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The Pangidi Anorthosite Complex, Eastern Ghats Granulite Belt, India: Mesoproterozoic Sm–Nd isochron age and evidence for significant crustal contamination

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The Pangidi Anorthosite Complex (PAC) is a small, magmatically layered body emplaced into high-grade supracrustal rocks and metamorphosed together with the host rocks in the southern sector of the Eastern Ghats Granulite Belt, South India. It is dominated by coarse-grained anorthosite and leuconorite, minor leucogabbronorite and ultramafics with chromitites. The anorthositic rocks contain plagioclase (An_{55-70}) + orthopyroxene (En_{50-60}) + augite + amphibole + ilmenite + magnetite with accessory olivine, biotite, apatite and rarely coronal garnet related to metamorphic reconstitution. Despite a less calcic plagioclase composition in the anorthosites, the major and trace element distributions are akin to comparable litho types (at similar SiO_2 wt%) of the Kondapalli layered anorthosite complex in close proximity. However, the PAC shows distinct effects of metamorphism and significant modal volume of secondary hydrous mineral phases unlike the latter. A five-point whole-rock Sm–Nd isochron gives 1739 ± 220 million years (Ma) (2σ) age for the complex, which constraints the younger limit to its intrusion and probably metamorphism under amphibolite to granulite facies conditions. The PAC is characterized by strikingly low $\varepsilon_{Nd\ (at\ 1750\ Ma)}$ of –14.4 ± 3.7, indicating the importance of crustal contamination in its genesis possibly involving significantly older (Late Archaean) crustal components.

ANORTHOSITE is a less abundant but fascinating rock composed almost entirely of calcic-plagioclase. Terrestrial anorthosite occurrences fall into a few genetic 'types' or 'associations' such as: (i) Archaean (> 2500 million years (Ma)) megacrystic, (ii) Proterozoic (2500–500 Ma) massif-type and (iii) components of layered mafic and ultramafic igneous plutons. The genesis of anorthosite complexes involves essentially a two-stage process of mantle magmatism (accumulation of typically Fe and Al-rich basaltic parental magmas at sub-crustal cites), followed by magma differentiation and emplacement of plagioclase-rich mushes into the crust at different tectonic settings[1,2]. Implicit in this model is assimilation of continental crust by the parental melts of the anorthosite intrusives primarily during differentiation and/or emplacement, so much so that their geochemical and isotopic signatures are being used not only to characterize their parental magmas and the mantle source, but also as a tracer of composition of the deep-crust, which they assimilate[1–3]. The Proterozoic Eastern Ghats Granulite Belt (EGGB) exposes several large and small anorthosite complexes most of which are 'massif-type'. However, examples of 'layered-type' anorthosite complexes like the Kondapalli anorthosite complex from the southern sector (south of the Godavari graben) are also well known[4]. The Pangidi Anorthosite Complex (PAC)[5], N16°41′: E80°32.5′, Krishna District, Andhra Pradesh is a small and less known, deformed and metamorphosed layered intrusion[5–10] (Figure 1). It is emplaced into the high-grade gneisses of the EGGB and was considered a part of the Kondapalli complex, which is located in close proximity[4,6]. However, it appears to be petrographically distinct from the Kondapalli complex because of its distinctly higher content of hydrous minerals and coarse pegmatoidal texture. The host rocks of PAC include multiple deformed

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mafic granulites, orthopyroxene granulites and metapelitic granulites[7–11]. Geochronological data in this sector of EGGB are meagre. Pegmatites in the region yielded U–Pb cooling ages of 1672 Ma for monazite and ~1600 Ma for allanite while retrograded hornblende gave an Ar–Ar age of ~1100 Ma, suggesting Grenvillian thermal overprint (up to amphibolite facies)[12,13]. Here, we report geochemical data and whole-rock Sm–Nd isotopic compositions for a set of representative samples from the PAC. We attempt a first-order appraisal of the geochemical characteristics of its parental melt and mantle source apart from placing constraints on the chronology of emplacement and metamorphism. In recent years, the EGGB has been viewed as a collage of distinct geological terranes that were assembled during the Late Proterozoic[13]. Data on the PAC presented here are relevant not only to constrain age of magmatic and tectonic events in the southernmost sector of the EGGB, but also chronology of the less-known layered anorthosite complexes in this region.

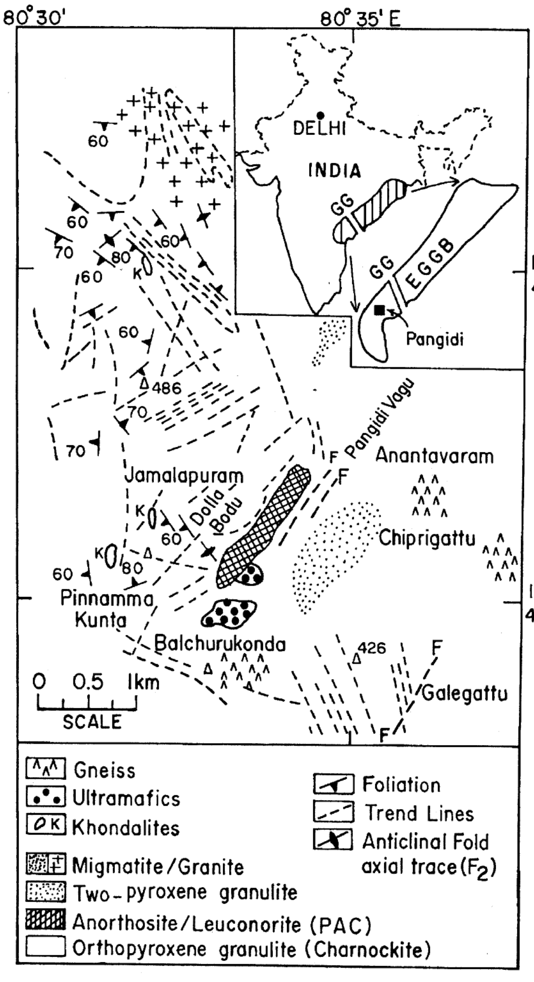

Figure 1. A generalized geological sketch map of the region around Pangidi Anorthosite Complex (PAC)[5], in the southern sector of the Eastern Ghats Granulite Belt (EGGB), south of the Godavari Graben (GG). Broken lines represent linear trends from aerial photographs.

The geology of the PAC has been described and reviewed[10,11]. Contacts of the PAC with the host rocks are invariably concealed and presumably tectonic. The anorthosite–leuconorite bodies (please note that the suffix 'meta' in rock nomenclature is ignored hereafter for convenience) around Pangidi show a variable trend (Figure 1), where a prominent outcrop strikes NNE–SSW and is exposed over a strike length of ~2 km with steep easterly dip. Rare ultramafic enclaves occur within the gabbronorite body. Apophyses of leucogabbronorite within anorthosite and anorthosite-containing fractures filled with pyroxenite are common. Three phases of deformation have been documented in the region[5], where the second phase of folding (F_2) related to the pervasive N–S trending fabrics is predominant. The Pangidi anorthosite, leuconorite and pyroxenite association is emplaced along the regional F_2-antiformal structures (Figure 1).

A detailed assessment of the genesis of the PAC based on mineral and geochemical data is beyond the scope of this communication. However, we attempt here a broad petrological, mineralogical and geochemical characterization of the suite in comparison to other well-documented, igneous-layered, anorthosite complexes particularly the adjoining Kondapalli complex. Although the PAC suite is metamorphosed to amphibolite/granulite facies, a variety of igneous textures and structures is locally preserved. These include small-scale slumped, folded layers, modally graded layers and coarse, sub-ophitic texture. Relict cross lamination (igneous) is locally observed. These features indicate that the PAC forms part of a disrupted layered intrusion. Primary minerals in the Pangidi anorthositic rocks include coarse plagioclase ($An_{55–70}$) (Figure 2) and interstitial orthopyroxene ($X_{Mg} = 0.55–0.65$) with lesser amounts of augite ($X_{Mg} = 0.68–0.75$), ilmenite and hornblende. The orthopyroxene in leuconorite is rich in schiller inclusions and Fe–Ti oxides. Although relict igneous textures such as cumulus plagioclase megacrysts are locally discernable, the textures of these rocks, largely, are of equilibrium-type, typical of metamorphic (solid state) recrystallization. Thus, the plagioclases comprise two modes: (i) primary megacrysts ($An_{55–70}$) and (ii) recrystallized ($An_{\sim 90}$) grains. The former occur as polygonal cumulates and exhibit planar boundaries and triple junctions. Twinning is on albite and percline laws. Secondary recrystallized plagioclases are smaller and exhibit no twinning. Metamorphic minerals in the recrystallized anorthositic rocks include hornblende, biotite, garnet and quartz. In leuconorites, where garnet is present, primary plagioclase ($An_{55–70}$) is thoroughly recrystallized to fine grained matrix ($An_{\sim 90}$)[8]. An important observation is that compared to the anorthite-rich ($An_{\sim 79}$) Kondapalli layered complex[6], the plagioclase in anorthosites and leuconorites in the PAC shows strikingly lower An contents ($An_{55–70}$) at a similar level of bulk SiO_2. However, An content of Pangidi plagioclase in anorthositic rocks is similar to plagioclase ($An_{56–70}$) in anorthositic rocks of Gangineni igneous complex[14] (a part of Kondapalli layered complex)[5]. Symplectitic and corona textures are well preserved in the leuconorites of PAC, consistent with recent observations in the Kondapalli complex[12] that revealed coronas of garnet or garnet–quartz symplectite along the contacts of pyroxene–plagioclase–ilmenite in gabbronorite as well as symplectitic intergrowths of orthopyroxene and hercynite in orthopyroxenite. Relict igneous pyroxenes are common in layered orthopyroxenite, and websterite cumulates. Most igneous pyroxenes are internally recrystallized to a sieve-like texture comprising exolved clinopyroxene and orthopyroxene lamellae with a fine discordant metamorphic overprint. Intercumulus plagioclase associated with spinel in rare hercynite-bearing orthopyroxenite is extremely calcic[7] ($An_{\sim 95}$). Cr-spinels (Cr/Cr + Al between 0.40 and 0.70)[7] occur as intercumulus material between and as inclusions within pyroxenes in pyroxenites. The PAC chromites plot in the fields typical of stratiform chromitites elsewhere.

Ten fresh samples, typically 10–12 kg, from the region around Pangidi (Figure 1) showing the widest possible variation in modal mineralogy have been analysed for major, minor and trace element including Rare Earth Element (REE) compositions. Table 1 presents geochemical data for a few representative samples. Cleaned chips were powdered to ~200 mesh using a steel jaw crusher and a ring mill. For Cr and Ni determinations, a small part of the homogenized coarse powder was manually pulverized to fine powder in an agate mortar. Major and minor elements, including Fe_2O_3 (T) were determined by Atomic Absorption Spectrometry (AAS), while FeO was determined by volumetric method. Trace elements and REE concentrations were determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS), using synthetic calibrated standards as well as international rock standards such as An-G, MRG-1 and W-2 at the National Geophysical Research Institute (NGRI), Hyderabad. The analytical details are given in Balaram *et al.*[15]. Analytical precisions for major and minor oxides range between 2 and 4% RSD, while those for trace elements range up to 7%.

Primarily, geochemical data are used here to ascertain the genetic relationship of the samples and the role of crustal contamination in their genesis. The PAC suite is

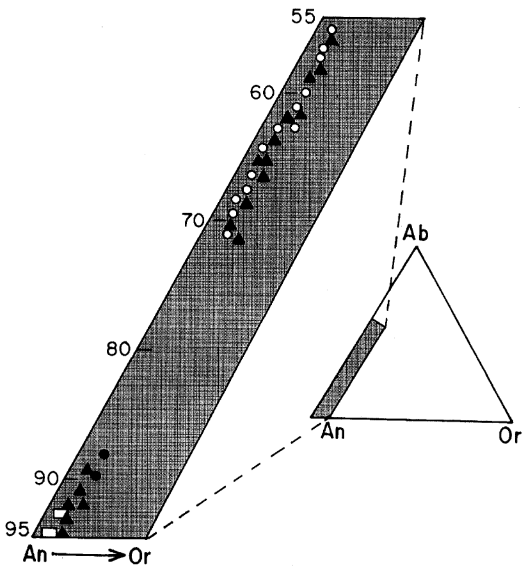

Figure 2. Compositional plot of plagioclase (mol%) in different rock types from the metamorphosed PAC: anorthosite (open circle), gabbronorite (filled triangle), ultramafic rock (open rectangle). Filled circles represent high-An plagioclase associated with garnet. High-An plagioclase (An_{95}) is also noted with spinel in orthopyroxenites.

Table 1. Whole rock major (wt%) and trace element (ppm) abundances of representative set of samples from the PAC

Rock type sample	A Q-42	A Q-43	LN Q-45	LN Q-46
SiO_2 (wt%)	47.39	47.86	48.80	49.25
TiO_2	0.14	0.13	0.18	0.16
Al_2O_3	29.24	29.37	26.42	27.12
FeO	2.86	1.94	4.50	3.10
Fe_2O_3	0.42	1.64	0.95	0.86
MnO	0.06	0.08	0.08	0.06
MgO	2.68	2.18	3.65	3.24
CaO	15.25	15.12	12.42	12.64
Na_2O	1.98	2.18	2.26	2.38
K_2O	0.18	0.10	0.17	0.22
P_2O_5	0.01	0.03	0.07	0.04
Sum	100.21	100.63	99.50	99.07
Sc (ppm)	10	16	19	32
V	78	84	88	94
Cr	16	18	32	28
Co	42	28	36	34
Ni	38	42	41	42
Cu	38	40	21	29
Zn	41	42	22	25
Ga	20	17	9	14
Ba	128	126	137	142
Rb	7	8	5	8
Sr	515	534	460	485
Y	7	3	6	4
Zr	16	18	16	18
Hf	0.32	0.35	0.28	0.25
Ta	0.15	0.12	0.10	0.08
Pb	14	12	8	7
Th	0.6	0.8	0.2	0.4
U	0.12	0.13	0.09	0.11
La	4.28	3.92	3.72	3.66
Ce	8.28	8.35	7.85	7.80
Pr	0.92	0.90	0.65	0.72
Nd*	2.06	2.08	4.21	4.10
Sm*	0.48	0.43	0.80	0.86
Eu	0.50	0.60	0.58	0.42
Gd	0.46	0.40	0.72	0.68
Dy	0.88	0.63	0.74	0.86
Er	0.52	0.41	0.39	0.42
Yb	0.46	0.43	0.42	0.43
Lu	0.08	0.09	0.07	0.09

*ID-TIMS values.

A, Metaanorthosite, LN, Metaleuconorite.

tholeiitic as noted by the trend of slight Fe-enrichment in AFM ternary plot. Although the samples analysed represent a narrow range of SiO_2, they show trends typical of differentiated magmatic suites on Harker and other plots against indices of differentiation[7], indicating that metamorphism may not have resulted in significant element remobilization, at least on the scale of sampling. The anorthosite–leuconorite samples are characterized by intermediate $X_{Fe} = 100[Fe^{2+}/Fe^{2+} + Mg_{(atomic)}]$ of 57–67. Within this suite, TiO_2, FeO, MnO and MgO increase from anorthosite to leuconorite, whereas Al_2O_3, CaO and Na_2O decrease, consistent with near-uniform plagioclase composition throughout the body. Compared to the anorthosites and leuconorites of the Kondapalli complex, the PAC rocks show a striking enrichment in Al_2O_3, CaO and K_2O and relatively low MgO and FeO. Anorthositic rocks show Light REE-enriched pattern, large positive europium anomaly (Eu/Eu* = ~2.2) (Figure 3) and high-Sr concentrations (726–960 ppm). The total REE = 0.5–20 times chondrite, typical of plagioclase cumulates in layered anorthosite complexes elsewhere (Figure 3). A prominent feature of the PAC samples is the enrichment in K_2O and the abundance of Rb, Rb/Sr, K/Rb and Zr. Together with the presence of appreciable modal volumes of hydrous minerals, these abundances could reflect possible effects of crustal contamination and/or hydrothermal metasomatic effects.

Sm–Nd isotopic analysis was carried out at NGRI. To avoid pooling of samples with different initial Nd isotopic compositions, the sampling for this study was restricted to a small area (< 200 m^2) within the quarried exposure near Pangidi. Approximately 100 mg of the fine powder was digested with concentrated double-distilled HF-HNO_3 in screw-capped Sevillex vials for 5–6 days at 60–70°C, evaporated and redissolved in HCl. Clear solutions were split into two aliquots for measurement of isotope compositions (IC) of Nd, and isotopic dilution (ID) estimates of Sm and Nd using a mixed ^{147}Sm, ^{146}Nd tracer. Nd (IC) and Sm + Nd (ID) fractions were extracted on separate columns of bio-beads coated with HDEHP. Detailed descriptions of analytical procedure are given in Bhaskar Rao *et al.*[16]. The blank levels of the whole process were less than 200 pg for both Sm and Nd. All isotope measurements were carried out on a VG 354 Thermal Ionization Mass Spectrometer (TIMS). During this study, the mean ^{143}Nd/^{144}Nd ratio for a La Jolla Nd standard was 0.511860 ± 0.000015 (n = 3). Ages were calculated using a two-error regression method, with a computer program ISOPLOT/Ex-2.49h after Ludwig[17], providing errors as indicated in Table 2, $\ddot{e}^{147}$Sm = 6.54 × 10^{-12} y^{-1}.

Sm–Nd isotopic compositions and elemental abundances (ID–TIMS) are given in Table 2 and depicted in the Nd evolution diagram (Figure 4). The analysed samples show a limited spread in ^{147}Sm/^{144}Nd from 0.114 to 0.141 and conform to a linear array (Mean Square Weighted Deviation, MSWD = 0.17) with an initial ^{143}Nd/^{144}Nd (Nd_i) of 0.50964 ± 0.00019 (2σ). Various lines of evidence suggest that this linear array is indeed an isochron and not a mere mixing line without any time significance. For instance, reiterating that samples are drawn from a small (~200 m^2) area, the petrological and geochemical data, especially compositional variations with reference to differentiation indices, presented in the foregoing indicate that the Pangidi anorthosite–leuconorite samples could be related by magmatic differentiation processes from a homogenous parental magma. Although these are cumulates, the data do not show a linear correlation between ^{143}Nd and 1/Nd that would be expected for a mixture of just two arbitrary components and when samples with low ^{147}Sm/^{144}Nd are considered, their model ages (T_{CHUR}, Table 2) show consistency; for instance, samples such as Q43, Q45 and Q46 with typical 'upper crustal' ^{147}Sm/^{144}Nd values of <0.14 give T_{CHUR} ages between 3000 and 3300 Ma. Thus, interpreting that the linear array for the Pangidi whole-rock samples (Figure 4) is indeed an isochron, we would like to argue that the 1739 ± 220 Ma age calculated from the isochron is geologically meaningful. The large error on this age is largely a reflection of the limited spread of ^{147}Sm/^{144}Nd in the samples analysed. Considering the ~1700–1600 Ma mineral ages

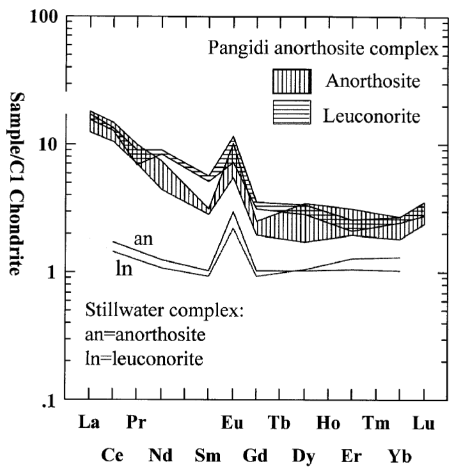

Figure 3. Fields of chondrite normalized REE patterns for rocks from the PAC: anorthosites (n = 5) and leuconorites (n = 3) along with REE pattern for a typical anorthosite and a leuconorite from the Stillwater layered complex, Montana[19] for comparison. REE normalized against average C1 chondrite[20].

Table 2. Sm–Nd isotopic data for the PAC

Sl. no.	Sm (ppm)	Nd (ppm)	^{147}Sm/^{144}Nd (atomic)	^{143}Nd/^{144}Nd (atomic) ± 2σ*	T_{CHUR} (Ma)
Q45	0.80	4.21	0.1140	0.510945 ± 34	3098.6
Q43	0.43	2.08	0.1244	0.511057 ± 44	3307.6
Q46	0.86	4.10	0.1261	0.511077 ± 30	3344.0
Q42	0.48	2.06	0.1406	0.511240 ± 32	3763.7
Q44	1.52	6.45	0.1419	0.511270 ± 36	3770.2

*Normalized to ^{146}Nd/^{144}Nd = 0.7219 and errors shown on least significant digits. T_{CHUR} calculated using ^{143}Nd/^{144}Nd CHUR = 0.512638, ^{147}Sm/^{144}Nd CHUR = 0.1967.

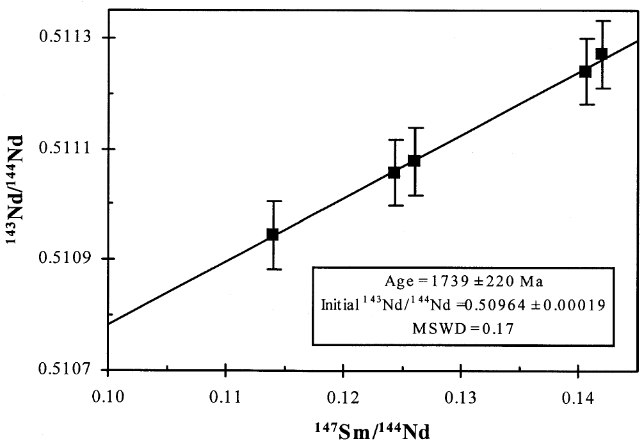

Figure 4. Sm–Nd whole rock isochron diagram for the PAC. For age calculation 0.15% error on $^{147}Sm/^{144}Nd$ and measured 2σ error on $^{143}Nd/^{144}Nd$ (Table 2) have been used in a computer program after Ludwig[17].

from the southern sector of the EGGB (summarized in the foregoing), we interpret the 1739 Ma age as a minimum age for the PAC and suggest that this may closely approximate the time of emplacement. Interestingly, the Sm–Nd isochron age of the PAC suite pre-dates the regional (ca. 1000 Ma) thermotectonic episode. The initial Nd_i for this suite corresponds to a $\varepsilon_{Nd(at\ 1750\ Ma)}$ of -14.4 ± 3.7, which is strikingly low, indicating unusually enriched Nd isotopic signature for the PAC. There could be several possible explanations for this: (1) a highly enriched mantle source, (2) unusually high degree of crustal contamination of the parental melt derived from a depleted mantle and (3) isotopic requilibration of a much older magmatic suite during Proterozoic thermotectonic event(s). Considering the syn- to late-D_2 intrusive relationship of the Pangidi complex with the host rocks, its rather small volume and the general antiquity of the host gneisses (mostly Late Archaean), we emphasize the role of significant crustal contamination in the genesis of the PAC, although isotopic resetting during the Proterozoic cannot be entirely precluded. Crustal contamination effects are commonly noted in many anorthosite complexes, although such extreme degrees of contamination are reported rarely. For instance, Nain complex, Labrador[18] $\varepsilon_{Nd} \sim -10$. Such enriched Nd isotopic signatures are expected when significantly older basement complexes such as the Late Archaean basement of the EGGB are involved in the assimilation process. In the present case, the ~3000 Ma to ~3300 Ma T_{CHUR} model ages of the PAC samples, their mineralogy and geochemistry are in accord with a scenario, wherein the partial melt of the PAC could have been contaminated by LREE-enriched Late Archean crust, especially during its differentiation and emplacement.

In summary, based on the lithology, mineralogy, textures, structures and geochemistry, the PAC represents a typical layered intrusion[1]. Recent age determinations in the region encompassing the southern sector of the EGGB and the adjacent Khammam, Nellore supracrustal-gneiss terrains[13] indicate a prominent pre-Grenvillian tectonometamorphic event around 1650–1550 Ma, unlike in the northern parts of the EGGB. The 1739 ± 220 Ma age for the PAC reported here is consistent with the foregoing view emphasizing the importance of Mesoproterozoic mantle magmatism in the study region.

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