Influence of CO₂ on melting of model granulite facies assemblages:  
a model for the genesis of charnockites

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Abstract
Partial melting studies at crustal pressures in SiO₂-rich portions of the system KAlSiO₄-
Mg₂SiO₄-H₂O-CO₂ can be used to model the anatectic origin of charnockites. The
univariant reaction

\[
\text{phlogopite + sanidine + quartz + vapor} \rightarrow \text{enstatite + liquid}
\]

produces a SiO₂-rich melt (granite analog) at 3 kbar; the vapor composition at the solidus is
buffered to high H₂O-contents by the coexistence of phlogopite with its breakdown
products. At higher pressures, 8 and 15 kbar, the fluid phase is buffered to higher CO₂-
contents and the melt composition becomes enriched in K₂O and MgO (charnockite
analog). Melting relations are controlled by the expansion of the quartz liquidus field
relative to the enstatite and sanidine fields with increasing pressure. Partial melts generated
at the base of the crust in the presence of a CO₂-rich fluid will be of an alkaline nature and
will crystallize enstatite at lower pressures.

CO₂-saturated melting of similar SiO₂-rich bulk compositions (phlogopite-absent) by the
reaction

\[
\text{enstatite + sanidine + quartz + CO₂} \rightarrow \text{liquid}
\]

occurs at temperatures in excess of 1000°C to about 15 kbar. Liquid compositions show
analogous trends, however, with increasing pressure, to those observed in the 5-component
system as a consequence of the expansion of the quartz liquidus surface relative to the
enstatite surface.

This partial melting model for charnockite genesis satisfies the constraints of observed
charnockite mineralogies, P and T estimations for charnockite assemblages (5–12 kbar and
750°–1000°C), and reports of high-temperature CO₂-rich fluid inclusions that are believed to
Also, observations of anatexitic precursory granulate facies metamorphism are reconciled:
Influx of CO₂ vapor (to a melt-crystal system) in sufficient amount to exhaust the vapor
phase buffer will result in H₂O extraction from the melt and crystallization of the melt,
although temperatures may continue to rise.

Introduction
Charnockites form a series of ultrabasic to felsic
composition rocks, containing orthopyroxene, clin-
opyroxene, mesoperthite (or perthite), orthoclase,
plagioclase, and quartz, as well as biotite, garnet,
amphibole, olivine, or opaques, which crystallized
(or recrystallized) during high-grade metamorphic
conditions (Pichamuthu, 1969). They are often tem-
porally and spatially associated with massif-type
anorthosites. Models for the genesis of charnock-
ites typically fall in 5 general categories:
(1) Intrusion of water-undersaturated magma in
dry crust during, or with subsequent, granulate
facies metamorphism (Martignole, 1979);
(2) in situ dry anatexitic during granulate facies
metamorphism (Martignole, 1979);
(3) charnockites are the resi dual after removal of
granitic melt (Pride and Muecke, 1980; Nesbitt,
1980);
(4) charnockites are the cumulates of igneous
fractionation (Field et al., 1980);
(5) granulate metamorphism involving volatiles
containing little H₂O (primarily CO₂), and possibly occurring at high crustal levels (Smith et al., 1979; Newton et al., 1980).

In this paper, experimental data on H₂O-deficient melting of granulite facies assemblages are presented. It is not an objective of this paper to select between the alternative modes of origin, all models being conceivable, but rather, the data will be used to constrain all the models.

**Physical and chemical constraints on charnockite genesis**

Observed mineralogies, measured and estimated volatile compositions, and thermobarometry estimates can be used to constrain conditions of charnockite genesis. The occurrence of orthopyroxene is an essential feature of the charnockite mineral assemblages (Pichamuthu, 1969). Its presence is reconciled in either of two ways: (a) by conditions of low a_H₂O (or low a_H₂O, if an occurrence is metamorphic in origin) resulting in orthopyroxene crystallization, whereas amphibole or biotite crystallization is favored by high a_H₂O, or (b) orthopyroxene crystallization may reflect more significant differences in composition between charnockites and granites than volatile content alone. In other words, charnockites may be compositionally distinct from granites giving rise to different mineralogies. Figure 1 shows SiO₂ vs. (Mg,Fe)O vs. (Na,K)₂O + Al₂O₃ (recalculated to 100%, wt.) for charnockites and granites from the Adirondacks (Lettaney, 1968) and SW Sweden (Hubbard and Whitley, 1979). If considered as a quartz vs. pyroxene-component vs. feldspar-component pseudoternary diagram, then charnockites are noticeably enriched in both ferromagnesian and feldspathic components relative to granites. Whether this distinction relates to a difference in genetic mechanism as well, has not been determined; however, variation of relative proportions of volatiles, especially H₂O and CO₂, in the source regions may be a significant genetic variable inasmuch as volatile compositions have been shown to have a strong effect on melt compositions (e.g., Mysen and Boettcher, 1975) and liquidus phase relations, in general (Eggler, 1974, 1975; Wyllie and Huang, 1975; Wendlandt and Eggler, 1980a,b).

Although some charnockite occurrences are believed to approach H₂O-saturation in the terminal stages of crystallization (Martignole, 1979), charnockites are thought to be the products of relatively dry processes. Mineral assemblages in both charnockites and granulites do not contain appreciable quantities of hydrous phases suggesting low a_H₂O. A
further observation, and one that deserves additional close scrutiny, is that high-temperature CO₂-rich fluid inclusions occur in both charnockite (Ormaasen, 1977; Konnerup-Madsen, 1979) and granulite facies minerals (Touret, 1971b) suggesting high $a_{CO_2}$. Unfortunately, the interpretation of what these CO₂-rich inclusions represent and how they originate is ambiguous. The proposed interpretations, summarized in Table 1, include suggestions that CO₂-rich fluid inclusions may be unrelated to charnockite genesis, due instead to oxidation of graphite, loss of $H_2$ from $H_2O-CO_2$ fluid inclusions by diffusion, or decarbonation of carbonate-bearing country rocks. A number of investigators contend, however, that the CO₂-rich inclusions are juvenile and their compositions may approximate peak metamorphic or magmatic fluid compositions. For the purposes of this study, it is assumed that the latter interpretation is correct at least in some instances.

Also bearing on the nature of volatiles associated with charnockite genesis is the observation of Blattner (1980) of high Cl and F contents in charnockites from Kondapalli, India.

Estimates of pressures and temperatures for the formation or crystallization of charnockites by igneous processes (Table 2) define a window from about 4 to 12 kbar and 750° to 1000°C; those by metamorphic processes may be formed at somewhat lower temperatures. The lowest estimated magmatic temperatures (ca. 750°C) are 100°-150°C above $H_2O$-saturated granite solidi for this pressure window (Tuttle and Bowen, 1958; Piwinskii, 1968; Boettcher and Wyllie, 1968) implying $a_{H_2O}$ significantly less than unity.

Experiments were designed to test the hypothesis that compositional features of felsic charnockites may be generated by partial melting of a $H_2O$-undersaturated source over a $P$-$T$ interval compatible with thermobarometry estimates.

**Experimental model**

Most models for charnockite genesis invoke a crustal derivation from salic gneiss or granulite facies material of pelitic or greywacke composition (e.g., Hubbard and Whitley, 1979). The SiO₂-rich portion of the system $KAlSiO_4-Mg_2SiO_4-SiO_2$ has been selected as a model for the volatile-absent source composition; a potassic phase in the source is assumed. In Figure 2, the starting compositions (solid dots) are shown relative to the 1-atm liquidus surface (solid lines) as determined by Schairer and Bowen (1955) and Luth (1966). All four compositions have protoenstatite as a liquidus phase at 1-atm. For anhydrous conditions, or when only CO₂ is present at crustal pressures, all compositions consist of orthopyroxene, feldspar and quartz, as shown by the 3-phase triangle, sanidine-enstatite-quartz. If any $H_2O$ is present in the source composition, then phlogopite is stabilized as a solidus phase at pressures above about 0.5 kbar (Luth, 1967). This alternative assemblage is shown by the other 3-phase region (projected from $H_2O$), phlogopite-sanidine-quartz. Both assemblages are models for simple granulite facies assemblages.

Volatile-absent, CO₂-saturated, and $H_2O$-under-

<table>
<thead>
<tr>
<th>Source of estimate</th>
<th>$P$, kbar</th>
<th>$T$, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saxena (1977)</td>
<td>2-4</td>
<td>800-900</td>
</tr>
<tr>
<td>Martignole (1979)</td>
<td>7-10</td>
<td>800-900</td>
</tr>
<tr>
<td>Ormaasen (1977)</td>
<td>12</td>
<td>$\approx 1000$</td>
</tr>
<tr>
<td>Konnerup-Madsen (1979)</td>
<td>5-6</td>
<td>700-800</td>
</tr>
<tr>
<td>Bohlen and Essene (1978)</td>
<td>1000 &amp; 100</td>
<td></td>
</tr>
<tr>
<td>Smith et al. (1979)</td>
<td>3-5</td>
<td>$\approx 600$</td>
</tr>
<tr>
<td>Jaffe et al. (1978)</td>
<td>9-12</td>
<td>750-800</td>
</tr>
</tbody>
</table>

Table 1: Possible origins of CO₂-rich fluid inclusions in charnockite and granulite minerals

| (1) Solidus vapor compositions | Ormaasen (1977), Konnerup-Madsen (1979) |
| (2) Juvenile (upper mantle) origin | Hoefs and Touret (1975) |
| (3) Oxidation of graphite or organic material in country rocks | Madsen (1977) |
| (4) Decarbonation of carbonate-bearing country rocks | Hollister and Burruss (1976) |
| (5) Dehydration of CO₂-$H_2O$ fluid by the reaction $Pyroxene + (H_2O-CO_2)_{fl} = Hornblende + (CO_2)_{fl}$ | Ashwal (1978), Smith et al. (1979) |
| (6) Diffusional loss of $H_2$ from mixed volatile inclusions | |
| (7) Evolved from proximal anorthosite or any basic magma body emplaced in the lower crust | |
saturated (mole fraction of H₂O in the vapor phase less than unity) melting relations have been determined for a pressure range corresponding to depths exceeding the thickness of the crust. Examples of the latter two types of reactions are shown schematically in Figure 3. This isobaric section depicts the solidus (heavy line) and subsolidus assemblages for one of the compositions. The CO₂-saturated system melts at the temperature on the extreme left of the section. The addition of H₂O stabilizes phlogopite, and where both phlogopite and enstatite coexist in the subsolidus, the phase rule predicts that univariant melting will occur. Furthermore, the vapor composition is buffered at a unique value for a given pressure and temperature in the region meaning that changing the H₂O/CO₂ ratio within this region changes the proportions of phases but not the assemblage or phase compositions. Two points are of interest:

(1) The interval of univariant melting expands to cover a wider range of volatile contents as the total amount of volatiles in the system decreases (Eggler, 1977b); and

(2) the vapor composition in the subsolidus is buffered to higher CO₂ contents with increasing pressure (Eggler, 1977b; Wendlandt and Eggler, 1980b). At temperatures above the solidus, for pressures corresponding approximately to the crust, the melt preferentially dissolves H₂O relative to CO₂; hence, if a volatile-rich fluid phase is present, then it is likely to be even more CO₂-rich. Furthermore, the lower the amount of total volatiles, the greater the compositional difference between the dissolved and fluid components (Kadik and Lukin, 1973; Eggler and Rosenhauer, 1978). The two melting reactions I have determined that are most applicable to charnockite genesis are: (1) The CO₂-saturated solidus; and (2) the univariant solidus characterized by high X₇ CO₂ relative to H₂O. Water-saturated melting occurs at even lower temperatures than this univariant portion of the solidus but has not been determined as most evidence summarized previously indicates that charnockites were not produced at high aH₂O conditions.

Existing experimental work applicable to this study include determinations of a CO₂-saturated granite solidus at low pressures (less than 3 kbar) by Wyllie and Tuttle (1959) and a granite solidus for a range of CO₂/H₂O compositions at pressures less than 5 kbar by Novgorodov and Shkodzinskiy (1974).
Methods

Experiments at pressures above 10 kbar were done with a solid-media, high-pressure apparatus (Boyd and England, 1960) using a "hot piston-out" technique without additional correction for the effect of friction on pressure. Talc-Pyrex furnace assemblies (1.27 cm diam) were used throughout. Nominal pressures were maintained at ±0.1 kbar.

Temperatures were measured with Pt-PtRh thermocouples and automatically controlled to ±2°C. No corrections have been made for the effect of pressure on the emf output of the thermocouple.

Experiments at pressures below 10 kbar were done with an internally heated, gas-media apparatus. Temperatures were measured with Pt-PtRh thermocouples and pressures were measured by strain gauge. Temperatures are precise to ±3°C and pressures are precise to at least ±100 bars.

Starting materials were synthetic crystalline phlogopite (Ph), enstatite (En), sanidine (Sa), magnesite (Mag), and quartz (Qz). Anhydrous phlogopite component (APh) consisted of crystalline forsterite, kalsilite, and leucite. Details of phase preparation have been reported elsewhere (Wendlandt and Eggler, 1980a). Starting mixtures were of the anhydrous compositions Sa26En13Qz6s, Sa32En13Qz5q, Sa36En22Qz3s, and Sa36F-na2Qz22 (wt). Two additional mixtures were used, (Phr5+APhr5)3sSa2sQz5s, which is a partially hydrated equivalent of Sa36En22Qz22, and Sa35Mag35Qz57, which is the carbonated equivalent of Sa36En22Qz22 (shown in Fig. 2). Carbon dioxide was added as Ag2C2O4 or as MgCO3. A Xco2 = 0.5 (mol fraction) and a total volatile content of less than 10 wt.% (H2O + CO2) was found (by trial and error) to be optimal for investigating the H2O-undersaturated melting reaction; H2O and CO2 were added as crystalline H2C2O4·2H2O.

Approximately 10 mg of the reactants, encapsulated in 3 mm Pt capsules by arc-welding both ends, were run at the pressure and temperature of interest. The solidi for all the reactions were determined by the presence of glass which is assumed to be quenched liquid. The H2O-undersaturated reaction was located by confirming the presence of both phlogopite and enstatite in the subsolidus; reaction stoichiometry was determined by the location of the solidus relative to the low pressure H2O-saturated univariant reactions determined by Luth (1967). The present data are not inconsistent with the topology of Luth's forsterite-, kalsilite-, and leucite-absent invariant point (labelled (v) in Fig. 4; Luth 1967), but do not constrain the location of the invariant point. Run durations ranged from 2.5 hours at 1600°C to 672 hours at 725°C. While temperature reversals were not accomplished, both water-undersaturated and CO2-saturated solidi were determined using different crystalline starting compositions: The former using both Ph + APh + Sa + Qz + H2O + CO2 and Sa + En + Qz + H2O + CO2, and the latter using Sa + En + Qz + CO2 and Sa + Mag + Qz mixtures. A close approach to equilibrium is inferred from the agreement of different starting compositions and from the lengthy run durations. Phases were detected by optical and X-ray diffraction techniques; segregations of glass sufficiently large to be analyzed by electron micro-probe existed only at temperatures 100°-300°C above the solidus.

Results

Table 3 summarizes the experiments defining the melting reactions

\[ \text{Sa} + \text{En} + \text{Qz} = \text{L} \]  
(1)

\[ \text{Sa} + \text{En} + \text{Qz} + \text{CO}_2 = \text{L} \]  
(2)

and,

\[ \text{Ph} + \text{Sa} + \text{Qz} + \text{V} = \text{En} + \text{L} \]  
(3)

In Figure 4, these reactions are shown in P-T projection. The CO2-saturated assemblage melts at about 1000°C over a considerable pressure interval. Only at pressures of about 15 kbar and higher does the difference between melting points for the CO2-saturated and the volatile-absent reactions become detectable. The H2O-undersaturated reaction occurs at about 750°C in the interval 5-10 kbar; H2O-saturated melting will occur at lower temperatures.

The slope, \( \frac{dP}{dT} \), of the CO2-saturated solidus (reaction 2) is approximately vertical. Novgorodov and Shkodzinskiy (1974) determined a slightly positive slope for the CO2-saturated solidus of a granite; they estimated a vertical slope for \( X_{\text{CO}_2} = 0.95 \). The possibility of generating small amounts of H2O (\( X_{\text{H}_2\text{O}} = 0.02 \)) by diffusion of H2 into the experimental charges of this investigation cannot be dismissed (Eggler, Mysen, and Hoering, 1974), and may be affecting the solidus determination in this study.

Discussion

Melt compositions and high pressure phase relations

Figure 5 summarizes the changes in the liquidus surface and, thus, in liquid compositions with in-
creasing pressure for the CO$_2$-saturated system. The trend of liquid compositions for the H$_2$O-undersaturated melting reaction is approximately the same. This is because $P_{CO_2}$ increases with increasing $P_{total}$ in both reactions. In reality, the reaction involving small amounts of H$_2$O will have a slightly more siliceous melt composition than will the higher temperature CO$_2$-saturated reaction at a given pressure.

With increasing pressure, the liquidus stability field of quartz expands relative to enstatite, and, as a consequence, liquid compositions become enriched in potash, alumina and magnesia. The shift of the enstatite–quartz cotectic with increasing pressure (shown in Fig. 5) is constrained in part by observed liquidus phases for the compositions investigated. Unfortunately, electron microprobe analyses of quenched melt cannot be obtained near the solidus because the melt does not segregate into masses sufficiently large to analyze (quenched melt occurred as glass rims on stable crystals). Analyses of melts from runs at much higher temperatures are possible, however, and have also been used to constrain the shift of the enstatite–quartz cotectic with increasing pressure. A glass analysis for a run at 1150°C and 3 kbar plots almost directly on the 1-atm curve; the analysis constraining the 15 kbar cotectic is at 1300°C, and the analysis along the 25 kbar cotectic is from a run at 1550°C.

The melt compositions of most interest are those generated at the solidi of the melting reactions. Although melt compositions near the solidus cannot be determined directly, the trend of evolution of liquid compositions with increasing $P_{CO_2}$ can be established: At 1 atm, the eutectic involving Sa + En + Qz + L is labelled P (Fig. 5), and, it can be demonstrated that with increasing $P_{CO_2}$, the liquid composition represented by this point shifts away from the SiO$_2$ apex toward higher alkali, magnesia and CO$_2$ contents. In the end member system, MgO–SiO$_2$–CO$_2$, as presented by Wyllie and Huang (1976) and Eggler (1974, 1975), the CO$_2$-saturated quartz liquidus surface is shown to intersect the enstatite–CO$_2$ join at a pressure between 42 and 55
kbar, and intersect the carbonate stability surface at a pressure surmised to be about 60 kbar. That is, Wyllie and Huang propose that the melting reaction En + CO₂ = Qz + L intersects the decarbonation reaction En + CO₂ = Qz + Mag at about 60 kbar and about 1600°C. In the system investigated in this work, containing the additional component of K₂O + Al₂O₃, the quartz stability volume will also expand with increasing P_CO₂ relative to the enstatite stability volume. It can be reasonably inferred that the liquid composition in equilibrium with Sa + En + Qz + CO₂ will intersect the Sa–En–CO₂ plane at
a pressure near 25 kbar because the melting reaction involving that assemblage (reaction 2) must intersect the same decarbonation reaction (shown in Fig. 4) as did the assemblage En + Qz + CO₂. Three experiments were made at 25-26 kbar and 850°-900°C to locate this decarbonation reaction (see Fig. 4); in the two higher temperature runs quenched liquid (mixed silicate and carbonate) was observed suggesting that reaction 2 may intersect the decarbonation reaction at pressures a bit below 25 kbar. This lower pressure of intersection, contrasted with 60 kbar in the system MgO-SiO₂-CO₂, is a consequence of the much lower melting temperatures (600°-700°) of the assemblage Sa + En + Qz + CO₂ as opposed to the assemblage En + Qz + CO₂. Because the H₂O-undersaturated reaction is also characterized by increasing P_{CO₂} (relative to P_{H₂O}) with increasing total pressure, similar evolution of liquid compositions can be inferred (toward higher feldspar and pyroxene components and lower SiO₂ contents). Analogous phase relations involving both CO₂-saturated and H₂O-undersaturated melting reactions in the silica-undersaturated portion of the system KAlSiO₄-Mg₂SiO₄-SiO₂-H₂O-CO₂ have been discussed in greater detail elsewhere (Wendlandt and Eggler, 1980a,b).

Conditions of charnockite genesis

The formation of silicic partial melts enriched in feldspar and orthopyroxene components (which may be defined as protocharnockitic) is enhanced by low a_{H₂O}. The physical conditions of partial melting to produce such melts are in concert with thermobarometry estimates for the genesis of natural charnockite occurrences (Table 2). Melting may be initiated in the pressure interval 4-12 kbar at temperatures near 750°C by reaction 3, or, in the presence of pure CO₂ at temperatures of approximately 1000°C for the same pressure interval by reaction 2. Melting by reaction 3 at pressures less than 4 kbar will produce melts with high SiO₂ contents (granite analogs) because the composition of the volatile-rich fluid phase at the solidus will be buffered at high X_{H₂O}. Similarly, melts generated at low pressures by reaction 2 will have higher SiO₂ contents than melts generated at higher pressures. At a given pressure, the melt generated by reaction 3 will have higher SiO₂ content than the melt generated by reaction 2 at the same pressure.

A possible scenario for which the data of this study might be applicable is as follows: Emplacement of an anorthosite or mafic magma in the lower crust preferentially releases CO₂ relative to H₂O during crystallization (Kadik and Lukanin, 1973; Eggler and Rosenhauer, 1978), or promotes decarbonation of carbonate-bearing country rocks, fluxing partial melting of the country rocks. This partial melt solidifies at high grade metamorphic conditions as the charnockite rock suite. A partial melt generated in the presence of CO₂-rich fluids at some pressure, perhaps 8-10 kbar, which crystallizes at some lower pressure, 5-8 kbar, will initially separate orthopyroxene and feldspar, followed by quartz. Differences in bulk composition of observed charnockites may have arisen from variations in depth of genesis (melting and crystallization), degree of partial melting, or the composition of the source material.

This model is analogous to that presented by Emslie (1978) for derivation of essentially bimodal anorthosite-granite suites. Emslie stressed the alkaline nature of the granitic rocks, including charnockites and rapakivi granites, associated with Grenville anorthosite massifs, and the relation of the suite to anorogenic magmatic processes. The reactions presented in this study reinforce his ob-
servation by predicting the alkaline, as opposed to calc-alkaline, nature of the granitic fractions. The compositions of partial melts generated near the base of the crust, in the presence of a CO₂-rich vapor phase, will be controlled by the expansion of the primary quartz field and characterized by enrichment of alkalis in the melt fractions.

A further application of the data of this study regards the common association of migmatites and felsic melts with charnockites (e.g., Quensel, 1950; Touret, 1971a; Sen, 1974; Weaver, 1980). Weaver (1980) and Phillips (1980) suggested that partial fusion may be a logical precursor to granulite facies metamorphism. Phillips argued that the reduced $a_{\text{H}_2\text{O}}$ necessary for granulite metamorphism may be due to partial melting (probably by biotite breakdown) with $a_{\text{H}_2\text{O}}$ decreasing with increasing temperature as H₂O transfers to an increasing fraction of melt. Weaver, on the other hand, suggested that fluctuations in the composition of the metamorphic fluid, from H₂O-rich to CO₂-rich, correspond with initial production of anatexitic melt followed by high-grade metamorphism at low $a_{\text{H}_2\text{O}}$. Elaboration on these models is possible in light of melting reaction 3 that has been presented here. Anatexis in the presence of an incoming CO₂-rich vapor phase will commence at approximately 750°C. The assemblage of liquid + crystals (including biotite) will persist with continuing CO₂ influx until the biotite is exhausted by H₂O extraction, at which point the vapor phase composition will be no longer buffered. Extraction of H₂O from the silicate melt will then occur, promoting melt crystallization despite temperatures which may continue to increase (Fig. 3). The resultant mineralogy of the quench melt is likely to be devoid of volatile-bearing minerals and more felsic (perhaps aplitic) than the surrounding terrain.

**Effect of Fe on the phase relations**

It is likely that the inclusion of additional components to the system investigated will result in depression of the melting temperatures. The most significant component is likely to be iron; charnockites have Fe/(Fe+Mg) (oxide wt) ratios on the order of 5–15. In this study, the objective was to present the phase relations of CO₂-saturated and H₂O-undersaturated melting in the most simple way possible, consequently, the added complexity of (Fe,Mg)O solid solutions was neglected. Some general observations may be in order, however. The melt fraction separating from a metapelite or meta-greywacke source will be enriched in Fe relative to Mg (MacRae and Nesbitt, 1980), and thus it is likely that melting temperatures will occur at lower temperatures than those determined in this study. Saxena (1969), however, analyzed coexisting biotite and orthopyroxene in charnockites and observed that the distribution coefficient for Fe/Mg between the two phases was approximately unity. He projected that a substantial shift of melting equilibria in systems involving (Fe,Mg)O solid solutions in both mica and orthopyroxene was unlikely. Accordingly, it is expected that the equilibrium temperature of reaction 2 will be shifted to lower temperatures by the addition of Fe, while the temperature for reaction 3 will decrease to a lesser degree.

**Conclusions**

A model has been presented for the melting of a simple granulite assemblage in the presence of CO₂-rich fluid phases. Melting can occur between 750–1000°C at crustal pressures, and these temperatures are well within the range estimated for regional metamorphism in, for example, the Adirondacks (Bohlen and Essene, 1977; Jaffe et al., 1978; Valley and Essene, 1980). For melting occurring at about 750°C in the presence of both H₂O and CO₂, pressures corresponding to the deep crust are required to generate a melt enriched in pyroxene and feldspar components. Melting in the presence of pure CO₂ at about 1000°C generates analogous melt compositions at lower pressures. The experimental melting reactions are in agreement with a number of observations constraining charnockite occurrences: Pressure and temperature constraints, mineralogical constraints, and constraints on the compositions of volatiles associated with peak conditions of charnockite formation.

**Acknowledgments**

Thorough reviews of this paper by Drs. W. I. Harrison and R. C. Newton are greatly appreciated. Low pressure runs were done by O. Mullins; his assistance was indispensable. The research reported in this paper was done while the author was a Staff Scientist at the Lunar and Planetary Institute which is operated by the Universities Space Research Association under Contract No. NASW-3389 with the National Aeronautics and Space Administration. The use of the experimental petrology lab at the Johnson Space Center is acknowledged. This paper is Lunar and Planetary Institute Contribution No. 439.

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Manuscript received, April 27, 1981 accepted for publication, July 20, 1981.