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Research Paper

Mantle heterogeneity, plume-lithosphere interaction at rift controlled ocean-continent transition zone: Evidence from trace-PGE geochemistry of Vempalle flows, Cuddapah Basin, India

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ABSTRACT

This study reports major, trace, rare earth and platinum group element compositions of lava flows from the Vempalle Formation of Cuddapah Basin through an integrated petrological and geochemical approach to address mantle conditions, magma generation processes and tectonic regimes involved in their formation. Six flows have been identified on the basis of morphological features and systematic three-tier arrangement of vesicular-entablature-colonnade zones. Petrographically, the studied flows are porphyritic basalts with plagioclase and clinopyroxene representing dominant phenocrystal phases. Major and trace element characteristics reflect moderate magmatic differentiation and fractional crystallization of tholeiitic magmas. Chondrite-normalized REE patterns corroborate pronounced LREE/HREE fractionation with LREE enrichment over MREE and HREE. Primitive mantle normalized trace element abundances are marked by LILE-LREE enrichment with relative HFSE depletion collectively conforming to intraplate magmatism with contributions from sub-continental lithospheric mantle (SCLM) and extensive melt-crust interaction. PGE compositions of Vempalle lavas attest to early sulphur-saturated nature of magmas with pronounced sulphide fractionation, while PPGE enrichment over IPGE and higher Pd/Ir ratios accord to the role of a metasomatized lithospheric mantle in the genesis of the lava flows. HFSE-REE-PGE systematics invoke heterogeneous mantle sources comprising depleted asthenospheric MORB type components combined with plume type melts. HFSE-REE variations account for polybaric melting at variable depths ranging from garnet to spinel lherzolite compositional domains of mantle. Intraplate tectonic setting for the Vempalle flows with P-MORB affinity is further substantiated by (i) their origin from a rising mantle plume trapping depleted asthenospheric MORB mantle during ascent, (ii) interaction between plume-derived melts and SCLM, (iii) their rift-controlled intrabasinal emplacement through Archean–Proterozoic cratonic blocks in a subduction-unrelated ocean-continent transition zone (OCTZ). The present study is significant in light of the evolution of Cuddapah basin in the global tectonic framework in terms of its association with Antarctica, plume incubation, lithospheric melting and thinning, asthenospheric infiltration collectively affecting the rifted margin of eastern Dharwar Craton and serving as precursors to supercontinent disintegration.

1. Introduction

Proterozoic magmatism represents a very important transition from the juvenile magmatic stages of the early Earth's evolution to the Phanerozoic style of magmatism that continues till today. Anorogenic volcanism, in space and time is often characterised by extensional tectonics, intracontinental rifts, mantle plume

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activities and hotspots. Intra-cratonic basins are known to occur globally since Early Archaean to Cenozoic but the mechanism of their formation still remain contentious. However, their excellent preservation within the earliest volcano-sedimentary sequences of the Earth has long been documented by workers (McKenzie et al., 1980; Bickle and Eriksson, 1982).

Development of large intracratonic sedimentary basins may be interlinked with plume activities leading to subsidence and crustal sagging followed by the deposition of extensive sedimentary units, commonly overlain by continental flood basalts and intruded/traversed by dyke swarms. The Centralian Superbasin in Australia (Walter et al., 1995), represents a classic example where crustal sagging began as a result of a mantle plume activity at about 826 Ma (Zhao et al., 1994), with the deposition of thick successions of marine and fluvial sands (Glass and Phillips, 2006). Magmatic processes within intracratonic basins play a key role in understanding the tectonomagmatic evolution of the basin. The Indian Peninsula also host a number of such intra-cratonic basins among which the prominent ones on the southern Indian Craton include the Cuddapah, Pranhita-Godavari, Chattisgarh basins. All the three basins are believed to have developed in a rift setting but the frequent occurrence of deposits representing tidal and storm influence links to an open seaway (Chaudhuri et al., 2002). The intracratonic Cuddapah basin is the largest sedimentary basin in the Indian sub-continent after the great Vindhyans. The magmatic/igneous rocks in and around the Proterozoic Cuddapah basin thus present a unique opportunity to study the proterozoic magmatic processes and will certainly throw some light on its role in the tectonic evolution of the basin. The Cuddapah basin is also interesting from a global tectonic perspective of supercontinent assembly and disintegration since, tholeiitic and high-Mg dikes of similar age and composition to that of Cuddapah tholeiites are also reported from east Antarctica, which was juxtaposed to the Cuddapah basin during Proterozoic (Chatterjee and Bhattacharji, 1998). Within the Cuddapah basin, extensive magmatic activities during the Proterozoic times are well preserved in the Vempalle and Tadpatri Formations in the form of syn-depositional basic lava flows and post-depositional sills with subordinate dikes. However, the integrated petrological, geochemical studies including Platinum Group Elemental (PGE) systematics of the Vempalle flows have not been attempted till date to infer their petrogenesis and tectonic setting.

PGEs are highly siderophile and chalcophile elements that prefer metallic phases which led to its sequestration into the Earth's core during its formation. Mantle-derived rocks may bear important information about the behaviour of PGEs during mantle melting which consequently aid in deciphering the planetary differentiation processes. PGEs (Os, Ir, Ru, Rh, Pt, Pd) are divided into two subgroups with contrasting geochemical characteristics: Iridium group PGEs (IPGEs: Ir, Os, Ru), which are siderophile and refractory and Platinum group PGEs (PPGEs: Pd, Pt, Rh), which are chalcophile and volatile. Such dual characteristics of the PGEs serve as effective geochemical tracers and provide complementary information about the evolutionary aspects of the Earth, core–mantle differentiation, mantle evolution, sulphide saturation history and magma genesis. The PGE abundances are controlled by several factors like mantle heterogeneity, enrichment/depletion processes of the mantle, partial melting, melt percolation, sulphide segregation and crystal fractionation (Woodland et al., 2002; Woodhead and Brauns, 2004; Dreher et al., 2005; Dale et al., 2009). Though high concentrations of PGE in ultramafic–mafic rocks are considered as economically beneficial, nevertheless, relatively lower concentrations of PGEs serve as potential petrological and petrogenetic indicators. The PGE abundances in the continental flood basalts (CFBs) are comparatively lower than lithophile elements, usually at parts per billion (ppb) or even upto part per trillion (ppt) levels. Nevertheless, they are the ideal markers of the magmatic process and source nature of the basalts (e.g., Momme et al., 2002; Crocket and Paul, 2004; Qi and Zhou, 2008; Qi et al., 2008; Song et al., 2009; Keays and Lightfoot, 2010). In fact, many earlier studies of PGEs in magmatic systems were inspired by the metal potentials of mineralized large igneous provinces (LIPs), such as the Permo-Triassic Siberian LIP (e.g., Brügmann et al., 1993). Among the continental flood basalts, PGE systematics of only Parana, Karroo, Siberian traps, Tarim LIP and Deccan traps have been studied by few workers. PGEs are known to concentrate as early crystallising phases during the evolution of mafic magma. Variations in the PGE abundances among mid-ocean ridge basalts and continental flood basalts are linked to the degree of mantle melting. The Deccan Traps of India and the Siberian Traps (at Noril'sk) are comparable as both are of similar areal extent and related to mantle activity. Geochemical and petrological studies have established variable crustal contamination in both the provinces (Crocket et al., 2013). In India, studies on PGE geochemistry of mafic volcanic rocks have been attempted by very few workers (Crocket and Paul, 2004; Mondal, 2011; Hazra et al., 2015; Singh et al., 2016). Present study address the maiden integrated major, trace, REE and PGE geochemistry of the lava flows from the Vempalle Formation, Cuddapah basin in order to evaluate their PGE potential, petrogenesis and geodynamic setting. It is an attempt to constrain geochemical attributes (major, trace elements, REE and PGE) of basic lava flows of the Vempalle Formation to understand the mantle upwelling processes, sulphide saturation history, tectonic regime and lithosphere-asthenosphere interactions associated with the evolution of the Cuddapah basin.

2. Geological background

The intracratonic Cuddapah basin resting over the Archean gneisses and granitoids of the Eastern Dharwar Craton is the largest Proterozoic basin in South India (Fig. 1A). During the Meso-Neoproterozoic Eastern Ghat Orogeny it was deformed into a crescent shaped basin (Goodwin, 1996). This basin occupies an area of 44,500 km^2 with N–S trending length of 450 km and a concave eastern margin extending over a length of 145 km in the middle. The arcuate north, south and western boundaries of the basin are defined by the profound Eparchaean unconformity. The eastern margin is marked by a prominent boundary thrust, which is parallel to the Nellore greenstone belt of the Eastern Ghats Mobile Belt (EGMB). (Fig. 1A; Bhat et al., 2012). The eastern part of the basin suffered intense folding and metamorphism during the Middle to Late Proterozoic ($\sim$1.3–1.6 Ga) Eastern Ghat Orogeny (Goodwin, 1996). On the contrary, the western part is characterised by gently dipping ($10^\circ-15^\circ$) sedimentary units with minor volcanics which are least affected by tectonic activity. The Cuddapah Basin is infilled by a thick sequence of terrigenous and chemogenic sediments and relatively minor intrusive and extrusive igneous rocks (Nagaraja Rao et al., 1987; Lakshminarayana et al., 2001; Anand et al., 2003; Chandrakala et al., 2013). The lithostratigraphy of the Cuddapah Basin is dominated by the Paleoproterozoic Cuddapah Supergroup and the Neoproterozoic Kurnool Sequence of which the former is predominantly arenaceous to argillaceous with subordinate carbonate (limestone and dolomite) units whereas the later are carbonate (limestone) facies sediments with subordinate clastics. The stratigraphic succession of the Paleo-Mesoproterozoic Cuddapah Supergroup comprises of three unconformity-bound sequences, namely the Papaghni Group, the Chitravati Group and the Nallamalai Group followed by the Srisailam Formation (Fig. 2). The Neoproterozoic Kurnool Group with a cumulative thickness of $\geq$500 m is divided into six formations viz., Banganapalli Formation, Narji

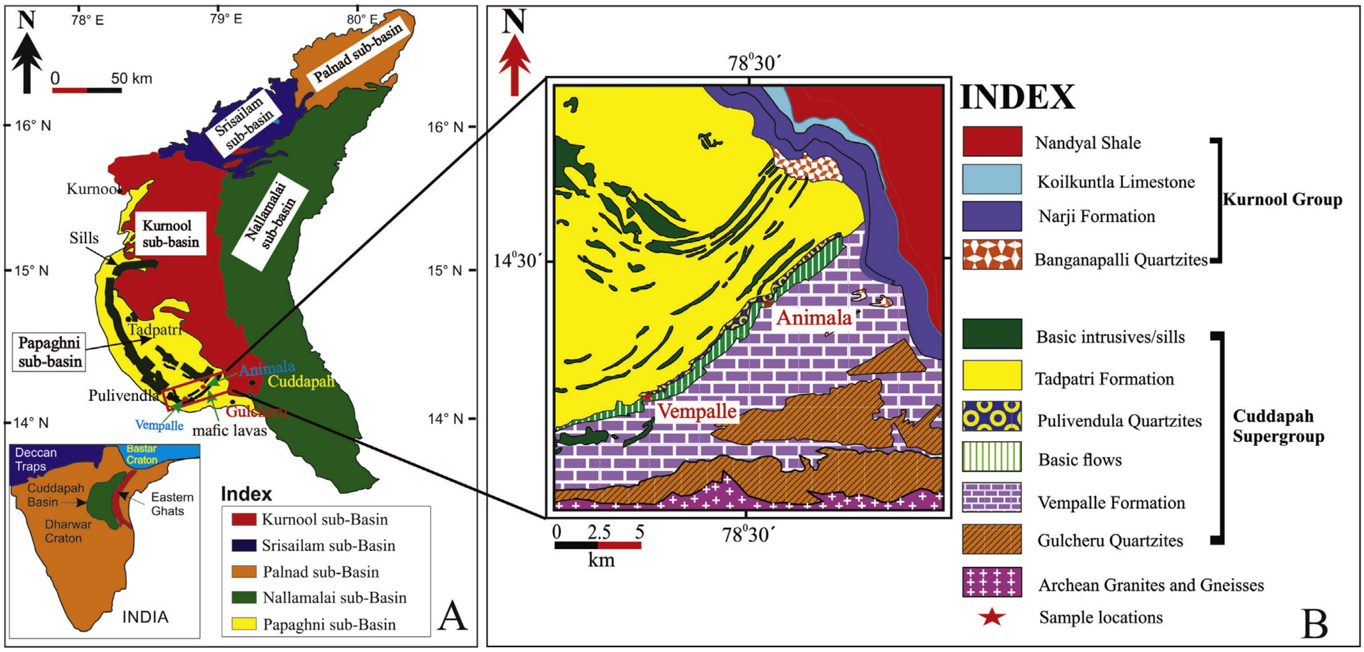
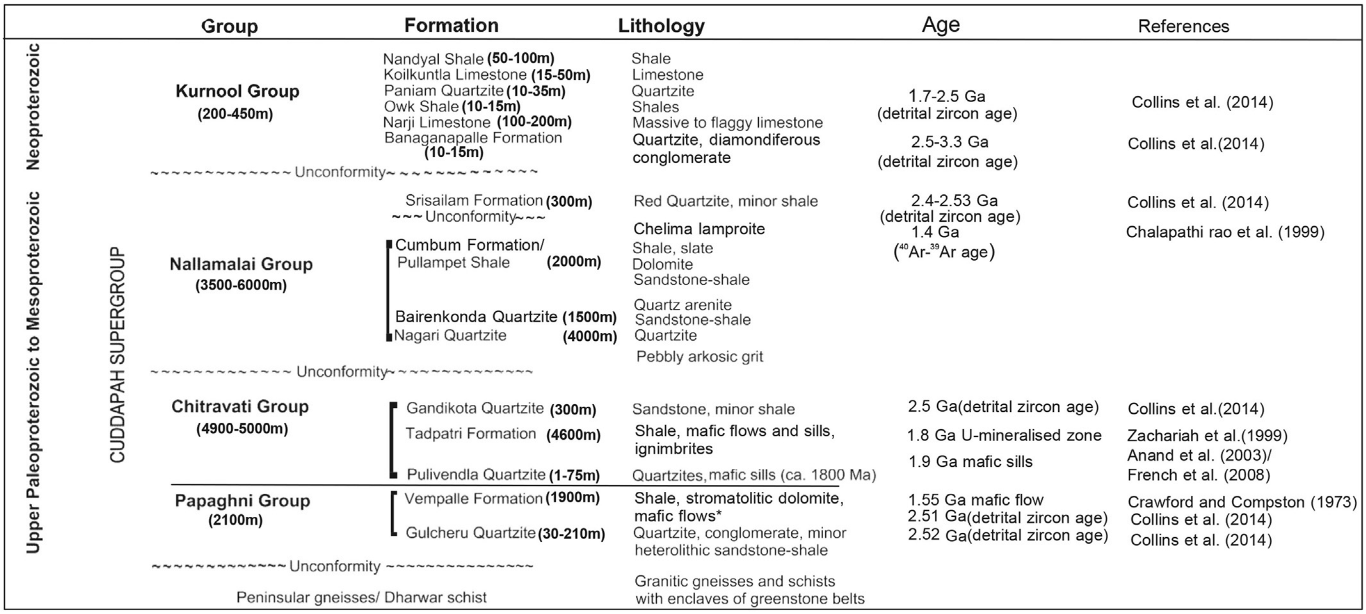


Figure 1. (A) Simplified geological map of the Cuddapah basin (after Nagaraja Rao and Ramalingaswamy, 1976), with inset showing the location of Cuddapah basin in India. (B) Detailed map showing the study area and sample locations (modified from DRM of Cuddapah, Geological Survey of India).

Limestone, Owk Shale, Paniam Quartzite, Koilkuntala Limestone and Nandyal Shale (Ramakrishnan and Vaidyanathan, 2008).

Extrusive and intrusive mafic magmatic activities are exposed at lower stratigraphic horizons of the basin viz. Vempalle and Tadpatri Formations of the Papaghni Group and cutting across the Vempalle sediments. The Vempalle and Tadpatri Formations of the Cuddapah basin are the storehouse of extensive igneous activities that are exposed in the form of basic flows and sills with subordinate dikes. The basic flows and sills are oriented in arcuate patterns parallel to the western periphery of the basin. The lithologies of the Vempalle Formation, which is ∼1900 m thick (Roy, 1947) comprises dolomite, limestone, chert breccias, shale, siliceous oolite and minor quartzite along with mafic sills and lava flows at the top (Fig. 1B). These basic lava flows overlie the Vempalle dolomites and mark the highest stratigraphic unit of the Papaghni Group.

The earliest attempt to date magmatic rocks of the Cuddapah basin by radiometric systematics was made by Aswathanarayana (1962a, b) and was followed by a number of workers (e.g., Crawford and Compston, 1973; Murthy et al., 1987; Bhaskar Rao et al., 1995; Chalapathi Rao et al., 1996, 1999). Crawford and Compston (1973) proposed an Rb-Sr age of ∼1550 ± 147 Ma for the mafic flows of Vempalle Formation later on revised by Bhaskar



		Group	Formation	Lithology	Age	References
Neoproterozoic		**Kurnool Group** **(200-450m)**	Nandyal Shale **(50-100m)** Koilkuntla Limestone **(15-50m)** Paniam Quartzite **(10-35m)** Owk Shale **(10-15m)** Narji Limestone **(100-200m)** Banaganapalle Formation **(10-15m)**	Shale Limestone Quartzite Shales Massive to flaggy limestone Quartzite, diamondiferous conglomerate	1.7-2.5 Ga (detrital zircon age) 2.5-3.3 Ga (detrital zircon age)	Collins et al. (2014) Collins et al.(2014)
		∼∼∼∼∼∼∼∼∼∼∼∼∼ Unconformity ∼∼∼∼∼∼∼∼∼∼∼∼∼				
Upper Paleoproterozoic to Mesoproterozoic	CUDDAPAH SUPERGROUP	**Nallamalai Group** **(3500-6000m)**	Srisailam Formation **(300m)** ∼∼∼ Unconformity ∼∼∼ Cumbum Formation/ Pullampet Shale **(2000m)** Bairenkonda Quartzite **(1500m)** Nagari Quartzite **(4000m)**	Red Quartzite, minor shale Chelima lamproite Shale, slate Dolomite Sandstone-shale Quartz arenite Sandstone-shale Quartzite Pebbly arkosic grit	2.4-2.53 Ga (detrital zircon age) 1.4 Ga (^{40}Ar-^{39}Ar age)	Collins et al. (2014) Chalapathi rao et al. (1999)
		∼∼∼∼∼∼∼∼∼∼∼∼∼ Unconformity ∼∼∼∼∼∼∼∼∼∼∼∼∼				
		Chitravati Group **(4900-5000m)**	Gandikota Quartzite **(300m)** Tadpatri Formation **(4600m)** Pulivendla Quartzite **(1-75m)**	Sandstone, minor shale Shale, mafic flows and sills, ignimbrites Quartzites, mafic sills (ca. 1800 Ma)	2.5 Ga(detrital zircon age) 1.8 Ga U-mineralised zone 1.9 Ga mafic sills	Collins et al.(2014) Zachariah et al.(1999) Anand et al. (2003)/ French et al. (2008)
		Papaghni Group **(2100m)**	Vempalle Formation **(1900m)** Gulcheru Quartzite **(30-210m)**	Shale, stromatolitic dolomite, mafic flows* Quartzite, conglomerate, minor heterolithic sandstone-shale	1.55 Ga mafic flow 2.51 Ga(detrital zircon age) 2.52 Ga(detrital zircon age)	Crawford and Compston (1973) Collins et al. (2014) Collins et al. (2014)
		∼∼∼∼∼∼∼∼∼∼∼∼∼ Unconformity ∼∼∼∼∼∼∼∼∼∼∼∼∼				
		Peninsular gneisses/ Dharwar schist		Granitic gneisses and schists with enclaves of greenstone belts		

Figure 2. Lithostratigraphy of the Cuddapah basin (modified after Nagaraja Rao et al., 1987).

Rao et al. (1995) using the same Rb-Sr systematics on differentiated sills from Tadpatri Formation and gave a much older age of 1817 ± 24 Ma. Since then, several workers have used a variety of systematics, that led to the general consensus that at least the differentiated sills of Tadpatri Formation have been emplaced around 1850 Ma while the Vempalle lavas, being stratigraphically lower, must have been erupted prior to that (Murthy et al., 1987; Bhaskar Rao et al., 1995; Zachariah et al., 1999; Anand et al., 2003; French et al., 2008). Zachariah et al. (1999) obtained an age of 1756 ± 29 Ma for a U-mineralized stromatolitic dolomite from the Tadpatri Formation using ^{206}Pb-^{204}Pb systematics which has been interpreted as a minimum age for carbonate sedimentation and dolomitization within the Cuddapah Supergroup. However, Anand et al. (2003) proposed a ^{40}Ar-^{39}Ar laser fusion age of 1899 ± 20 Ma on phlogopite mica obtained from the mafic-ultramafic sill complex of the Tadpatri Formation and constrains the initiation of volcanic activity in the Cuddapah basin at 1.9 Ga. Further, French et al. (2008) obtained an age of 1885 ± 3 Ma for the mafic sills of the Tadpatri Formation using U-Pb systematic of baddeleyite by thermal ionization mass spectrometry. Recently, U-Pb detrital zircon ages were reported from Gulcheru (2.52 Ga), Vempalle (2.51 Ga), Gandikota (2.52 Ga), Srisailam (2.53–2.48 Ga), Banaganapalle (3.3–2.5 Ga) and Paniam quartzites (2.5–1.7 Ga) documenting the protolith of Neoarchean (to the west of Cuddapah basin) for the Cuddapah sediments (Collins et al., 2014). Available radiometric ages of mafic dykes emplaced in the Eastern Dharwar craton around the margin of Cuddapah basin suggest episodic volcanism from 1900 Ma to around 640 Ma (Mallikarjuna Rao et al., 1995; Chatterjee and Bhattacharji, 2001). However, there is no precise age data for the lava flows that are cutting across the lower Cuddapahs (in the south) that are exposed in the Vempalle Formation.

3. Characterisation and correlation of the Vempalle flows

Primary volcanic structures provide one of the most useful tools for the identification of lava flows in the field and their correlation (Tomkeieff, 1940; Wentworth and Macdonald, 1953; Waters, 1961; Macdonald, 1967; Swanson, 1967; Long and Wood, 1986). Columnar joints are characteristic of typical subaerial lava flows and some shallow sheet-like intrusions (Winter, 2015). Within a columnar structure, in the ideal case, there are four sub-divisions – a thin vesiculated and brecciated flow top, an upper and lower colonnade with fairly regular straight columns, and a central entablature that has more irregular columns which are typically curved and skewed. These three main divisions are not uniformly developed may vary greatly in thickness, sometimes absent, or occur repeatedly within a single flow. Various models have been proposed for the growth of the columnar joints in lava flows based on convection currents (Long and Wood, 1986; Budkewitsch and Robin, 1994). A three-tier classification of lava flows based on systematic arrangement of vesicular zone, entablature zone and colonnade zone (De, 1972, 1974; Ganguly et al., 2012, 2014) provide reliable criteria to identify and distinguish lava flows from each other.

Within the Vempalle Formation, six lava flows have been identified on the basis of their morphological features. Amygdales of various dimensions ranging from 3–30 cm characterise the upper surfaces of flows and are usually filled with epidote, calcite and zeolite. The flows exhibit columnar joints in the middle portion and display vesicular tops indicating their subaerial nature of eruption. The lava flows are exposed at Pulivendla, Vempalle and Animala (up to 50 m) Malkapuram, Bethamcherla, Gorumanukonda (~30 m) and Tallireddipalli in the southern and northern parts of the basin respectively. The thickness of the lava flows is high in the southern part with the presence of intertrappeans beds (red boles) compared to the northern part. The basic lava flows occurring in the northern part of the basin are devoid of intertrappeans but exhibit similar features with their southern counterparts such as vesicles and amygdales and hydrothermal alteration (mostly chloritic and carbonaceous) along fractures/joints displaying cooling cracks structure at the Tallireddipalli area.

Based on their morphological features, primary volcanic structures and arrangement of vesicular, entablature and colonnade zones (Fig. 3), six lava flows have been identified from the Vempalle Formation of the lower Cuddapahs. Among them flow-I is exposed on either side of the Pulivendula-Vempalle road (N14°23.594′; E78°26.654′). Flows II to V are exposed in the canal section near Vempalle (N14°24.741′; E78°27.967′) and flows IV and V are also exposed at Animala (N14°27.988′; E78°31.295′). Flow I is characterised by massive basalt in the lower portion followed by vesicular-amygdular type in which epidotization is commonly observed towards top (Fig. 4A–D). Flows II and III are exposed in the canal section exhibiting similar features separated by a red bole horizon (Fig. 5A). In the canal section all the flows are underlain by Vempalle dolomite and overlain by Pulivendula Quartzite. Numerous vesicles are observed in the middle part of the flow which are sometimes filled with amygdales in the uppermost part. Amygdales of various dimensions and colours exhibiting vug structure are observed in the upper part of the flow-II which ranges from a few cm to almost 30 cm in length (Fig. 5B). Huge (3 m × 1 m) columnar basalts are exposed in flows III and IV (Fig. 5C). Epidotization is common at the contact of shear zones. Flows IV and V are separated by an intertrappean bed which is different from the red bole horizon and relatively coarse grained (Fig. 5D). Flow V is predominantly columnar with minor development of vesicles. Flow VI is exposed at Tallireddipalli (N14°32.603′; E78°03.071′) and exhibit cooling cracks structures (Fig. 5E) with secondary infillings along the cracks. These are predominantly vesicular with amygdales ranging in size from 3 to 20 cm (Fig. 5E). The flows IV and V which are exposed at Animala are predominantly massive with minor development of vesicles and amygdales (Fig. 5F).

4. Petrography

Vempalle flows are intergranular porphyritic basalts where the phenocrystal phase is dominated by lath shaped plagioclase and prismatic clinopyroxenes (Fig. 6A). Groundmass composition is generally marked by micro-phenocrysts, plagioclase, pyroxene, devitrified glass and opaque minerals. Opaque grains are secondary after clinopyroxene and occur along the rims of the clinopyroxene grains. Plagioclase phenocrysts are mostly lath-shaped with occasional presence of tabular crystals. Clinopyroxene is one of the well preserved essential mineral in the Vempalle flows after plagioclase, commonly present as subhedral and anhedral crystals (Fig. 6B). It also occurs in both phenocrystal and groundmass phases. Clinopyroxene phenocrysts (Fig. 6C) are mostly prismatic. Devitrification is also observed in some places. Well-developed amygdaloidal and vug structures (Fig. 6D) have been observed within the vesicular zones of these basaltic flows. The overall textural pattern of these lava flows is defined by intersertal, intergranular, microporphyritic and pilotaxitic textures.

5. Sampling and analytical techniques

Relatively fresh and unweathered samples were collected during the fieldwork avoiding shear zones, brecciated domains, zones of multiples veins and amygdales. After petrographic screening for hydrous minerals and carbonatization, forty-two samples of the

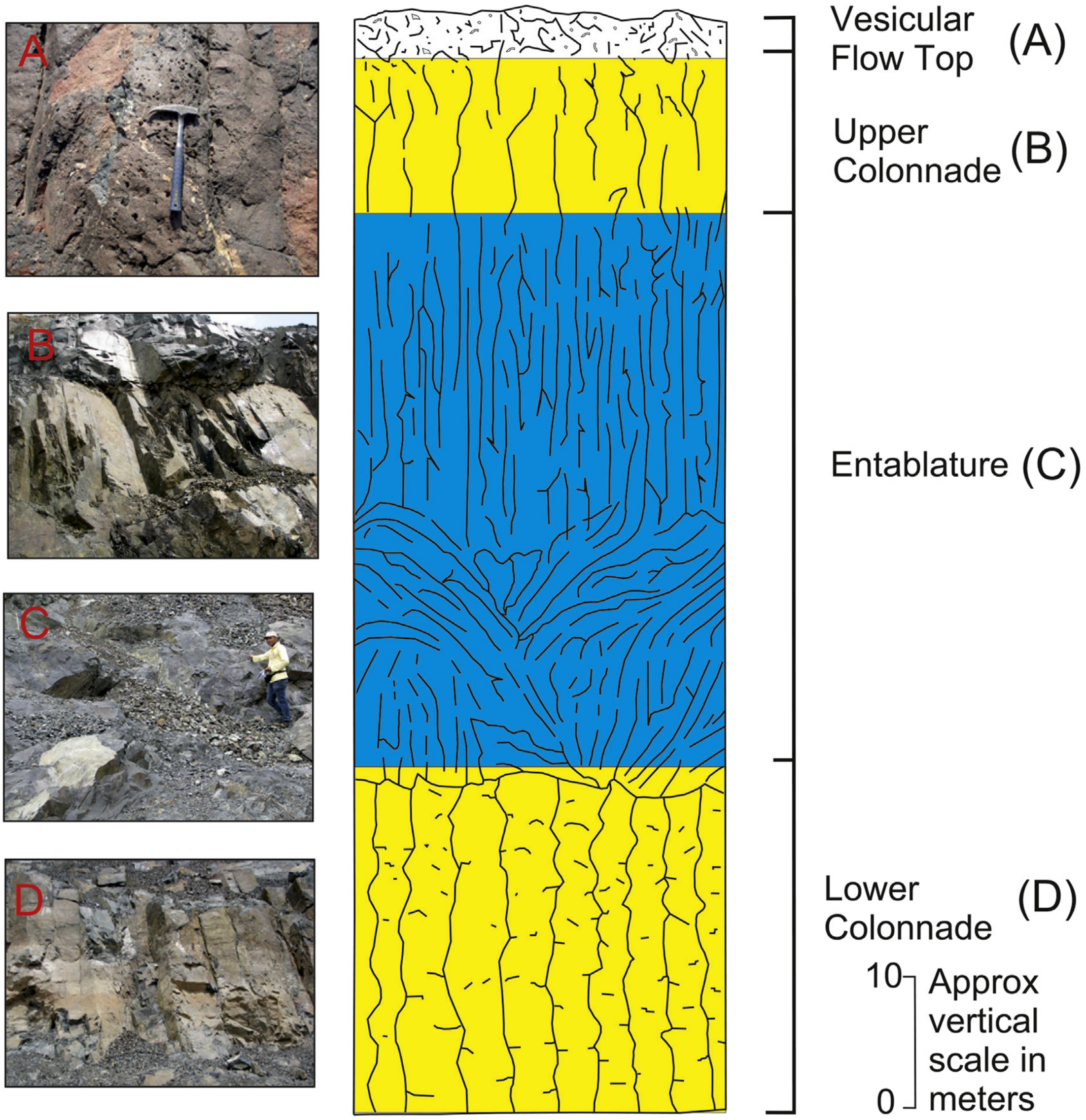


Figure 3. Morphological features of the Vempalle flows (A–D), as referred to the four common sub-divisions of a typical flow (Long and Wood, 1986).

Vempalle lava flows were selected for major, trace and rare earth elements and twenty-three samples for PGE studies. Samples were crushed and pulverised to fine powders manually by using the agate mortar and pestle. Major element abundances were determined by using pressed powder pellets on XRF (Phillips MAGIX PRO Model 2440) following the method of Krishna et al. (2007) at the CSIR-National Geophysical Research Institute (CSIR-NGRI), Hyderabad. Trace elements (including REE) were analysed by using closed vessel digestion method. Trace element concentrations were determined at NGRI by High resolution inductively coupled mass spectrometer (HR-ICP-MS; Nu Instruments Attom, UK) in jump-wiggle mode. The analytical procedure, precision and accuracy for HR-ICP-MS are reported in Manikyamba et al. (2014, 2016). ^{103}Rh was used as an internal standard and external drift was corrected by repeated analyses of standards which were also used as calibration standards accordingly. Precision and reproducibility obtained for international reference materials BCR-1 and BCR-2 are as reported in Manikyamba and Kerrich (2011). PGE concentrations were estimated by using the nickel sulphide fire-assay pre-concentration method following the procedure after Balaram (2008) and estimated using High Resolution ICP-MS (HR ICP-MS) at NGRI. Precision and accuracy of WPR-1 and WMG-1 which are used as international reference materials are referred to Manikyamba and Saha (2014).

6. Geochemistry

6.1. Major and trace elements

All the six lava flows have similar geochemical characteristics and exhibit a restricted range of SiO_2 (45.05–51.73 wt.%), Al_2O_3 (10.29–14.6 wt.%) and total alkalis ($Na_2O + K_2O$; 2.11–5.58 wt.%) contents (Supplementary Table S1). The MgO contents of the Vempalle flows range between 6.1 wt.% and 10.86 wt.% while CaO shows a wide variation ranging from 8.45 wt.% to 18.18 wt.%. The studied flows are characterised by Mg# ($Mg\# = [100 \times MgO/(MgO + FeO^T)]$ ranging from 29 to 46 indicating their highly evolved nature. Although the studied samples occupy the field of andesite/basalt in the HFSE/HFSE ratio plot (Fig. 7A), their basaltic nature is justified through petrography as well as MgO and SiO_2 contents

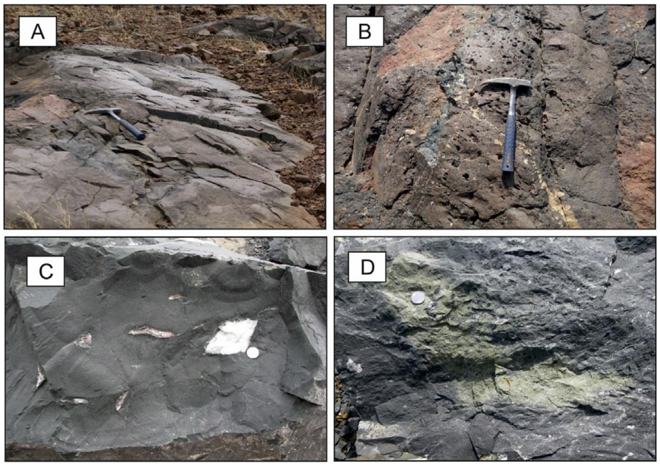


Figure 4. Field photographs of the mafic flows of the Vempalle Formation showing (A) massive nature at the lower part, (B) vesicular structures in upper vesicular zones, (C) amygdaloidal structure in upper vesicular zones of the flow and (D) epidotisation in the mafic flows.

(Supplementary Table S1). Further, it also observed that these samples are discriminated as sub-alkaline tholeiitic basalts with MORB affinity in the Nb/Y vs. Ti/Y discrimination diagram (Fig. 7B). CIPW normative compositions (Cox et al., 1979) of these basaltic flows marked by the presence of quartz and hypersthene which suggest that they are silica-oversaturated and tholeiitic in nature. The Differentiation Index (D.I.) [normative quartz (Q) + orthoclase (Or) + albite (Ab) + nepheline (Ne) + kalsilite (Ks) + leucite (Lc); Thornton and Tuttle, 1960] ranges from 16 to 53 with overlapping values and reflects moderate degree of differentiation of primary melts. Solidification Index (S.I.) [100 × {MgO/(MgO + FeO + Fe_2O_3 + Na_2O + K_2O)}] (Kuno, 1964) ranges from 15 to 26 reflect pronounced fractional crystallization during the evolution of these flows (I–VI). Most of the major and trace elements such as SiO_2, TiO_2, P_2O_5, Th, Zr, Y and La exhibit negative correlation with MgO whereas Al_2O_3 correlated positively indicating the involvement of clinopyroxene and feldspar during fractional crystallisation (Fig. 8). Hydrothermal alteration effects are negligible in these flows, as evidenced by their low LOI values (1–4 wt.%).

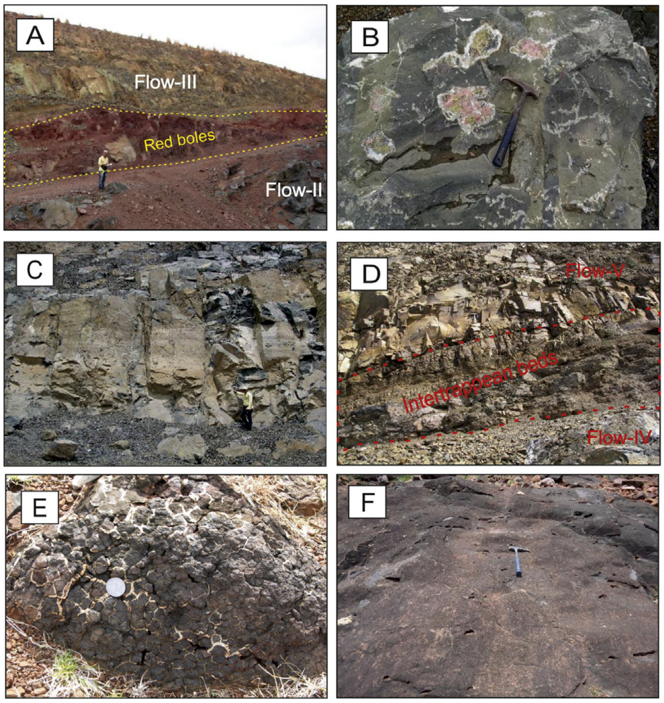


Figure 5. Field photographs of the Vempalle flows showing (A) intertrappean bole beds (red boles) between flows II and III in the canal section, (B) amygdales of various dimensions and colours exhibiting vug structure, (C) gigantic columnar structures (3 m × 1 m) in the upper colonnade zone of flow III, (D) Intertrappean beds separating the flows IV and V, (E) cooling cracks with secondary fillings in flow VI exposed at Tallireddipalli area and (F) massive flows with minor vesicles at Animala.

Among the transition metals, the Vempalle flows have moderate concentrations of Ni (40–108 ppm), Co (29–189 ppm) and Cr (3–317 ppm). The chondrite normalized rare earth element (REE) patterns of the Vempalle flows (Fig. 9A, C, E, G, I, K) exhibit moderate to pronounced Light REE (LREE) enrichment over Middle REE (MREE) and High REE (HREE). These REE signatures are further substantiated by $(La/Sm)_N$ = 1.61–2.81, $(La/Yb)_N$ = 2.23–5.55 and $(Gd/Yb)_N$ = 1.26–1.86, consistent with prominent LREE/HREE, moderate to high ratios of LREE/MREE and MREE/HREE. The investigated samples show negative to slightly positive Eu anomalies (Eu/Eu* ranging from 0.27 to 1.15) on chondrite-normalized REE distribution patterns (Fig. 9A, C, E, G, I, K). These flows are characterized by higher abundances of Large Ion Lithophile elements (LILE), High Field Strength elements (HFSE) and LREE. Primitive mantle normalized trace element abundance patterns (Fig. 9B, D, F, H, J, L) for the Vempalle flows show relative enrichment in LILE compared to HFSE and LREE with positive anomalies at Ba, K, La, Ce, Nd and negative anomalies at Nb, Ta, Zr, P and Ti.

6.2. *Platinum group elements (PGEs)*

The PGE contents of the Vempalle flows (I–VI) are significantly low (<100 ppb) in which ΣPGE ranges from 5.89–38.82 ppb. The PPGE abundances are marked by 5.27–36.80 ppb with 2.42–15.56 ppb Pd, 1.91–15.21 ppb Pt and 0.39–11.47 ppb Rh. Among IPGEs, Iridium, Osmium and Ruthenium range of 0.08–0.32 ppb, 0.20–1.36 ppb and 0.30–0.81 ppb, respectively. The PPGE/IPGE ratios for the Vempalle flows range from 5.95 to 19.07 while Pd/Ir, Pd/Pt and Pt/Pt* [$=Pt_N/(Rh_N \times Pd_N)^{1/2}$] ratios ranges from 19.69–89.43, 0.48–2.90 and 0.07–0.85 respectively which are higher than that of primitive mantle (Pd/Ir = 1.01; Pd/Pt = 0.53, Pt/Pt* = 1.27) and chondrite (Pd/Ir = 1.0; Pd/Pt = 0.53, Pt/Pt* = 1.28) ratios. The Ni/Cu ratios for the studied samples show a range from 0.34 to 1.84. Chondrite-normalized PGE patterns of the Vempalle flows (Fig. 10) are characterized by relative enrichment in Pd, Pt, and depletion in Ir, Ru and Os.

7. Discussion

7.1. *Crustal contamination and assimilation-fractional crystallisation (AFC)*

Mantle-derived magmas migrating through continental crust to the surface are subjected to variable degrees of contamination by different crustal components, which lead to their compositional diversity (Hawkesworth et al., 1984; Mahoney, 1988; Carlson, 1991; Hergt et al., 1991; Arndt and Christensen, 1992; Gallagher and Hawkesworth, 1992; Saunders et al., 1992; Arndt et al., 1993; Sweeney et al., 1994; Song et al., 2001, 2008). Geochemical signatures like high Al_2O_3, low Zr contents, negative Sr and Ti anomalies, Nb depletion relative to La on primitive mantle-normalized multi-element diagrams (Fig. 9B, D, F, H, J, L) may be attributed to varying degrees of crustal contamination or derivation from a heterogeneously metasomatized mantle source. De Paolo (1981) suggested that the wall rock assimilation and fractional crystallisation take

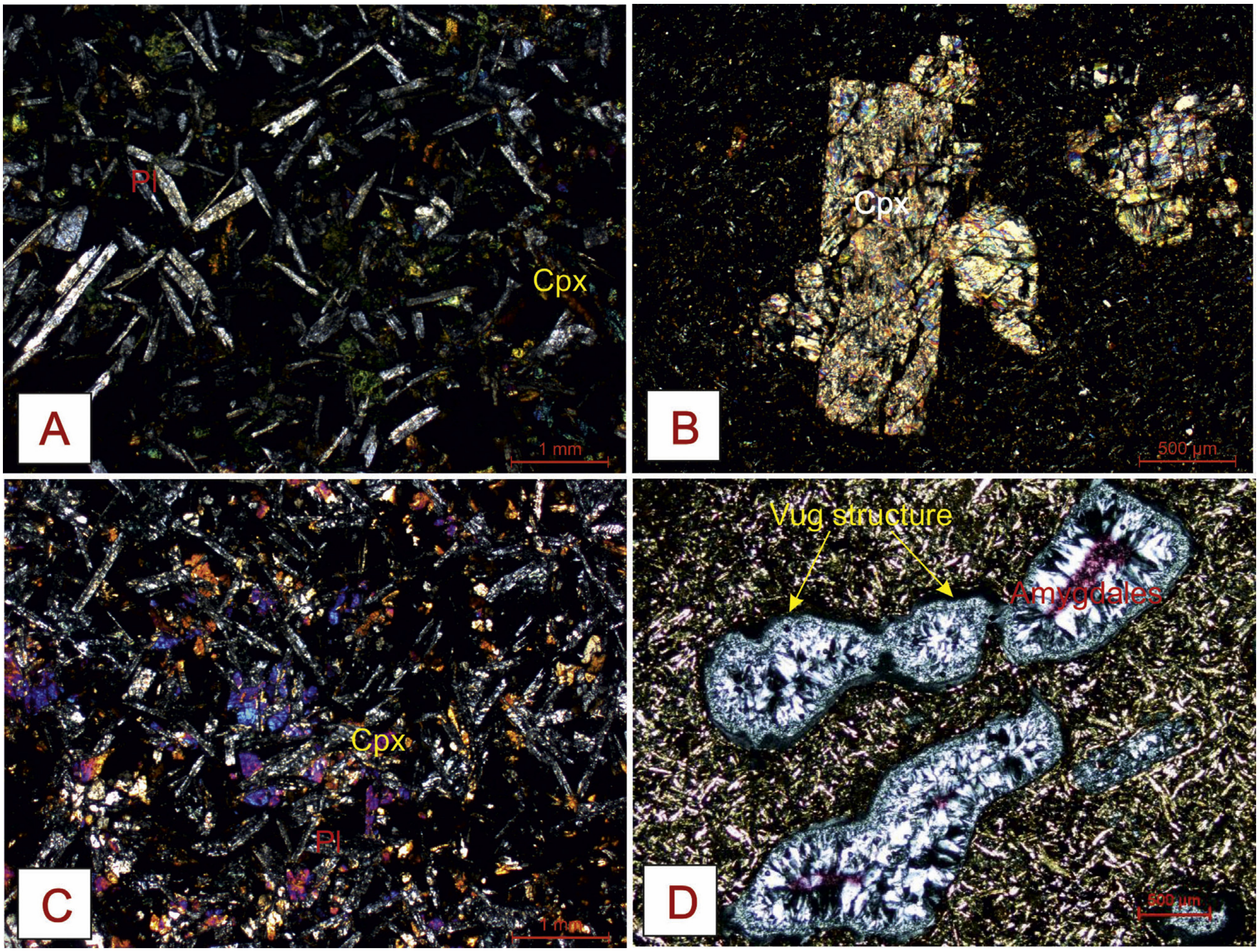


Figure 6. Photomicrograph of Vempalle flows showing (A) lath shaped plagioclase (pl) and prismatic clinopyroxenes (cpx) enclosing opaques and glass exhibiting intersertal texture, (B) clinopyroxene phenocryst within the groundmass of microlites, glass and opaques, (C) cluster of plagioclase (pl) and clinopyroxene (cpx) phenocrysts forming glomeroporphyritic texture and (D) occurrence of vug structure in the upper vesicular zone (UVZ).

place simultaneously in the magmatic systems as evidenced by the studies on isotopic and trace element systematics. The Vempalle flows report variable crustal contamination in the LILE/HFSE ratios such as Nb/Th, Th/Ta, Ta/La, Th/Yb, Zr/Nb, La/Yb, La/Nb, Th/Nb. These ratios when compared with their REE distribution indicate fractional crystallization as the dominant magmatic process relative to wall rock assimilation as these mafic melts are pulsative and less viscous. The reported value for Nb/Th ratio of primitive mantle is 8, whereas in continental crust it is ~1.1 (Taylor and McLennan, 1985; Sun and McDonough, 1989; Rollinson, 2008). However, the studied Vempalle flow have Nb/Th < 8 (Nb/Th: 0.29–4.22) which implies contamination of magma by continental crust. Besides, Th/Ta (0.83–3.49), Nb/Ta (4.06–15.90) and Ta/La (0.05–0.2) ratios suggest variable degrees of crustal contamination during the ascent of the magma to the surface. Based on La/Nb ratio, Thompson et al. (1984) have studied the index of crustal contamination in magmas. It has been formulated that OIB, continental alkali basalts and kimberlites have La/Nb < 1, while that in CFB magmas range from 0.5 to 7. In the Vempalle flows, the La/Nb ratios ranging of 1.84–3.06 are similar to that of CFB magmas and this wide range of La/Nb reflect variable degrees of crustal contamination (Wilson, 1989). Higher Zr/Nb (12.37–50.30) and Th/Nb (0.09–0.83) ratios of these basaltic lava flows with respect to those of OIB (Zr/Nb $= 4.2$; Th/Nb $= 0.06$) and Nb-negative anomalies on spider diagrams (Song et al., 2008; Lai et al., 2012) suggest contamination of magma during ascent through continental crust (Huppert and Sparks, 1985). Pearce (2008) stated that Nb, Th and Ta are reliable geochemical proxies for understanding the crustal contamination during magma genesis manifested in terms of magma–crust interaction (assimilation and contamination), crustal recycling and subduction. In terms of Nb/Yb vs. Th/Yb relations (Fig. 11A; Saccani et al., 2015), the studied samples show a trend away from the oceanic MORB-OIB array towards higher Th/Yb values reflecting the role of lithospheric mantle in the genesis of parent magma and magma–crust interactions. The studied Vempalle flows are porphyritic basalts where the phenocrystal assemblage is dominantly represented by clinopyroxene and plagioclase (Fig. 6C). The presence of clinopyroxene and plagioclase (and relatively lesser olivine) as phenocrystal phases in the studied flows/rocks suggest the involvement of fractional crystallization of magma prior to its eruption in a magma chamber. The moderate enrichment in MgO (6.1–10.86 wt.%), Ni (40–108 ppm) and Cr (8–230 ppm) concentrations suggest an evolved nature of the lava flows of the Vempalle which have undergone fractional crystallization. The observed major oxide and trace element variation patterns of the Vempalle flows (Flow-I to VI) are consistent with fractionation process within the flows. The negative correlation between SiO_2 and FeO^T, with MgO and the positively correlated Al_2O_3 reflects on the role of clinopyroxene and feldspar as fractionating assemblages in the studied Vempalle flows.

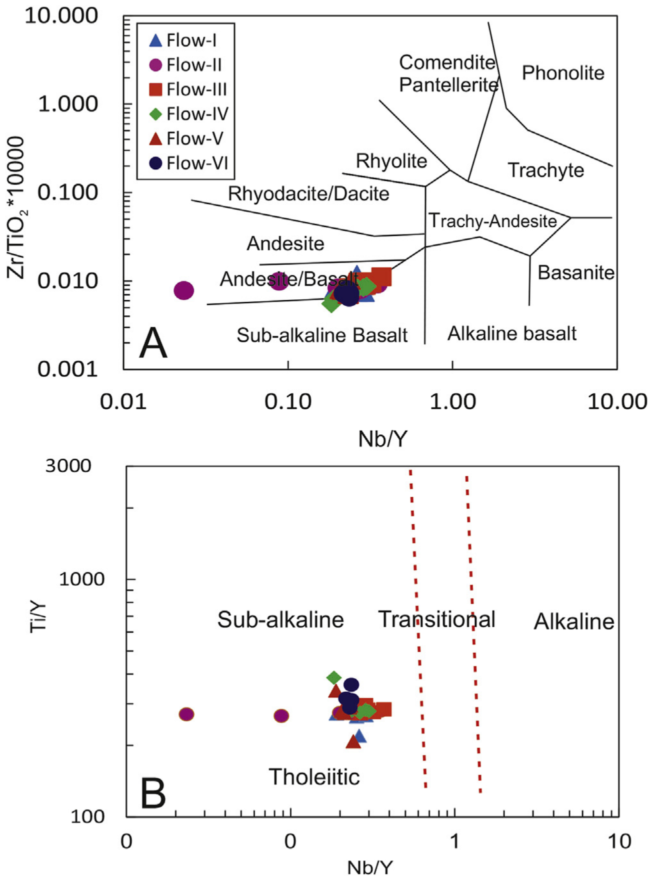


Figure 7. (A) Nb/Y vs. Zr/TiO_2 diagram (after Winchester and Floyd, 1977) in which the studied mafic flows straddle the fields of sub-alkaline basalt and andesite/basalt, (B) Nb/Y vs. Ti/Y plot (Saccani et al., 2015) in which the Vempalle flows are showing their MORB and tholeiitic characteristics.

7.2. Mantle melting and source characteristics

Rare-earth elements are one of the vital proxies for understanding the mantle melting conditions as their relative abundances in mantle-derived melts reflect the degree of partial melting and the nature of aluminous phase (spinel or garnet) in the mantle source (Lassiter et al., 1995; Reichow et al., 2005; He et al., 2010; Manikyamba et al., 2015). It is a general consensus that HREE, especially Yb, is compatible in garnet and has high garnet/melt partition coefficients, whereas La (LREE), Sm and Gd (MREE) are incompatible and have low garnet/melt partition coefficients (Irving and Frey, 1978; Kelemen, 1990; Rollinson, 1993). La/Yb and Sm/Yb are strongly fractionated when melting occurs in the garnet stability field and in contrast to this La/Yb is slightly fractionated and Sm/Yb is nearly unfractionated during melting in the spinel peridotite domain (Yaxley, 2000; Xu et al., 2005; Lai et al., 2012). The REE signatures of the Vempalle flows marked by $(La/Yb)_N = 2.23–5.55$, and $(Gd/Yb)_N = 1.26–1.86$ (Supplementary Table S1) with consistently lower Dy/Yb ratios along with variable La/Yb ratios suggest their generation at a shallower depth corresponding to the stability field of spinel peridotite (Fig. 11B). Furthermore, the incompatible-compatible (La/Sm) vs. moderately incompatible-compatible (Sm/Yb) REE relationship endorse a polybaric melting realm starting from garnet (low degree melting) continued to greater extent of melting in the spinel lherzolite field reaching ~10% (Saccani et al., 2013, 2014, 2015; Fig. 11C). The low Th/Yb (0.69–3.5), Ta/Yb (0.04–0.52), Zr/Y (3.11–5.30) and Zr/Nb (0.04–0.39) ratios along with LREE enrichment endorse the NMORB affinity of the Vempalle flows (Saccani et al., 2013). Progressive crustal contamination or AFC can be visualized through Nd vs. Ce relationship (Fig. 11D) where the studied samples plot along the line of AFC and restrict above the chondrite line without passing through the origin indicating ~10% partial melting of the mantle (Ahmad and Tarney, 1991; Kumar and Ahmad, 2007). Therefore, the HFSE-REE signatures account for variable degrees and depth of partial melting extending from garnet to spinel lherzolite compositional domains with contributions from heterogeneous mantle components which are responsible for the generation of Vempalle melts.

Primitive mantle-normalized trace element abundances (Fig. 9B, D, F, H, J, L) and chondrite normalized REE patterns (Fig. 9A, C, E, G, I, K) of the Vempalle flows show relatively higher abundances of LILE and LREE respectively which is suggestive of generation of parent magma from a mantle source which had experienced sufficient enrichment in these elements. The mantle source characteristics for the studied basaltic flows have been documented in terms of HFSE concentrations and HFSE/HFSE ratios (Pearce and Parkinson, 1993; Pearce, 2008). Zr/Sm (26.04–31.92) and Nb/Ta (5.33–24.98) ratios of the studied flows are comparatively higher than that of primitive mantle (Zr/Sm = 25; Nb/Ta = 17) (Frey et al., 1980; Menzies et al., 1991), thereby suggesting an enriched mantle affinity. Erlank and Kable (1976), Pearce and Norry (1979) and Le Roex et al. (1983) have emphasized the importance of Zr/Nb ratio as indicator of the 'depleted' or 'enriched' nature of the source region for basaltic magmas. The Zr/Nb ratios of the investigated samples range from 12.27 to 50.30 suggesting an enriched mantle source. However, plume type basalts generally have lower Zr/Nb ratios in comparison with N-MORB (Zr/Nb >30). Therefore, the Zr/Nb values (12.27–19.37) of the Vempalle flows exhibit a comparatively lower range reflecting a plume signature of the magma which generated these flows. Zr/Ba ratio can also be considered as an effective proxy to discriminate lithospheric sources (Zr/Ba = 0.3–0.5) from asthenospheric sources of parent melt (Zr/Ba >0.5) (Menzies et al., 1991; Greenough et al., 1998; Kurkcuoglu, 2010; Ganguly et al., 2014). La/Nb ratios (1.26–7.70) of the studied flows reflect the role of asthenospheric mantle in the generation of parent magma. Zr/Hf ratios ranging from 37.3 to 41.9 reflect the role of metasomatic enrichment of the mantle source that may be correlated with interaction of plume type melts with a metasomatized sub-continental lithospheric mantle (SCLM). The chondrite normalized REE distribution pattern (Fig. 9) suggests that the slight HREE depletion might have been due to the presence of garnet at the source thereby suggesting garnet peridotite as the source of these lavas. Thus, the LILE-HFSE-REE systematics for the Vempalle lava flows invoke origin of parent magmas from a heterogeneous mantle source carrying signatures of (i) melts derived from melting of upwelling plume head (ii) depleted asthenospheric mantle components entrained by ascending plume and (iii) enriched and metasomatized SCLM.

7.3. PGE-REE systematics and sulphide saturation history

PGEs are proxies for the mantle characteristics and its geodynamic evolution (Lorand et al., 2000, 2008, 2013). These highly siderophile elements are also sensitive to record the changes brought out by processes such as seafloor hydrothermal metamorphism (Wood, 2002; Said et al., 2011), mantle metasomatism, crystal fractionation and fractional crystallization (Lorand et al., 2004). The PGEs residing in the host sulphides and chromitites (as alloys) forms a meagre portion of the Earth's mantle, hence very systematic approach is required to probe them in diverse tectonic settings. Basalts are unique lithological entities present

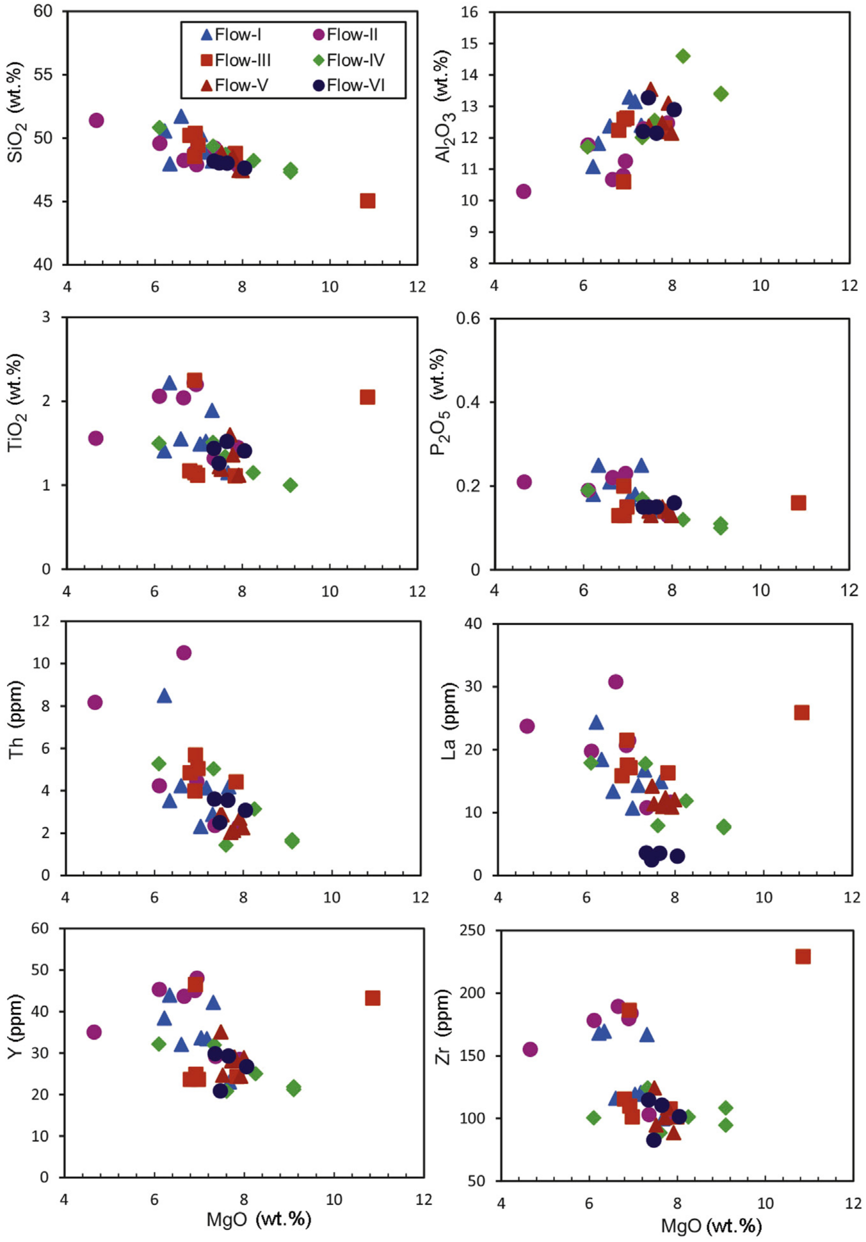


Figure 8. Selected major and trace element variations with MgO of the Vempalle flows.

in various geodynamic settings having variable trace and PGE concentrations. The geochemical behaviour (major, trace, REE and isotopic) of these rocks is well understood but the detailed studies on PGE geochemical systematics reflecting the mantle characteristics and PGE potentiality are very sparse. Most of the PGE deposits under exploitation are hosted in the mafic-ultramafic complexes where mineralisation occur in mantle xenoliths within basalts (Alard et al., 2000) and in Ti-rich highly fractionated and differentiated basalts of Skeargaard (Crocket, 1979; Nielsen and Brooks., 1995; Mome, 2000). In this study, an attempt has been made to understand PGE systematics and their petrogenetic implications for the Vempalle flows and to test the established hypothesis of mantle melting, fractional crystalisation, and effects on PGE in relation to major, trace and rare earth element geochemistry.

The iron-loving platinum group elements are expected to be stored in the Earth's core at low abundances (Os-Ir ~1–3 ppm; Ru 2.2–4.2 ppm; Pt 3.3–5.5 ppm, Pd 1.7–3.15 ppm and Rh 0.4–0.8 ppm; Lorand et al., 2008). Mantle derived rocks record very low PGE concentrations but the inferred PGE composition of the hypothetical primitive mantle show enrichments in Ru, Rh, and Pd compared to the chondritic PGE signatures, which argue for the reworking of PGEs by igneous processes within the Earth's mantle and core mantle interaction (Lorand et al., 2008).

The Vempalle flows exhibit positive correlations of various PGEs (ΣPGE, Pt, Pd, Ir, Ru, Rh) with MgO (Fig. 12) reflect on PGE fractionation during primary magmatic process such as fractional crystallization. The older flows with higher Mg# record relatively high abundance of PGE (upto 38 ppb for Flow-I) when compared to the younger flows (up to 9 ppb for Flow-VI) reflecting on their evolved nature (Fig. 13). The ΣREE abundances correlate positively with $(La/Yb)_N$ (Fig. 13) indicating fractional crystalization. The ΣPGE abundances correlate positively with Mg# indicating the control of mafic lithologies (silicate magma) in holding the PGE

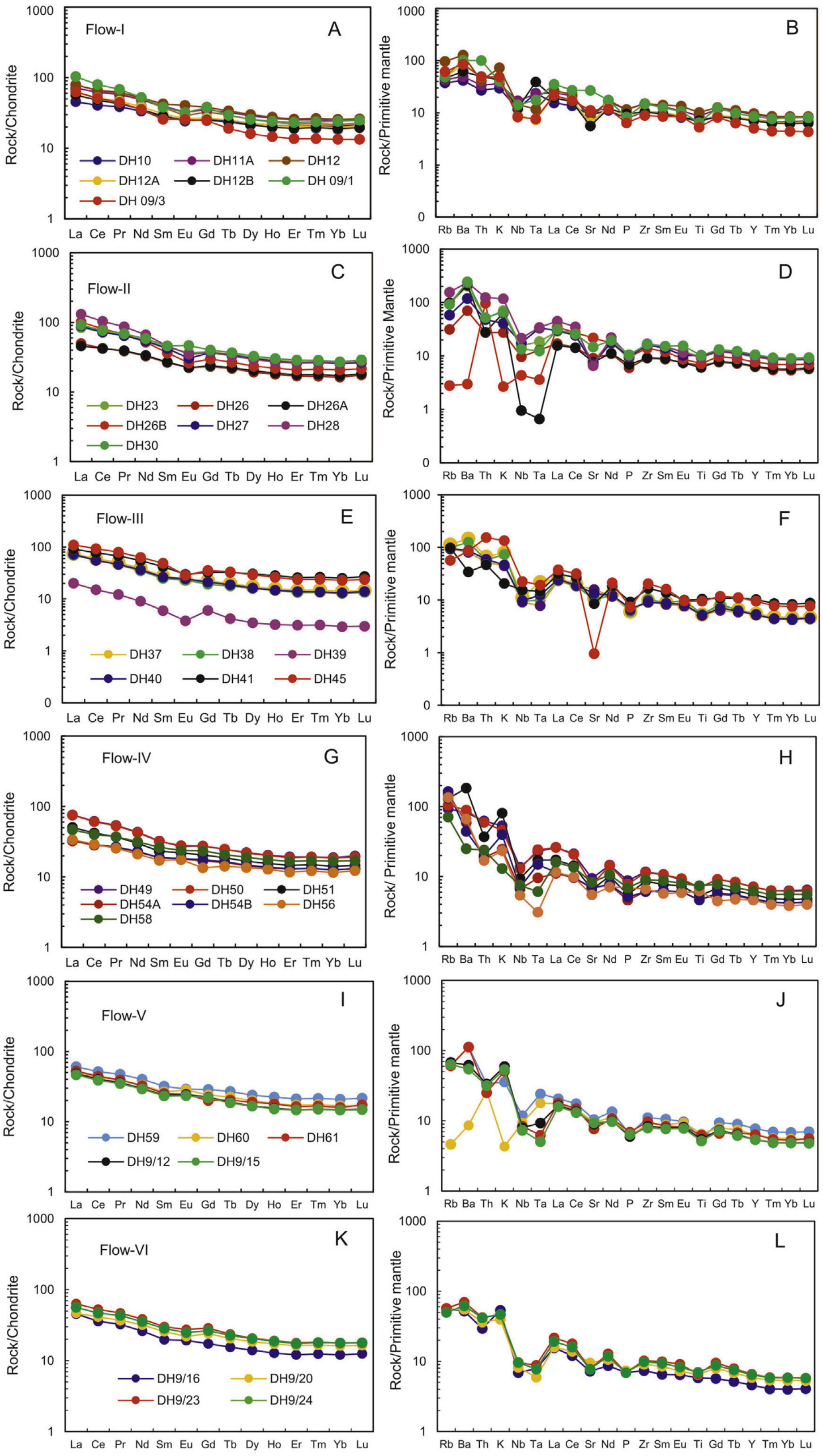


Figure 9. (A, C, E, G, I, K) Chondrite normalized rare earth element (REE) patterns of the Vempalle flows; (B, D, F, H, J, L) Primitive mantle normalized trace element patterns of the Vempalle flows. Normalizing factors are from McDonough and Sun (1995).

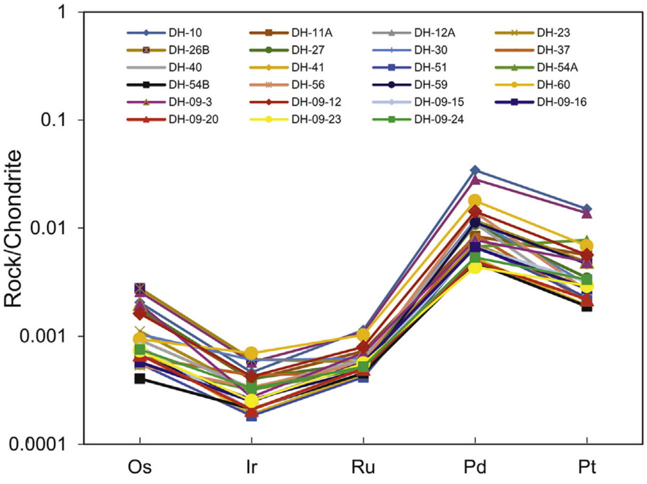


Figure 10. Chondrite-normalized PGE patterns of the Vempalle flows. Normalizing factors are from McDonough and Sun (1995).

phases (Rehkamper et al., 1999; Yang et al., 2017). Based on the argument of Lesnov (2010), with the increasing degree of partial melting in each subsequent portion of basalt melt, the total REE content will be lower than in the previous portions whereas the PGE content will slightly increase in the later melts due to their refractory nature. In other words, low REE portions will have slightly high PGE abundances in basaltic melts. This is also true when we consider the general hypothesis which states that the mafic magmas are partial melts of ultramafic rocks where the highly refractive Ir is preferentially retained with olivine mineral, hence Ir is extremely depleted in mafic rocks (Crocket, 1979). The sympathetic relationship between ΣPGE vs. Mg# and $(La/Yb)_N$ vs. ΣREE (Fig. 13) envisage significant role of fractional crystallization which is further evidenced by the binary relationship between Pt/Pt* and Pd/Ir (Fig. 14A). Garuti et al. (1997), Zheng et al. (2004) and Singh et al. (2013) described the Pt-anomalies which are represented as Pt/Pt* which is a measure of Pt deviation from the normal trend of the sample. Pt/Pt* values > 1 or <1, reflect on the petrogenetic processes of the analysed sample. Vempalle flows record negative Pt-anomalies (<1) where (flows I to VI have 0.62, 0.42, 0.25, 0.49, 0.58 and 0.61 respectively). Further, Garuti et al. (1997) and Kepezhinskas et al. (2002) suggested the Pt-negative anomaly is a consequence of (1) Pt-Pd-Rh fractionation which may be caused due to melt extraction from a mantle source leaving a refractory Pt-Fe alloy in residue, thus relative enrichment of Pd or Rh in the melt is possible, (2) during the early stages of crystal fractionation, extraction of Pt-alloys from a magma leading to negative Pt-anomaly in the restite or late stage magma. Both the above conditions apply for the present study as low degree partial melts have undergone fractional crystallisation. Pd/Ir, Ni/Cu, and other ratios further support this contention. The Pd/Ir (Pd/Ir = 1, PM) values being considered as "Index of Fractionation" which increases with differentiation in magmatic fractionation processes, and should be lower than unity in residual mantle material, decreasing with increasing degree of partial melting. On the other hand, the Ni/Cu ratio displays opposite behaviour with (PM Ni/Cu = 71.4), the value increase with partial melting and decrease

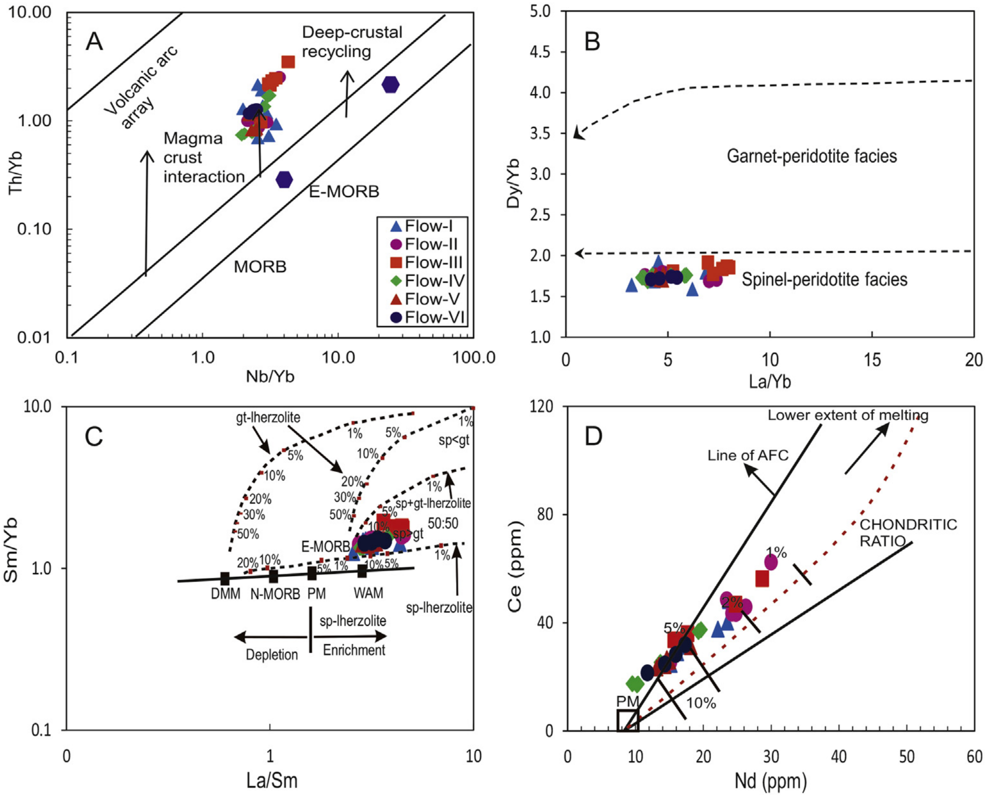


Figure 11. (A) Nb/Yb vs. Th/Yb plot (after Pearce, 2008) showing a trend away from the oceanic MORB-OIB array towards higher Th/Yb ratios reflecting the role of lithospheric mantle in the genesis of parent magma and magma–crust interactions, (B) La/Yb vs. Dy/Yb plot indicating their generation at shallow depth in spinel-peridotite stability field (after Jung et al., 2006), (C) La/Sm vs. Sm/Yb plot (after Aldanmaz et al., 2000) showing polybaric partial melting of Vempalle flows in the spinel + garnet lherzolite domain (where spinel > garnet) starting from the garnet-facies (with low degrees of partial melting) and continuing to larger degrees in the spinel stability field and (D) Nd vs. Ce binary plot (after Ahmad and Tarney, 1991). Heavy lines show the chondrite ratio after Sun and McDonough (1989). Dashed lines show the calculated different extent of melting of garnet lherzolite source (mineralogy and melting proportion from Hanson, 1980). Primitive mantle (PM) value is taken from Sun and McDonough (1989). Archean upper crust (AUC) and Archean total crust (ATC) are from Taylor and McLennan (1985).

with increasing degree of fractionation during magmatic crystallization (Garuti et al., 1997). Barnes and Maier (1999) opined that komatiites produced by high degree of partial melting have high Ni and Ir contents as well as low Pd/Ir and high Ni/Cu ratios, whereas basalts by low degree partial melting of mantle usually have low Ni and Ir contents, with high Pd/Ir and low Ni/Cu ratios. The Vempalle flows record very high Pd/Ir and very low Ni/Cu values in the range of 19–89 and 0.3–1.8 respectively, clearly indicating involvement of low degree of partial melting along with high degree of magmatic fractionation in the genesis of these basaltic flows. On the plot of Pd/Ir versus Ni/Cu, the Vempalle flows plot in the field of high-Mg basaltic rocks (Fig. 14B), indicating low to moderate degree of partial melting. Cu/Pd ratio is proxy for sulphur saturation in the magmas. It bears an indirect link with degree-depth of melting and PGE mineralisation. Keays (1995) estimated minimum partial melting of mantle as 25% which is necessary to extract all the sulphides in the mantle. As the Cu/Pd ratio of PM is 6850, its enrichment in the rock indicate early sulphide segregation. In contrary to this, Naldrett (2010) proposed the partial melting at 18% minimum for the complete dissolution of sulphides into melt by leaving their source. Taking 18% partial melting as maximum for a given magma, Naldrett (2010) modelled the release of Pt + Pd contents at 18 ppb maximum. Based on this, when extent of partial melting in case of Vempalle flows is back calculated, results in <10%, since the Pt + Pd concentrations are in the range of 4–34 ppb (34.1 and 29.5 ppb are only recorded in two

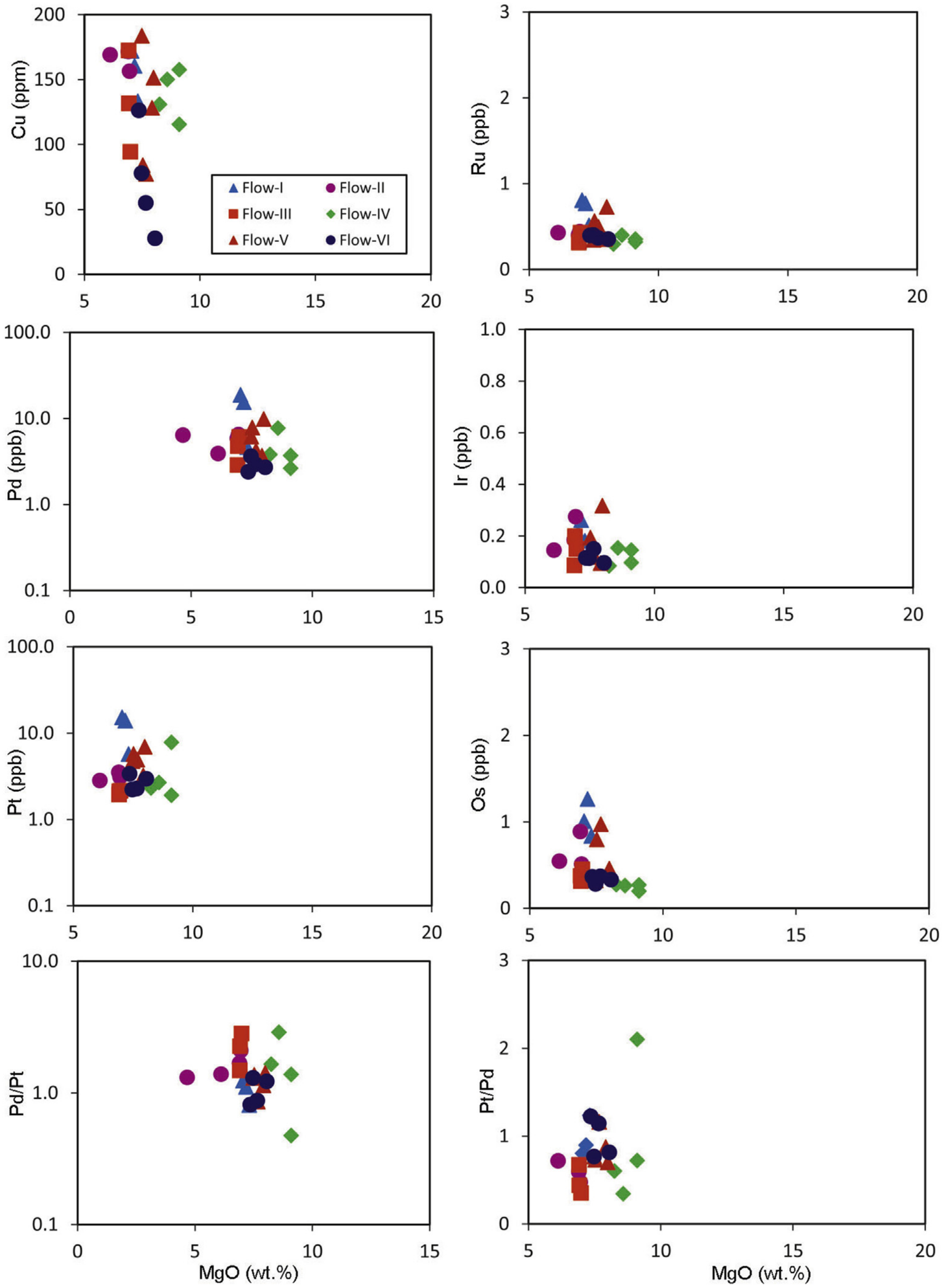


Figure 12. MgO vs. Cu, selected PGE and their ratios for the Vempalle flows exhibiting a cluster.

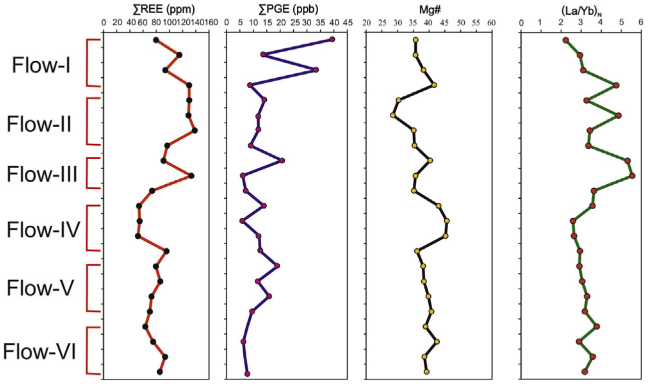


Figure 13. Relation between ΣREE, ΣPGE, Mg# and $(La/Yb)_N$ ratio from flow I to VI (top to bottom) showing sympathetic relationship between Mg# vs. ΣPGE and ΣREE vs. $(La/Yb)_N$.

samples in flow I; in general, the range is restricted to 4–16 ppb in the remaining flows). This range of total Pt + Pd in Vempalle flows also indicate the involvement of different degrees of partial melting in their evolution.

The negative anomalies of Pt relative to Pd, which are common features in many mafic rocks (Fryer and Greenough, 1992; Greenough et al., 1993), occur as a result of decoupling behaviour of Pt and Pd during early fractionation of magmas and also due to their similar partition coefficients (Chen and Xia, 2008). Cu vs. Pd plot (Fig. 15C) shows S-saturated nature of the Vempalle flows. In the Ni/Pd versus Cu/Ir plot (Fig. 14C), the studied flows are falling in the MORB field showing a trend consistent with sulphide fractionation which attests to the role of sulphur as a main phase to control the fractionation between the PGEs from Ni and Cu. The MORB signature for the Vempalle flows is further substantiated by the depleted nature of the samples on Pd vs. Cu/Pd plot (Fig. 15A).

Cu/Pd ratios of the residual magma will be low because Pd has much higher partition coefficients between sulphide melt and silicate melt than Cu (Barnes and Maier, 1999). Therefore, the moderate to high Cu/Pd ratios observed in case of Vempalle flows range from 9112 to 59,659 indicate that the magmas experienced early sulphide segregation, either in the mantle or during the evolution of magmas through a magma chamber where they segregated (Barnes et al., 1985). The binary diagrams Cu/Pd versus Pd and Cu versus Pd (Fig. 15B and C) indicate that PPGE are controlled by sulphide phases which have undergone late stage sulphide fractionation. Other PGE inter-element binary diagrams also show clustering of sample points indicating S-saturation has no significant role in changing the PPGE element concentrations of ascending silicate magmas prior to eruption as lavas (Hughes et al., 2015). The Pd/Pt ratios show a range from 0.5–3.0 in Vempalle flows which can be correlated with the Siberian native Fe basalts/flows (Howarth et al., 2017). On Cu/Pd vs. Pd/Ir plot (Fig. 15D) the Vempalle flows fall within fields for PGE-undepleted basalts of Siberian Traps and continental flood basalts of East Greenland. Besides decoupling behaviour of Pt and Pd, the enrichment of Pd over Pt has been explained by Howarth et al. (2017) who demonstrated that Pt and Pd can fractionate from one another in a variety of processes that result to variable Pd/Pt ratios within the basaltic suites, involving crystallization of sulphur saturated/undersaturated melts with Pd/Pt values from 1–2 and 1–8 respectively. In case of S-saturated melts, the silicate melts will be depleted in Pt and Pd whereas for S-undersaturated melts, the segregation of olivine-chromite and metallic Pt along with IPGE increase the Pd/Pt ratios from 1-8. Further, the depletion of PGE contents of Vempalle flows may be due to the retention of sulphide phases in the mantle due to low and variable degrees of partial melting. In other words, the high values of Ni/Pd and Cu/Ir ratios suggest that the magma has experienced a sulphide segregation event before emplacement. As a consequence of segregation of sulphides in the upper mantle, sulphide phases that surround the minerals scavenge the available PGEs which results in depletion of PGE in case of more or less evolved magmas (Mitchell and Keays, 1981; Naldrett and Wilson, 1990).

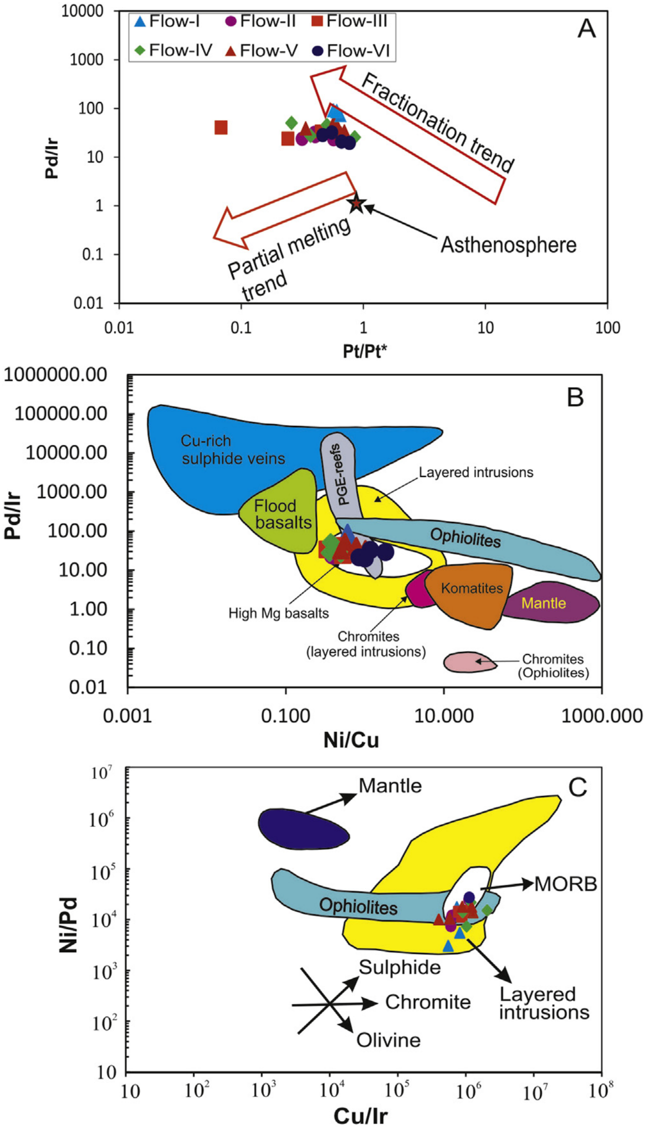


Figure 14. (A) Plot of Pt/Pt* $[=Pt_N/(Rh_N \times Pd_N)^{1/2}]$ vs. Pd/Ir of the studied mafic lava flows showing significant role of fractional crystallization. Fractionation and partial melting trends are from Garuti et al. (1997). (B) Ni/Cu vs. Pd/Ir diagram (after Barnes, 1990) showing the Vempalle flows falling in the field of high-Mg basaltic rocks indicating low to moderate degree of partial melting. (C) Cu/Ir vs. Ni/Pd diagram (after Barnes and Maier, 1999) relationship shows Vempalle flows in MORB field and consistent sulphur fractionation trend.

7.4. Tectonic implications

The studied lava flows from Vempalle straddle the fields between within plate basalts (WPB) and MORB on Zr/Y vs. Zr tectonic discrimination plot (Fig. 16A). On Th_N vs. Nb_N plots (Fig. 16B and C) of Saccani (2015) for classifying basalts of subduction-unrelated and subduction-related tectonic settings, the studied samples fall

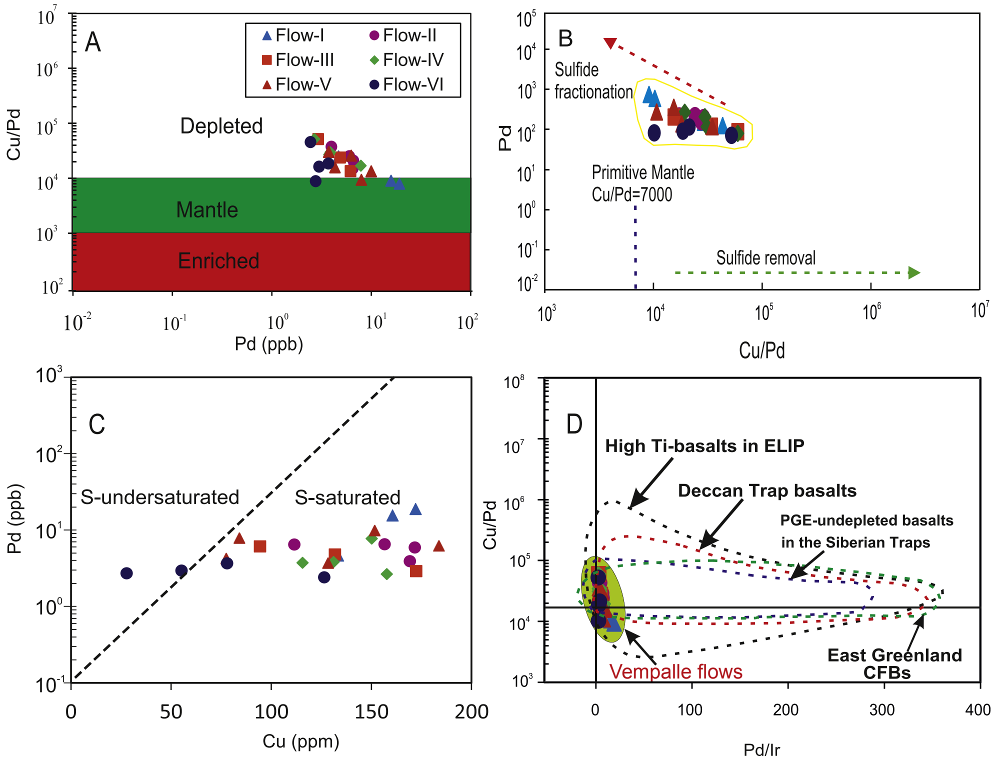


Figure 15. (A) Pd vs. Cu/Pd depicting depleted nature of the Vempalle flows (after Barnes and Maier, 1999), (B) Cu/Pd vs. Pd plot showing sulphide fractionation trend (after Barnes and Maier, 1999), (C) Cu vs. Pd plot showing sulphur saturated nature of the Vempalle flows (after Hoatson and Keays, 1989) and (D) Scattergram of Pd/Ir vs. Cu/Pd showing the Vempalle flows plot in the PGE-undepleted basalts field of Siberian Traps and continental flood basalts of East Greenland (after Li et al., 2012).

within the domain of oceanic subduction-unrelated setting and rifted margin corresponding to an ocean-continent transition zone (OCTZ). The studied lava flows further corroborate P-MORB tectonic affinity which strengthens the trace and PGE signatures of depleted asthenospheric MORB mantle trapped by ascending plume (Saccani et al., 2013). The MORB affinity and the depleted mantle signatures as reflected by the HFSE/LILE compositions and ratios, further substantiated by PGE geochemistry and involvement of asthenosphere in melt generation process collectively endorse the role of depleted MORB-type asthenospheric mantle components in the genesis of these Vempalle lava flows. The involvement of 5%–16% polybaric partial melting of MORB type mantle influenced by plume type components in an asthenospheric mantle with an upwelling plume source ascending from deep to shallow mantle depths has been explained for the generation of two types of basalts from the Sarve-Abad ophiolites of Kurdistan region of Iran (Saccani et al., 2014). Geochemical attributes pointing towards intraplate tectonic setting for the Vempalle lava flows in a subduction-unrelated ocean-continent transition zone (OCTZ) environment support their origin from (i) a rising mantle plume trapping depleted asthenospheric MORB mantle during ascent (ii) plume-lithosphere interaction and (iii) rift-controlled intra-basinal melt emplacement through Archean-Proterozoic cratonic blocks. Geophysical investigations have recorded a gradual decrease in lithospheric thickness from western to eastern sectors of Dharwar Craton with shallow mantle signature and thinned lithosphere-asthenosphere boundary (LAB; Kumar et al., 2013; Borah et al., 2014). Paleomagnetic reconstruction of Permian Gondwanaland and estimation of lithospheric architecture by geophysical studies suggest an association of eastern Dharwar Craton including Cuddapah basin and Antarctica with a thinned lithosphere and shallow lithosphere-asthenosphere boundary (LAB; Kumar et al., 2007; Chandrakala et al., 2017). The 550 Ma Pan-African metamorphism and associated thermal anomalies, mantle plume activity beneath Permian Gondwanaland account for lithospheric melting and stretching, asthenospheric upwelling and plume-asthenosphere-lithosphere interaction beneath Cuddapah basin (Kumar et al., 2007, 2013). The evolution of the Vempalle flows of Cuddapah basin can be correlated with these conjectures from global tectonic perspective. The geochemical coherence between tholeiitic magmas of Cuddapah basin and Antarctica, lithospheric melting and thinning of LAB by mantle plume incubating beneath older cratonic blocks collectively attribute to rift-controlled intraplate magmatism in Cuddapah basin along rifted cratonic margins at ocean-continent transition zone (OCTZ). Saccani et al. (2015) reported similar tectonic setting for the basalts of the continent margin ophiolites of Adria, Ligurian units of northern Apennines, Albanide-Hellenide orogenic belt and explained their derivation from compositionally distinct mantle sources that are effected by plume events in an uprising asthenospheric mantle. The authors envisaged that the magma poor continental margins/little surface magmatism are the characteristic features of continental margins related to the OCTZ exemplified by Iberia-Newfoundland conjugate margin pair.

7.5. Tectonic model

A tectonic model has been proposed based on the integrated field, petrographic and geochemical attributes which explains the basin initiation during 1.9–2.0 Ga due to thermal perturbations/mantle plume that resulted in lithospheric stretching followed by crustal sagging (Anand et al., 2003; Ravikant et al., 2014). The lithosphere-asthenosphere interaction resulted in the generation of the Vempalle melts (Fig. 17A) as also evidenced by the geophysical studies for the existence of shallow Lithosphere Asthenosphere Boundary (LAB; 15–20 km), extensive magmatic underplating

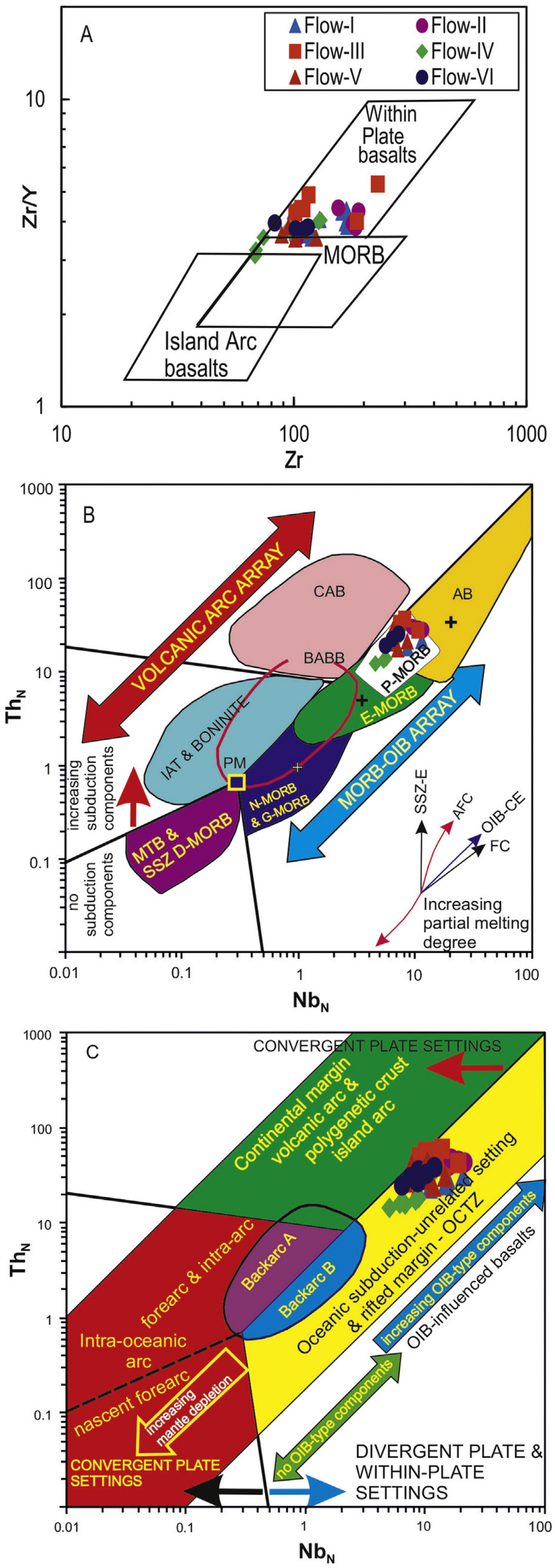


Figure 16. (A) Zr vs. Zr/Y tectonic discrimination diagram (after Pearce and Norry, 1979) showing the Vempalle flows in the field of Within Plate Basalts (WPB). (B and C) Th_N vs. Nb_N diagram (after Saccani, 2015) showing different tectonic settings for magmatic rocks of diverse compositions. The studied Vempalle lava flows fall within the domain of oceanic subduction-unrelated setting and rifted margin corresponding to an ocean-continent transition zone (OCTZ). Vectors indicate the trends of compositional variations due to the main petrogenetic processes. SSZ-E: supra-subduction zone enrichment; AFC: assimilation-fractional crystallization; OIB-CE: ocean island-type (plume-type) component enrichment; FC: fractional crystallization.

above Moho, intricate network of thrust and rifts, broken subducted slab below Cuddapah basin, high bouguer anomalies etc. (Kaila et al., 1979; Gupta et al., 2003; Ramesh et al., 2010; Chandrakala et al., 2015, 2017). The low degree partial melting of the asthenospheric mantle given rise to moderate quantity of melts erupted in a sub aerial environment. The inset figure in the model is depicted by the presence of a combination of dyke and sill network supplied by the melts from underplated magma above the shallow Moho, thus allowing fractional crystallization of plagioclase and clinopyroxene in the basalts emplaced in the Vempalle Formation during 1.88 Ga (Fig. 17A; Ravikant, 2010). These melts were generated in a continental rift setting under the influence of a shallow mantle plume as a result of polybaric melting in a garnet-spinel lherzolite melting regime. The dyke-sill complex is a manifestation of the above attributes which are coeval and cogenetic. Simultaneous opening of juvenile oceanic crust led to the deposition of marine stromatolitic carbonates, shales, cherts etc. of the Vempalle Formation (Fig. 17B). As the proposed plume appears to be at a shallow depth (within the lower crust), the temperature was not sufficient enough for the decompressional melting of the mantle and hence the magmatic activity was pulsative, short lived and resulted into small scale flows. The east to westward compressional force acted at different intervals in the geological past during various episodes of supercontinent assembly and dispersals might have brought these litho-units together as seen in the present day scenario (Fig. 17C). The tectono-magmatic processes resulted in the co-existence of shallow marine sediments and within continental plate magmatic rocks in the form of sub-aerial mafic lava flows in the Vempalle Formation. Further geochronological studies on these flows need to be undertaken to envisage the role and timing of mafic magmatism in the initiation and evolution of the Cuddapah basin which will have implications on the shaping of the continental margin of Indian plate.

8. Conclusions

(1) Vempalle lava flows have been identified and distinguished on the basis of morphological features and systematic three-tier arrangement of vesicular-entablature-colonnade zones.
(2) Petrographically, the studied flows are porphyritic basalts with plagioclase and clinopyroxene representing the dominant phenocrystal phases reflecting the role of fractional crystallization as a dominant magmatic process.
(3) Geochemical characteristics reflect LILE-LREE enrichment with relative HFSE depletion collectively conforming to plume-related intraplate magmatism with contributions from sub-continental lithospheric mantle (SCLM), crustal assimilation and fractional crystallization of sub-alkaline tholeiitic magmas.
(4) PGE chemistry of Vempalle lavas attest to sulphur-saturated nature of magmas with pronounced sulphide fractionation. Negative Pt-anomaly (Pt/Pt*) of the Vempalle flows indicate that Pt has been extracted during the early stages of crystal fractionation. Enrichment of Pd over Pt in Vempalle flows demonstrates decoupling behaviour of both the elements before emplacement.
(5) PPGE enrichment over IPGE and higher Pd/Ir ratios due to early sulphide segregation and late stage sulphide fractionation

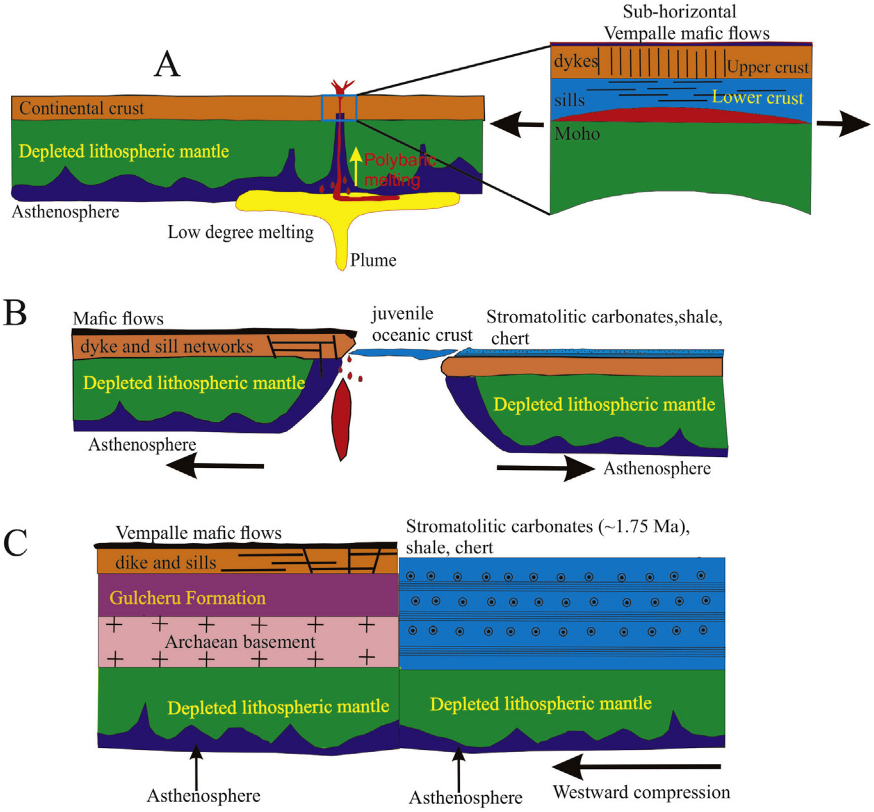


Figure 17. Schematic tectonic model for the emplacement of the mafic flows of the Vempalle Formation, Cuddapah basin. (A) Asthenospheric upwelling due to shallow mantle plume, thinning of crust leading to the emplacement of dyke-sill complex and Vempalle flows (Inset), (B) opening of juvenile ocean due to the influence of plume and deposition of marine sediments and (C) east to westward compressional forces due to various supercontinent amalgamation and dispersals resulted into the juxtaposed terranes that brought flows, dyke-sill complex and sediments together.

reflecting the role of a metasomatized lithospheric mantle in the genesis of these lava flows.

(6) PGE correlations suggest that the Vempalle lava flows are analogous to fertile CFBs of Siberia and Greenland implying a mantle plume-type origin with lithospheric inputs.

(7) The polybaric partial melting process initially started deeper in the garnet facies domain and continued to the shallow level in the spinel facies regime of the mantle where higher degrees are attained involving plume-type melts and depleted asthenospheric MORB manle that are entrained by ascending plume and enriched SCLM metasomatized by ancient subduction processes.

(8) Rift-controlled intraplate setting associated with an ocean-continent transition zone (OCTZ) marked the tectonic environment for the emplacement of Vempalle lava flows.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.gsf.2017.12.013.

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