ABSTRACT

Palghat Gap is the only major breach within the Western Ghats, and constitutes a very conspicuous geomorphic feature in the landscape of Peninsular India. Widely contrasting and contradicting hypotheses exist on its origin, advocating marine and fluviatile erosion, crustal upwarp and consequent development of joints and fractures, as well as tectonic processes such as block faulting. This clearly shows that the origin of the Palghat Gap is still a controversy, and evinces further geological interest. The present study was initiated in this backdrop, with the prime object of elucidating the geologic setting and metamorphic evolution of a segment of the Palghat Gap with contrasting geological features.

Geological mapping of the study area (about 100 km²) in 1:25,000 scale, comprising a part of the Gap proper and a part of its northern flank within Kerala, reveals the presence of two distinct rock units: 1. Garnet-biotite-sillimanite + graphite gneissess (khondalite sensu stricto), ubiquitously associated with calc granulites and crystalline limestones, with a subordinate group of sillimanite-free gneisses and pockets of cordierite-bearing gneisses, exposed towards the flank, and 2. Fissile migmatitic rocks comprising biotite and biotite-hornblende gneisses showing discontinuous and boudinaged bands of amphibolites and associated granites and pegmatites occurring within them.
Field investigations indicate that the rocks of this area experienced three deformation episodes with certain geological evidences in favour of mylonitisation in khondalites and intense fracturing of calc granulites in the northern flank. The first phase \((D_1)\) resulted in a compositional layering \((S_1)\), observed more distinctly in khondalites and migmatitic gneisses. The second phase \((D_2)\) is evidenced by E-W symmetrical to isoclinal folds, defined by \(S_1\) with an easterly gentle plunge, observed in calc granulites and migmatitic gneisses with an associated lineation \(L_1\). The third phase \((D_3)\) is marked by the development of gentle or open N-S folds and N-S, NE-SW and NW-SE trending fractures. Boudinage in amphibolites is attributed to \(D_1\)-deformation stage whereas the \(D_1\)-\(D_2\) transition is characterised by extensive migmatisation. More pervasive migmatisation is coeval with the \(D_2\)-event.

Equal area lower hemisphere projection of 184 measurements of joints in the Gap and 50 measurements in the flank, revealed the presence of two prominent sets trending ENE-WSW and N-S in the flank and the additional presence of NW-SE joints in the Gap.

Khondalites are medium-to coarse-grained, typically polymetamorphic, porphyroblastic rocks showing extreme dynamic effects like crushing and granulation of minerals. The sillimanite-free varieties are constituted mainly by
quartz and feldspar (50-60 modal %) with 15-22 % of biotite, as compared to khondalites (sensu stricto) with 40% quartz and about 9% biotite. Sillimanite percentage is highly variable from 0 to 21%. Two generations of sillimanite are distinguished, an earlier generation of prismatic and elongate crystals and a later fibrolitic sillimanite associated with biotite, as a breakdown product. Three generations of biotite are identified; one as inclusions in garnet, the second as a phase coexisting with garnet as well as sillimanite and the third is formed after garnet. Cordierite appears to have grown by a progressive mineral reaction involving consumption of biotite, sillimanite, quartz and plagioclase. Characterised by a wide variation in SiO₂ values (46-66 wt %) and high wt % of Al₂O₃ (13-39 %), the khondalites correspond closely to the Al-rich petrochemical types. A pelitic-to arenite parentage is suggested by the geochemical plots.

Intimately associated with the garnet-biotite-sillimanite + graphite gneiss (khondalite sensu stricto) and crystalline limestones, the calc granulites are characterised by their fine-grained, xenomorphic granular texture. Based on mineralogy and modal proportions, two types (type I and type II) have been distinguished. Type I is characterised by K-feldspar + calcite + vesuvianite + scapolite + diopside + grossularite + sphene assemblage while in type II, garnet is conspicuously absent and sphene is present in much more
abundant proportions. Geochemical data reveal a predominance of K₂O (2.87 wt %) over Na₂O (1.76 wt %) for type I while, the reverse holds true for type II with Na₂O (2.51 wt %) predominating over K₂O (1.97 wt %). Petrogenetic characterisation implies a protolith of impure, silica-rich calcareous sediments admixed with phyllosilicates and clays.

Crystalline limestones are medium-to coarse-grained rocks with typical crystalline texture, often passing over to elongated granoblastic texture. Geochemical characterisation of the limestones into two groups, based on elemental concentrations, is also borne out by the modal analyses. Group I marbles are richer in CaO and poor in other major elements. Presence of diopside, sphene, hornblende, magnetite, muscovite and higher percentages of quartz are characteristic of group II marbles. The ubiquitous association of dolomite with silicates suggests that dolomite is a product of silicate + calcite reaction and is presumed to be not of primary origin. Geochemical plots imply a protolith consisting of an admixture of limestone with variable proportions of marly impurities.

Migmatitic rocks comprise biotite- and biotite-hornblende gneisses. A stromatic structure, often grading into surreitic and schollen types is exhibited with rafts of amphibolite boudins preserved in them. They are medium-to coarse-grained rocks, displaying xenomorphic granular texture. Biotite gneiss is typically coarse-grained with a
mineralogy of K-feldspar (46 modal %), quartz (36 %), plagioclase (12 %) and biotite (5 %). Biotite-hornblende gneiss is an intensely deformed, medium-to coarse-grained rock, chiefly composed of quartz + plagioclase + biotite + hornblende + K-feldspar assemblages with accessory phases of apatite, magnetite and sphene. Increased proportions of hornblende towards the flank and occurrence of biotite as an alteration product of amphibole are noteworthy features. A calc-alkaline trend is indicated by the AFM and Ca - Na - K plots. Negative linearity is indicated by almost all the major elements. Decreasing trend of Al$_2$O$_3$ and CaO with SiO$_2$ indicate anorthite fractionation. Depletion trends of MgO, FeO and TiO$_2$ as well as increasing trend of K$_2$O are consistent with the progressive removal of hornblende, with synchronous K-enrichment.

Amphibolites occur as xenolithic masses of various sizes and shapes within the migmatitic gneisses. Intricately permeated by granitic material, typifying a paleosome-neosome relationship, these lenticular, discontinuous patches or boudins pass quite imperceptibly into migmatitic gneisses. Medium-to coarse-grained, they exhibit an inequigranular, xenoblastic texture. Petrographic observations reveal textures suggestive of partial or complete replacement of clinopyroxene by hornblende and biotite is observed to occur as a hornblende-break down reaction product. Major and trace element signatures speak of a basaltic and more distinctly, a
quartz normative tholeiitic origin. In the absence of REE data, their tholeiitic nature could not be established conclusively. However, a general basic igneous trend is indicated by the ACF and Niggli mg-c plots while, TAS and AFM plots suggests a possible, homogeneous mantle source for them.

Granites have intrusive relationships with the amphibolites and exhibit faint foliation towards periphery. These are phanerocrystalline, medium - to coarse-grained rocks with typical granitoid texture. Mineralogical peculiarities include a two-feldspar composition with perthites dominating over plagioclase. Plots in K$_2$O Vs. CaO and K$_2$O Vs. Na$_2$O as well as normative An-Ab-Or diagram show a range between granodiorite and granite. High ratios of K$_2$O/CaO (1.43) and Fe$_2$O$_3$/CaO (0.69) are also characteristic. Increase in A/CNK values from 1.114 to 1.29 towards periphery, compared to the core portions reflect the increasing peraluminous nature of biotite-hornblende granites. This is attributed to the removal of the metaluminous phase (hornblende) through fractional crystallisation, which is also consistent with the observed increase in Na$_2$O and decrease in TiO$_2$ and Sr contents. Exsolution textures, general high potash contents exceeding soda and formation of microcline after plagioclase argue in favour of a late potash metasomatism. They typically correspond to late-post kinematic types (Marmo, 1971), while
discrimination of tectonic environments based on their geochemical characteristics point to their classification as POG (post orogenic granitoid) groups. Alkali feldspar (av) - plagioclase (av) temperature of 527°C obtained for one of the granites (Ps.11) at 5 Kbars closely corresponds to the retrogressive reequilibration event in granulitic rocks and to the temperature estimated for the migmatites of the Gap proper.

Pegmatites exhibit concordant to discordant relationships with the country rocks and are assigned to two intrusion episodes; one with predominantly white feldspar, folded along E-W direction and another, with pink feldspar, showing pinch and swell effects. They are unzoned and have a simple mineralogy with quartz (40-42 modal %), microcline (25-35 %), perthite (14-25 %), biotite (4-10 %) and plagioclase (3-8 %) as the major minerals. Pegmatites within the metasedimentary sequence contain additionally garnet (2-10 %) and muscovite (6 %). Mineralogical composition supports a migmatitic origin of the pegmatitic melts. Temperature estimates obtained for the pegmatites (av.547°C) correspond well with the retrograde temperatures of khondalites (av.521°C).

Microprobe analyses of garnets in khondalites and associated gneisses show that they are almandine-rich, with low Mn contents. Zoning profiles provided for garnets from the metapelitic rocks show many characteristics typical of
granulite terrains. Enrichment of almandine from core to rim is also expressed in chemical terms by a lower \( X_{Mg} \). Garnet in calc granulites are remarkably high in grossular content (59-61 %) while, almandine is distinctly low at 36-38 mol %.

Individual grains of biotite show the effect of re-distribution of elements during retrogression. The general Mg-enrichment trends observed in biotite from matrix - to contact zones - to inclusions indicate chemical exchange with host garnets and is well illustrated also by plots of \( Al^{iv} \) Vs. \( Mg/(Mg + Fe) \) and \( X_{Mg} \) Vs. Ti, where the matrix biotite composition corresponds to the Fe-rich varieties (Mg:Fe < 2:1) while, the rims and especially the inclusions tend towards Mg-rich (Mg:Fe > 2:1) or phlogopite composition. On the basis of their increasing Mg and decreasing Ti and Fe concentrations (atomic proportions), three groups of biotite (biotite I, II and III) have been distinguished, an assumption which goes well with the petrographic evidences too.

The alkali feldspars are characterised by small Ca (0.013 p.f.u, average) and Fe (0.004 p.f.u, average). Anorthite content of alkali feldspar is largely controlled by the rock chemistry, especially the \( Na_2O/(Na_2O + K_2O) \) ratio of the host rocks. Towards plagioclase contacts, 'Or' increases and 'Ab' shows a corresponding decrease. Higher Fe concentrations in perthites of granites, compared to matrix
alkali feldspar, is reflected in the higher temperature estimates for the former.

Plagioclase grain is unzoned and exhibits more or less a uniform composition. In sillimanite-bearing and absent-metapelitic rocks, plagioclase composition corresponds to oligoclase and in cordierite-bearing rocks, it becomes albitic. In calc granulites, an andesine composition is reported.

Cordierites are Mg-rich (8.43 wt % MgO) and contain appreciable amounts of FeO also (7.84 wt %). They are relatively poor in Na and K (< 0.03 p.f.u and 0.001 p.f.u respectively) and Mn is reported only in trace amounts (< 0.004 p.f.u). $X_{Fe}$ shows a slight decrease from core to rim.

Clinopyroxene of calc granulites shows a wide variation from hedenbergitic to diopsidic composition. The large variation in Mg/(Mg + Fe) and Ca/(Ca + Fe + Mg) of the two sets of clinopyroxene implies that the mechanism of equilibration was a combination of cation exchange and solution regrowth. More specifically, the change in composition may be related to the incomplete re-equilibration during decrease in temperature (from 808 to 775°C) and a pressure drop from 4.39 to 2.20 Kbars, whereby the clinopyroxene changed by diffusion processes, towards a diopsidic composition.
Amphiboles of both the calc granulites and migmatitic gneisses correspond to calcic types with a calcium content in the range of 1.9-2.0 (p.f.u). In the binary plot of (Na + K) vs. Al<sup>iv</sup> of Robinson et al (1971), amphiboles from granulites lie close to the hornblende composition and the amphiboles from migmatitic gneisses lie towards pargasite field. In the Giret et al (1980) diagram, they plot respectively in the fields of hornblende and ferro-magnesio-hastingsite field. Total aluminium content of amphiboles in calc granulites is higher, compared to that in migmatitic gneiss, reflecting their higher temperature and increased grade of metamorphism.

Based on an approach of 'centre to centre' compositions of equilibrium assemblages and 'rim to rim' compositions of contacting grains of cordierite, garnet, biotite etc., quantitative data on the peak, as well as the retrograde temperature of metamorphism were estimated through the use of a variety of exchange and solvus thermometric methods.

A peak metamorphic temperature of ~ 800°C has been assumed, based on phase equilibria constraints such as the coexistence of plagioclase and scapolite in calc granulites, XMei content of 74-79% in scapolite of calc granulites and absence of evidences in favour of anatexis in the granulites. The ubiquitous presence of sillimanite in the granulites and its stability relations along with the P-T constraints exerted by cordierite + almandine + sillimanite + quartz
assemblages, limits the peak pressure to \( \sim 8 \) Kbars.

However, average temperatures calculated at peak pressures of \( \sim 8 \) Kbars by various garnet-biotite thermometers (Thompson, 1976; Ferry & Spear, 1978; Holdaway & Lee, 1977; Hodges & Spear, 1982; Perchuk & Lavrent'eva, 1983; Indares & Marignole, 1985; Bhattacharya & Raith, 1987) reveal a temperature range from \( 759^\circ C \) to \( 1000^\circ C \) for the khondalites and associated gneisses. Garnet-cordierite 'pressure-independent' thermometers (Holdaway & Lee, 1977; Perchuk & Lavrent'eva, 1983; Bhattacharya et al., 1988) yield a lower range from \( 802 \) to \( 813^\circ C \) for the cordierite-bearing khondalite, which is conformable to the perthitic alkali feldspar-plagioclase (average) temperatures (\( 828^\circ C \)) of Green & Usdansky's (1986) Na-distribution model, at 5 Kbars. Garnet-clinopyroxene temperatures of the calc granulites, estimated by Ellis & Green (1979) method also indicate a peak temperature of \( 792^\circ C \).

Retrogressive metamorphic conditions estimated by various methods, using mineral phases in contact with each other, give a mean temperature value of \( 852^\circ C \) (av). Garnet (rim)-biotite (secondary) temperatures of khondalite are lower at \( 521^\circ C \), comparable to the garnet (rim)-newly formed biotite (biotite III) temperatures of pegmatite (\( 547^\circ C \), av). Plagioclase-amphibole equilibrium temperature by amphibole Al\textsuperscript{T} content (Plyusnina, 1982), from one of the hornblende-biotite migmatitic gneiss samples (close to a granite
occurrence), is estimated to be 530°C. This is comparable to the alk-Fs (av)-plag (av) temperature (527°C) obtained for the granite sample at 5 Kbar pressure. Neominalisation associated with migmatisation and granitic emplacement is therefore, fixed at 532°C (mean).


Extensive application of Moecher et al (1988) geobarometer for the present study has been limited due to the compositional constraints introduced by extensive solid solution between hedenbergite and diopsidic compositions of clinopyroxene grains.

Rim pressures corresponding to peak temperatures, calculated for the khondalites and associated gneisses are
estimated to be 6.50 Kbars. Pressure values by plagioclase-
hornblende geobarometer of Plyusnina (1982) for one of the
migmatitic gneiss samples close to a granite occurrence, is
4.66 Kbars at a temperature of 530°C. Barometers of
closely corresponding values of 4.72 and 4.92 Kbars
respectively. Pressures estimated by the cordierite-garnet
goobarometers for $P_{H_2O} = 0$ conditions range from 2.84 to 3.84
Kbars which approximate to the average neomineralisation
pressures of pegmatites. Thus, the neomineralisation episode
associated with migmatisation and attendant granitic
emplacement is fixed at an average pressure of 4.97 Kbars.

Results obtained from the garnet-biotite thermometers
indicate a pressure dependence of 3.6 to 5.4°C/Kbar. It is
5.1°C/Kbar for garnet-cordierite and 12-14°C/Kbar for two-
feldspar thermometers. Ghent's (1976) pressure estimates
have a dependence of 12.5 to 14 bar/degree and for Koziol &
Newton (1989), it is 14.5-16.5 bar/degree. Precision and
accuracy determinations of the various thermometric sensors
indicate that uncertainties do not exceed ± 60°C and the
obtained results have been confirmed by the use of
intersecting GPAQ pressure-temperature lines as well. The
reported values of peak metamorphism of 800°C and 8.4 Kbars
are comparable to the P-T conditions of granulites world over
and also fall in Bohlen's (1987) best fit P-T box of 7.5 ± 1
Kbar and 800°C ± 50°C for granulites.
Fluid inclusion studies in selected quartz plates from granulitic rocks reveal the presence of three types of inclusions: 1. An early CO$_2$-rich inclusion 2. Mixed carbonic-aqueous inclusions and 3. H$_2$O-rich inclusions, which have a bearing on the fluid evolution history of granulitic rocks. Freezing and heating studies suggest CO$_2$ density of 0.8-0.9 g/cm$^3$ for the carbonic inclusions, which in turn fixes the pressure at 4.9 and 4.1 Kbars respectively, corresponding to peak as well as retrograde temperatures obtained by mineral thermometry.

Since P-T estimates of granulites are the minimum estimates of the actual metamorphic conditions (Frost & Chacko, 1989), the presently estimated values can be suggested as the lower limit of the P-T maxima attained by the granulites of the study area. The possibility is further amplified by the high P-T values for the pelitic units of the Nilgiri Hills reported by other workers.

The overall P-T array defined by the maximum and minimum pressure-temperature limits of the granulitic rocks of the study area suggests a steep cooling curve corresponding to isothermal depression (ITD) path, which is corroborated by the crossings of P-T lines also. The obtained P-T path is consistent with the typical evolution path of south Indian khondalites and can be ascribed to the net result of tectonic thickening combined with the vertical redistribution of heat.
through syn to post-thickening magmatism, followed by extension. Lack of correspondence between the geometry of the ITD paths with the model paths of erosion (England & Thompson, 1984) preferentially favour a tectonic extension setting, which is also consistent with the findings of Van Reenan et al (1987), Sonder et al (1987) and Harley (1989). An element of IBC component generally observed towards the closing stages of an ITD path, as the one obtained for the study area, coinciding with the reequilibration-granite emplacement stage, further supports this.

K-Ar dating of muscovite and biotite samples from pegmatites belonging to the post D2 syn-D3 deformation episode, located within the migmatitic gneisses and the metasedimentary sequence yields ages ranging from 484-512 m.y. Field relations preclude the possibility of any significant metamorphic or tectonic episode to have affected the pegmatites, which is also substantiated by the close correspondence of age results from the central and peripheral portions of large mica flakes and concordance of ages between muscovite and biotite samples.

The reported K-Ar ages (484-512 m.y.) of biotite and muscovite from the Palghat Gap region correspond with the prominent Late Precambrian-Early Paleozoic acid magmatic emplacement phase observed in Kerala and elsewhere in south India. Since, pegmatite emplacement is known to be
associated with the closing stages of tectono-magmatic cycles, it is reasonable to suggest that the reported ages represent the closing stages of a tectono-magmatic event in Palghat Gap, presumably related to isothermal depression during crustal uplift associated with the retrogressive event. This in turn would suggest that the tectonic framework for the formation of the Palghat Gap was initiated during this period.