in SE and passes through Pulivendla town where it attains maximum width of 600 m. Stratigraphically, this ultramafic sill falls in the lower part of the Tadpatri Formation. In this context, the Table-1, will be useful to view various magmatic rocks (with geographical locations and ages) occurring at different stratigraphic horizons in the Cuddapah Supergroup.

Earlier the Pulivendla sill was identified names as "picrite" (Murthy, 1964; Somayajulu & Singhal, 1968; Nagaraja Rao et al., 1987; Sesha Sai, 2011); "mafic-ultramafic sill" (Anand et al., 2003; French et al., 2008) and "mafic-ultramafic sills of gabbroic and dolerite composition" (Chakraborty et al., 2016). Recent petrographic studies and modal analyses of 20 representative samples (thin sections) collected from the length of the sill indicated that this rock is predominantly made of olivine (36% to 44%). Among the pyroxene, enstatite is dominant and ranges from 25 to 28%, while the modal content of augite ranges from 15 to 22%. Both the orthopyroxene (enstatite) and the clinopyroxene (augite) together make upto 40%. Plagioclase varies from 5% to > 10%. Olivine (Figure 3g) is noticed as equant chadacrysts that are enclosed in larger oikocrysts of orthopyroxene, clinopyroxene and plagioclase resulting in poikilitic texture; a magmatic co-precipitation texture formed due to variation of rate of nucleation and rate of growth of the olivine chadacrysts enclosed in larger oikocrysts. Enstatite occurs as large euhedral grains showing well developed cleavage and high relief in plane polarised light (Figure 3h). Phlogopite varies from 5 to 8%. In IUGS Olivine-Pyroxene-Plagioclase diagram (Streckeisen, 1976), mineralogically the rock falls in the field of plagioclase bearing ultramafic to olivine gabbro norite. Samples with plagioclase < 10% fall in the field of plagioclase bearing ultramafic, while samples with > 10% plagioclase fall in the field of olivine gabbro norite (For mineral analyses, see Anand et al., 2003; Sesha Sai, 2011).

Concealed high velocity igneous body beneath the SW part of Cuddapah basin

On the basis of a significant geophysical study, the 'presence of a high velocity igneous body was indicated beneath the southwestern part of the Cuddapah basin' (Tewari and Rao, 1987). A positive gravity anomaly in the central part of the concentric sills points out the presence of a lopolith that probably originated through mantle upwelling during the early part of the basin's history (e.g., Mishra and Tiwari, 1995; Tewari and Rao, 1987; Chatterjee and Bhattacharji, 2001; Reddy et al., 2004). Bouguer anomalies indicate presence of a basic lopolith beneath the western part of the Cuddapah basin (Singh and Mishra, 2002). In the southwestern part of the basin, possible exhumation of mid crustal layer is indicated (Chandrakala et al., 2013), while Lakshmi and Rambabu (2002), through basement structure studies indicated a NW-SE elongated depression within a 10-km depth near Muddanuru. Based on geophysical studies (Chandrakala et al., 2010), a possible plume origin for the magmatism in the southwestern part of the Cuddapah basin was suggested. Sesha Sai (2011) observed that the mafic - ultramafic sills in SW part of the basin are the surface expression of a concealed high velocity igneous body as indicated by Tewari and Rao (1987). We observe that, through geophysical studies it is important to ascertain the exact depth of this high velocity igneous body, since a large ultramafic body is a potential host for Cr-Ni ± PGE orthomagmatic mineralisation.

Nallamalai Group

The southern part of the Nallamalai sub basin (Figure 1), is characterized by the presence of extensive sequences of dolomite and argillites with intercalated carbonaceous - variegated tuffaceous rocks (see GSI, 1981; Nagaraja Rao et al., 1987). The Mangampeta baryte deposit (Neelakantam, 1987), in Pullampet sub basin is perhaps the world's largest single bedded baryte deposit.

Karunakaran (1976) ascribed a volcanogenic origin for the bedded baryte near Mangampeta. Deb and Bheemalingeswara (2008) suggested the role of barium rich hydrothermal solution in submarine conditions with prolific biologic activity for the origin of the bedded baryte. Presence of fine dusty opaque material and two generations of pyrites and detrital clastic components are noticed in the carbonaceous shale of Pullampet Formation (Sesha Sai and Rajesham, 2010). Manikyamba et al., (2008) studied the geochemical aspects of black shale in Cuddapah basin. Ultra-potassic rocks, mafic sills and rhyolite have been recorded in the Pullampet sub basin (Reddy, 1999; Das and Chakraborty, 2017).

DISCUSSIONS

The clastic sediments of Gulcheru Formation and non-clastic sediments of Vempalle Formations of Papaghni Group in the western part of the basin are the earliest sedimentary sequences in Cuddapah Supergroup (see GSI, 1981). Initiation of sedimentation took place along the western margin of the Cuddapah basin with the deposition of Gulcheru red beds (Sesha Sai, et al., 2016a). The dolomite-chert non-clastic sequence of Vempalle Formation overlies the Gulcheru Formation. Establishing the 'Pb-Pb age of 1900-2000 Ma for the deposition, dolomitisation and the uranium mineralization associated with the Vempalle dolomites' by Rai et al., (2015) is a significant contribution. Aspects like the tectonic foundation, lithospheric substrate and proximity to a plate margin need to be considered for classification of basins (e.g. Allen et al., 2015). Lithospheric stretching can result in subsidence during the early stages in the extensional continental arc basins (eg. Busby, 2012). The Proterozoic Cuddapah basin of EDC, at its earliest stage of evolution, was a destiny to the craton derived clastic sediments constituting the Gulcheru Formation along its arcuate western margin. Confinement of the ~ 1.9 Ga ultramafic-mafic sills within the basin, but close to its western margin of the basin signifies a localised thermally active Paleoproterozoic magmatic domain. Further, the spatial association of the felsic volcanics with the Paleoproterozoic basic volcanics, ultramafic-mafic sills within the craton derived clastic and shallow marine non-clastic sequences in the Cuddapah Supergroup indicate a continental arc extensional setting. The ~1.9 Ga ultramafic / mafic magmatism associated with concomitant intracontinental rifting and basin development preserved along much of the south-eastern margin of the south Indian shield is a widespread geologic phenomenon on Earth (French et al., 2008). The fragments of Kenorland reassembled and attained maximum packing around 1.8 Ga to form the supercontinent Columbia (Ernst et al., 2013); an event that was marked by formation of a Large Igneous Province (LIP) in the Southern Indian Block (French et al., 2008; Ernst and Srivastava, 2008).

Role of subsidence and initiation of sedimentation

Subsequent to an Eparchaean interval of ~ 400 Ma, sedimentation in the Cuddapah basin was initiated during ~2.1 - 2.0 Ga over a thermally active magmatic domain along the eastern margin of Dharwar craton. The ~ 1.9 Ga mantle derived ultramafic-mafic sills indicate the role of deep seated mantle originated tectono- magmatic processes and its implications of the possible subsidence in SW part of Cuddapah intracratonic basin. Geophysical studies indicate that the Cuddapah basin was initiated in its western part due to the down faulting of the crustal block during the Paleoproterozoic (Kaila and Tewari, 1985). DSS studies (Kaila et al., 1987) indicate a gentle easterly dipping shallow basement in the western part of the Cuddapah basin near Parnapalle. Incidentally the linear pyroclastic mafic agglomerate zone (Sesha Sai, 2014) falls in the southern continuity of Parnapalle. In the recent significant works dealt with the origin of Proterozoic basins; the role of magmatism in extensional setting and its implications on the initiation of the intra cratonic basins of Africa have been discussed (e.g., Hartley and Allen, 1994; Armitage and Allen, 2010). Heine et al., (2008) noted that deep seated processes may result in subsidence in intra cratonic domains that have attained tectonic stability.

Disposition of the mafic-ultramafic rocks in SW part of the Cuddapah basin

Presence of the ~1.9 Ga mafic-ultramafic sills disposed in an arcuate manner in the SW part of the Cuddapah basin, indicates the existence of deep seated linear fracture system for emplacement of mantle derived rocks. Presence of deep-seated faults has been identified by geophysical studies near Parnapalle-Tonduru areas in the Cuddapah basin (Reddy et al., 2004). Absence of such linear ~ 1.9 Ga mafic-ultramafic sills outside the western margin of the basin indicates the confinement of the thermally active regime beneath the SW part of Cuddapah basin. The mafic-ultramafic sills in the Papaghni and Chitravati sub basins are perhaps, the surface expression of the concealed ultramafic body beneath the SW part of Cuddapah basin (Tewari and Rao, 1987).

CONCLUSION

The Proterozoic Cuddapah basin of Peninsular India, one of the largest sedimentary basins in the world during its early evolution witnessed Paleoproterozoic ultramafic-mafic-felsic magmatism. Subsequent to an Eparchaean interval of ~ 400 Ma, sedimentation in the basin was initiated over a thermally active magmatic domain along the eastern margin of the stabilised Dharwar craton during ~2.1 - 2.0 Ga. The high density igneous body beneath the SW part of Cuddapah basin possibly represents a concealed ultramafic feeder for the mafic-ultramafic sills in the Papaghni and Chitravati Groups. The linear zone of Paleoproterozoic ultramafic-mafic sills is confined to the Papaghni and Chitravathi sub basins. Further, configuration of the ultramafic-mafic sills parallel to the basin`s arcuate western margin, associated Paleoproterozoic felsic volcanics, association of these magmatic rocks with the craton derived clastic sediment and shallow marine non-clastic sequences indicate a continental arc extensional setting for the evolution Paleoproterozoic segment of Cuddapah basin, India.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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