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GRANULITE FACIES ROCKS FROM GUAXUPÉ, MG: GNEISS-FLUID SEQUENCES AND P-T CONDITIONS

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RESUMO

Gnaisses de fácies granulito nos arredores de Guaxupé formaram-se em condições de P-T estimadas em 8-9 Kb/800-900° C, e depois sofreram descompressão P-T-t em virtude do soerguimento. O limite inferior deste caminho é estimado em 5-6 Kb/600-700° C. Estudos de inclusões fluidas mostram fluidos de CO_2, N_2 e H_2O dentro dos vários tipos de rochas pertencentes a esta sequência gnáissica, que resultaram da evolução da região. As isócoras para o CO_2 estão compatíveis com a estimativa do limite inferior de P-T, dentro do fácies anfibolito. Entretanto, nenhum pico de fase rica em CO_2 dos fluidos metamórficos foi detectado, podendo ser que o metamorfismo aconteceu sob as condições de ausência de fluido. Efeitos de alteração incipiente induzidos por fluidos na paragênese de fácies granulito sugerem que o fluido pode não ter sido pervasivo, como é comumente assumido para os terrenos de fácies granulito.

INTRODUCTION

With the increasing interest in crustal evolution processes granulite terrains have gained considerable importance owing to their being keys to the understanding of the lower and middle continental crust in general and high-grade metamorphism in particular.Several recent studies have focussed on petrological and geochemical aspects of granulites and the P-T-t paths they have gone through.In addition,petrographic and fluid inclusion studies reveal the nature of fluids that were present during metamorphism.Opinions differ as to the mechanism responsible for the formation of granulites and the reason for the stability of anhydrous mineral assemblages. In actual fact, there may be several ways by which granulites form, and possibly none of the processes invoked is mutually exclusive.One of the most popular views, and probably one of the most important processes, is the formation of granulites by flooding of lower crustal rocks by CO_2-rich fluids (Newton 1986), but this concept has now been expanded (Newton 1990).Also, the universal action of pervasive CO_2 fluid flow as the ultimate cause of granulite facies metamorphism has been questioned by a few workers (Lamb and Valley, 1984; Moecher and Essene, 1991; Valley, 1992; Raith and Srikantappa, 1993).In the present study, we look at the granulite facies terrain around Guaxupé from a slightly different angle, and focus our attention on the changing nature of fluids in the high-grade gneiss sequences.The results presented here are based on field studies, petrography, P-T estimates and fluid inclusion studies.

GEOLOGY

The high-grade gneisses of the study area belong to the Guaxupé Massif as defined by Almeda *et al.*(1981). In a more recent definition, this region is a part of the Varginha-Guaxupé Complex (Cavalcante *et al.* 1979), and is underlain on a regional as well as outcrop scale by high-grade quartz-feldspar gneisses and rocks of intermediate and mafic compositions (Figure 1). The regional distribution of these rocks has been dealt with by Oliveira (1984), while Morales *et al.* (1992 1994) have discussed the metamorphic and structural aspects.

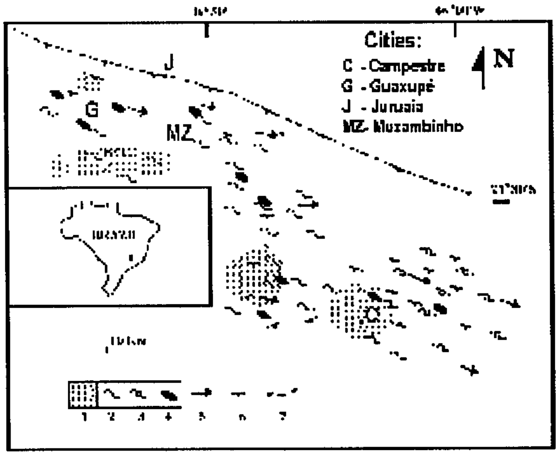

Figure 1: Areal distribution of the studied rocks: 1 - granitic rocks; 2 - charnockitic and enderbitic gneisses; 3 - charnockitic augen gneiss; 4 - mafic bodies; 5 - mineral lineation; 6 - tectonic foliation; 7 - low angle thrust fault.

According to Haralyi *et al.*(1985), this region evolved by crustal thickening by which the high-grade rocks were thrust over lower grade rocks to the north, similar to the model of Oliveira (1984).Recent work by Schrank *et al.*(1990), however, shows that tectonic transport involved a WNW-ESE tangential uplift for

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the formation of the Gauxupé nappe.The regional foliation follows this direction, as do the stretching lineations, and marks the trend of an extensive ductile shear zone that is responsible for the gneissic banding of the granulites. The intense ductile deformation in this zone also affects the pink potassic migmatites that have injected the granulites at various places. These injections are parallel to the general foliation, and cross-cutting relations, though present, are rarely observed. Structural studies by Morales *et al.* (1992) confirm the sense of movement as well as indicate that metamorphism and deformation went together in what appears to be a single tectonic event. Furthermore, according to these authors, granulite facies conditions prevailed at the beginning of deformation, continuing into the amphibolite facies with the same structural style with decreasing temperature and pressure, and that during this period partial melting, remobilization and granitic intrusions also occurred. In this respect the granulite facies terrain of Guaxupé is distinct from that of South India where there is evidence of charnockitization of amphibolite facies gneisses, and the gradation of lower grade terrains to higher grades (Condie *et al.* 1982; Newton 1990). It should perhaps be mentioned that there are a few exceptions to the general trend, and these are local N-S stretching lineations noted by these authors, and also measured by us in the field, in the western section of the area.So far it has not been possible to assess the tectonic significance of this variation.

The age of the Guaxupé rocks is uncertain, although whole-rock Rb-Sr determinations (Campos Neto *et al.* 1988) and U-Pb dates of zircons (Oliveira *et al.* 1986) point to an age span of 600 to 700 Ma.We have observed relict zircons with overgrowths in some of the felsic granulites, so that the rocks are possibly older and have been isotopically reset by the regional migmatization and nappe formation events.

ROCK TYPES AND TEXTURES

The most common rock types in the area are enderbites, mafic enderbites, charnockite and charnockitic augen gneisses. Frequently, mafic two-pyroxene granulites occur as long folded bands or layers within the above gneisses, as well as larger boudinaged bodies around 1-2 km in size.Pink granitic rocks are associated with the high-grade rocks, either as masses or in the form of migmatites; garnet-biotite +/- sillimanite gneisses with subordinate sillimanite-garnet quartzites are much less common, in places they enclose narrow bands of mafic granulite. Mafic migmatite with tonalitic leucosomes have also been recorded in this area, and are considered to have formed by local melting of mafic rocks or injection of tonalitic melts (Choudhuri *et al.* 1992), as observed in other high-grade terrains (Tait and Harley 1988; Pattison 1991; Sawyer 1991).

In the field, the enderbitic gneisses are typically dark grey rocks with a marked banding and thin mafic bands. This is seen to be a foliation formed by granoblastic quartz-plagioclase assemblage with trails of pale green diopside, pale pink pleochroic hypersthene, and minor olive green hornblende.The pyroxenes have stretched, long prismatic to sigmoidal shapes, while the hornblende occurs as wedge-shaped grains.These textures are taken to indicate that the rocks were subjected to strong plastic deformation at granulite facies conditions. Plastic deformation of amphiboles and pyroxenes is not well understood, but Brodie and Rutter (1985) have suggested that the lower limit for the onset of the deformation is in excess of 600° C ; the amphiboles and pyroxenes apparently deform by slip along (100) , which is also the plane parallel to the Si-O tetrahedral ring chains and chains in the structure of these minerals.

The charnockitic augen gneisses consist of mesoperthite megacrysts in a matrix of stretched quartz-feldspar bands and quartz ribbons;green diopside and strongly pleochroic hypersthene form trails around the deformed megacrysts. Rare garnet occurs as tiny grains nucleating at the borders of opaque minerals, or as relict islands surrounded by a plagioclase moat separated from hypersthene.The latter probably reflects garnet breakdown consequent to nappe uplift and decompression, as we shall see below. The massive and fairly homogeneous nature of these rocks suggest syntectonic emplacement of granitic melts in the granulite facies.

Mafic granulites are made up of the usual clinopyroxene-orthopyroxene-plagioclase +/- hornblende combinations with granoblastic textures.Occasionally, however , they show textures typical of decompression, as described by Harley (1989).Garnet first grew along the borders of large hypersthene grains by the reaction

orthopyroxene + plagioclase = clinopyroxene +
garnet + quartz

Later, decompression caused the reaction to reverse giving rise to orthopyroxene-plagioclase symplectite (Fig.2). Following Green and Ringwood's data (1967), garnet probably formed at pressures above 8 kb, and subsequently broke down to this symplectite.In another case , a different kind of symplectite also gives a similar pressure estimate: in a metagabbro body, clinopyroxene-green spinel symplectite formed by the reaction

olivine + plagioclase = orthopyroxene +
clinopyroxene + green spinel

This reaction has a gentle slope in P-T space, and from the work of Kushiro and Yoder (1966) a lower pressure estimate is around 8 kb (Choudhuri *et al.* 1990). For two mafic granulites maximum and minimum P-T conditions were obtained by analysis of cores and rims of garnet coexisting with pyroxenes (Iyer *et al.* in press), and these are 8-9 kb/ 800-900° C , and 8-9 kb/ 800-850° C for the upper limit, and 5-6 kb/ 600-700° C and 5.5-6.5 kb/530-700° C for the lower estimate. This records the decompression path from granulite facies to amphibolite facies shown in Fig. 5. The P-T-t path recorded is between an isothermal

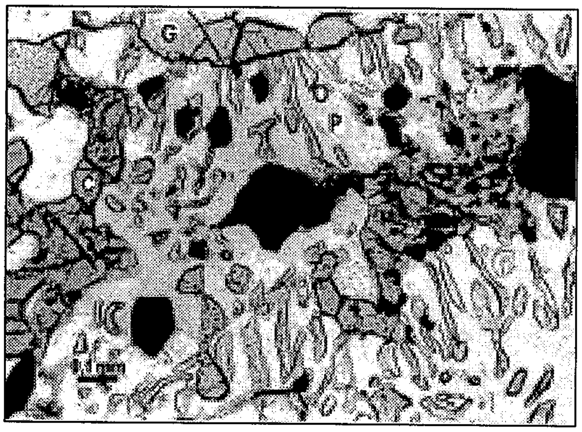

Figure 2: Symplectite of orthopyroxene and plagioclase resulting from decompression (see paths in Figure 5): O=orthopyroxene; P=plagioclase; G=garnet; C= clinopyroxene.

decompression path and an isobaric cooling path, and agrees with the tectonic model of uplift and cooling as a result of nappe emplacement. Otherwise, there are other possibilities for example isothermal decompression followed by isobaric cooling, but this must be checked in more detail in the future.

GNEISS SEQUENCES AND FLUIDS

The complex gneiss associations in a high-grade terrain represent the structure and composition of the lower-middle crust that has evolved by metamorphic and magmatic processes. Apparently, the Guaxupé region formed in a series of stages, starting deep down in the granulite facies, continuing in the granulite facies during uplift, and ending with the injection of pink granitic material in the amphibolite facies, and locally even lower. These stages can be detected by way of fluid induced alteration of granulite facies parageneses.Alteration effects can be roughly grouped into high temperature and low temperature types corresponding to deeper and shallower levels, and can be linked to a relative chronological sequence between the gneisses.This sequence is dealt with first ,and then related to the alterations observed in thin sections.

Although most of the structures have been parallelized as a result of high strain deformation, the relationships between the gneisses can still be recognisd in the field by careful examination:

1. At one place there is a clearly discordant contact between underlying coarse grained charnockitic gneiss and finely banded enderbitic gneiss containing thin mafic granulite bands.The contact is irregular, and both rocks stand out by their grain size and structure, so that the charnockitic gneiss appears to have been emplaced in the overlying rocks.
2. A thin enderbitic vein crosscuts a large metagabbro body and was probably injected during mobilization in the granulite facies.
3. There are no signs of discordance between enderbitic gneiss and the mafic granulite bands in them, whatever the thickness of the latter.In some places,however, igneous textured tonalitic bands traverse mafic granulite, splitting the latter in two without cross-cutting it.
4. Dioritic to tonalitic segregation veins occur in folded and banded amphibolite and mafic granulite, and are cross-cut by pink granitic gneiss.
5. Finally, there are largely concordant pink migmatite injections in banded mafic granulite and enderbitic gneiss with rare cross-cutting relations.The injections are igneous textured and granitic in composition and are probably related to the pink granitic gneiss that has been subjected to high strain deformation. These are considered to be late tectonic features as they are similar to pink massive granites in the area. Massive grey granite is also found in some outcrops, with the difference that they have pink discolouration veins with fracture filled epidote, indicating the passage of aqueous fluids at this late stage. Pink pegmatite dykes cut all the rock types in many places.

Characteristic of the above rocks and the position in the evolving sequence to which they belong is the kind of fluid-induced alteration that the granulite facies parageneses have undergone.Rock type and the nature of fluids are discussed further on.

High-temperature fluid-induced alteration gives rise to hornblende at the expense of pyroxenes, though hornblende continues to be stable in the mafic granulites after this.Another mineral that forms at high temperatures is scapolite (Ca-rich, high birefringence), possibly at the expense of plagioclase by the action of CO_2-rich fluids; where it occurs, scapolite has recrystallized and is stable with the granulite facies minerals.High CO_2 activity has been proposed by Moecher and Essene (1991) for the occurrence of scapolites in granulites.

Low-temperature alteration results in the formation of biotite at the margins of pyroxene and hornblende grains, often at the expense of the amphibole after a partial substitution of pyroxnes by the latter mineral. There are also carbonate veins in microscopic fracture fills, and carbonate corroding pyroxenes in irregular veins.Biotite accompanies the carbonate in many cases, and is itself replaced by late chlorite in rare instances;as mentioned earlier, epidote is a late hydrothermal mineral in vein and fractures in alteration zones.

At one outcrop, we have observed profuse injections of quartz veins that have, however, caused little retrogression in the enderbites which they traverse. The quartz was possibly deposited from high temperature hydrothermal solutions, since silica shows high solubility in aqueous fluids at high temperatures and pressures (Kennedy,1950). All the alteration effects described are incipient or very localized, and granulite facies assemblages are to a great extent preserved throughout the area, indicating lack of large quantities of fluids as well as absence of pervasive fluid flow.

FLUID INCLUSIONS

Analytical techiniques

The samples were studied using 100 µm thick double polished sections, and microthermometric determinations were carried out on a Linkam THMSG 600 programmable heating/freezing stage cooled with liquid nitrogen, attached to a Zeiss Jenapol transmitted light microscope.

Isochore (density curve in P-T space) determinations were made using Holloway equations in software - FLINCOR - (Brown 1989).

To check for presence of N_2 besides CO_2, fluid inclusions have been analysed with a multichannel with a CCD T64000 JOBIN-YVON laser-Raman microprobe in the Fluid Inclusion,Laboratory of the Geoscience Institute of the State University of Campinas. The laser Ar^+, wavelength was 5145(green).

Nature, Distribution and Petrography of Fluid Inclusion

Basically, the fluid inclusions analysed in the this study occur along trails, planar array, small clusters and isolated inclusions. Four compositional fluid types have been recognized: type 1: CO_2-rich; type 2: N_2; type 3: H_2O; type 4: high-salinity H_2O fluids. Type 1 inclusions are distributed in the charnockitic gneiss, charnockitic and enderbitic gneiss. Type 2 occur only in charnockitic gneiss, whereas type 3 occur in charnockite and sometimes in charnockitic gneiss. Type 4 inclusion occur in granitic gneiss.

Type 1: CO_2-rich fluids

In the present samples CO_2 inclusions are the dominant type and occur as planar arrays and in trails, sometimes isolated, as one phase at room temperature.However, it is possible that small amounts of H_2O are present, because H_2O typically wets the wall of inclusion cavity as a thin film (Crawford and Hollister 1986).

Three-phase inclusions($H_2O + CO_2$) have also been observed, but are rare.

Type 2: N_2 fluids

These inclusions are one phase, occur in clusters and sometimes isolated. The size of the inclusions range from 5 to 30 µm but is generally about 15 µm.

Type 3: H_2O fluids

These inclusions are two-phase at room temperature, with a vapour phase occupying about 10 % of total volume.These inclusions occur isolated or even in planar arrangement.The size of the inclusions is generally between 2 and 15 µm.

Type 4: high-salinity H_2O fluids

These are three-phase at room temperature, with a solid cubic salt and a gas bubble rimmed by liquid. The vapour occupies about 10 vol.% of the inclusion and the solid phase occupies about 5 vol.% of the inclusion. These inclusions are arranged along planes that locally cut across crystal boundaries. The size of the inclusions is typically in the 2-15 µm range. The inclusion are regular and irregular shaped.

All microthermometric data presented below are from inclusions in quartz.

Results

From the microthermometric data, melting temperature (Tm) of CO_2 and homogenization (Th) of CO_2 of the inclusions are displayed in Fig.3. The carbonic phase is pure carbon dioxide as these inclusions exhibit melting temperature of solid CO_2 between -56.4°C and -56.7°C (CO_2 triple point is -56.6°C), except a few that exhibit melting temperature of solid CO_2 between -57.1°C and -58.0°C. CO_2 melting temperatures below -56.6°C indicate presence of other dissolved gases, which are commonly interpreted to be CH_4 and/or N_2 (Burrus 1981; van den Kerkhof 1988). Raman analysis showed the presence of N_2 for these inclusions whose melting temperature is lowered. Furthermore, no CH_4 was detected by Raman analysis. Theses fluid inclusions bearing N_2, are generally along healed fractures near or cross-cut cluster of inclusions of pure N_2 (see Fig.4), this suggests that the N_2 inclusions are older than the CO_2 trails.These relatively

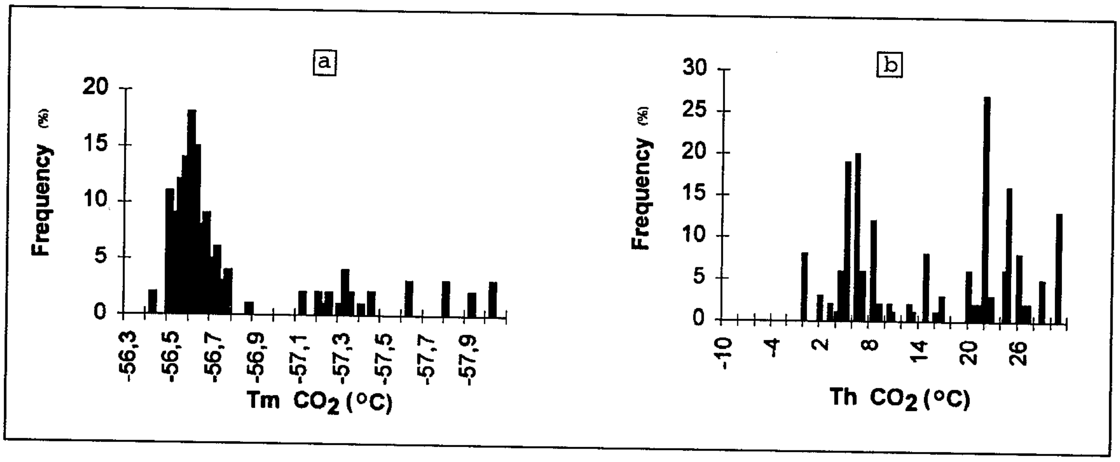

Figure 3: Microthermometric data for CO_2-rich inclusions (a) Tm CO_2, temperature of melting of solid CO_2, (b) Th CO_2, homogenization to liquid.

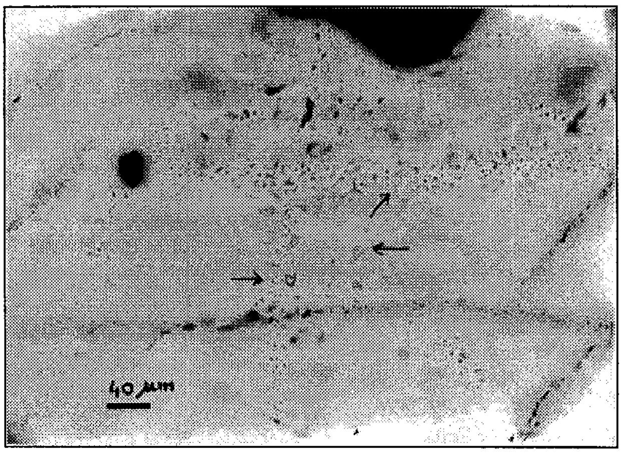

Figure 4 - Horizontal arrows point to clusters of pure N_2 inclusions; diagonal arrow shows CO_2 trails; other planes of inclusions are also visible in the photograph.

rare N_2 -rich inclusions homogenize (vapor) between -157°C and -152°C.

Homogenization temperature of CO_2 vary from -1.5°C to +29,3°C whose densities can be divided into two ranges (Fig.5): (I) medium-density inclusions (0.830-0.937 g/cm³) with T_h varying from -1.5°C to +14°C; (II) low-density inclusions (0.622 - 0.830 g/cm³) with T_h varying from +14°C to + 29.3°C.

The aqueous inclusions (type 3) are less common than CO_2 ones, except for the granitic gneiss (see table 1), that has high-salinity inclusions. The preliminary microthermometric study of these inclusions indicates that there is a fairly dilute fluid between 0 to 1.32 wt% NaCl equivalent. This is detected by melting temperatures of ice between -0.1°C and -0.8°C.

High-salinity inclusions show occurrence of halite (daughter mineral) inside, where the ratio liquid/solid is constant. It is suggested that a saline oversaturated solution was trapped in places(Roedder 1984), and may have a metapelitic source (Touret and Dietvorst 1983).

COUNTRY ROCK	FLUID INCLUSION CHARACTERISTICS (d = density in g/cm³)
Enderbitic gneiss	pure CO_2 => d = 0.767 pure CO_2 => d = 0.937
Charnockitic gneiss (1)	pure N_2 => d = 0.171 pure CO_2 => d = 0.905 pure H_2O =>ice melting = -0.1ºC
Charnockitic gneiss (2)	pure N_2 => 0.137 CO_2 + N_2 => 0.897 pure CO_2 => 0.881
Charnockite	pure CO_2 => 0.622 pure CO_2 => 0.739 CO_2 + H_2O => 0.871 pure H_2O =>ice melting = -0.1ºC
Granitic gneiss (1)	aqueous brines inclusions (daughter mineral)
Granitic gneiss (2)	aqueous brines inclusions (daughter mineral)

Table 1: Fluid inclusions characteristics in different types of country rocks.

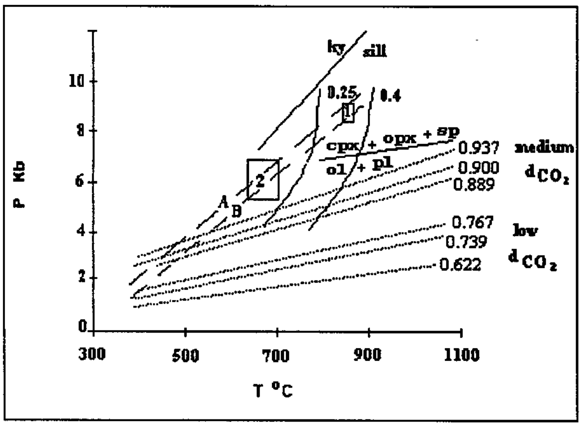

Figure 5: P-T diagram showing: isochores for CO_2 fluid inclusions in granulites (dotted lines), isochores are for low and medium CO_2 density (dCO_2) fluid inclusions; boxes (1&2) for maximum and minimum P-T estimates for two Guaxupé mafic granulites (A & B); dashed lines A & B represent possible uplift paths from box 1 to box 2, from granulite to amphibolite facies; kyanite-sillimanite boundary from Pattison (1992); curves 0.25 and 0.4 are X_{H2O} for hornblende breakdown from Wells (1979); and the reaction olivine + plagioclase = orthopyroxene + clinopyroxene + spinel from Kushiro and Yoder (1966).

DISCUSSION

The results show no isochores crossing the peak P-T box (Figure 5), and so far no CO_2-rich peak metamorphic fluids have been detected, and a case may be made for fluid-absent granulite formation (Stevens & Clemens 1993). Fluid -absent metamorphism can occur when effectivily there does not exist pervasive contact between fluid phase (if present) and minerals (+/- melting) in a rock (Clemens 1990). Fluid-absent metamorphism and/or partial melting are generally used to explain cases where the terrain has gone through processes of desiccation during earlier tectono-thermal events.

However, the nature of fluids can be related to a retrograde amphibolite facies stage in the granulite belt (Figure 5), the fluid inclusion data can be summarized as follows (densities in g/cm^3):

1. medium density pure CO_2 in banded enderbites - 0.937, low density pure CO_2 inclusions in the same enderbites - 0.767 (Figure 5);
2. medium density CO_2 - 0.900 (Figure 5), pure aqueous and N_2 inclusion as well as $CO_2 + N_2$ inclusions in charnockitic gneiss - 0.889;
3. low density CO_2 - 0.739 and 0.622 (Figure 5), and H_2O inclusions in charnockite;
4. late stage grey granite gneiss with aqueous-brine inclusions with saturation crystals - possibly a metapelitic source (see e.g. Touret & Dietvorst 1983; Newton 1986).

Separate CO_2 and N_2 inclusions may represent different fluid pulses as both of them are otherwise miscible.

Low density N_2 inclusions are considered to be enigmatic (Newton 1986). If, however, tonalitic or even enderbitic melts are produced by melting of amphibolite or amphibole-bearing rocks, it might be possible that N_2 in amphiboles (if present as in feldspars and micas) is set free, dissolving in the melt and being trapped as pure N_2 inclusions.

The trapping of these fluids (CO_2 and N_2) might also reflect a residual fluid that remained after the dissolution of water in partial melts under high-grade conditions.Some of the charnockitic gneisses may have formed this way - by syntectonic emplacement of partial melts at depth, as suggested previously (Choudhuri *et al.* 1992). This mechanism may also explain the desiccation or water dissolution during high-grade metamorphism in fractions of partial melts that were removed from the rock.

On the whole, the nature of fluids can be related to high or low temperature alteration effects. Futher studies require that we integrate our observations over a large area and look for peak metamorphic fluids.

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