Volcano-Sedimentary Interactions in the Tadpatri Formation

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Southern India's Early Crustal Processes

By

Sukanta Goswami

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DECLARATION

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PREFACE

Volcano-sedimentary systems form an integral part of Earth's geological archives, especially within sedimentary basins that developed over ancient cratonic blocks. These basins, formed due to deep-seated tectonic processes such as rifting, offer crucial insights into the dynamic interplay between volcanism, sedimentation, and tectonic evolution of the continental crust. The present volume delves into one such important geological phenomenon—the genetic linkage between volcanic eruptions and associated sedimentary processes, with a special emphasis on the volcano-sedimentary sequences preserved in the Proterozoic Tadpatri Formation of the Cuddapah Basin, southern India.

Volcanic eruptions within sedimentary basins are often intricately controlled by the deep-seated structural architecture—particularly basement faults, syn-sedimentary tectonics, and crustal-scale rift systems. These structural features act as conduits for magma and fluids and govern the style, geometry, and facies pattern of the erupted volcanic materials. The hydrological setting during eruption, basin slope, depositional environment, and post-eruption processes further influence the development of distinct volcanic facies.

The Cuddapah Basin, one of the most expansive and tectonically significant Purana basins of India, preserves a thick succession of sedimentary and volcanic units that date back to the Paleoproterozoic–Mesoproterozoic. Of particular interest is the ~1.86 Ga Tadpatri Formation, which offers an exceptional window into early continental processes, including shallow marine sedimentation, bimodal volcanism, and basin evolution. The bimodal nature of the volcanism, marked by both mafic and felsic units, and its association with rifting processes, make the Tadpatri sequence an ideal natural laboratory for decoding crustal-mantle interaction, magma evolution, and sedimentary responses to volcanism.

This work presents a detailed field and petrographic investigation of the felsic volcaniclastic and volcanic rocks within the Tadpatri Formation. Through lithofacies analysis, textural classification, facies mapping, and microscopic studies, the book attempts to classify the types of volcanic products, elucidate their eruption mechanisms, and define their spatial-temporal distribution. The structural and depositional textures, including pyroclastic surge deposits, lapilli-tuffs, fall tuffs, flow deposits, and reworked volcaniclastics, are categorized into multiple sub-facies. These are interpreted in the context of volcano-sedimentary processes and used to develop a comprehensive facies model of the sequence.

Particular emphasis is placed on the diagnostic textures that reflect stages of eruption, post-eruptive alteration (e.g., devitrification, carbonatization), and their interaction with sedimentary processes. The text also explores geochemical characteristics, including rare earth element patterns, trace element anomalies, and major oxide trends, which shed light on the magma genesis, crustal contamination, and mantle-crust interaction.

The presence of glass shards, spherulites, and lithophysae, along with structural features such as flow foliations and beddings, indicates a dynamic volcanic environment that evolved through violent explosive phases to subdued effusive activity, often interfacing with shallow water bodies or subaqueous environments. The felsic volcaniclastic units are shown to interdigitate with clastic and chemical sedimentary rocks, reflecting their evolution within a rift-controlled depositional basin.

This study ultimately contributes to the broader understanding of volcano-sedimentary processes in rift settings, emphasizing their implications for basin development, resource exploration (e.g., volcanogenic mineralization), and Proterozoic crustal dynamics. The integration of field, petrographic, and geochemical observations builds a coherent narrative of how bimodal volcanism, rift tectonics, and sedimentary basin architecture co-evolved in this ancient geological terrain.

It is hoped that this book serves as a valuable resource for students, researchers, geologists, and academicians engaged in the fields of volcanology, sedimentology, structural geology, and Proterozoic basin studies. By shedding light on one of the most intriguing volcano-sedimentary records in the Indian shield, it contributes meaningfully to the growing body of knowledge on intracratonic basin evolution and their significance in global geological context.

CHAPTER 1

THE AREA AND OBJECTIVES OF THE STUDY

1.1 INTRODUCTION

Volcanic and associated volcaniclastic rocks in a sedimentary basin can exhibit a great diversity in composition, texture and structure. This variation is due to frequent changes in eruption style, fast accumulation of volcanic materials and changes in mineralogy and chemistry. The chemical changes of volcanic and volcaniclastic rocks suggest interaction of lava with sediments, water, and other rocks during eruption and transportation from the source towards the deposition sites (Nemeth and Martin, 2007). In case of volcaniclastic deposits considerable variation can develop within a small section of rock column. The different flow beds can have different physical attributes and chemical properties. Generally, the transportation and deposition of volcaniclastic materials is quick and thus thick rock column is developed rapidly, which makes them useful in studying facies analysis to interpret past volcanic eruption conditions. Apart from the facies analysis, both mafic and felsic volcanic and volcaniclastic rocks can provide information on tectonic condition. The co-occurrence of felsic and mafic volcanic rocks is called bimodal association, which is generally observed in continental rift settings (Brewer et al., 2004; Kim et al., 2006; Dostal et al., 2017). Modern day examples of rift associated bimodal volcanism exhibits gentle nature of basaltic eruption as compared to that of felsic volcanic eruptions, which commonly show sudden shifts between powerful explosive eruption and gentle effusion of lava (Nguyen et al., 2014). The consequence of high and low magma ascent rates and gas bubble content lead to such phenomenon of different types of eruption. The origin of bimodal volcanic eruption is explained and mostly the emplacement process is linked with rifting mechanism (Zellmer et al., 2008; Wadge et al., 2016). Thus, the record of bimodal volcanic rocks within ancient sedimentary basins may be useful in interpreting magma history and eruption mechanisms which in turn is related to geodynamic processes related to rifting.

Volcanic eruptions can produce coherent rocks (directly solidified from a melt) and clastic debris (through different types of fragmentation, transportation and depositional processes). The term "volcaniclastic rock" is used to represent deposits composed predominantly of volcanic particles of any shape and size (Fisher, 1961). There are four main genetic categories of volcaniclastic deposits viz. autoclastic, pyroclastic, resedimented and volcanogenic sedimentary deposits. Each one of them have sets of distinguishing features and further subdivisions. Volcaniclastic facies analysis is important in understanding vertical and lateral facies variation and evolution of volcanic gravity current with time. Diversity of facies within volcaniclastic sequences can be used to reconstruct magma genesis, mechanism of volcanic eruption and flow, and subsequent modifications as well as physical and chemical processes associated with them.

Identification of different textures and structures within volcaniclastic rocks in field and under microscope can provide significant insights into eruption history. The textures in volcanic deposits develop in three main stages: (1) during eruption and emplacement processes, (2) subsequent modification by syn-volcanic processes (e.g., oxidation, degassing, hydration, vapour phase alteration, high-temperature devitrification, hydrothermal alteration) and (3) modification by post-volcanic processes (e.g., hydration, devitrification, hydrothermal alteration, diagenesis, metamorphism, deformation, weathering). Volcanic eruption style may be either explosive or effusive. In the case of effusive eruption lava steadily flows out of a volcano onto the ground. Explosive eruption is characterized by violent expulsion of magma from a volcano into air.

Effusive eruptions are most common in the case of basaltic magmatism. They can also outpour volatile-poor intermediate and felsic magmas and produce lava flows and lava domes that comprise coherent and autoclastic (Namiki and Manga, 2008; Nguyen et al., 2014). Volcanic eruptions within sedimentary basins are often controlled by deep basinal architecture, structures (mainly faults) within basement and the tectonic setting. The different volcanic facies reflect the hydrological condition during eruption, transport and depositional mechanism, palaeo-slope and wind direction and interaction with chemical and clastic sedimentation. Bimodal volcanism in cratonic sedimentary basins, characterized by close association of mafic and felsic volcanic and volcaniclastics rocks, is of special interest. Investigations on such association has significant implications for understanding formation and evolution of intracratonic basins, the role of rifting in formation of accommodation space and channelization of magma and heat flow within the continental crust (McKenzie, 1978; White and McKenzie, 1989; Manatschal, 2004; Koptev et al., 2016).

The Indian subcontinent is physiographically divided into three broad domains from north to south i.e. the Extra-Peninsular India, the Peninsular India and the Indo-Gangetic Alluvial Plain (Fig 1.1). The Peninsular India comprises Archaean cratons like Dharwar, Bastar, Singhbhum, Aravalli and Bundelkhand. They are bordered by mainly Proterozoic mobile belts like Central Indian Tectonic Zone, Eastern Ghats and Southern Granulite Terrain. The Dharwar Craton in southern India consists of 3.6–2.5 Ga Archaean granite-greenstone belts (Jayananda et al., 2018) and younger mafic dyke swarms. The craton stabilized at about 2.5 Ga followed by cratonic sedimentation in three Proterozoic basins viz. Cuddapah, Bhima and Kaladgi (Fig. 1.2). These basins are important archives of surface processes, volcanism and biological and atmospheric evolution that occurred over a prolonged period. The largest amongst the three, the crescentic Cuddapah basin, hosts a thick (~12 km) succession of platform sediments exposed over about 44,500 sq. km area (Fig 1.3). This basin comprises five sub-basins (viz. Papaghni, Nallamalai, Srisailam, Kurnool and Palnad). The present study area is situated in the southwestern part of the basin which comes under Papaghni sub-basin. The Papaghni sub-basin comprises Papaghni and Chitravati Group of rocks. Chitravati Group is further sub-divided in to Pulivandula, Tadpatri and Gandikota Formations.

The present work focuses on the ~1.86 Ga felsic volcanic and tuffaceous volcaniclastic rocks of Tadpatri Formation (Sheppard et al., 2017), which consists of about 4.6 km thick package of shale, quartzite and carbonate rocks with an aerial extent of about 1000 sq.km. (Nagaraja Rao et al., 1987). The upper part of Tadpatri Formation consists of a variety of igneous rock types like mafic flows and sills as well as felsic volcanic and volcaniclastic rocks suggesting bimodal volcanism. Such bimodal association of mafic and felsic rocks is of broad scientific interest because they are generally associated with continental rift setting.

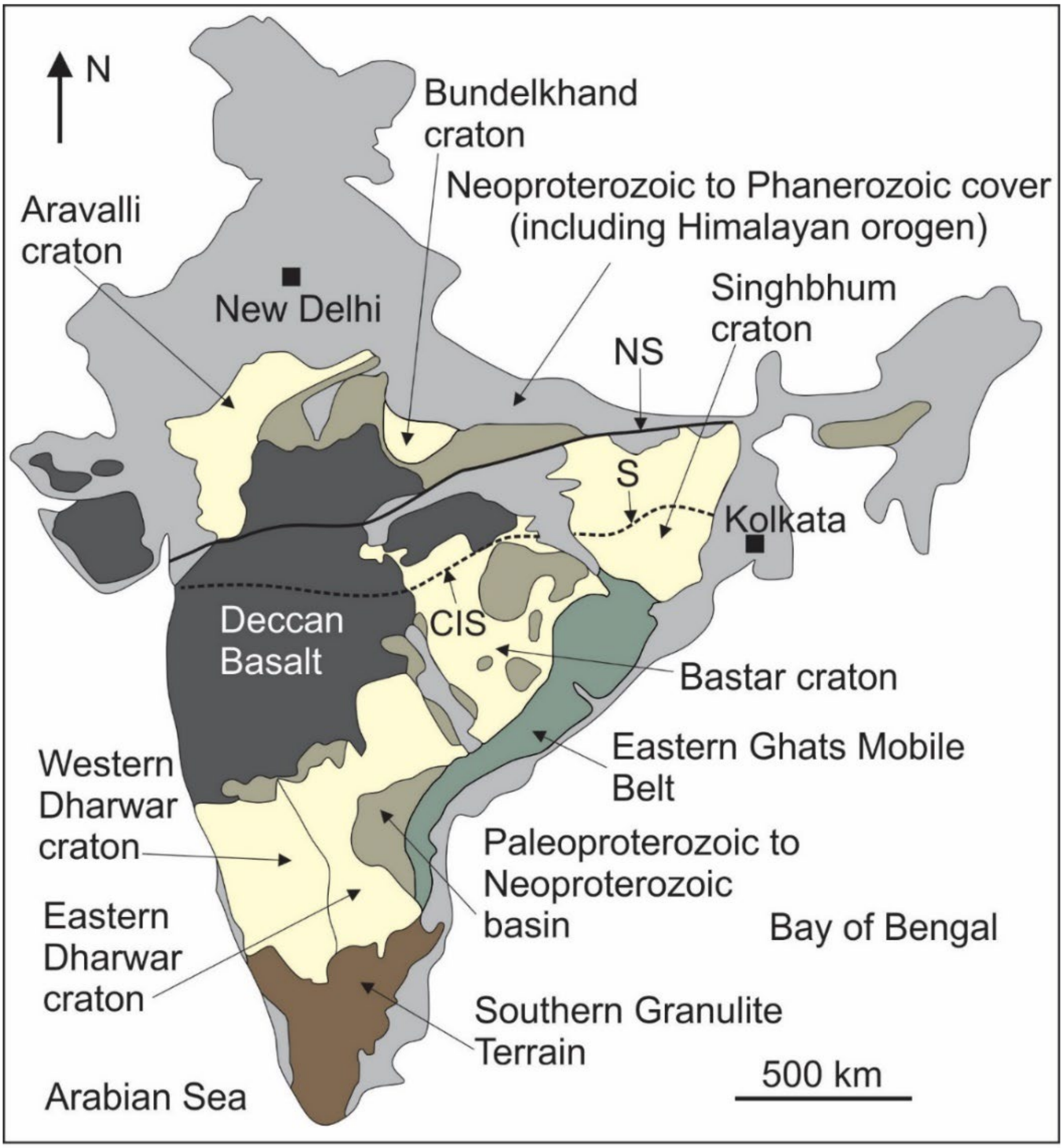

Fig 1.1 Simplified geological map of India showing different cratons, mobile belts and Proterozoic and younger sedimentary basins (modified after Geological Map of India, Geological Survey of India, 1998). CIS – Central Indian Shear Zone, NS – Narmada-Son Fault.

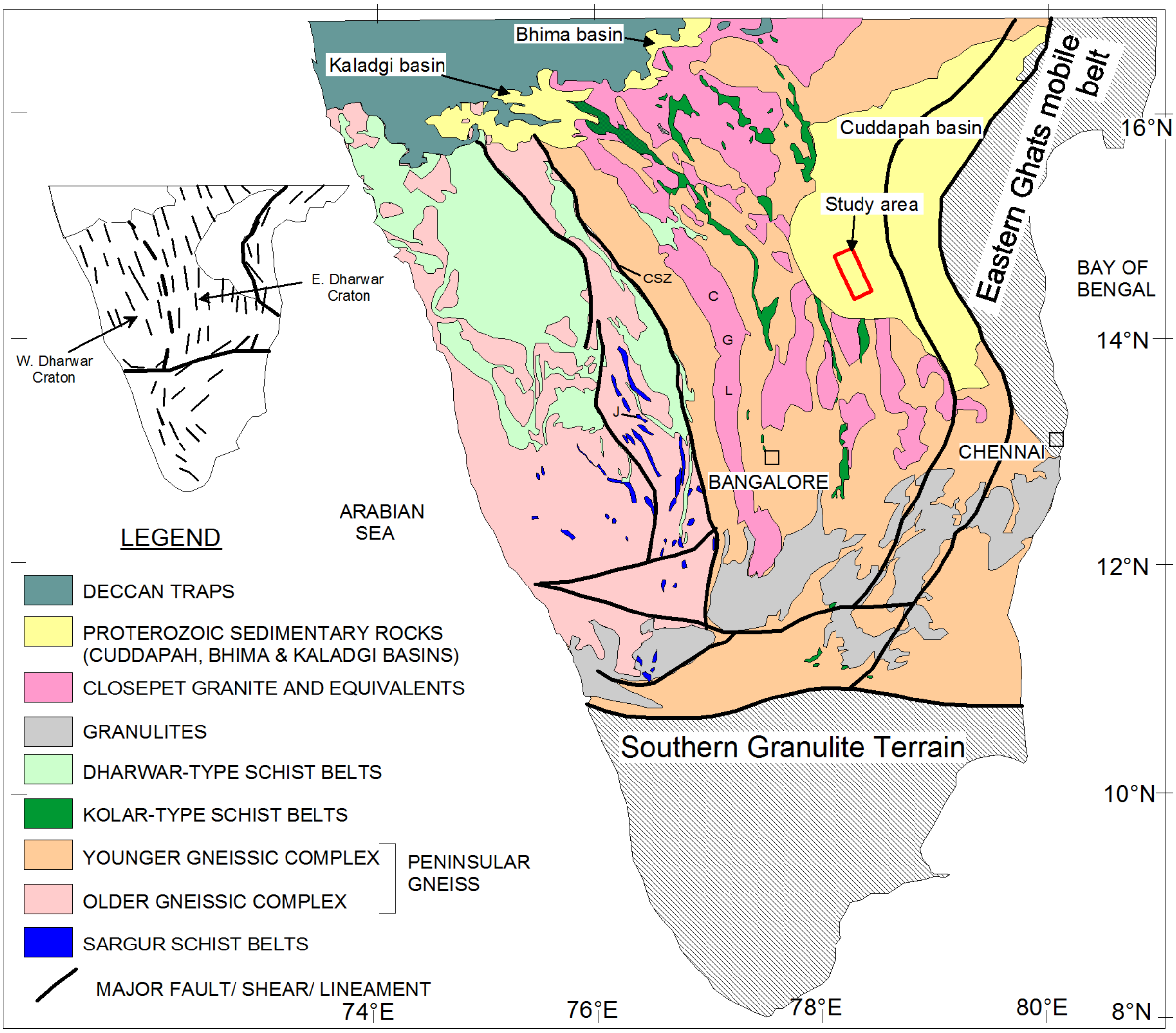

Fig 1.2. Geological map of the Dharwar craton, southern India (modified after Vasundhara Project, Geological Survey of India, 1994). CSZ – Chitradurga shear zone, CGL – Closepet Granite. The location of the Cuddapah basin and the study area are shown.

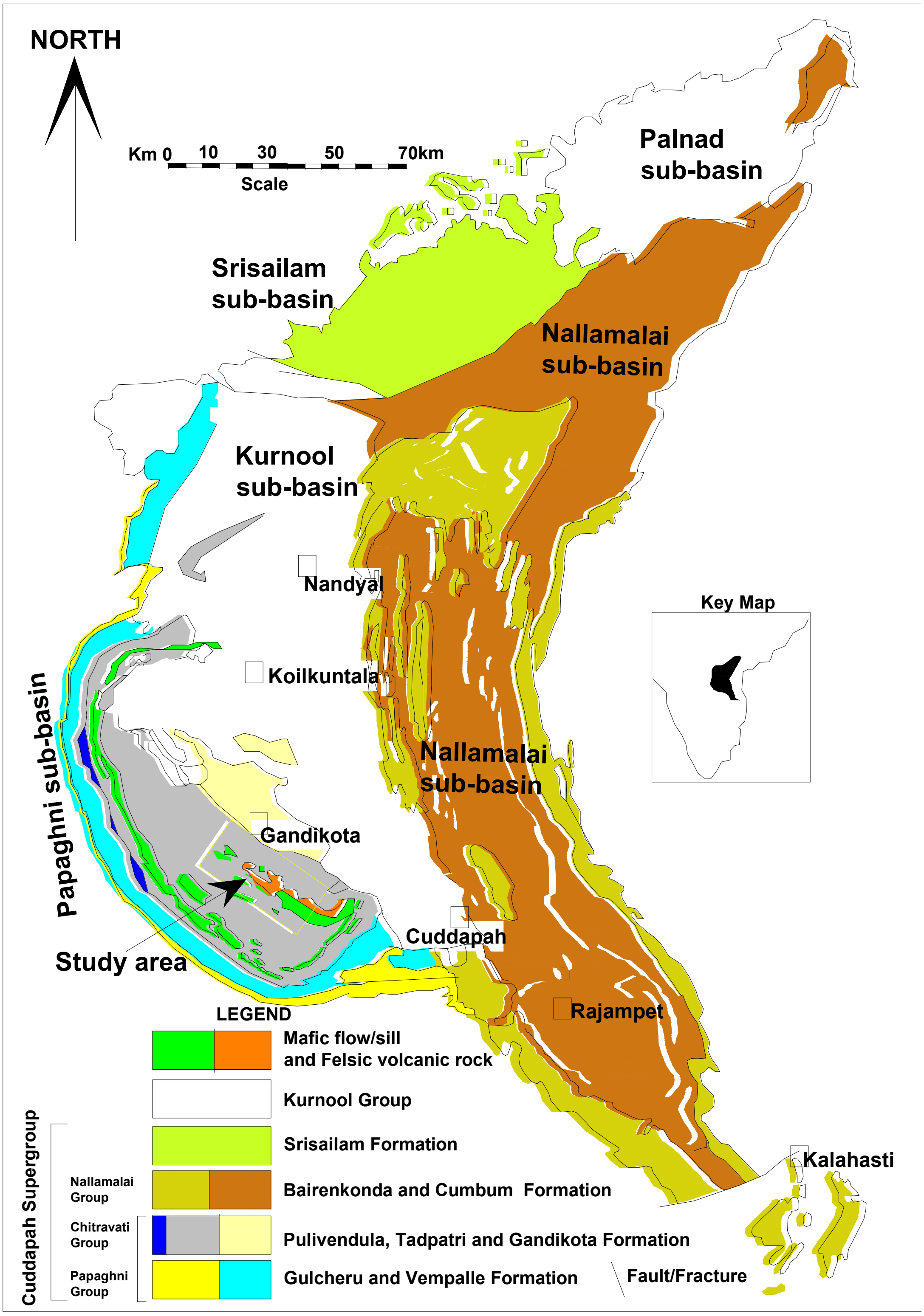

Fig 1.3. Geological map of the Cuddapah basin (modified after Nagaraja Rao et al., 1987) showing different sub-basins. The rectangular block represents the study area.

Some workers mapped the mafic flows and sills of the Tadpatri Formation and published geochemical and geochronological data (GSI, 1981; Murthy et al., 1987; Bhaskar Rao et al., 1995; Anand et al., 2003; French et al., 2008; Chakraborty et al., 2016). However, information on the felsic volcanic and volcaniclastic rocks is very scanty. The extrusive environment of felsic lavas with associated ash fall tuffs and the resedimented volcaniclastic components is not well characterized. The exposures of felsic volcanic and tuffaceous volcaniclastic components are limited and mostly altered. During the course of this work, the outcrops of felsic volcaniclastic and volcanic rocks are demarcated on the map and the wide range of structures and textures, lithological variation and facies associations shown by them are documented. The study has implications for understanding the physical processes producing the diverse kind of volcanic rock types, mechanism of syn-sedimentary volcanism and tectonics.

1.2 LOCATION AND ACCESSIBILITY

The study area can be accessed easily. It is located in the Kadapa (Cuddapah) district within the state of Andhra Pradesh at about 250 km NNE of Bengaluru (Bengaluru (Bangalore)) city, 50 km NW of Kadapa town and 35 km north of Pulivendla. The area is well connected with these cities through National Highways nos. 28, 51, 30 and 54D. The south-central railway track also passes along the area with Kadapa and Tadpatri as the prominent railway stations.

1.3 GEOMORPHOLOGY

Geomorphologically, the area can be divided into two prominent units, namely (i) denudational landforms comprising (a) hills, ridges, inselbergs, and hogbacks (b) pediment and dissected pediment and (ii) depositional landforms such as (a) alluvial fans and colluvial fans (b) alluvial valley fills along river courses.

1.4 CLIMATE, VEGETATION AND DRAINAGE

The climate is semi-arid with a dry season from December to May and a monsoon season from June to September. The summer (March to May) is very hot when the temperature varies from 28 to 44 °C. The area receives rainfall from both the southwest monsoon as well as the northeast Monsoon. The temperature falls appreciably (range 25 to 35 °C) with the onset of Monsoon. The average annual rainfall is 670 mm. The winter season (November to February) is comparatively milder (18 to 30 °C). This is the best season for field work. The rivers Penner, Chitravati, Papaghni, Mandavi and Cheyyeru flow easterly through the area.

The main vegetation is scattered jungles of open scrub. Other vegetation types are rain-fed and irrigated crops that are mainly grown in the plains. Major crops grown include paddy, oats, cotton, sunflower, groundnut and chilly. The chief economic activities include agriculture and mineral exploitation (quarries of limestone and construction slabs).

1.5 STATEMENT OF PROBLEM

The felsic volcaniclastic and volcanic rocks of the Tadpatri Formation have received little attention. Earlier studies have only reported occurrences of felsic volcanic rocks and tuffs without detailed maps. No detail facies analysis, in conjunction with Petro-mineralogical and geochemical studies, have been reported till date. Little information is available on the classification of the felsic volcaniclastic and volcanic rocks of the area, their eruptive/ emplacement mechanism and role in basin evolution. Therefore, to reduce the knowledge gaps, the objective of the present work is to address the following scientific issues:

i) What was the relationship between different volcanic lithofacies? What was the depositional condition of the felsic volcaniclastic rocks?
ii) What was the physical nature (i.e., explosive or effusive or combined type) of volcanism in the area?
iii) What was the relationship between felsic and basic magmatism?
iv) What was role of volcanism in contemporary basin evolution?
v) What was the possible geodynamic process involved in volcanic eruption?

1.6 METHODOLOGY

To fulfill the above objectives the following methodology have been followed:

i) Consultation of available literature and maps

ii) Field studies

- Geological mapping (1:100,000 scale) over 500 km^2 area along Tadpatri-Tonduru tract in the Tadpatri Formation, where outcrops of felsic volcaniclastic rocks are well exposed.
- Identification of volcaniclastic facies based on different lithological attributes (e.g., colour, grain sizes and shapes, internal organization of textures and structures etc.)
- Preparation of lithologs and study of spatial relationship between different volcaniclastic facies.
- Identification and interpretation of facies associations.
- Systematic sampling of the lithounits.
- Construction of volcanic stratigraphy of the area.

iii) Laboratory and analytical works

- Study of mineral composition, texture and alteration of the felsic volcaniclastic and volcanic rocks using conventional petrological microscope.
- Study of glass shards and devitrification structures like spherulites, lithophysae and other altered minerals.
- Study of whole rock major and trace element composition to classify the rocks and examine their origin.

iv) Compilation and interpretation of data to interpret petrogenesis, construct facies model and suggest tectonic setting of the volcanism.

CHAPTER 2

GEOLOGY OF THE CUDDAPAH BASIN

2.1 INTRODUCTION

The Cuddapah basin in southern India extends for a length of about 445 km along the arcuate eastern margin with a mean width of about 100 km. This N-S elongated Cuddapah basin covers an area of about 44,500 sq. km. (Nagaraja Rao et al., 1987). The basin name is coined after the town Cuddapah (now renamed as Kadapa) situated within the basin. The basin is nonconformably lying above Archaean granitoids and greenstone belts of the East Dharwar Craton (EDC) in the north, south and west (Fig 1.2). The eastern margin of the basin is a tectonic margin along which metamorphosed Nellore schist belt rocks has been thrusted up on the rocks of the Cuddapah basin. King (1872) was the first to give a detailed account of stratigraphy, structure and tectonics of the basin. The rocks of Cuddapah basin are divided into Cuddapah Supergroup and Kurnool Group. Stratigraphically the Cuddapah Supergroup is divided into three Groups i.e. Papaghni, Chitravati and Nallamalai Groups. The Table 1 shows the stratigraphy, igneous episodes, available age data and mineral wealth of the Cuddapah basin. The basin has about 12 km thick succession of sedimentary rocks with volcanic flows and sills. The basin is characterized by quartzite-shale-carbonate cycles and the early sediments of the basin are interspersed with mafic volcanic flows and sills. The arcuate eastern margin is deformed by a prominent thrust which is parallel to the Eastern Ghats mobile belt and the East Coast of India (Figs. 1.1 and 1.2). The western part of the basin is relatively less affected by tectonic activity and sedimentary rocks dip gently (10 -15^0). The relatively unreformed western part of the basin consists of four sub-basins (Papaghni, Kurnool, Srisailam and Palnad) (Fig. 1.3). The rocks of Nallamalai Group in the east are intensely folded, with intensity and complexity of folding increasing from west to east. The Papaghni sub-basin comprises Papghni and Chitravati Formations. The Nallamalai sub-basin is regarded as a fold belt and made up of Nallamalai Group of rocks. Srisailam Quartzite is found in the Srisailam sub-basin. Kurnool rocks are found within the Kurnool and Palnad sub-basins.

Table 1 Composite log showing stratigraphy (after Nagaraja Rao et al., 1987) igneous events and mineral resources of the Proterozoic Cuddapah basin, southern India.

	Formation	Lithology	Thickness	Igneous activity	Isotopic Age	Minerals
KURNOOL GROUP	Nandyal Shale	Shale	50-100m		913 ± 11 Ma (Detrital Zircon) [H] Maximum age	Limestone Building materials
	Koilkuntla Limestone	Limestone	15-50m			
	Paniam Quartzite	Quartzite	10-35m			
	Owk Shale	Shale	10-15m			
	Narji Limestone	Limestone	100-200m			
	Banganapalle Quartzite	Quartzite + Conglomerate	10-50m			
CUDDAPAH SUPERGROUP	Srisailam Quartzite	Quartzite + Shale	~300m			U
	Cumbum (Pullampet) Shale	Shale/Phyllite Quartzite & Dolomite	~2000m	Lamproite dykes, Syenite stock, Dolerite sills and Granite intrusives; Felsic volcanic rocks and tuffs	1418±8 Ma (Ar/Ar Phlogopite from chelima lamprolite)[G], 1354±17 Ma and 1070±22Ma (Rb/Sr Chelima and Zangamarajupalle Lamprolite respectively)[F] 1371±45 Ma (K/Ar chelima lamprolite)[A]	Barite, Pb, Cu, Zn
	Bairenkonda (Nagari) Quartzite	Quartzite, Shale, Conglomerate	1500-4000m	Dolerite sills		
	Gandikota Quartzite	Quartzite, Shale	~300m	Siliceous tuff and felsic vocaniclastics, Dolerite, Picrite and Gabbro sills and dykes, basaltic flows		
	Tadpatri Formation	Shale, Tuff, Quartzite, Dolomite, Felsic and mafic volcanic rocks	~4600m		1862±9 Ma U-Pb Felsic volcanic rock (Zircon age)[I], 1817±24 Ma (Rb/Sr Mafic sill; whole rock)[E], 1899±20Ma (Ar/Ar phlogopite from mafic sill)[D]	

					1756±29 (Pb/Pb age of U mineralisation and minimum age of dolomite) [C] 1885±3.1Ma (U/Pb Beddeleyite from mafic sills) [B]	
	Pulivendla Quartzite	Quartzite, Conglomerate	1-75m			U
	Vempalle Formation	Dolostone, Mudstone, Quartzite	~1900m	Dolerite, Picrite and Gabbro Sill and Dykes, basaltic flow		U. Asbestos, Barite
	Gulcheru Quartzite	Quartzite, Conglomerate	28-210m	Dolerite dykes		U

2.2 NATURE OF BASEMENT

The Cuddapah basin is nonconformably lying above the basement rocks, which belong to a part of the Eastern Dharwar Craton (EDC). The Dharwar Craton (DC) is divided into two parts viz, Western Dharwar Craton (WDC) and Eastern Dharwar Craton (EDC) with Chitradurga Shear Zone (CSZ) in between (Swami Nath and Ramakrishnan, 1981; Naqvi and Rogers, 1987; Chadwick et al., 2000, 2007; Jayananda et al., 2006, 2015; Chardon et al., 2008, 2011; Jayananda, 2018). (Fig 1.1 and 1.2). The WDC is dominated by 3.4–3.0 Ga Tonalite -trondhjemite-granodiorite (TTG) gneisses interspersed with coeval Sargur-type greenstone belts (e.g., Beckinsale et al., 1980; Meen et al., 1992; Dey, 2013; Jayananda et al. 2015; Lancaster et al., 2015). This craton stabilized at around 3.17 Ga (Guitreau et al., 2017). The TTG gneisses and Sargur-type greenstone belts are overlain by 2.9–2.55 Ga sediments and volcanic rocks of the Dharwar-type greenstone belts (Chadwick et al., 2000; Manikyamba et al., 2017; Jayananda, 2018). The EDC is composed of mainly greenschist facies 2.7 Ga greenstone belts and 2.7–2.5 Ga calc-alkaline felsic plutonic and volcanic rocks (e.g., Jayananda et al., 2000, 2013; Chardon et al., 2002; Dey et al., 2012, 2016; Manikyamba and Kerrich, 2012; Manikyamba et al., 2017). Older (3.3–3.0 Ga) granitoids and metasediments are rare in the EDC and only present as remnants (Jayananda et al., 2000; Bidyananda et al., 2011; Maibam et al., 2011; Dey, 2013). The EDC is regarded as an Archean accretionary complex containing several arc- and plume-related terranes which accreted at around 2.55 to 2.50 Ga (Manikyamba and Kerrich, 2012; Manikyamba et al., 2017). The craton stabilized at 2.5 Ga with intrusion of voluminous K-rich granitoids (Dey, 2013; Jayananda, 2018). The Dharwar Craton shows N-S to NNW-trending structural fabric which is ascribed to transcurrent shear deformation because of crustal scale shortening in a Neoarchaean (2.56–2.51 Ga) convergent set up (Chardon et al., 2008). The N-S trending linear greenstone belts like Kadiri and Veligallu as well as granitoid plutons form basement for the Cuddapah sediments. These Archaean granitoids and grenstone belts of the Dharwar craton are intruded by numerous mafic dykes and quartz reefs. The dykes are emplaced along different trends viz, N-S, NW–SE, E–W and NE–SW. Most of the dykes are doleritic to porphyry basalt in composition (French and Heaman, 2010; Belica et al., 2014; Goswami et al., 2017c). The initiation of sedimentation in the Cuddapah basin is started after this dyke emplacement (i.e., ~2200-2082 Ma) in the basement (French and Heaman, 2010; Anil Kumar et al., 2015). Therefore the initiation of sedimentation within the Cuddapah basin should be less than 2 Ga. Over the Archaean granitoids and greenstone belts and Proterozoic dyke's widespread platform sedimentation took place at 1.9–0.6 Ga which are now preserved within the Cuddapah basin. The basin has received sediments from the surrounding basement (Saha and Mazumder, 2012; Saha and Tripathy, 2012).

2.3 BASIN STRATIGRAPHY

There are differences in opinion regarding the stratigraphic classification of the Cuddapah basin due to complexity of lithounits of different sub-basins. It was believed that Nallamalai Group of rocks are a part of the Cuddapah Supergroup, which comprises Papaghni, Chitravati and Nallamalai Groups (Nagaraja Rao and Ramalingaswamy, 1976; Nagaraja Rao et al., 1987; Matin, 2015). However, according to Saha and Tripathy, (2012) Nallamalai succession is an allochthonous unit and the basal thrust has brought up the Nallamali Fold Belt (NFB) in its present position. The Kurnool Group is lying above the Cuddapah Supergroup. The thickness of sedimentary rock units of Cuddapah Supergroup is not uniform. The cyclic sequence of quartzites, shale and limestone units together form Papaghni Group (2100m), Chitravati Group (6000m), Nallamalai Group (3500m) and Kurnool Group (520m).

The Papaghni sub-basin hosts the lowermost Papaghni Group and the Chitravati Group, separated by an unconformity (Lakshminarayana et al., 2001; Chaudhuri et al., 2002; Saha and Tripathy, 2012). The Papaghni Group consists of the Gulcheru and Vempalle Formations. The Gulcheru Formation consists of conglomerates, orthoquartzites and grits with siltstones (Chakrabarti et al., 2009). The Vempalle Formation comprises mainly of dolomite and shale with some interlayered sills, tuffs and lava flows in the upper part. The Chitravati Group, lying disconformably above the Papaghni Group, consists of three formations viz, Pulivendla Quartzite, Tadpatri Shale and Gandikota Quartzite. The Pulivendla Quartzite has mostly small and patchy outcrops which are often restricted in strike continuity. This unit is mainly areneceous with well-sorted quartz arenite and lag pebbles observed in the basal part. Trough cross-bedded units with azimuth of trough axes varies between north and west (Dasgupta and Biswas, 2006). The Pulivendla Quartzite grades upward into a fine shale and calcareous sandstone unit of heterolithic nature. This heterolithic unit, dominated by shale, forms the Tadpatri Formation. The upper part of this formation contains mafic flows and sills and felsic volcanic and volcaniclastic rocks. All of the lithounits are broadly striking NW-SE and dipping gently (~10º) due NE.

The Gandikota Quartzite is conformably overlying the Tadpatri Formation in the downdip direction. This is a texturally mature medium- to coarse-grained quartz arenite (Saha and Tripathy, 2012). The Papaghni and Chitravati Groups represent two cycles of sedimentation in the Papaghni sub-basin. The rocks of the Nallamalai Group stratigraphically occupy a position above the Chitravati Group with angular unconformity in between according to conventional interpretation (Nagaraja Rao et al., 1987). The Papaghni sub-basin is structurally less deformed as compared to the Nallamalai sub-basin, the latter being intensively folded and thrusted. Therefore, the Nallamalai sub-basin is often called as a fold belt (Nagaraja Rao et al., 1987; Saha and Tripathy, 2012). The lowermost Bairenkonda Quartzite (also called Nagari Quartzite) of the Nallamalai Group is characterized by a fining upward shallow marine aranaceous sequence (Saha and Tripathy, 2012). Further up in the stratigraphy occurs the Cumbum Formation (also called Pullumpet shale). According to Dasgupta and Biswas (2006) volcaniclastic rocks are present within this shale. The Srisailam Formation in the Srisailam sub-basin occur disconformably on the Chitravati Group (Patranabis-Deb et al., 2012; Collins et al., 2015). The Neoproterozoic Kurnool Group unconformably overlies the Cuddapah Supergroup and represents two cycles of sedimentation depositing arenaceous-carbonate-shale sequence (Sharma, 2011; Collins et al., 2015). The first cycle includes lower part of Kurnool Group, which is made up of Banganapalle Quartzite, Narji Limestone and Owk shale. The upper part of the Kurnool comprising Paniam Quartzite, Koilkuntala Limestone and Nandyal Shale represents the second cycle. Collins et al. (2015) suggested that the Gandikota Formation is correlatable with the Kurnool Group.

2.4. STRUCTURE

The Cuddapah basin has a less-deformed western part (comprising Papaghni, Srisailam, Kurnool and Palnad sub-basins) and highly deformed eastern part. The eastern part is known as Nallamalai fold belt (NFB). The less-deformed and highly deformed parts are separated by a deep crustal fault called Rudravaram line (cf. Meijerink et al., 1984).

The Rudravaram line is also called as Maidukuru Thrust (Fig 2.1) (Saha et al., 2010), along which the Nallamalai Group is thought to be transported and come up on the Papaghni Group (Saha and Tripathy, 2012). The structural maps of the Cuddapah basin proposed by Chakraborti and Saha (2006) and Saha et al. (2010) document major faults, including boundary thrusts, and other geological details. Within the Nallamalai Fold Belt the intensity of folding increases progressively from west to east in the NFB (Meijerink et al., 1984). The open folds is common in western part whereas tight to isoclinal folds are common in the eastern part of NFB.

Deformational structures in basement complexes as well as Cuddapah basinal sedimentary rocks indicate at least three events of tectonism (Mukherjee et al., 2018). These deformation events are responsible for present basin configuration. The crescent-shape of the Nallamalai fold belt in the east is due to E-W compression related to thrusting followed by NNE-SSW compression (Mukherjee et al., 2018).

According to Chetty (2011) the evolution of Cuddapah basin is genetically related to the collisional processes and associated crustal-scale transpressional tectonics during Proterozoic in the basement at the eastern margin.

The most common E–W and N–S extension joints in the southern part of the Papaghni sub-basin indicate that the older E-W joints were formed by maximum compression (σ_1) along E-W and minimum compression (σ_3) along N-S direction (Goswami et al., 2012; 2016a). Later N-S joints are related to some modification in stress field. The conjugate joint sets with NE–SW and N15^{0}W–S15^{0}E trends indicate ~ N15°E–S15°W acute bisector (σ_1) direction. Therefore, the maximum compression (σ_1) direction switched from E-W to NNE-SSW with time and later stress is mostly responsible for shear fracture and N-S extension fracture development depending upon rheology and orientation of litho-unit (Goswami et al., 2012; 2016a).

The transverse faults in the western margin of Cuddapah basin, viz. the Gani–Kalva and Kona faults, record signatures of extensional/strike-slip regime crustal deformation related to rifting (Tripathy and Saha, 2009; Tripathy, 2011). According to Saha and Tripathy (2012), the initial opening of the Cuddapah basin in the west is related to transverse faulting along these faults. A late contractional deformation is proposed from structural analysis of Palnad sub-basin (Saha and Chakraborty 2003; Chakraborti and Saha, 2006). This contractional events of late Neoproterozoic was correlated with amalgamation of Gondwanaland (Saha and Chakraborty 2003; Chakraborti and Saha, 2006).

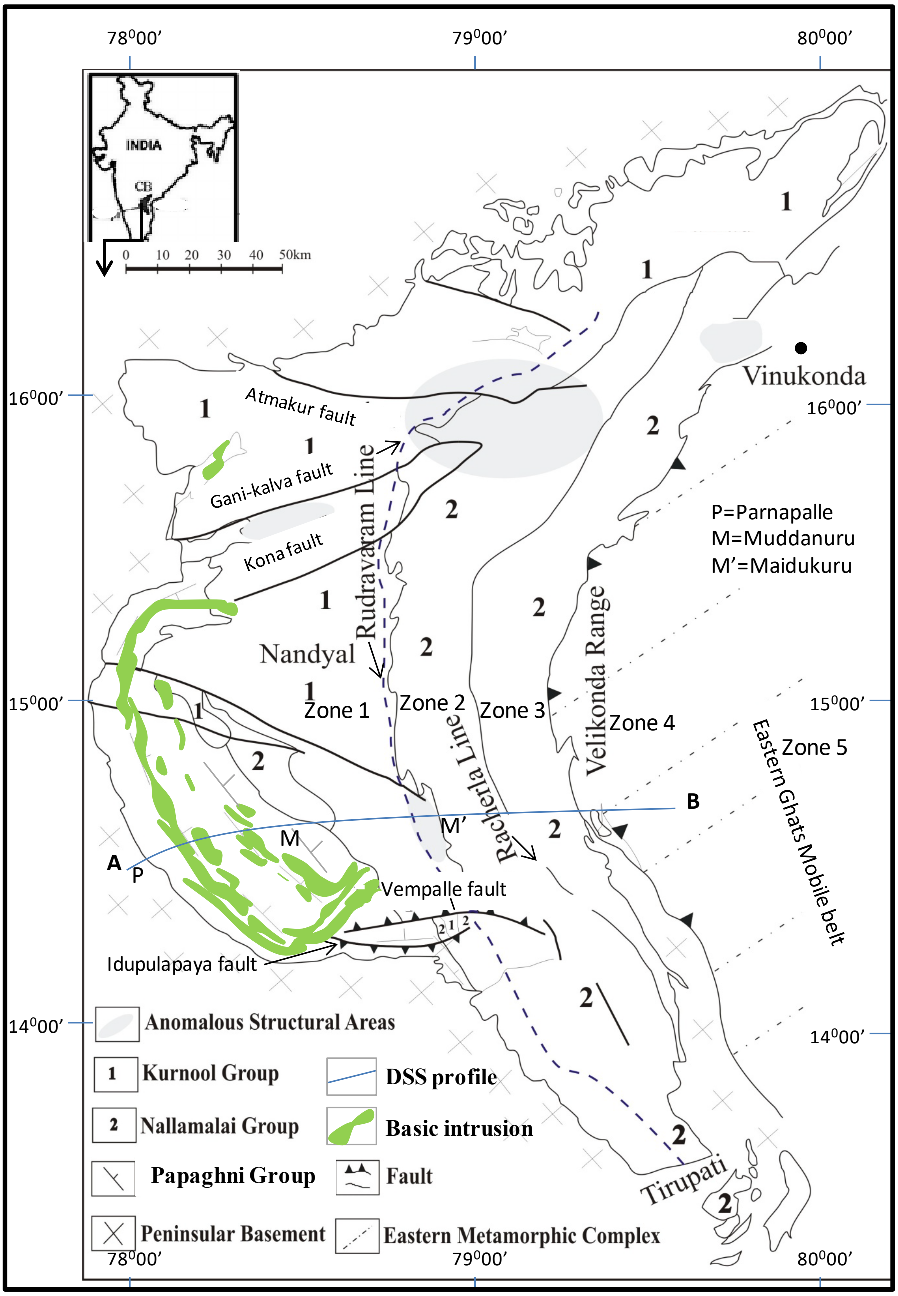

Fig 2.1. Structural map of the Cuddapah basin (modified after Meijerink et al., 1984) showing the mafic igneous emplacements following the periphery of Papaghni sub-basin margin. Along the blue line, geological section (AB) was prepared by Geological Survey of India (1981) based on DSS profile data (Kaila et al., 1979). Anomalous structural areas are marked to indicate highly deformed and structurally complicated areas by Meijerink et al. (1984).

2.5 IGNEOUS EPISODES

Within the Papaghni sub-basin mafic flows and sills, occur as arcuate bodies in parallelism with the western margin of the of the basin (Nagaraja Rao et al., 1987) (Fig. 2.1). Sesha Sai et al (2017) reported a detail account of the ultramafic-mafic-felsic magmatic events and described those events as contemporaneous with the sedimentation of Cuddapah Supergroup. Major igneous suites associated with the Vempalle and Tadpatri Formations of Papaghni sub-basin in the western part of the Cuddapah basin are dolerite, picrite and gabbro sills, basaltic flows, felsic volcanic rocks, ignimbrites and ash fall tuffs. The Nagari/Bairenkonda Quartzite and Pullumpet/Curnbum Formations of the Nallamalai Fold Belt are traversed by dolerite sills. Kimberlite dykes and syenite stocks are reported from the Cumbum Formation. Exposures of granite/gneissic rocks with domal structures within the Cumbum Formation are variously interpreted as either intrusives into the sedimentary pile or reactivated portions of the basement gneisses.

A brief description of the igneous suite in the different stratigraphic levels of Cuddapah basin is shown below:

2.5.1 Vempalle Formation:

First phase of igneous activity commenced with the eruption of basic lava flows, sub-aerially during the end phase of Vempalle Formation. Tholeiite, andesite and spilite lava with vesicular texture and amygdaloidal at the top, are the most common volcanics of this Formation (Srikantia, 1984; Sesha Sai, 2011, 2014 and references therein). Amygdales are usually filled with epidotes, calcite and zeolite. Dolerite sills are also fairly common and geochemical signatures of the Vempalle lavas and sills have suggested a riftogenic set-up for their emplacement (Chakraborty et al., 2016).

2.5.2 Tadpatri Formation:

Mafic sills and flows of Tadpatri Formation has been studied by different workers (Chatterjee and Bhattacharji, 2001; Anand et al, 2003; Chakraborty et al., 2016; Sesha Sai et al., 2016) and five different types of sills (viz, 1. differentiated mafic sill, 2. long slender clino-pyroxene bearing doleritic sills, 3. gabbro sills with trachytoid, 4. dolerite sills and 5. fine grained basaltic sills) with different petrographic and geochemical characteristics are identified within the Tadpatri Formation (Chakraborty et al., 2016). The Vempalle and lower Tadpatri Formations were intruded by dolerite, gabbro and picrite sills. This extensive igneous activity represents the possible second phase, and it is observed that these phases are responsible for different ore mineralization like asbestos and barite. Felsic volcanic and volcaniclastic rocks along with tuffs and shales are also found in upper part of Tadpatri Formation. The felsic and mafic volcanic activity contemporaneous with sedimentation in the Tadpatri succession represents the third phase of igneous activity.

2.5.3 Nagari Quartzite:

Sills of olivine dolerite are reported within the Nagari quartzite Formation (Dutt, 1975, Nagaraja Rao and Mahapatra,1977; Sesha Sai et al., 2017) in the southern part of Nallamalai fold belt.

2.5.4 Pullampet Formation/Cumbum Formation:

Barium-rich felsic volcanic rocks and tuffs with abundant baryte rossettes form part of the well-known Mangampeta barite deposit (Karunakaran, 1973, 1976; Deb and Bheemalingeswara, 2008). Carbonated dolerite sills were also found in the southern part of Nallamalai Fold Belt (Nagaraja Rao and Mahapatra, 1977). Ultra-potassic volcanic rock within the tuffaceous sequence of the Pullampet Formation was reported by Reddy (1999).

In the northern part of Nallamalai Fold Belt (NFB) Pullampet Formation is known as Cumbum Formation. In this Cumbum rocks emplacements of kimberlite, lamprophyre and syenite in association with dolerites constitutes an important alkaline province (Leelanandam, 1980; Das and Chakraborty, 2017). Intrusive granite bodies were also reported at the north-eastern margin of the (NFB) (Sen et al, 1964). Dasgupta and Biswas (2006) reported volcaniclastics within the Cumbum shale.

The contemporaneous volcanic activity which is mainly felsic with barium and iron-oxide rich phase in the Pullampet/Cumbum Formation represents the fourth phase of activity. The basic intrusive activity into the Nagari Quartzite, Pullampet and Cumbum Formation reflects the fifth phase of igneous activity. Finally, the granitic intrusions into the Cumbum in domal forms in the north-eastern part of the basin represents the sixth and final phase of igneous activity.