Spinel (hercynite) adcumulate from the Chimakurti gabbro-anorthosite pluton, Prakasam District, Andhra Pradesh, India: Evidence for plagioclase buoyancy and magma mixing

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A spinel (hercynite) adcumulate cuts across the leuco-gabbro unit of the Chimakurti gabbro-anorthosite pluton. The rock is composed of cumulus hercynite (≈ 95% by volume) and intercumulus magnetite (≈ 5%) and it displays impeccable framework of touching mineral grains. Magnetite also occurs as exsolved linear trails and minute dust within hercynite. Spinel shows invariably homogeneous chemistry without any intragranular compositional zonation or intergranular variation. Al_2O_3 and FeO are the two major oxides but appreciable amounts of MgO and Fe_2O_3 are also recorded. Chromium is significantly low in these spinels. Both intercumulus and exsolved magnetites show exactly the same composition. It is proposed that the mixing of primitive basaltic liquid with an earlier evolved plagioclase-supersaturated residual liquid has brought the composition of hybrid liquid into the spinel stabilization field. Consequent to its crystallization, extreme sorting, separation and accumulation has produced the spinel (hercynite) adcumulate.

LIQUIDUS phases or primocrysts crystallizing from a magma get sorted-out and settle down on the floor and to the walls of the magma chamber under the influence of gravity or convection currents. Compaction of such primocrysts with pore-space liquid produces 'cumulate rocks'. The primocrysts are designated as 'cumulus phases' and the pore-space liquid is called 'intercumulus liquid'[1]. Apart from gravitational and convection settling, *in-situ* crystallization[2] and convective fractionation[3] are the other two mechanisms proposed for the formation of cumulate rocks. These processes are more significant in basic magmas than the acidic ones due to viscosity constraints. Based on the amount of intercumulus material, the cumulate rocks are classified as adcumulates (intercumulus liquid < 7%), mesocumulates (7–25%) and orthocumulates (> 25%) (ref. 4). In general, there exists a continuum of rock types from the former to the latter within a magma chamber.

Rates of accumulation which promotes or inhibits *diffusional exchange* between pore-space liquid and overlying magma chamber influence the kind of cumulate rocks form within a homogeneous magma chamber. But recent studies have shown that *convection in interstitial liquid*, rather than diffusion, is responsible for the formation of a variety of cumulate rocks. An extreme case of convection of pore-space liquid produces adcumulates.

The Chimakurti gabbro-anorthosite pluton[5–7] (CGAP; N. Lat. 15°40′; E. Long. 79°50′) in the Prakasam alkaline province, contains a central olivine-clinopyroxenite enveloped by a major gabbro-norite unit with intervening arcuate bands of anorthosite and leuco-gabbro units. All the rock units exhibit cumulate textures and they represent ad-, meso- and orthocumulates. The present communication is mainly aimed at reporting the occurrence of hercynite spinel adcumulate within the CGAP and to discuss its petrogenetic significance. Basic plutons, especially the layered intrusions crystallize spinel on liquidus which accumulates to form spinel adcumulate but the composition of spinel would be Cr-rich or even chromite. Strikingly, the composition of spinel in the spinel adcumulate from the CGAP is Fe and Al-rich, and Cr-poor hercynite. We are not aware of any such occurrence elsewhere in the world.

The hercynite adcumulate occurs as a band within leuco-gabbro juxtaposed to olivine-clinopyroxenite unit in the NE corner of the pluton. It extends for 50 m with a uniform thickness of 4 cm. The contact between the spinel adcumulate and the host is sharp without any chilled margins. The cross-cutting nature of the adcumulate unit suggests that it has formed later than the leuco-gabbro. Megascopically the rock is melanocratic, compact, dense and exhibits metallic lustre. The framework of touching mineral grains is evident even in a hand specimen. The grain size ranges from 3 mm to 5 mm.

Plagioclase, olivine, clinopyroxene and orthopyroxene are the major cumulus phases which accumulate in various proportions and combinations, with changing saturation levels, to produce the observed lithologies in the CGAP. Cr-rich as well as hercynite spinels occur as intercumulus material within early formed olivine-clinopyroxenite which clearly suggests that the hercynite spinel was not on liquidus during the early stages of differentiation of CGAP. But the formation of hercynite adcumulate requires it to be a liquidus phase. The mechanism of bringing hercynite on liquidus will be discussed later in the paper.

The modal mineralogy of spinel adcumulate is hercynite (≈ by volume 95%) and magnetite (≈ 5%). Hercynite in thin section appears transparent, dark green and clouded with minute magnetite dust, especially at the centre of the grains (Figure 1). The rim portion of spinel is free from clouding. Network of euhedral hercynite cumulus grains exhibit well-developed triple junctions. Magnetite occurs as irregular to triangular intercumulus material as well as very small linear trails within hercynite.

The chemistry of hercynite and magnetite along with calculated mineral formulae on 4 oxygen-3 cation basis is given in Table 1. Fe_2O_3 is calculated using the AX program of Tim Holland (Department of Earth Sciences, University of Cambridge, UK). Al_2O_3 and Fe_2O_3 are the two major oxides in the hercynite spinel but appreciable amounts of MgO and Fe_2O_3 are also present. Extreme compositional homogeneity is the characteristic feature of these spinels. The spinels do not show even minimal intragranular compositional zonation or intergranular variation, suggesting that there is no change in the composition of the parent magma from which they have grown. Minor increase in Fe_2O_3 content from core to margin is due to exsolution of magnetite at the central portion of the grains, and absence of it at the rims. Chromium content is characteristically low in these spinels; Mg numbers of the spinels are constant and average around 0.46.

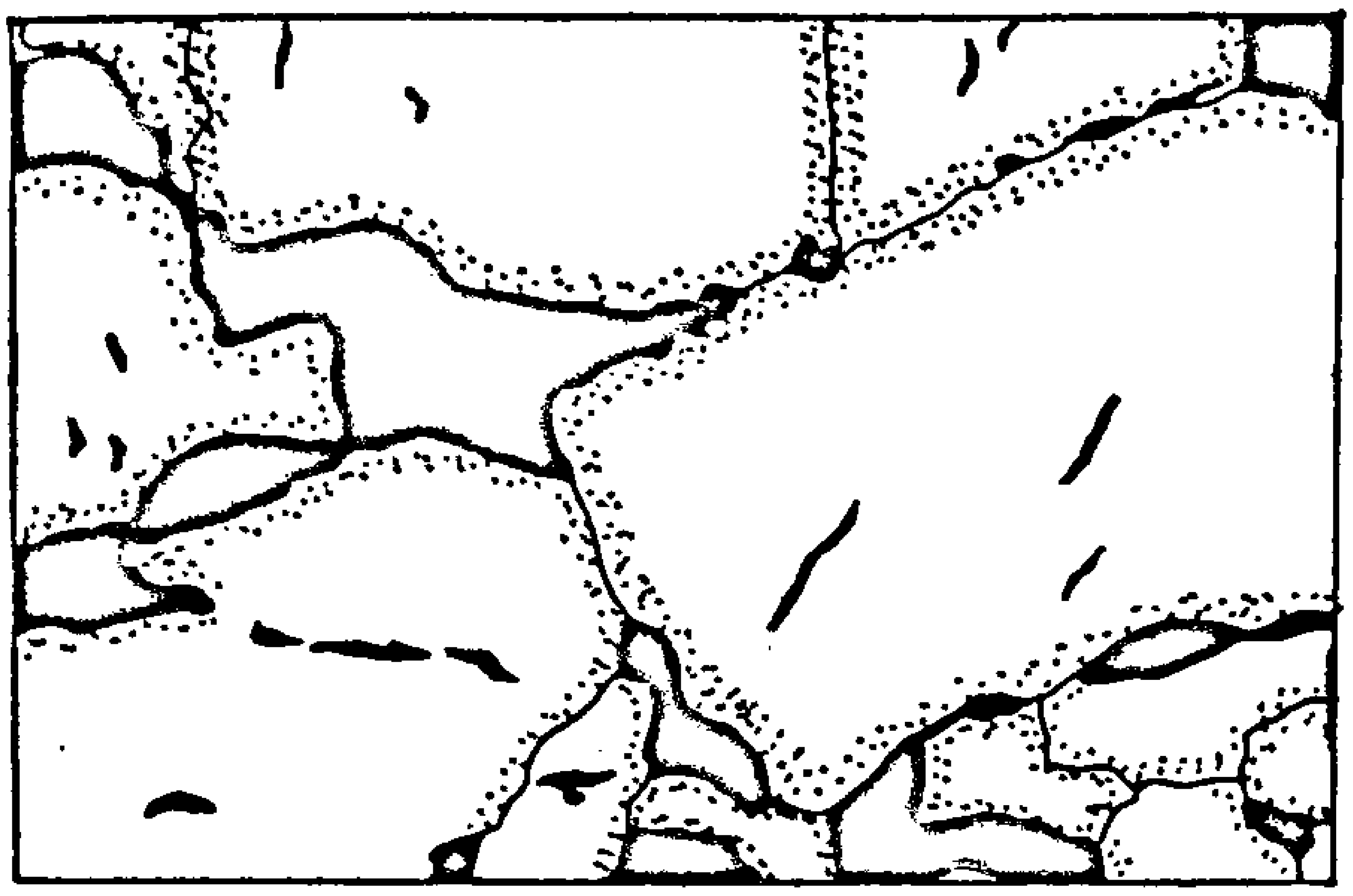

Figure 1. Line trace of photomicrograph exhibiting cumulus hercynite and inter-cumulus magnetite (black grains) within a spinel adcumulate (length of the photograph is 5.35 mm).

The chemistry of both intercumulus and exsolved magnetite is exactly the same. Intra- and inter-phase chemical variation is not recorded. Fe_2O_3 and FeO are the only two major oxides and all other oxides put together are less than 2 wt%. Extremely similar chemistry of both exsolved and intercumulus phases suggests that the latter is also a product of sub-solidus exsolution from the original spinel. It is well established that below 850°C the phase region of exsolution of magnetite from hercynite increases. If the intercumulus material is also an exsolved phase of spinel, then the Fe_2O_3 and FeO

Table 1. Chemistry of hercynite and magnetite determined with electron probe analysis by wavelength dispersive spectrophotometry using 20 keV accelerating voltage, 15 nA beam current and 1–10 μm beam diameter using CAMECA CAMEBAX SX50 electron probe

Mineral	Hercynite grain 1 (core)	Hercynite grain 1 (rim)	Hercynite grain 2 (core)	Hercynite grain 2 (rim)	Magnetite intercumulus	Magnetite exsolved
Oxides/cations						
SiO_2	0.00	0.00	0.00	0.06	0.09	0.00
TiO_2	0.10	0.01	0.06	0.01	0.49	0.00
Al_2O_3	59.79	59.24	59.50	58.81	0.75	0.81
Cr_2O_3	0.05	0.00	0.15	0.09	0.17	0.11
Fe_2O_3	4.95	5.09	5.67	6.84	66.61	67.43
FeO	23.61	23.67	22.97	22.59	31.46	31.29
MnO	0.33	0.18	0.20	0.23	0.00	0.00
MgO	11.58	11.28	11.68	11.61	0.06	0.01
CaO	0.00	0.00	0.00	0.00	0.03	0.02
Na_2O	0.00	0.00	0.09	0.20	0.00	0.00
K_2O	0.00	0.00	0.04	0.01	0.02	0.00
Total	100.42	99.48	100.36	100.45	99.68	99.67
Oxygens	4.0	4.0	4.0	4.0	4.0	4.0
Si	0.000	0.000	0.000	0.002	0.003	0.000
Ti	0.002	0.000	0.001	0.000	0.014	0.000
Al	1.894	1.897	1.886	1.867	0.034	0.037
Cr	0.001	0.000	0.003	0.002	0.005	0.003
Fe^{3+}	0.100	0.104	0.115	0.139	1.926	1.954
Fe^{2+}	0.531	0.538	0.516	0.509	1.011	1.008
Mn	0.008	0.004	0.005	0.005	0.000	0.000
Mg	0.464	0.457	0.468	0.466	0.003	0.001
Ca	0.000	0.000	0.000	0.000	0.001	0.001
Na	0.000	0.000	0.005	0.010	0.000	0.000
K	0.000	0.000	0.001	0.000	0.001	0.000
Sum	3.000	2.999	3.000	3.000	3.000	3.003
$Mg/Mg + Fe^{2+}$	0.47	0.44	0.48	0.48	0.00	0.00

contents of original spinel are much higher than the present value.

Formation of any adcumulate requires extreme sorting and separation of cumulus grains, and removal of intercumulus liquid to restrict post-cumulus changes. Spinel accumulation can be expected if the primitive magma is supersaturated in spinel or if there is a mixing of two contrasting liquids which may bring the hybrid liquid within the spinel stabilization field. Alternatively, the interaction of basic magma with pelitic material would result in higher Al content in the former and crystallize abundant plagioclase and hercynite spinel[8]. But the occurrence of hercynite rock towards the inner side of the pluton rather than at the margin and its extremely cumulus nature precludes such a mechanism. In the former case, spinel should be the first mineral to crystallize in the sequence of differentiation, but the field, petrographic and geochemical evidences suggest that the hercynite was on liquidus after the removal of olivine + clinopyroxene + plagioclase in the CGAP. Phase relations[9] (Figure 2) indicate that spinel can never be on the liquidus once the parental magma reaches ternary eutectic. Apart from this constraint, the Fe- and Al-rich and Cr-poor composition of spinel imply that it crystallized from an evolved liquid. Therefore it is difficult to visualize that the hercynite adcumulate is a fractionation product of primitive basaltic magma.

Mixing of evolved and primitive magmas may bring the resultant liquid within primary phase volume for spinel but, as evident from Figure 2, for such a mechanism to occur the residual liquid should lie in the plagioclase liquidus volume. Unless the residual magma is supersaturated with plagioclase crystals, the mixing will not shift the hybrid liquid into the spinel stabilization field. The assumed mechanism of the formation of hercynite adcumulate is shown in Figure 2. The primitive magma of composition 'X' crystallized olivine on liquidus and as the magma evolved, clinopyroxene joined olivine in the crystallization sequence (path A to B). Separation of this mixture (ol + cpx) has produced olivine–clinopyroxenite unit, and as a result of this fractional crystallization the residual liquid took a course towards ternary eutectic ('C'). At the point 'C' olivine + clinopyroxene + plagioclase crystallized together from the liquid. Since the density contrast between plagioclase and the basaltic liquid is too low, the plagioclase would not separate from the liquid as quickly as olivine and clinopyroxene. Consequently, the magma becomes supersaturated in plagioclase crystals. An important effect of this plagioclase buoyancy within the magma chamber is that the composition of porphyritic mixture (liquid + supersaturated crystals) lies in the plagioclase primary phase volume[10].

The actual position of the melt within plagioclase liquidus field depends on the amount of plagioclase suspended within the magma. Predicted composition of plagioclase-supersaturated liquid is marked as 'Y' in Figure 2. Replenishment of primitive magma to this porphyritic mixture will change the composition of resultant hybrid liquid (± crystals) along the mixing arrow as shown in Figure 2. The exact composition of the mixed magma depends on the relative proportions of residual plagioclase-supersaturated liquid and the replenishing primitive basaltic liquid. The mixed liquid may lie within plagioclase, olivine or spinel primary phase volumes depending upon the mass of the magma chamber and mass of the primitive liquid[10]. Such a mixing might have shifted the liquid into the spinel stabilization field (marked 'Z'). Spinel of hercynite composition would be the liquidus mineral crystallizing from such liquid since the mixed magma will have higher 'Fe' and 'Al' components than the primitive liquid due to its evolved nature and plagioclase supersaturation respectively. Extreme 'sorting' and 'dumping' of this spinel has produced the hercynite adcumulate. Sub-solidus exsolution has given rise to the intercumulus magnetite. High Fe_2O_3 component in the hercynite suggests local high f_{O_2} conditions.

A combination of processes, such as plagioclase buoyancy and magma mixing, facilitated the formation of hercynite adcumulate in the Chimakurti pluton.

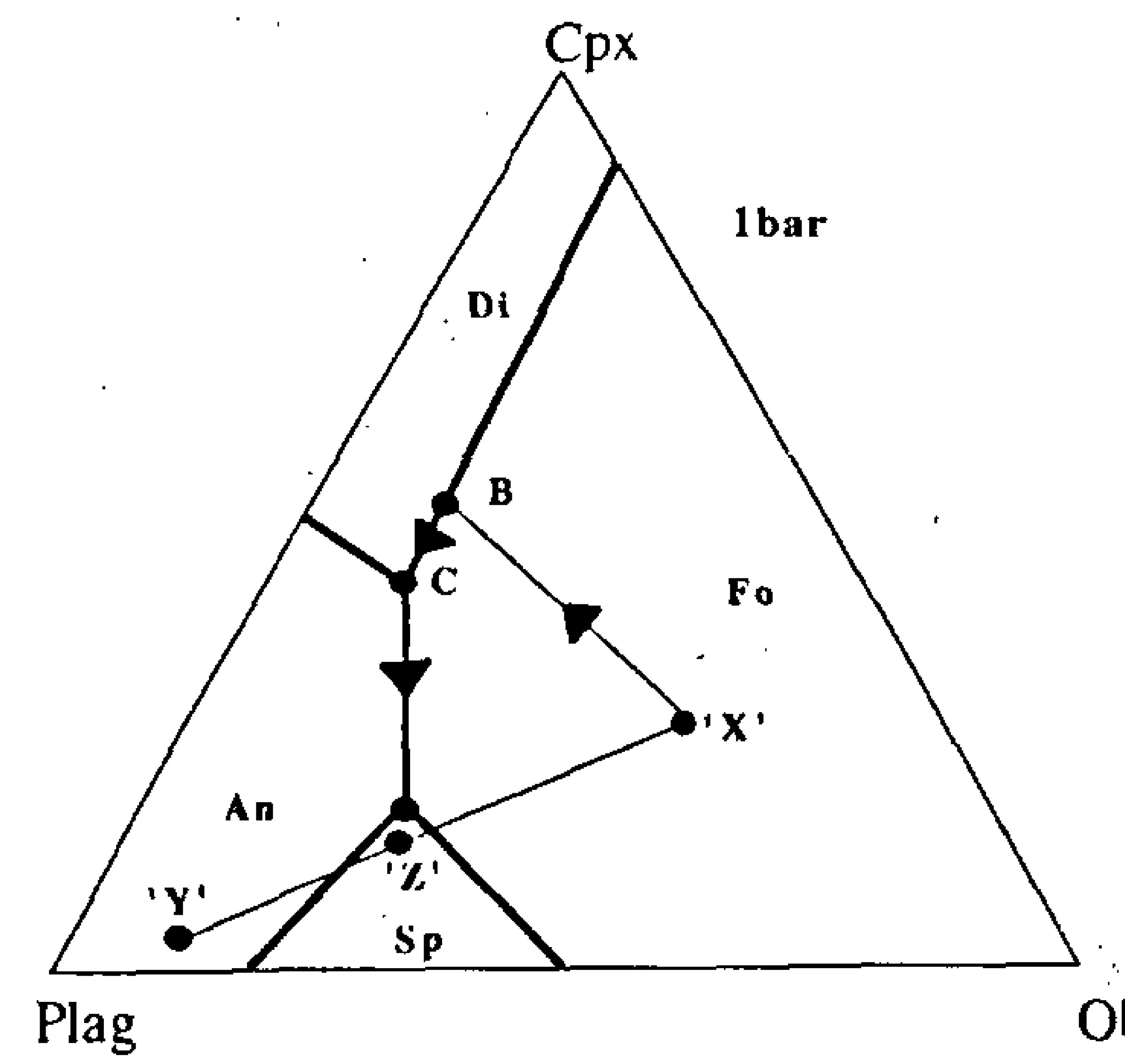

Figure 2. Plagioclase (An)–olivine (Fo)–clinopyroxene (Di) pseudo liquidus-phase diagram[9] showing predicted fractionation trend for CGAP. For details see text.

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Proterozoic intracratonic Godavari rift development at right angle to the Eastern Ghat Mobile Belt: An example for collision-induced rifting in SE India

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Genetic relationship is indicated between two spatially related geological terrains with contrasting tectonic styles, namely the NE-SW trending Eastern Ghat Mobile Belt (EGMB) and NW-SE oriented Godavari rift (GR). The late Archaean pelite dominated Eastern Ghat sedimentary terrain was subjected to major reworking events around 3.0 Ga, 2.6 Ga, 2.0 Ga, 1.5 Ga, 1.0 Ga and 0.5 Ga. Along GR development of extensional basins, viz. Pakhal (Middle Proterozoic) and Sullavai (Late Proterozoic) was induced by 1.5 Ga and 1.0 Ga reworking events respectively in the EGMB. A sag/protorift formed along the tectonic join between the Dharwar and Bhandara cratonic blocks, in response to 1.5 Ga event in EGMB, paved way for the initiation of the Middle Proterozoic Pakhal sedimentary basin. Evolution of this basin into Late Proterozoic Sullavai sedimentary rift basin is perhaps triggered by an extensive tectonothermal rejuvenation associated with 1.0 Ga reworking event in the EGMB.

THE Proterozoic sedimentary basins of the Godavari valley include Pakhal (Middle Proterozoic) and Sullavai (Late Proterozoic). Stratigraphic record and structural framework of these basins embody testimony to a rare Precambrian rift-related sedimentary basin development at right angle to the growing curvilinear Eastern Ghat Mobile Belt (EGMB). Geology of the Godavari valley and its environs was first worked out by William King[1]. Subsequently, a host of workers have attempted to refine stratigraphy, sedimentation and tectonics[2–6] of the area. Nevertheless, understanding of the origin and initial phase of basin development along the Godavari valley continued to be in its infancy. The present study underscores the importance of the EGMB reworking events in inducing the Precambrian extensional sedimentary basin development of the intracratonic Godavari rift (GR).

An outline of geological framework and chronology of major tectonic events in the GR and EGMB are shown in Figure 1 and Table 1 respectively.

Along the southeastern margin of the Indian Peninsula, the NNE-SSW to NE-SW oriented curvilinear EGMB extends over a length of 700 km with a maximum width of about 200 km in the north and tapering end in the south (Figure 1). Major lithounits in the EGMB are classified according to their parentage into Khondalite (sedimentary) suite, Charnockite (igneous) suite and migmatites. Besides, there are several igneous intrusives, viz. anorthosites, nepheline syenites and chromite-bearing layered complexes[7,8]. There is a lateral zoning in the distribution of rock units in the EGMB – charnockites being predominant in the west followed by khondalites in the centre and migmatites in the east[9].

Along the western margin of the EGMB the charnockites show lithological gradation with the Peninsular gneiss, granites and amphibolites of the shield area[10]. This gradational zone is usually referred to as the Eastern Ghat Front marked by ductile shearing, metasomatism and igneous activity[11]. The gradation zone between EGMB and the Dharwar Craton is also referred to as 'Marginal Zone' which is characterized by the presence of garnetiferous gneiss and its granitic protoliths (± garnet) with enclaves of two pyroxene granulites and arrested charnockites[12]. Supracrustals of Khammam schist belt, anorthosites and amphibolite intrusives are located in this zone.

Lithounits of the EGMB were subjected to polyphase deformation and metamorphism. Although the age of folding could not be established on a regional scale with a great deal of accuracy, in Chilka lake area, the NE-SW set of folds and the coaxial refolded folds (F1) were formed during 3.0 Ga and 2.6 Ga tectonic events respectively. Formation of E-W oriented cross folds with westerly plunge was linked to 1.5 Ga tectonic event[13]. Besides folding, a major phase of granulite metamorphism is also associated with the 1.5 Ga and 1.0 Ga events[14].

Localized bodies of anorthosites, alkaline rocks,