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# REPLY

The comments made by C. R. L. Friend on our paper entitled 'Progressive charnockitization of a leptynite-khondalite suite from Kerala, India—Evidence for formation of charnockites through decrease in fluid pressure?' are mainly confined to the relationship between formation and emplacement of Closepet-type granites and the process of charnockitization at Kabbaldurga. In fact, since Weaver (1980) suggested that K-rich rocks in the Madras granulite terrane were formed by fluid metasomatism and partial fusion prior to their inversion to charnockite by the advance of a $CO_2$ front, this idea has strongly influenced most of the recent models of 'Kabbaldurga-type arrested charnockitization'. Janardhan *et al.* (1982), Holt and Wightman (1983), Condie *et al.* (1982), Friend (1983) argue that K-metasomatism of Archaean gneisses and anatectic development of granite in southern Karnataka were caused by a wave of aqueous fluids pushed upwards by an ascending front of 'charnockitizing' carbonic fluids of deep-seated origin. This point has been briefly discussed in our paper to emphasize that the imperative connection between potash metasomatism, granite formation and 'Kabbaldurga-type' charnockitization as propagated by these workers did not exist in the case of southern Kerala and is also questionable in the case of Kabbaldurga as evidenced by recent investigations (Hansen *et al.*, 1987; Stahle *et al.*, 1987; Raith *et al.*, 1987). In this context, some of the comments raised by C. R. L. Friend are examined.

1) Nowhere in our paper did we imply formation of granites in the Closepet plutonic belt by potassium metasomatism. We fully agree with the concept that these granites were generated by partial melting of tonalitic to granodioritic gneisses during upper amphibolite facies metamorphism 2.5 b.y. ago. As indicated by

Friend, this process is well documented in a series of active quarries in the area around Ramanagaram and the best quarry is located near Ammainahalli, 3 km west of Ramanagaram town (Jayanand, pers. comm.). At Kabbaldurga, Archaean gneisses (3.4 b.y. U-Pb zircon upper intercept data; Buhl, 1987) have also undergone intense migmatization about 2.5 b.y. ago (U-Pb zircon data, Rb-Sr whole rock isochron; Buhl, 1987) resulting in a complex ensemble of grey gneisses, metatexites, various types of diatexites and anatectic granites generally intruded along the foliation of the gneisses. In complete agreement with Friend (1984, 1985) we assign these granites to the Closepet granites *s. str* . . .

2) In keeping with our observations, there is now a general consensus that charnockitization at Kabbaldurga was a late, structurally and fluid-controlled process which followed high-grade metamorphism and partial anatexis of the gneisses (cf. Hansen *et al.*, 1987; Stahle *et al.*, 1987; Raith *et al.*, 1987, 1988). Charnockitization evidently proceeded along a set of ductile shears which transect the migmatitic structure as well as syn-migmatitic granite veins. The same conclusions were reached by Friend (1985, p. 247): 'There appears to be irrefutable evidence that the partial melting event which gave rise to the Closepet granites took place in mid-crustal amphibolite facies gneisses and occurred prior to the inversion of the rocks to charnockite.' It was never questioned by us that charnockites at Kabbaldurga locally have developed over the older anatectic granites. We, however, wanted to point out that charnockitization at Kabbaldurga was evidently not preceded by small-scale granitization due to fluid metasomatism along the same pathways, although substantial metasomatic changes occurred during charnockitization itself (Hansen *et al.*, 1987; Stahle *et al.*, 1987).

3) The migmatitic gneisses and charnockitized zones at Kabbaldurga are transected by a network of coarse-grained to pegmatitic pink granite veins. It is this type of granite we referred to as Closepet-type granite in our paper, and it is obvious that this terminology created much of the confusion. A typical feature of these late 'Closepet-type *s.l.*' granite veins is the irregular reddened contact zones indicating extensive infiltration of fluids into the wall rocks (i.e. the gneisses, older anatectic granites and charnockites). While according to us, the pinkish granite veins clearly postdate the formation of charnockite, Friend (1985, p. 246) states that they form the lateral extensions of the charnockite network and argues that the lithologic changes reflect the spatial change in the volatile composition, which in front of the invading $CO_2$-rich fluids were increasingly $H_2O$-dominated. The close spatial relations between charnockite and pinkish granite argued by Friend (1985), however, are questionable. The idea that an ascending front of 'charnockitizing' carbonic fluids will create and push ahead a wave of 'migmatizing and granite producing' aqueous solutions is unrealistic (Raith *et al.*, 1987). The composition of pore fluids in an ascending front of charnockitization are controlled by the influx of external carbonic fluids and the internal release of $H_2O$ through the breakdown of hornblende and/or biotite. In order to maintain the dehydration process, the fluids have to be strongly water-deficient ($XH_2O \approx 0.25$; cf. Hansen *et al.* 1987, Fig. 13 A). A change towards water-dominated compositions can only be achieved through external control, i.e. by a change in the composition of the invading fluid. In this case, the dehydration reactions and internal fluid production would cease; partial melting, could however be initiated.

It is obvious that, for a discussion of possible genetic relations between granite and charnockite development, it is imperative to carefully differentiate between the various types of 'Closepet' granite on the basis of field relations, isotopic age data, and petrographic and chemical characteristics.

4) Our concept that '*in-situ*' charnockitization in southern Kerala possibly was an internally-generated phenomenon has been further substantiated by detailed petrological and geochemical studies on selected exposures (Raith *et al.*, 1987, 1988; Klatt and Raith, 1987, Klatt *et al.*, 1988). It is evident from these investigations that charnockitization in Kabbaldurga and southern Kerala was controlled by different mechanisms, a view which is now agreed upon by other workers (Hansen *et al.*, 1987). In both cases, however, the final product was the same, i.e., a coarse-grained hypersthene-bearing rock of granitic composition (charnockite *s. str.*).

An internal generation and buffering of the pore fluids involved in the gneiss-charnockite transformation in southern Kerala is indicated by the fluid inclusion characteristics and stable isotope data (Klatt *et al.*, 1988). The fluid inclusions record a comparable evolution of pore fluids in both the gneisses and associated charnockites. The earliest metamorphic fluids are represented by relic briny inclusions ( + salt). They were followed by $CO_2$-dominated fluids now preserved in several sets of medium to low-density carbonic inclusions (0.70 to 0.86 $g/cm^3$; 4-10 mol % $N_2$, $< 1$ mol % $CH_4 + C_2H_6$). This indicates partial to complete physical equilibration of these fluids by progressive leakage and reentrapment during the decompression of the rock complex. Almost pure nitrogen inclusions ($\leq 14$ mol % $CO_2$, $< 1$ mol % $CH_4 + C_2H_6$) obviously were formed during distinct events of devolatilization of $NH_4$-bearing biotite and K-feldspar. The latest pore fluids are represented by medium-density watery inclusions (0.89–0.94 $g/cm^3$; $< 4$ mol % equiv. NaCl). The $\delta^{13}C$ data on graphite (gneiss: −14 to 17‰; charnockite:—19 to 22‰) and entrapped carbonic fluids (gneiss and charnockite: −7 to −15‰) provide evidence that graphite and carbonic fluids in both the gneisses and the charnockites were internally derived from the progressive degradation of organic matter and have attained isotopic equilibrium near peak metamorphic temperatures. An estimate of fluid composition from graphite-fluid equilibria in the C-O-H-N system indicates strongly water-deficient and reduced compositions ($fO_2$ close or lower than defined by the QFM buffer). That both rock types were characterized by a comparable, internally buffered fluid regime ($fH_2O$, $fCO_2$, $fO_2$) is also evident from the identical opaque phase mineralogy (ilmenite, pyrrhotite, graphite ± rutile) and the identical chemical composition of coexisting silicates (garnet, biotite, feldspars). Last but not the least, the internal nature of pore fluids is substantiated by the identical oxygen isotope composition of gneisses and associated charnockites ($\delta^{18}O = 10.3$‰) which precludes massive influx of carbonic fluids with mantle isotopic signature ($\delta^{18}O \sim 8$‰).

P-T estimates obtained from up-dated calibrations of garnet-biotite thermometry and garnet-plagioclase-quartz-ilmenite-rutile barometry on gneiss-charnockite transitions at Kottavattam indicate isothermal-isobaric equilibration of the gneiss and charnockite assemblages at $750° \pm 10°C$ and $5.6 \pm 0.2$ kb lithostatic pressure.

When considered together, the above data substantiate our concept of an internally-controlled mechanism for '*in situ*' charnockitization in southern Kerala. This process occurred long after high-grade regional metamorphism and migmatization, when during uplift the rheological properties of the gneisses changed from ductile to brittle. Decompression resulted in an increase of pore fluid pressure ($P_{fluid} > P_{lith}$) which ultimately, in a regime of anisotropic stress, triggered or at least promoted the opening of conjugate fractures. At this stage, the simultaneous release of pore fluids from bursting fluid inclusions into the developing fracture system resulted in a drop of fluid pressure ($P_{fluid} > P_{lith}$). Since evidence for a concomitant change in fluid composition (i. e. decrease of water activity) and metasomatism as in the case of Kabbaldurga is lacking, we maintain our view that the dehydration reactions possibly were initiated by a drop in fluid pressure in the order of a few hundred bars.

5) The intention of C. R. L. Friend in the last paragraph of his comments is not clear. The basic problem appears to be the feasibility of crack propagation at deep crustal levels. In this regard, we would like to refer to recent petrological work and fluid inclusion studies on a traverse through the Moyar and Bhavani shear zones north and south of the Nilgiri granulite block (Srikantappa *et al.*, 1988). It has been shown that shearing of enderbitic rocks extended down to a depth of about 20 km in a brittle to semi-brittle state. Within the shear zones, shearing and fracturing resulted in an almost complete destruction of fluid inclusions and escape of fluids to upper crustal levels. On the other hand, comparable but undeformed enderbitic rocks in the Nilgiri granulite block contain abundant high-density carbonic fluid inclusions. These findings support the idea of Stahle *et al.* (1987) that the carbonic fluids causing charnockitization at Kabbaldurga were tapped by shear deformation from an extensive reservoir of 'fossil' carbonic fluids in deeper-crustal granulites. This model offers a promising alternative to the currently discussed deep-seated origin of the carbonic fluids, i.e., their generation by degassing of underplated basaltic intrusions, decarbonation of upper mantle or subducted sedimentary carbonates (cf. Hansen *et al.*, 1987).

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