

Genesis of chrysoberyl in the pegmatites of southern Kerala, India

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ABSTRACT. In southern Kerala, India, chrysoberyl occurs in granitic pegmatites in association with quartz in alkali feldspar and is thought to crystallize earlier than beryl and sillimanite. The pegmatites are thought to have derived from the residual melts of granitic liquids formed by partial melting of the khondalites. In the absence of pyrometamorphic, desilication or aluminium-contamination processes, the genesis of chrysoberyl is explained by the CO_2 activity in residual melts. This model is at variance with the known concepts and may also explain the genesis of chrysoberyl in Sri Lanka where it is still controversial.

KEYWORDS: chrysoberyl, pegmatites, Kerala, India.

CHRYSOBERYL is rather rare in granitic pegmatites, though known from those which intrude high-grade mica schists and also from reaction zones of those which cut across ultrabasic rocks (Okrusch, 1971; Arem, 1977; Burt, 1982). Fersman (1940) and Beus (1960) have postulated that granitic pegmatites with obvious aluminium contamination may contain chrysoberyl. Subsequently, Heinrich and Buchi (1969) described a number of such pegmatites containing chrysoberyl. In the Trivandrum district, southern India, chrysoberyl and its varieties occur in pegmatites, localized along fractures in the khondalite suite of rocks. Chrysoberyl + quartz seems to be the common assemblage in many pegmatites in Trivandrum. Such an assemblage is stable at high temperatures or at intermediate temperatures and high pressures (Franz and Morteani, 1981). The present paper reports the results of studies on chrysoberyl pegmatites of the Trivandrum district with particular reference to the genesis of chrysoberyl.

Geological setting. The pegmatite field is localized within the rocks of the Precambrian crystalline basement complex of south Kerala, which are largely the products of granulite-facies metamorphism. The rock assemblages show structural evidence of polyphase deformation and anatectic 'mixing' in the manner described by Mehnert (1971) for migmatites. Common rock types in the area are

garnet-sillimanite gneiss \pm graphite and garnet-biotite gneiss belonging to the khondalite suite of rocks. Discrete patches, veins, and sills of quartz-feldspar-garnet assemblages are found at places in the khondalites. Occasional bands of enderbites are also seen in the area (fig. 1).

Recent investigations have shown that the precursors of garnet-sillimanite gneiss \pm graphite and garnet-biotite gneiss were high alumina terrigenous sediments, while enderbites were formed as a result of K-metasomatism of the two-pyroxene granulites. Quartz-feldspar-garnet assemblages have a granitic composition with the volume percent mode when plotted on the QAP diagram falling in the granite field (Soman, 1984) and were possibly produced by the partial melting of dry granulite-facies rocks as suggested by Rollinson (1983) for the Scourian Complex of NW Scotland. Pegmatites of Early Palaeozoic age (Soman *et al.*, 1982) are spatially associated with the garnet-granite and show good petrochemical affinity with it (Soman and Nair, 1983). The pegmatite field of the Trivandrum district has an areal extent of 50-70 \times 30-35 km and further extends southward to the adjoining state of Tamil Nadu. Pegmatites are ubiquitous within the metasedimentary sequence and are localized along fractures trending NW-SE, N.-S., and WNW-ESE, and have sharp contacts with the country rocks (fig. 2). Those concordant with the strike of foliation of the country rocks (NW-SE) have thickness ranging from 0.5 to 4.0 m and strike extension of tens of metres or more, while the cross-cutting bodies are thinner (0.05 to 1.0 m). Concordant bodies often pass into cross-cutting positions. Pegmatites are undeformed and their emplacement, based on structural studies, is attributed to post fracture-cleavage deformation stage of the country rocks (Soman, 1984). They rarely show zonation.

Classification of pegmatites. Mineralogically, the pegmatites of the Trivandrum district may be classified into (1) simple—consisting of quartz, feldspars, biotite, garnet, apatite, and monazite, and

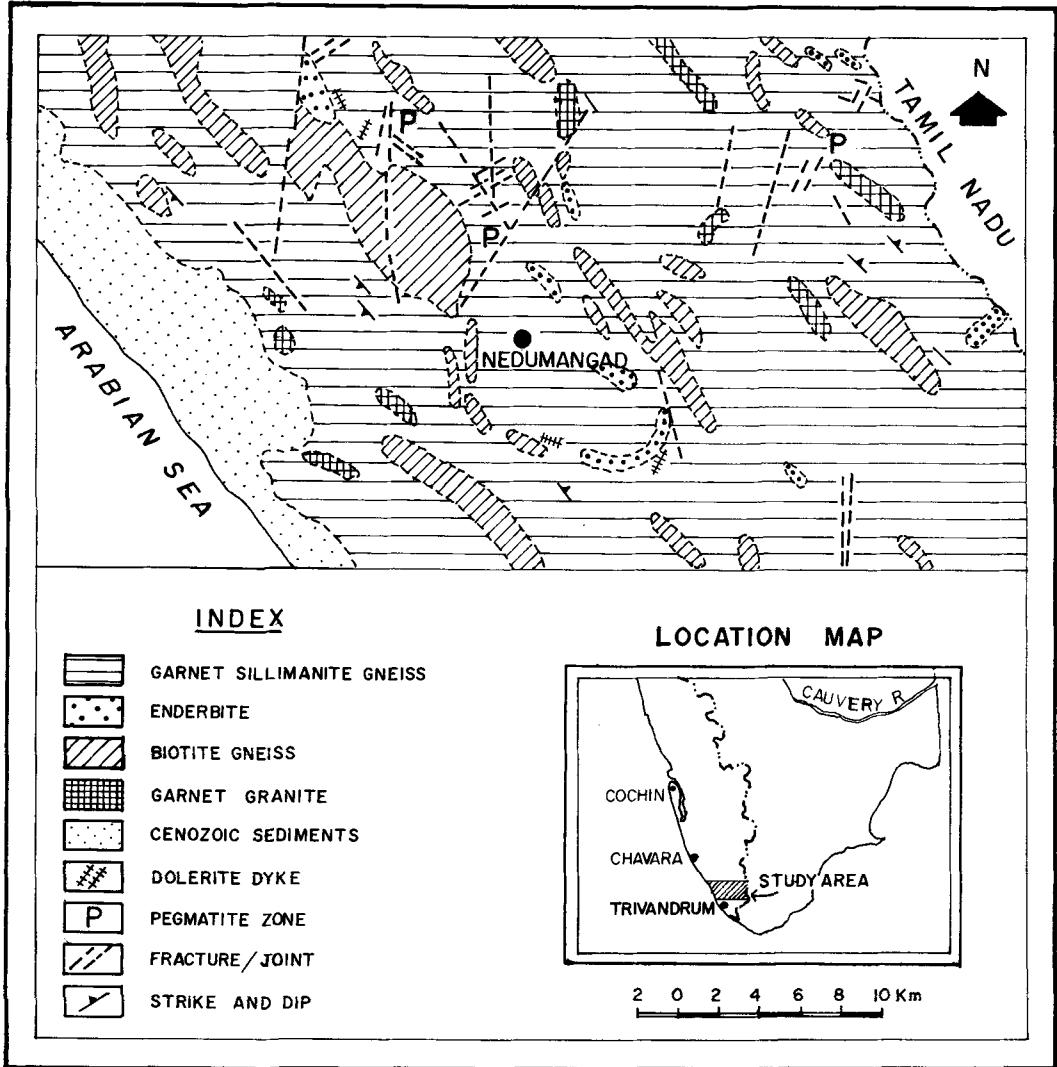


FIG. 1. Schematic geological map of Trivandrum, south Kerala.

(2) complex—containing additionally beryl, muscovite, tourmaline, sillimanite, andalusite, chrysoberyl, cordierite, corundum, etc. Mineralogical assemblages of the pegmatites correspond to the specifications of types II, III, and partly IV pegmatites as per the classification of Fersman (1940). Characteristic features of the type II pegmatites are the predominance of potassium and rare elements, and volatile-free minerals. Schorl and muscovite are typical of type III, and beryl of type IV pegmatites. Chrysoberyl crystallizes towards the end of geophase C, i.e. at approximately 650°C. (Fersman, 1940).

The metamorphic grade of host rocks, the close correspondence in mineralogy of the pegmatites and host rocks, the large scale migmatization, etc. make it possible to attribute the formation of pegmatites at maximal depths (> 11 km) as per the classification of Ginzburg *et al.* (1979). This is further substantiated by fluid inclusion studies, and mineralogical thermometry based on garnet-biotite pairs, giving a temperature interval of 500–745°C for the pegmatite process, and a pressure range of above 2.5 kbar (Soman, 1984).

Textural relations of the minerals. The study of megascopic and microscopic features of the Trivan-

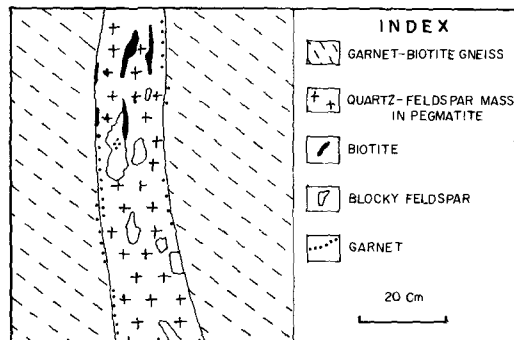


FIG. 2. Diagram showing interrelationship between pegmatite and host rocks.

drum pegmatites reveals that, apart from the commonly observed pegmatitic texture, they also show textures such as blocky, graphic, apographic and, rarely, aplitic, as described by Solodov (1962). Graphic intergrowths of quartz and feldspar (30:70 ratio), tourmaline and quartz, and beryl and quartz are characteristic of complex pegmatites. Often coarse graphic intergrowths of quartz and feldspar are replaced by apographic textures along the contact with host rocks. Large aggregates (3 to 5 × 8 cm) of garnets of almandine-pyrope composition (Table I) are observed within the pegmatites near the contact zones. Less frequently, smaller isometric grains of garnet are found engulfed in alkali feldspar within the pegmatites. Books of biotite (up to 10 cm across) coexisting with garnet are seen associated with plagioclase of oligoclase-andesine composition (Table I). Smaller biotite flakes of a later generation are found in lesser quantities.

Chrysoberyl is embedded in alkali feldspar (mostly microcline-micropertthite) which in turn replaces plagioclase. Blocky quartz and veins of quartz and tourmaline are found in alkali feldspar. Tourmaline also occurs as intergrowths with quartz. Beryl (Table I) forms intergrowths with quartz and is associated with muscovite. Muscovite is also associated with alkali feldspar and found partly derived from biotite.

Sillimanite occurs as tabular crystals (up to 5 to 12 cm long) and radial aggregates in alkali feldspar and replaces biotite. Andalusite appears to be later than sillimanite. Ilmenite occurs in association with quartz and feldspars. The paragenetic sequence in the Trivandrum pegmatites, based on textural and petrographic studies in conjunction with theoretical considerations and mineral stability data, is summarized in fig. 3.

Chrysoberyl. Gem-quality chrysoberyl occurs in association with quartz, within alkali feldspar in the pegmatites, as short prismatic, tabular crystals and

TABLE I. Chemical composition of minerals from the Trivandrum pegmatites

	Plagioclase*	Garnet*	Beryl†
SiO ₂	61.04	39.13	66.76
Al ₂ O ₃	24.40	21.19	18.80
Fe ₂ O ₃	—	—	0.41
FeO	—	29.49‡	—
BeO	—	—	13.22
MnO	—	0.65	—
MgO	—	8.22	0.08
CaO	6.18	1.15	0.21
Na ₂ O	7.72	—	0.13
K ₂ O	0.45	—	0.05
Total	99.79%	99.83%	99.66%

O	32	O	24	O	36
Si	10.88	Si	6.08	Si	12.04
Al	5.12	Al	3.88	Al	4.00
Ca	1.20	Fe ²⁺	3.83	Fe ³⁺	0.06
Na	2.60	Mn	0.09	Be	5.73
K	0.12	Mg	1.90	Mg	0.02
		Ca	0.19	Ca	0.04
Mol. %	{ Ab 66	Almandine	63.7	Na	0.01
	{ An 31	Pyrope	31.6		
	{ Or 3	Spessartine	1.5		
		Ca-garnet	3.2		

* Microprobe.

† Wet chemical analyses, IGEM, Academy of Sciences, USSR.

‡ Total iron shown as FeO.

aggregates of honey yellow and greenish yellow colours often showing striations. A seam of small muscovite flakes coat the chrysoberyl crystals. Their specific gravity ranges from 3.69 to 3.73 and refractive indices from 1.754 to 1.760. In thin section, pseudo-hexagonal forms are observed, often exhibiting twinning, with 2 V of 52°. Chrysoberyl crystals are cracked and in places corroded. Fine flakes of muscovite are formed near the corroded

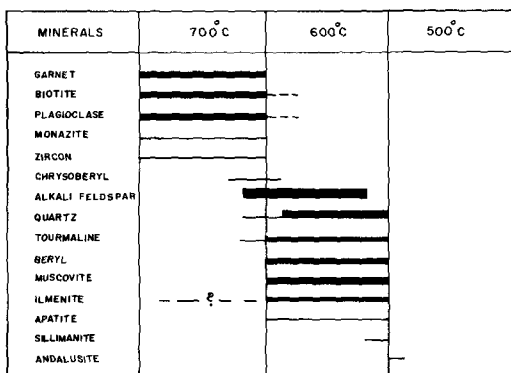


FIG. 3. Mineral paragenesis in chrysoberyl pegmatites from Trivandrum.

faces. SEM examination reveals that chatoyancy in chrysoberyl is caused by the presence of acicular crystals of sillimanite along fractures (Soman and Nair, 1985).

TABLE II. Chemical composition of chrysoberyl (wt. %)

	Trivandrum*	Sri Lanka†
SiO ₂	2.05	0.02
TiO ₂	0.10	—
Al ₂ O ₃	77.89	78.82
Cr ₂ O ₃	Trace	0.002
FeO	0.47	1.30
BeO	19.13	19.70
MnO	—	0.006
MgO	0.06	—
CaO	0.27	0.006
Na ₂ O	0.12	—
K ₂ O	0.25	—
H ₂ O ⁻	0.23	—
Total	100.57%	99.85%

* Wet chemical analyses.

† Franz and Morteani, 1981.

Results of chemical analysis of the chrysoberyl are given in Table II which lead to the calculated formula $(\text{Be}_{0.97}\text{Si}_{0.04})_{\Sigma 1.01}(\text{Al}_{1.94}\text{Fe}_{0.01}\text{Ca}_{0.01})_{\Sigma 1.96}\text{O}_4$. For comparison results of chemical analysis of chrysoberyl from Sri Lanka are also included in the table. Trace element data on chrysoberyl are given in Table III. Plots of trace element data of chrysoberyl from Trivandrum have a close correspondence with those from Makanjoratha, Madagascar, and Americana, Brazil (Kuhlmann, 1983). The Sri Lanka chrysoberyl contains 1.30% Fe and 20 ppm Cr (Franz and Morteani, 1981) which are comparable with those from the above localities. The greenish yellow and honey yellow colours of the Trivandrum gems are due to the presence of Fe. The increased Cr content of Sri Lanka chrysoberyl appears to be the reason for its yellowish green colour.

Fluid inclusion studies. For estimating the thermo-barogeochemical conditions of formation of the pegmatites, fluid inclusions in doubly polished 0.25 mm thick sections of quartz, beryl, feldspar, and garnet were studied. Microscopic study revealed the presence of three types of inclusions based on composition (i.e. number and types of phases present). The three types are: (1) carbonic-aqueous inclusions, (2) carbonic inclusions, and (3) multiphase inclusions.

TABLE III. Trace element content of chrysoberyl from Trivandrum (ppm)

Sample no.	Sc	Ti	V	Cr	Fe	Cu	Sn
GC 75	—	715	—	Trace	8130	3	407
GR 30	—	707	—	Trace	8040	3	338
GC 116	—	812	—	Trace	8110	3	457

Analyses by Emission Spectroscopic method. Courtesy Professor G. Moh, University of Heidelberg.

The carbonic-aqueous inclusions are the predominant type in all the minerals studied, except garnet which has more carbonic inclusions with negative crystal shapes. This type contains a gas bubble of 5–10 and rarely 15–20 vol. %. Liquid CO₂ constitutes about 12–15 vol. % in these inclusions (based on freezing data). Carbonic inclusions often contain a small gas bubble at room temperature depending on the density of CO₂. These two types of inclusions occur both on the fracture planes (secondary inclusions), healed fractures (pseudo-secondary inclusions) and with no obvious planar arrangement (primary inclusions). Multiphase inclusions contain a gas phase (15–20 vol. %), liquid CO₂, two or more solid phases which have not been identified and show no planar arrangement.

Heating and freezing experiments were carried out in the laboratory of IGEM, Academy of Sciences, USSR, on primary and pseudosecondary inclusions, using a heating stage and a heating and freezing stage with accuracies of $\pm 2^\circ\text{C}$ and $\pm 0.2^\circ\text{C}$ respectively.

Heating experiments gave homogenization temperatures (into liquid) ranging from 300 to 360°C for primary and pseudo-secondary inclusions. An unidentified irregular shaped black solid phase in quartz dissolved at a temperature of 500°C. In other inclusions the solid phases could not be dissolved, as the inclusions exploded at a temperature range of 410–440°C and rarely 510–530°C during very slow heating. Freezing data indicated a pressure of 2.5 kbar at a homogenization temperature of 400°C and a total salinity of 29% (NaCl + KCl). Pressure corrections for fluid inclusion homogenization temperatures, based on the experimental results of Khetchikov *et al.* (1968), amount to 185°C, while these are 195 to 210°C based on NaCl content (Potter, 1977). This would indicate an entrapment temperature of 485 to 570°C, which is consistent with the melting temperature of the solid phase in quartz at 500°C. Chrysoberyl-quartz stability data by Franz and Morteani (1981), in conjunction with the fluid inclusion data and the

paragenetic sequence of formation of chrysoberyl, permit deduction of a temperature interval of 570–630 °C for the formation of chrysoberyl at $P = 2.5$ kbar. This is at variance with our earlier reported values (Soman and Nair, 1983), based on preliminary fluid inclusion and decrepitation data.

Gas chromatography confirmed the presence of CO_2 and H_2O in chrysoberyl. Results of gas analyses in garnet, chrysoberyl, and quartz fractions are given in Table IV. Temperature intervals of gas analyses were predetermined from decrepitation peaks in these minerals.

TABLE IV. Results of gas analysis (sample weight 400 mg)

Mineral	Temperature °C	CO_2 (cm ³)	H_2O (mg)	CO_2 g/kg H_2O
Garnet	380	0.0057	0.1466	76.55
	600	0.0094	0.1392	133.00
Chrysoberyl	380	0.0137	0.1672	167.78
	500	0.0228	0.1599	280.82
Quartz	400	0.0086	0.0266	631.50
	650	0.0143	0.0266	1052.50

Analysis: IGEM, Academy of Sciences, USSR.

Genesis. Fersman (1940) briefly discussed the genesis of chrysoberyl in his monumental book on pegmatites. Beus (1960) classifies various types of deposits in which chrysoberyl occurs as: (1) pyrometasomatic deposits with fluorite, magnetite, vesuvianite, mica, garnet, etc., (2) desilicated pegmatites with corundum, spinel, chlorite, margarite, phlogopite, muscovite, plagioclase, fluorite, apatite, etc., and (3) granitic pegmatites subjected to aluminium contamination and having assemblage of kyanite, staurolite, garnet, muscovite, plagioclase, beryl, quartz, etc. Chrysoberyl in the Trivandrum district occurs well within the pegmatites, which are spatially related to garnet-granites. The intrusive nature of the pegmatites, absence of pyrometasomatic or desilication processes, and mineralogical features, preclude the possibility of chrysoberyl being related to the first two types of deposits.

Current views on chrysoberyl formation in granitic pegmatites by the breakdown of beryl are summarized by Heinrich and Buchi (1969) and Franz and Morteani (1981). According to Heinrich and Buchi (1969) interaction of beryl and sillimanite yields chrysoberyl + quartz or beryl, and aluminous solutions interact to form chrysoberyl + sillimanite + quartz. In the paragenetic sequence of mineral crystallization, chrysoberyl is formed earlier

than beryl and sillimanite (fig. 3). This evidence, coupled with the absence of alterations in beryl, eliminates the possibility of chrysoberyl formation by the interaction of beryl- and alumina-saturated minerals or solutions. The mineral assemblage containing andalusite, sillimanite, garnet, chrysoberyl, and muscovite would indicate that the pegmatite melts were saturated in alumina. These pegmatites are suggested to have been formed from residual melts of granitic liquids derived from partial melting of the crust, consisting of high alumina terrigenous sediments (Soman and Nair, 1983).

Fluid inclusion data would suggest that beryllium in pegmatitic residual melts was transported, possibly in the form of carbonato-beryllates as suggested by Govorov *et al.* (1963) for alkaline solutions. Carbonic compounds of beryllium facilitate concentration of this element in residual melts, unlike fluoride compounds of beryllium, which mostly concentrate in later hydrothermal stages (Beus, 1960). The presence of CO_2 results in less siliceous partial melts (Eggler, 1978; Wyllie and Huang, 1976) while chloride ions facilitate transport and precipitation (Wyllie, 1969). Thus chrysoberyl, a beryllium aluminate mineral, possibly crystallized from high-alumina residual melts with low silica solubility, caused by the presence of CO_2 at the beginning of the pegmatite process, and was later embedded in alkali feldspar. The relatively enlarged field for the primary crystallization of quartz, compared to feldspar, in the pegmatites (fig. 3) is probably due to the strong reactive effect of Cl, as suggested by Wyllie (1969). Fluid inclusion data, along with gas chromatography, further suggest that the role of CO_2 decreased by 40% towards the end of the pegmatite process, exemplified by the release of less CO_2 at lower temperature intervals during gas chromatography (see Table IV). This invariably leads to high silica solubility in the melts towards the end of the pegmatite process which is a constraint on the formation of chrysoberyl. Thus the formation of chrysoberyl, as well as the preponderance of volatile-free minerals in the gem pegmatites of Trivandrum during the early stages, are suggested to result from pervasive CO_2 activity.

The above scheme clearly explains the formation of chrysoberyl in granitic pegmatites in the marked absence of external desilication processes or later aluminium contamination or a post-pegmatitic high P - T overprint as discussed by Franz and Morteani (1984). Geological similarities of Trivandrum and the gem-bearing areas of Sri Lanka and Madagascar, close correspondence in their magmatic histories, and the comparable trace element levels in chrysoberyl of these areas suggest a similar

genesis. In the light of this, the vast khondalite territory of Eastern Ghats in India, having similar geological and tectonic history as in south Kerala, may possibly yield pegmatites with chrysoberyl mineralization.

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