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Olivine Composition in Picrite Basalts in Pulivendula-Vemula section, South-Western part of the Proterozoic Cuddapah Basin, Andhra Pradesh, India

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Abstract

In the evolution of Dharwar craton mafic –ultramafic magmatism is an integral part, having taken repeatedly at various stages of its development. Basaltic sills and lava flows (~1.88 Ga) are commonly intercalated with sediments in the lower part of the sedimentary sequence in the intra-cratonic, mid-Proterozoic Cuddapah basin of southern India. Across the study area argillaceous rocks are mainly represented by shale exhibiting olive green colour which very often as a result of oxidation grades to purple colour. A large number of sills, varying in thickness from about a metre to 50 metres, intruding the argillaceous pile of rocks have been sampled. The mafic sills within the Tadpatri Formation occur at various stratigraphic levels. The thicker sills form NW-SE trending ridges with steep slope towards south and very gentle slope towards north. From south to north intervening areas in between the successive ridges are characterised by low grounds which are chiefly occupied by shale. The differentiated sills in the lower part of the Tadpatri Formation, the doleritic sills at different stratigraphic horizons and basaltic sills in the upper part of the formation have been identified by a thick differentiated gabbro sill (olivine gabbro to leucogabbro) occur in the lower part of the Formation. The olivine gabbro sills are emplaced at least at two different stratigraphic levels. All the sills are trending NNW-SSE to NW-SE.

Keywords: *Picrite sills, Litho-Stratigraphy, Petrology, Cuddapah basin, Pulivendula-Vemula*

1. Introduction

The petrogenesis of flood basalt lavas, particularly their often iron-rich character, was a long-term interest of Keith Cox (e.g. Cox, 1980; Cox & Hawkes worth, 1985; Cox & Mitchell, 1988; Scarrow & Cox, 1995). Recognition that the earliest liquids produced during partial melting of peridotite are Mg rich, combined with the widespread but volumetrically minor occurrence of picritic rocks in flood basalt provinces, provides an important basis for the discussion of basalt genesis in these settings. In the IUGS classification scheme (Le Bas, 1999) a picrite or picrite basalt contains [12% MgO, <52% SiO_2 and >3% Na_2O + K_2O). Picrobasalts have compositions intermediate between basalts and picrites as defined here. Thus in a suite of mafic rocks, a spectrum of compositions may occur, ranging from primitive picrite basalts to picrobasalts and basalts. Rocks with picritic chemical characteristics can arise in a variety of ways; for example, as primitive picritic liquids that are little-modified melts of upper-mantle peridotite, by accumulation of early formed olivines from such primary picritic liquids, or by accumulation of olivines from 'normal' basaltic magmas. Under equilibrium conditions, olivine compositions will reflect the composition of the magma from which they crystallize; thus the composition of olivine phenocrysts in picrites is a valuable clue to their petrogenesis. This is the approach used by

Krishnamurthy & Cox (1977), who examined a suite of mafic lavas recovered from boreholes in Western India that were first described by West (1958). The Proterozoic Cuddapah basin of Peninsular India covering an area of around 44,000 km^2 in the state of Andhra Pradesh, is one of the well-known Proterozoic sedimentary basins in the world (Nagaraja Rao and Ramalingaswamy, 1976). Contemporaneous with the sedimentation, Cuddapah basin has witnessed number of phases of igneous activity during the course of its evolution six phases of igneous activity are recorded in Cuddapah basin (Nagaraja Rao et al., 1987). Sub-aerial eruption of basic lava flows after the deposition of Vempalli Formation marks the first phase of igneous activity within the basin.

The volcanic activity represented by fine grained basic rocks and tuffs with in theTadpatri Formation represents the second phase of igneous activity and intrusion of sills of picritic and doleritic composition into the Vempalle and Tadpatri succession marks the third phase of igneous activity. The barium and iron oxide rich volcanic activity which was contemporaneous with the Pullampet/Cumbum Formation represents the fourth phase, while intrusion of basic dykes and alkaline rocks (riebeckite syenites of Giddaluru- Racherla-Idamakallu-Dhupadu and Chelima Lamproite) into the rocks of Nallamalai Fold Belt represents the fifth phase of igneous activity. The sixth phase of igneous activity is represented by intrusion of granitic rocks into the Nallamallai group in the north eastern fringes of the Cuddapah basin. Howeverlater work (Sesha sai,2005) revealedthe Nakerikallu and Ipuru granitods are traversed by dolerite dykes.

2. Study area

The study area is covered by Survey of India toposheet numbers 57J/3, J/7, and is bounded by latitudes 14°15’00” to 14°45’00” and longitudes 78°00’00” to 78°30’00”. The most important locality within the area is Pulivendla (14.4167°N, 78.2333°E). Distance of Pulivendla from Hyderabad is around 432 kilometres and can be approached from Hyderabad via NH-7 up to Kurnool or Anantapur from where south-eastward/westward roads lead to Pulivendla town. Distance of Pulivendla from district headquarter Cuddapah is ~ 64 kilometres and it is 74 km, 158 km and 35 km respectively from the towns of Anantapur, Kurnool and Kadiri from each of which it may be approached via metal roads. Another important locality within the study area is Vempalle which is around 26 kilometres south of Pulivendla. Fig 1 shows the sample location of the study area.

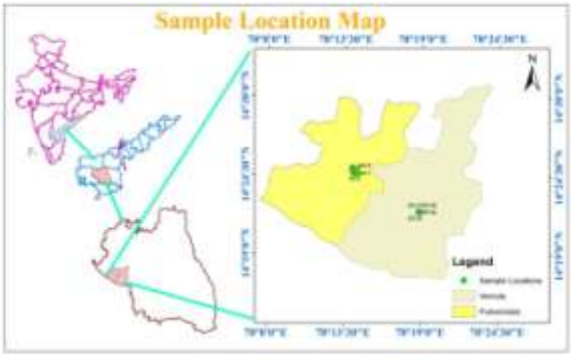

Fig 1 Sample location of the study area.

2.1 Primitive picrite basalts and the volcanic cycle:

The primitive picrite basalts identified in the Deccan can be examined in terms of Cox’s volcanic cycle model for the Karoo (Cox, 1972). According to this model, the volcanic cycle has a very early low-degree-of-melting stage, characterized by alkaline and ultra-alkaline rocks, followed by a thermal peak (the culmination stage) that is represented by High-Mg primitive picritic basalts. The thermal peak is followed by a steady-state stage during which basalts constituting the bulk of the province erupt. These typically have fairly uniform major element chemical compositions. A crustal stage, dominated by rhyolite rocks, may closely follow or be coeval with the basalts. The end of the cycle is again characterized by alkaline and acidic rocks produced as low-degree melts.

Broadly speaking, volcanism in the Deccan appears to have followed a similar pattern. Among the oldest known Deccan rocks are alkaline complexes at Sarnu (68·5 Ma) and Mundwara (68·5 Ma) in the north, representing the very early, low partial melt stages (Basu *et al.*, 1993). This is probably followed by the sequences found in Kutch, Saurashtra and Narmada. In Kutch, tholeiitic and ultra-alkaline rocks are almost synchronous, giving ages of 67–64 Ma (Pande *et al.*, 1988). Field evidence appears to place the primitive picrite basalts of the borehole sequence, as well as those of Paragraph, below the tholeiitic of the Western Ghats in the stratigraphic sequence. The primitive picrites would thus represent the culmination stage in Cox’s model, and probably originated in the high-temperature Reunion plume head. Deep-seated faults along the Narmada rift and Cambay graben aided rapid transport of these dense magmas to thesurface. The predominant evolved tholeiitic basalts of the Deccan province, well represented in the Western Ghats, were erupted during the steady-state phase of the volcanic cycle. Cox (1980) envisioned sill-like complexes of ponded, picritic magmas in the lower crust, or at the crust–mantle boundary, from which such lavas evolved. The bulk of the tholeiitic lavas probably erupted near 65 Ma (Duncan & Pyle, 1988; Venkatesan & Pande, 1996). The Deccan volcanic cycle apparently closed with late-stage alkaline complexes such as Phenaimata (65·0 Ma; Basu *et al.*1993) and Ambadongar (65·0 Ma; Ray & Pande, 1999).

The coarse-grained mafic – ultramafic sills of Tadpatri Formation are relatively fresh in contrast to the lavas; the best exposure is seen near Pulivendla. Markedly the base of the sill is coarse-grained, ultramafic rock in which crystals of olivine, pyroxene and sometimes phlogopite are easily identifying in hand specimen. This unit grades upward into a medium-grained, leucocratic gabbro. The base of the mafic-ultramafic differentiated sill samples mainly consist of euhedral or subhedral olivines enclosed by pyroxene or plagioclase feldspar and crystals are up to 2 mm in length. The majority of the orthopyroxene analyses plot in the enstatite field. Orthopyroxene does not occur in the olivine-poor and highly differentiated portions of the sill or in any other sill or lava sample. Augite is by far the most dominant Ca-rich pyroxene in the Tadpatri sills. Phlogopite forms an accessory phase in the most olivine-rich portions of the sill and appears to have crystallized from inter-cumulus liquid trapped between early-formed oliivines.

The olivine is completely serpentinized in the differentiated part of the sill but clinopyroxenes are relatively fresh and form large sub-ophitic crystals. Towards the top of the sill, altered clinopyroxene and plagioclase grains dominate over olivine and orthopyroxene.The Tadpatri sills almost exclusively contain plagioclase feldspars.

2.2 Igneous Activity in Tadpatri Formation in Pulivendla-Muddanuru Section

A number of mafic-ultramafic sills exhibiting sharp contact with the shales and dolomite of Tadpatri Formation are noticed around Pulivendla, Dondlavagu, Tonduru-Mallela section and Velupucherla area in south western part of Cuddapah basin. A NNW-SSE to NW SE trending composite sill made of two components i.e. picrite and dolerite has emplaced the shales and dolomites of Tadpatri Formation and is exposed over a stretch of 12 km from Peddakudala in northwest to Velpula in southeast. Field relationship indicates that dolerite cuts the picrite sill (Sesha Sai, 2006). Dolerite is medium grained, mesocratic, and massive showing spheroidalweathering and petrographically composed of laths of plagioclase, subhedral augite (altered at places to amphibole), accessory ilmenite and pyrite.

Development sub-ophitic and ophitic textures are common in dolerites.The cause of partial melting of such heterogeneous mantle during Cuddapah sedimentation is conjectural. Small amount of rifting related decompression might have led to partial melting of upper mantle. However, rifting would generally lead to formation of alkaline magmas in its initial stage. William King (**1872**), in his memoir, has reported lava flows of alkaline affinity from Tadpatri Formation. Detailed field, petrographic and petrochemical studies in course of present work has definitely established albititic rocks from Tadpatri Formation. The chilled margin is consisting of plagioclase, clinopyroxene, orthopyroxene and olivine with minor phlogopite, spinel, chalcopyrite and pyrite.

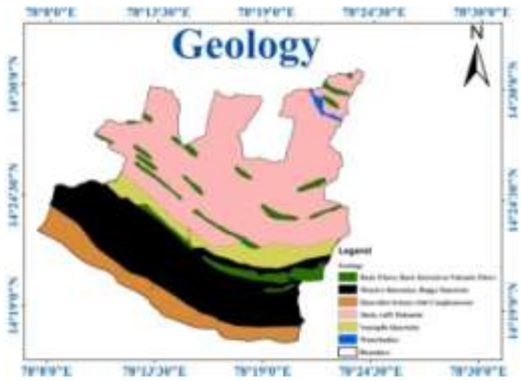

Fig 2: Geological map of South western part of Cuddapah basin showing disposition of basic flows over Vempalle Formation and picrite and dolerite sills in Tadpatri formation.

The plagioclase are medium to fine grained and are long and slender, often with branching and bifurcating terminals indicating rapid quenching. Swallow tail structures and hollow crystals in plagioclase are common features. Pyroxene occurs as fine granular aggregate within the interstices of plagioclase. The olivine, however, are medium grained and are generally euhedral to subhedral. The coarse to medium grained olivine gabbro is dominated by olivine, orthopyroxene, plagioclase and clinopyroxene (40 to 45% olivine, 20 to 35% plagioclase and ~ 40% pyroxene,proportion of orthopyroxene is greater than that of clinopyroxene. Phlogopite, ilmenite, spinel, bravoite, vaesite, pyrite and chalcopyrite are the accessory minerals. The texture is dominantly poikilitic with euhedral to subhedral medium grained olivine inclusions within coarse subhedral plagioclase, orthopyroxene and clinopyroxene. Olivine grains that are not included within pyroxene or plagioclase are of similar size and shape. Zoned Cr-Fe spinel occurs as partial to complete inclusions within olivine and also outside olivine while magnetite is generally associated with serpentine along the fractures of the olivine grains. Spinel grains are generally zoned with more Magnesian cores and Fe-rich rims. At times entire olivine grains and partially orthopyroxene grains are serpentinised while plagioclase grains are largely saussuritised. Bravoite and vaesite are present as small grains in the matrix.

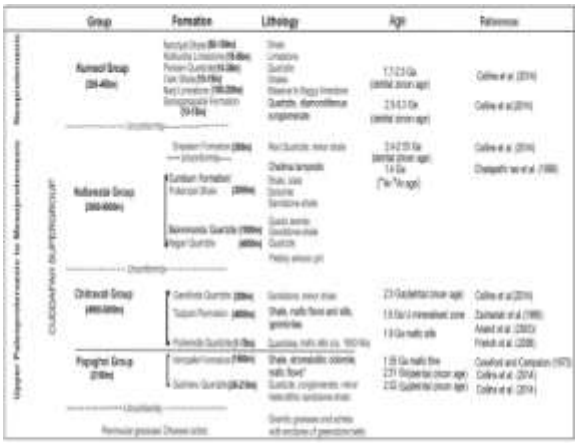

Figure 3. Lithostratigraphy of the Cuddapah basin (modified afterNagaraja Rao et al., 1987).

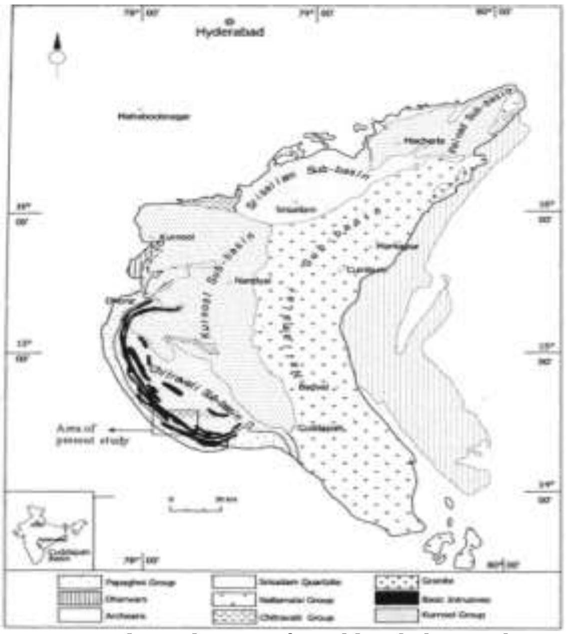

Fig-4 Geological map of Cuddapah basin showing the spatial distribution of igneous rocks (after Nagaraja Rao et al., GSI 1987). *Inset* map showing the position of Cuddapah basin in India.

Oxide (wt %)	Olivine	Opx	Phlogopite	Cpx	Plagioclase	Magnetite
SiO_2	37.65	55.58	38.00	55.72	49.3	0.00
TiO_2	0.00	0.35	2.63	0.38	0.00	5.67
Al_2O_3	0.01	1.05	13.95	2.63	30.32	5.56
MnO	0.01	0.29	0.01	0.44	0.00	0.34
MgO	40.25	29.43	20.72	19.50	0.10	2.43
FeO	21.62	10.65	8.24	7.56	0.86	56.89
CaO	0.12	1.96	0.01	11.24	14.73	0.00
K_2O	0.00	0.00	6.93	0.01	0.17	0.01
Na_2O	0.00	0.06	1.25	0.77	3.15	0.04
Cr_2O_3	0.00	0.37	0.85	0.00	0.00	23.15
NiO	0.13	0.10	0.14	0.16	0.00	0.18
Total	**99.78**	**99.84**	**92.73**	**98.41**	**98.63**	**94.28**
Cations						
Si	0.987	1.953	5.568	2.122	9.098	0.000
Al	0.000	0.048	2.386	0.111	6.568	2.134
Ti	0.000	0.010	0.292	0.011	0.000	1.394
Fe	0.445	0.362	1.001	0.229	0.132	15.628
Mn	0.005	0.008	0.001	0.013	0.000	0.089
Mg	1.547	1.543	4.450	1.060	0.028	1.182
Ca	0.004	0.074	0.001	0.437	2.879	0.002
K	0.000	0.000	1.296	0.001	0.040	0.006
Na	0.000	0.004	0.359	0.053	1.146	0.025
Cr	0.000	0.007	0.103	0.000	0.000	6.003
Ni	0.003	0.002	0.016	0.003	0.000	0.050
Species	Forsterite	Enstatite	Phlogopite	Augite	Labradorite	Magnetite

Table-1: Average Mineral chemistry of Picrite sills.

3. Results and Discussion:

3.1 Olivine compositions and variations:

Average olivine composition for samples from the various picrite compositions are given in Table 1, and the ranges of MgO concentrations, provide further details of the range of compositions encountered, including CaO and NiO concentrations.The primitive picrite basalts sampled from the Pulivendula-Vemula as well as the surface samples at Pulivendula, all contain forsteritic olivine phenocrysts. The samples showing the olivines exhibit limited chemical variability although the phenocryst rims are generally more iron rich.

3.2 Variations in minor element compositions:

Minor and trace elements such as Ca, Mn and Ni show significant variations among the analysed olivines. There is a general positive correlation between Ni and forsterite contents , with NiO reaching as high as 0·13wt % for the most forsteritic olivines, although there is a significant range in Ni at a given olivine composition.CaO also shows wide variations. Forsterites from the primitive picritic basalts contain CaO (0.12% CaO) than those from pulivendula-vemula .The picrite basalts and picrobasalts from the Pulivendula also no of forsteritic olivines, and they exhibit the maximum chemical variation observed among the analysed olivines suggest that there are minor compositional gaps among the analysed samples,but these may simply be the result of the relatively small number of grains analysed. The wide range of olivine compositions observed cannot be in equilibrium with a single magma type. They probably reflect the enrichment of Fe in residual melts during crystal fractionation, or mixing of evolved and less-evolved magmas, or both. Intra-flow differentiation within a compound lava flow, as observed by Deshmukh (1988), might also be responsible for some of the large compositional variations.

In general, phenocryst and groundmass olivine CaO contents are higher for olivines from samples with higher whole-rock CaO contents. There is a conspicuous absence of olivines with <0·1% CaO, perhaps not surprising as such low CaO contents are characteristic of olivines from deep-seated plutonic complexes and ultramafic inclusions (Simkin & Smith, 1970). MnO contents in general are consistently low in for-steritic olivines (<0·1%), except for samples from Pulivendula . In a few of the picrite basalts, olivine compositions show relatively minor deviations from the equilibrium field; broadly, these picrites must have formed from little-modified magma compositions, similar to those observed in anhydrous melting studies of upper-mantle peridotite.

33 Magma chamber processes and their influence on olivine compositions:

It has been claimed by a number of workers that in the Western Ghats extensive gabbroic fractionation produced basalts with MgO contents in the range of 7% or less, and that an initial stage of olivine ± aluminous clinopyroxene accumulation resulted in samples with >7·5% MgO (Sen, 1988, 1995; Cox & Mitchell, 1988; Lightfoot *et al.*, 1990).However, Cox & Hawkesworth (1985) questioned an accumulative origin (which had been based solely on olivine compositions) for some mafic lavas, such as the Khamshedi picrite basalts. According to Cox & Hawkes-worth, the Khamshedi rocks could be primitive picrites erupted at the beginning of a new compositional cycle. They overlie the Fe-rich flows of the Lower Poladpur Formation, and although the magma may initially havebeen trapped in a magma chamber because of its high density, it could have mixed with evolved, Fe-rich magmas of the previous cycle before eruption. Hybrid magmas of this sort would be anomalously rich in iron and Mg poor compared with the original picrite liquid (note that the Khamshedi lavas contain >15% Fe_2O_3). Crystallizing olivines would also be relatively Fe rich. Thus picritic basalts of the Khamshedi type may derive from true picrite magmas, in spite of the presence of low-Mg olivine phenocrysts. The establishment of well-developed magma chambers, and the operation of RTF (replenished, trapped, fractionated) type processes (O'Hara & Mathews, 1981) may ensure that unmodified primitive picrite basalts are not erupted directly (Huppert&Sparks, 1980, 1985). In the Deccan, the restriction of most primitive picritic lavas to the early parts of the sequence may at least in part be related to the fact that such magma chambers were not established until later in the volcanic cycle.

3.4 Trace and REE Geochemistry:

Trace element analyses of the cumulus picrite indicate Cr content of 122-649 ppm and Ni contents of 25-146 ppm (Table 2). Forestrite which is the most abundant mineral with ~ 38% by mode and with 0.13% NiO has controlled the Ni partitioning while, enstatite (0.37% Cr_2O_3), Magnetite**(**$Cr_20_3$23.15%) and chrome –spinel(Cr_2O_3 – 36.61%)Relatively enriched HFSE contents i.e. Zr (50-247 ppm) and Y (6-25 ppm), La/Sm ratios (3.3–3.6) and Sm/Yb ratios (1.10–1.17)Ce/Y ratios (0.8-1.8) and relatively La/Nd ratios (0.4-6.5) however indicate partial crustal contamination. Relatively dense picritic magmas may be trapped at or near the base of the crust where they become contaminated with lower crustal wall rocks and dif-ferentiate to form layered sills with gabbroic upper parts and olivine + pyroxene cumulate lower parts (Arndt and Goldstein, 1989). Trace element and rare earth element analyses of Picrite sill in Tadpatri formation from Peddakudala-Pulivendla-Velpula area in south western part of Cuddapah basin

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	Sesha sai (1994) Velpula-Pulivendula area, SW part of Cuddapah basin.		Anand et al. (2003) Pulivendula area SW part of Cuddapah basin	
Ba	41	42	97	106
Co	130	134	106.3	108.2
Cr	2,157	2,162	2,857	2,898
Cu	62	63	48.9	59.5
Nb	1.5	1.8	1.77	2.37
Ni	981	982	919	919
Rb	9.6	12	14.3	19.2
Sc	29	30	22.8	28.3
Sr	48	49	66.4	67.9
V	151	153	117	137
Y	8.6	10.6	8.47	10.63
Zr	25	27	32.8	44
La	2.69	2.71	6.40	7.93
Ce	4.56	4.60	15.4	19.1
Pr	1.28	1.31	1.4	1.8
Nd	2.04	2.14	5.83	6.91
Sm	0.63	0.83	1.3	1.53
Eu	0.14	0.13	0.42	0.53
Gd	0.36	0.39	1.64	2.07
Tb	–	–	0.27	0.32
Dy	0.76	0.78	1.75	2.08
Ho	–	–	0.36	0.44
Er	0.94	0.96	1.06	1.37
Tm	–	–	0.17	0.18
Yb	0.26	0.47	1.11	1.22
Lu	0.15	0.17	0.16	0.17
Rb/Sr	0.2	0.24	0.21	0.28
Zr/Y	2.90	2.54	3.8724	4.1392
Sm/Yb	2.42	1.76	1.17	1.25
La/Sm	4.26	3.26	4.92	5.18
Sm/Nd	0.30	0.38	0.22	0.22

Table 2 Trace element and rare earth element analyses of Picrite sill in Tadpatri formation from Peddakudala-Pulivendla-Velpula area in south esatern, north western part of Cuddapah basin

Pulivendula –Vemula NW-SE Direction part of Cuddapah basin		
Ba	56.657	183.283
Co	85.25	180.376
Cr	122.494	568.235
Nb	0.269	11.791
Ni	25.63	146.525
Rb	10.409	18.883
Sc	26.662	54.666
Sr	54.147	439.899
V	97.349	576.389
Y	6.807	25.092
Zr	50.875	247.218
La	2.382	26.357
Ce	5.80	52.583
Pr	0.676	5.075
Nd	3.294	25.312
Sm	0.753	4.945
Gd	0.919	5.058
Tb	0.167	0.786
Dx	0.219	0.815
Ho	0.251	0.815
Tm	0.122	0.454
Yb	0.732	2.476
Lu	0.127	0.325
Ce/Y	0.865	1.0305

Table 2 Trace element and rare earth element analyses of Picrite sill in Tadpatri formation from Peddakudala-Pulivendla-Velpula area in south esatern, north western part of Cuddapah basin

4. Conclusions

Emplacement of the forsterite rich picrite sill along the NW-SE to NNW-SSE trending deep seated fractures within the lower Cuddapah Tadpatri sediments indicates a major phase of mantle derived Early Proterozoic magmatism contemporaneous with sedimentation within the stable intracratonic Cuddapah basin in southern Peninsular India. Conspicuous poikilitic relationship between cumulus plagioclase and olivine in picrite indicate co-precipitation of both the phases. Super coiling results in early, precumulus crystallisation of metastable, non-equilibrium plagioclase, followed by co-precipitation of cumulus plagioclase and olivine. Forward modelling of trace and major elements and inverse modelling of REE suggest that the primary melts that gave rise to emplacement of mafic-ultramafic sill Complex in Tadpatri Formation was generated due to partial melting of Iherzolite mantle source.

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