concentrated brines have necessary low water activity, high alkali mobility and high infiltration ability. These studies have therefore indicated brines as feasible granulite-facies fluids.

In the southern granulite terrain, especially in Palghat region, two types of charnockite, namely banded charnockite and incipient charnockite belonging to two different periods are noted. Banded charnockites (regional granulite) are recognized as the earliest, deep crustal product while arrested charnockites evolved later, perhaps during uplift. It is known that rocks undergo long and complex fluid–rock interaction during their ascent. The role of fluids, especially on the brines and accompanying changes in the post peak metamorphic history is less studied because they have a very low tendency to be captured as fluid inclusions. In this context we have examined a large number of samples from the Palghat region. We recognize K-feldspar veins enveloping orthopyroxene, and along the margins of plagioclase, similar to the observations made from other major high-grade terrains. In this paper we illustrate several instances of K-feldspar veining and examine the role of alkali-rich fluids in the evolution of charnockites in the Palghat region.

The Palghat region in central Kerala is a part of the granulite belt of south India. The region is considered to mark a zone of contact between the northern Archean block and dominantly Proterozoic block to the south (Pandyan Mobile Belt). Major rock types in the region include, in order of abundance, hornblende–biotite gneiss, biotite gneiss, charnockite (regional granulite), amphibolite, granite and pegmatite. Occurrence of incipient charnockite overprinting hornblende-biotite gneisses has been reported recently. Three deformation phases are recognized as F1, rootless isoclinal folds within the compositional bands of gneisses and amphibolites; F2, folds occurring as isoclinal to tight folds along EW; and F3, folds as warps with gentle plunges. Ages of rocks and metamorphism are poorly constrained. Recent K-Ar dates of mica in pegmatites, which cross-cut the gneisses, have yielded ages ~ 500 m.y.

All the major rock types like hornblende–biotite gneiss with enclaves of amphibolite and pyroxene granulite bodies, banded charnockite and biotite gneiss show evidence of extensive migmatization and deformation. Late coarse-grained pink quartz-feldspathic pegmatites intrude all the rock types. Field relations indicate that the banded charnockite and grey hornblende–biotite gneiss are the earliest units as they are co-folded, co-planar and show imprints of similar deformation and migmatization. Banded charnockites are extensive on a regional scale but on outcrop scale they may be noted as patches when pink quartz-feldspathic pegmatite veins retrogress them at immediate contacts. Mafic minerals such as clinopyroxene, orthopyroxene, hornblende and biotite define the foliation. The banded charnockites are granoblastic with an equigranular to inequigranular texture. Patches of unretrogressed, banded charnockites in grey retrogressed gneiss show continuation of foliation and similarity of grain sizes when traced into the gneiss. The incipient charnockites on the other hand, occur as small isolated patches or veins with granoblastic texture and grain size coarser than the surrounding gneiss. They are also characterized by lack of foliation and low concentration of mafic minerals. Structural control in the formation of incipient charnockite is evident in the field as they are always associated to foliation planes or foliation boudins or axial planes or shear zones. They are also seen at places as margins to biotite-rich dykes. It is observed that incipient charnockites are localized in the migmatitic hornblende–biotite gneiss, particularly to leucosomes or modified palaeosomes and are absent within pink granitic–biotite gneiss.

Micro-textural aspects commonly observed are a dominant granoblastic texture with effects of shearing under high ductility. Prograde textures of biotite + quartz ⇒ orthopyroxene + K-feldspar + fluid are observed in the transformation of hornblende biotite gneiss to incipient charnockite. The biotite grains involved in the biotite + quartz reaction show exsolution of opaque grains and in the charnockite portion these opaque exsolution accumulate to form large grains of hemo-ilmenite. The most interesting aspect is the recognition of late K-feldspar veining textures observed in the banded charnockite, hornblende–biotite gneiss and incipient charnockite. Textural studies document K-metasomatism as (a) rims of K-feldspar (Figure 1a) along orthopyroxene (Figure 1b), clinopyroxene, opaque (Figure 1c) and microline, (b) veins of secondary K-feldspar in larger plagioclase, orthopyroxene, hornblende and quartz grains (Figure 1d).

Vein type K-metasomatism is the most common form and is traced along weak planes like sutures and cleavage planes. The vein types in some cases tend to increase the size of blebs within the perthite grain (Figure 2). Detailed studies of such textures are also reported by Sazonov et al. on incipient charnockite formation of Kurunegala, Sri Lanka. Sometimes they exhibit more than one generation as they show cross cutting relationship (Figure 3). This could indicate that K-metasomatism could have occurred over a long period. In some cases it is observed that these K-rich fluids have formed into larger secondary K-feldspar grains. In cases where patches invading plagioclase grains are seen, the polysynthetic twin lamellae are obliterated and patches of K-feldspar of irregular shapes are formed within larger plagioclase (Figure 4). This type of potash metasomatism is commonly observed in banded charnockite. It is also noted against orthopyroxene (Figure 5), clinopyroxene and perthites.

The effect of K-metasomatism is most pronounced and intensive in pink granites and pegmatites. Perthite grains rimmed by K-feldspar are also documented. This texture indicates that the granite was less viscous, enriched in

CURRENT SCIENCE, VOL. 79, NO. 11, 10 DECEMBER 2000 1595
volatile-rich fluids, which are highly penetrative moving along grain boundaries and sutures. These kinds of K-metasomatism effects are termed by Weinberg and Weinberg and Searle as 'autometasomatism', as these are considered to be residual fluids of granitic magmas that are volatile enriched with low viscosity with penetrative nature, and tend to consume the earlier formed grains.

The cause for dehydration and low water activity is still debated. Either infiltration of CO₂ or internal buffering of fluid composition is considered to have been responsible. The detailed work so far in south India suggests that carbonic fluids derived from either mantle or tapped from 'fossil' reservoir have been the cause for charnockitization. In this context patchy charnockite development in Palghat is important. Ravindra Kumar and Raghavan recognized large-scale granulite-facies metamorphism immediately preceding or before patchy charnockite development. This metamorphism is likely to have transformed the immediately vulnerable H₂O-poor granodioritic gneisses and destroyed their major mineral H₂O reservoir assemblages, leaving portions where charnockites could not form, either due to compositional inertness or because of presence of held up water. Such zones where H₂O and K₂O-rich fluids have permeated, which are incidentally the non-charnockitic pockets within the granulites, are locales for strong migmatization leading to metasomatic modification of the rock types. Presence of K-feldspar veins as product of alkali exchanging grain-boundary fluid in all the rock types lends credence to this observation.

It has been well understood that preceding anatexis influences arrested charnockite formation in Palghat. The important observation is that the arrested charnockite occurs preferentially in leucosomes and/or in modified palaeosome, suggesting possibilities of the leucosome portions representing the partial melt portions extracted and mobilized. Fluid inclusion study by Sukumaran et al. (unpublished) documents that aqueous brines containing up to 21 wt% NaCl are present in arrested charnockite of Palghat. Newton et al. consider that saline brines have high wetting ability. Saline brines are normally consumed at mid to lower crustal regions in mineral reactions and melt generation, in other words help induce dehydration reactions in regions of low aH₂O. The excess H₂O and halides in such locales are removed a short distance.

**Figure 1.** Photomicrographs documenting K-metasomatism in the form of K-feldspar veinlets. a, Rimming of K-feldspar by K-feldspar II; b, Enveloping orthopyroxene; and c, Around opaque; d, K-feldspar veins seen as late veins in larger quartz grains. Scale bar in all photographs is 2 mm across. K-felds, Potash feldspar; Opx, Orthopyroxene; Cpx, Clinopyroxene; Opq, Opaque; Qtz, Quartz.
away by the generation of leucocratic melt halos, leaving behind a bulk of CO₂ fluid inclusion in the system. This could be a reason for the greater abundance of carbonic fluids and lower concentration of H₂O-rich fluids in the charnockites. Another reason could be that brines have a very low tendency to be captured as fluid inclusions as against CO₂-rich inclusions in high-grade metamorphic regime.

The regional granulites (banded charnockite) in the study area formed in CO₂-rich fluid environment at lower crustal levels, where high temperature and pressure (800–900°C and 9–10 k bars) prevailed. At temperatures greater than 700°C, CO₂–H₂O fluids present in the mantle flow pervasively in the lower continental crust that help in the formation of regional granulites. The dominance of CO₂-rich mantle fluids is indicated by the presence of modal amounts of clinopyroxene in these rocks.

The charnockite alteration is not spatially related to macroscopic fractures or veins and therefore must result from reactive fluid flow that itself is pervasive at the grain-size scale.

K-feldspar veins are considered to occur due to the influx of complex, supercritical, low H₂O activity brines shortly after peak metamorphic conditions. These fluids represent the first stage in a series of fluid influxes in which the H₂O activity increased as uplift continued. Harlov and others further state that reaction of these brines with potassium undersaturated plagioclase grains formed K-feldspar veins along grain boundaries and fractures. We record in the Palghat region, formation of orthopyroxene and K-feldspar from biotite + quartz reaction by the influx of low aH₂O-enriched brine solutions at lower temperature and pressure and at higher crustal levels. The pink pegmatites and large volume of pink biotite granite

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**Figure 2.** K-feldspar veins in the form of enlarged blebs along sutures in exsolution perlites (Per). Scale bar ~ 2 mm across.

**Figure 3.** K-feldspar veinlets seen as pervasive K-metasomatic fluids along sutures in perlitic (Per) grains. Increase in the size of the blebs and different periods of veining are also seen because of cross cutting relationship. Scale bar ~ 2 mm across.

**Figure 4.** K-metasomatic fluids invading and obliterating polysynthetic twin lamellae of plagioclase (Plag.) grains, and forming irregular patches of K-feldspar within larger plagioclase. Scale bar ~ 2 mm across.

**Figure 5.** Potash feldspar veins noted against orthopyroxene (Opx), also seen are myrmekitic K-feldspar rimming the orthopyroxene grain.
documented as thrust sheets into the Palghat region have the potential to be the heat source and in providing saline brines to aid low aH₂O. We record from PT data that banded charnockites (regional granulite) evolved at deep crustal levels corresponding to a depth of ~30 km, which could have been influenced by large-scale CO₂ influx, whereas the arrested charnockites formed at midcrustal levels at a depth of about ~20 km. This region can be compared to the zone of K-metasomatism and anatexis in the model proposed by Janardhan et al., with the saline brines playing a major role and CO₂ having a subordinate role.


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Tree-ring indications of recent glacier fluctuations in Gangotri, western Himalaya, India

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A 410-year-old (AD 1590–1999) ring-width chronology of Himalayan pine (Pinus wallichiana) based on large replication of samples derived from a pure, mixed age stand growing on thick soil with almost even topography near Chiribasa, Gangotri has been developed. This makes the longest chronology of this species developed so far from the Indian region. The chronology shows abrupt surge in tree growth during the late 20th century, with the highest growth indices recorded in the 1990s. Strong correlation noted between tree growth and winter temperature shows that the winter warmth is one of the main factors responsible for the twentieth century growth surge. This growth surge is closely associated with the area vacated by the Gangotri glacier. Low growth prior to the 1950s reflecting cooler conditions indicates that the glacier should have been stationary for a long time with some episodic advances.

GANGOTRI glacier, around 30 km in length covering an area of 143 km², flowing north-west, is one of the largest valley-type glaciers in the western Himalaya. It originates from Chaukhamba group of peaks at an altitude of 7100 m asl. Observational records show that during 1935–1996, the Gangotri glacier has retreated around 1147 m (ref. 1). Such a fast retreat of the glacier, a major freshwater resource for the people of the peninsula region in India, is of great concern to the human society. As the climate change directly influences the size, flow rate and even the existence of glaciers, there is now a growing belief that the anthropogenically-induced warming is one of the major contributing factors to the accelerated pace of glacier recession. To develop a better understanding of the linkage between glacier and climate dynamics, high-resolution, long-term data are needed. The glacier fluctuations measured with geological, geomorphological and other proxy methods could be calibrated with long-term climate records. Tree-rings provide valuable proxy of various environmental parameters with the resolution of calendar years. Such long-term proxy records developed from tree-rings covering the ‘Medieval Warm’ and ‘Little Ice Age’, recognized major climatic events of the pre-industrial period, would provide valuable database to estimate the magnitude of anthropogenically-induced warming on glacier dynamics.

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