"..........The story of granulite fluids is just beginning to be told...........

-Prof. Robert C. Newton

CHAPTER 6

FLUID INCLUSION STUDIES
6.1 INTRODUCTION

The thermodynamically isolated micro geochemical systems entrapped in various minerals during their growth are popularly known as "fluid inclusions". Fluid and melt inclusions provide a wealth of information on the genetic and evolutionary history of the mineral assemblages in a rock or ore formation as they furnish valid clues for the physico-chemical interpretations. They represent ideal samples of the fluid or melt, which were in equilibrium with host mineral either during its genesis or at later stages. These fluids can be trapped in a crystal along the growth zones or crystal edges or in any imperfection of the crystal growth. These are called primary inclusions. When a mineral is fractured during growth syngenetic micro-cracks will be healed in the presence of a fluid, which may be trapped as pseudosecondary inclusions. Any stress after crystal growth will lead to epigenetic fractures and secondary inclusions may be the result of their recrystallisation. Primary and pseudosecondary inclusions will thus contain the fluid from which the host crystal has grown. Therefore they can provide information on the fluid composition of the corresponding environment (magmatic hydrothermal fluids, basinal brines, heated meteoric waters, etc.) (Shepherd et al. 1985). But secondary inclusions provide information on the later geological history of a crystal. A fluid inclusion represents a closed (isochoric) system, which is defined by pressure (P), temperature (T), volume (V) and chemical composition (X). Two of these parameters (V, X) are fixed during formation of an inclusion while P and T remain variable after trapping.
At room temperature most fluid inclusions contain two phases, a vapour bubble and (aqueous) solution. But other phase combinations as two immiscible liquids (liquid CO$_2$ and water for example) with or without a vapour bubble are also common. Different occurrence of fluid inclusion and their classifications are illustrated in table 6.1.

Table 6.1 Classification of Fluid-Inclusions

<table>
<thead>
<tr>
<th>TYPE</th>
<th>BRIEF ACCOUNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Vapor / Gas-rich / Monophase Fluid Inclusion</td>
</tr>
<tr>
<td>II</td>
<td>Biphase, Vapor / Gas-rich Fluid Inclusion (Gas&gt; Liquid)</td>
</tr>
<tr>
<td>III</td>
<td>Biphase, Liquid-rich Fluid Inclusion (Liquid&gt;Gas)</td>
</tr>
<tr>
<td>IV</td>
<td>Triphase, Immiscible Liquid-rich Fluid Inclusion (Aqueous Phase &gt;CO2 Liquid &gt;CO2 Gas)</td>
</tr>
<tr>
<td>V (a)</td>
<td>Polyphase, Gas-rich, High Saline (Gas &gt;Liquid &gt;Solid)</td>
</tr>
<tr>
<td>V(b)</td>
<td>Polyphase, Liquid-rich, High Saline (Liquid &gt;Solid &gt; Vapor)</td>
</tr>
<tr>
<td>V(c)</td>
<td>Polyphase, Solid-rich, High Saline (Solid&gt;Liquid&gt;Gas)</td>
</tr>
</tbody>
</table>

Additional solids may occur, which are termed daughter crystals if they are precipitated from the trapped solution. Halite is by far the most common solid phase observed. A distinction is made between these solids and 'captive' or captured mineral phases accidentally trapped together with a proportion of the fluid. In practice a distinction between captured and daughter minerals is difficult. The best way is to visually check the phase ratios. It will be more or less constant in inclusions of different size in a
given generation, since the probability of trapping captive minerals giving constant liquid/solid volume ratio is very low. Also the captive minerals will be often anomalously large compared to their host inclusion. Thirdly, if the solid phases also occur as solid inclusion with in the crystal it is quite likely, that they represent accidental trapping of materials nucleating or settling on to the surface of the crystal. As a general rule, only one crystal of each daughter mineral is developed within a single inclusion in geological samples.

The aim of any fluid inclusion study is the reconstruction of the PTVX properties. The most applied method is microthermometry which, means the observation of individual fluid inclusions on a heating and freezing stage under the microscope at a temperature range of -180°C (i.e. cooling with liquid nitrogen) to +600°C. After complete freezing (solidification) the inclusions are carefully warmed or heated and any observable phase change up to total homogenization (one-phase state) is recorded. Initial melting of any solid phase permits the identification of the involved aqueous and also gaseous systems (H2O-NaCl, H2O-CO2, CO2-CH4, etc.). Final melting temperatures (or temperatures of dissolution) point to the concentration of individual components in the corresponding system. The freezing-point depression of ice in aqueous inclusions, for example, is a measure of the total salt concentration (salinity), which is commonly expressed as weight percent NaCl equivalent. The temperature of total homogenization of an inclusion defines its density. Furthermore the homogenization temperature means the minimum trapping temperature (Roedder, 1984; Belkin, 1994 etc).
6.2 CRITERIA FOR RECOGNITION OF THE ORIGIN OF FLUID INCLUSIONS

The distinction of various types of inclusions is quite significant in fluid inclusion studies. The main features of different categories of inclusions as given by Roedder (1984) are summarised below.

6.2.1 Primary origin

Fluid inclusions of primary origin usually are found as single crystal with or without evidence of direction of growth or growth zonation. It will occur as a single inclusion (or isolated group) in an otherwise inclusion free crystal. The other notable characteristics include:

- Large size of inclusion(s) relative to enclosing crystal and of equant shape.
- Isolated occurrence of inclusions away from other inclusions.
- Random three-dimensional occurrences of inclusions in crystal.
- Occurrence of daughter minerals of the same type as occurs as solid inclusions in the host crystal or contemporaneous phases.

6.2.1.a Single crystals showing evidence of directional growth

- Occurrence of inclusions along boundary between two different stages of growth.
- Occurrence of inclusions in a growth zone beyond a visible healed crack in earlier growth stage.
• Occurrence of inclusions between boundaries between sub-parallel growth zones.
• Occurrence of inclusions at intersection of growth spirals.
• Occurrence of relatively large, flats inclusions in the core or parallel to external crystal faces.
• Occurrence of inclusion(s) at the intersection of two crystal faces.

6.2.1.b Single crystals showing evidence of growth zonation

• Occurrence of different frequencies or morphologies of fluid inclusions adjacent growth zones.
• Occurrence of planar arrays outlining growth zones (unless parallel to cleavage directions).

6.2.1.c Crystals evidencing growth from heterogeneous or changing fluid

• Occurrence of inclusions with differing contents in adjacent growth layers (e.g. gas inclusions in one layer, liquid and water in another layer etc.
• Occurrence of inclusions containing some growth, medium at points where crystals has overgrown and surrounding adhering globules of an immiscible phase (e.g. oil droplets).
• Occurrence of primary appearing inclusions with "unlikely" growth medium (e.g. Mercury in Chlorite, oil in Fluorite and Calcite etc).
6.2.1.d Host other than single crystal

- Occurrence of inclusions at growth surfaces of non-parallel crystals (these have been often leaked and could be secondary.
- Occurrence of inclusions in polycrystalline hosts.
- Occurrence in non-crystalline hosts.

6.2.2 Secondary origin

The major criteria for the identification of secondary inclusions are:

- Occurrence of inclusions in planer groups along planes those cross cut crystals or that parallel cleavages.
- Occurrence of very thin, flat and obviously "necking-down" inclusions.
- Occurrence of primary inclusions with filling representative of secondary conditions.
- Occurrence of inclusions along a healed fracture.
- Occurrence of empty inclusions in portions of crystals where all other inclusions are filled.
- Occurrence of inclusions that exhibit much lower (or more rarely, much higher) filling temperature than adjacent inclusions.

6.2.3 Pseudo-secondary origin

- Occurrences of secondary like inclusions with a fracture visibly terminating within a crystal.
• Occurrence of equant and negative crystal shaped inclusions.
• Occurrence of inclusions in each pit crosscutting growth zones.

6.3 CHANGES IN FLUID INCLUSION SINCE TRAPPING

Most fluid inclusions will be trapped as a homogeneous fluid at elevated temperatures and pressures. During the subsequent cooling, the fluid may have separated into liquid and vapour, because the fluid contracts much more than the solid host mineral. Immiscible fluids may separate on cooling, and daughter crystals, usually halite or sylvite, may precipitate as saturation of fluid occurs. Many inclusions do not now have the shape they originally had because of solution and deposition in different parts of the inclusion cavity. In general, inclusions will tend, by solution and re-deposition, to reduce surface area to become more equant. Through this process, elongated inclusions may separate into several more equant inclusions as a result of "necking down". If the necking down occurs after biphase separation, the process may isolate the vapour bubble in one of the new inclusions while leaving another new inclusion completely fluid filled. As a result, neither inclusion would be representative of the originally trapped fluid, nor the information that could be derived accurate. Larger flat primary inclusions or secondary cracks may undergo considerable recrystallisation in which one large inclusion is reduced to many small ones occupying the same region within the crystal. Leakage, the movement of material in or out of the original inclusion, can occur but is not that common; one exception may be high grade metamorphism in which recrystallisation
can markedly alter inclusions. It is evident, however, when one observes planes containing large number of inclusions, all of which are empty. Generally, quartz, fluorite, calcite and sphalerite are free from leakage problems; barite and gypsum are more prone to such problems.

6.4 COMPOSITION OF FLUID INCLUSIONS

By far the most abundant type of fluid inclusion is that which contains a low viscosity liquid and a smaller volume of gas or vapour bubble. The liquid is generally aqueous has a pH within one unit of neutral, and contains a total salt concentration between 0 and 40 weight percent. The salts contain major amounts of Na⁺, K⁺, Ca²⁺, Mg²⁺, Cl⁻ and SO₄²⁻ ions, with minor amount of Li⁺, Al³⁺, BO₃³⁻, H₄SiO₄, and bicarbonate and carbonate ions. Na and Cl ions are usually dominant. CO₂ in both liquid and gas form and liquid hydrocarbon are fairly common. Liquid hydrogen sulphide has also been observed, but is rare. Carbon dioxide occurs as a supercritical fluid above 31°C, its critical point. Daughter minerals, usually cubes of halite or sylvite form when nearly saturated fluids cool from the initial temperature of entrapment. Other crystals that are observed but are not simple precipitates of a supersaturated solution include sulphides, quartz, anhydrite, calcite, hematite and gypsum. Such crystals either form before the inclusion was finally sealed, as a result of secondarily introduced fluids or even through oxidation resulting from hydrogen diffusion (Roedder, 1979).
6.5 FLUIDS IN METAMORPHIC ROCKS

Studies on the genesis, composition and petrological relationship of the inclusive fluids in the metamorphic minerals have become one of the most active fields of research in metamorphic petrology. Fluid phase plays an essential role in metamorphic rock forming processes (Touret, 2001). Element transport, kinetics of crystal growth etc are some among them. But a good amount of complexity and difficulties are employed in the study of this fluid-mineral interaction. Therefore most of the workers are doubtful on the reliability of this study. This attitude is not justified since fluid inclusions are the part of the rock and they occupy as almost the same volume of the accessory minerals present in a rock. Studies on fluid inclusion in rocks of different metamorphic grade shows that there is a consistent relation of composition of fluids found in inclusion to the metamorphic conditions and the variation will be only according to the difference in grade (Crawford, 1981; Touret, 1981; Roedder, 1984; Crawford and Hollister, 1986). In a host mineral, the inclusions behave as closed volumes and during its path to exhumation in a definite P-T trajectory it maintains ‘isochoric behaviour’ (Touret, 1992). So in high-grade metamorphic rocks all most all the generation fluids are well preserved rather than in low-grade rocks which makes the studies much easier. (Touret, 2001; Frezzotti et. al., 2004).

6.6 ANALYTICAL PROCEDURES

The conventional fluid inclusion analysis includes three major steps ie., the observation, measurements and interpretation. Observation usually focuses on the identification and the determination of relative chronology of
major inclusion types using a petrological microscope. The measurements are made usually by non-destructive microthermometric analysis to specify the composition and density of different fluid types. The interpretation part is based on the P-T conditions of metamorphism and the fluid inclusion isochores.

6.6.1 Optical examination of fluid inclusion

Fluid inclusions are best seen and studied in cut mineral plates that are thick enough to contain the undamaged inclusion, but thin enough to readily transmit light and are doubly polished to minimize the interference of the sample imperfections and excessive diffuse light scattering. For most samples 1-1.5 mm thickness is quite satisfactory. The samples are then polished and reduced in thickness on the lapping machine using 80 mesh and 220 mesh carborundum powder in succession. After this, polishing is carried out on a glass plate using carborundum powder of 400, 600, 800, 1000 and 2000 mesh sizes respectively. Polishing using chromium oxide on the canvas cloth follows this. The final polishing is done on a satin cloth. The inclusions vary in size between 10 microns- 40 microns and a large variety of geometrical sizes were observed as perfectly rounded, tubular, rectangular, cubical, triangular and ellipsoidal. The inclusions very largely in size and can mostly be seen with a 50X magnification.

A surprising amount of data can be obtained on the physical and chemical properties of fluid inclusions using simple optical examination. One of the most important parameters is the overall density of the inclusion at the time of trapping. The density estimate can then be utilized to define
an approximate P-T isochore and thereby calculate the minimum trapping
temperature. The \( \text{CO}_2: \text{H}_2\text{O} \) ratios in inclusions containing immiscible \( \text{CO}_2 \)
rich liquid aqueous solution can also be determined from phase ratios and
the partial homogenization temperature of the \( \text{CO}_2 \) phase.

### 6.6.2 Degree of fill (F) and calculation of overall density

The degree of fill (F) is defined as the volumetric proportion of liquid
\( V_L \) relative to the total volume of the inclusion \( V_{TOT} \).

\[
F = \frac{V_L}{V_L + V_V}, \text{ where } V_V + V_L = V_{TOT}
\]

F is related to the total density of the inclusion \( D_{TOT} \) by the following
expression:

\[
D_{TOT} = D_L F + D_V (1-F)
\]

Where, \( D_L = \) density of the liquid phase, \( D_V = \) density of the vapour
phase

In most cases it can be assumed that the density of the vapour
phase is zero.

Thus, \( D_{TOT} = D_L F \)

The value of \( D_L \) for a salt solution varies linearly as the salt
concentration.

### 6.6.3 Estimation of phase proportions

Fluid inclusion volumes are relatively easy to estimate if the
inclusions have a regular geometrical shape. Measurements of various
dimensions in the plane of focus of the microscope are easily made with a
calibrated, graduated ocular, and reasonable estimates also made of the
depth dimensions of the inclusions. Bubble diameters fix the volume of the
vapour bubble (provided it is free to move and is not flattened) enabling the
V_L and V_V to be calculated. Appropriate measurements for the solid phase
allow V_s to be calculated. The procedure is even more straightforward if the
inclusions are very flat since the assumption that “area=volume” is valid.

6.7 FLUID INCLUSION STUDIES IN THE MGB

Previous works on the fluid inclusions in the metamorphic rocks of
the SGT include Santosh and Tsunogae (2003), Mohan et al. (1996a),
Santosh (1991), Santosh et al. (1991), Santosh (1986a) etc from the MGB;
some studies from the adjacent Kerala Kondalite Belt by Nandakumar and
Harley (2000), Santosh (1986b); Raith et al. (1990), Srikantappa and others
(1992) from Nilgiri granulites; and Satish-Kumar et al. (2001), about the
fluid rock interactions in Ambasamudram area in the ACS.

Even though several studies are there on the fluids of the SGT in
general, it is intricate to portray the complete picture about the types of
fluids found in the different rocks of the terrain, the MGB in specific. But in
garnet free terrains like the MGB, where the PT calculation, especially the
palaeopressure calculations are difficult using the conventional methods of
EPMA fluid inclusion studies is an effective tool. Santosh (1998) studied the
fluid inclusion in the massive charnockites of the MGB and has found that
pure CO_2 with uniform densities was the ambient fluid species during peak
metamorphic time.

There are many other studies also concentrating on the carbonic
inclusions and their role in the charnockiization processes. Mohan et al.
(1996a) studied quartz from the charnockites of Kodaikanal massif and has
reported three fluid inclusion types: (1) monophase high density CO$_2$-rich (0.968–1.014 g/cm$^3$) as the dominant fluid phase; (2) aqueous biphasic CO$_2$-H$_2$O (0.888–0.915 g/cm$^3$) and (3) late minor aqueous H$_2$O inclusions with no visible CO$_2$. CO$_2$-isochores for the high density fluid inclusions yield a pressure limit of ca. 6.5 kb, at granulite facies temperatures of ca. 800°C, which is in accordance with the estimation from mineralogical thermobarometry. The P-T path delineated from combined mineralogical and density data on carbonic inclusions is characteristically T-convex suggesting an isothermal decompression path and rapid uplift followed by cooling of a tectonically thickened crust. Recently, Sukumaran et al. (2005) in his study on the fluid inclusions from different rock types of Palghat brought out three generations of fluid inclusions viz., CO$_2$, CO$_2$-H$_2$O, and CO$_2$-H$_2$O-NaCl. The CO$_2$ inclusions are of variable densities between 1.03 g/cm$^3$ and 0.71 g/cm$^3$ and it is stated that the inclusions were trapped at different stages of high-grade metamorphism. From the Trivandrum Block (TB), Fonarev et al. (2003) has also identified three generations of CO$_2$ bearing inclusions among which one is a high-density species (1.041-1.012 g/cm$^3$). Relatively fewer amounts of aqueous inclusions and their low salinity are pointed out there to rule out any metasomatic processes involved in charnockite formation. However the three generations of CO$_2$ rich inclusions are very much common in the charnockites and associated rocks in and around the MGB. Thus the presence of CO$_2$ bearing inclusions and its role in high-grade metamorphism and charnockite building processes is the unique feature in all the studies carried out so far. High-
density carbonic fluids, which corresponds to the peak metamorphic time is reported in most of the studies.

6.8 PRESENT STUDY

Though the earlier fluid inclusion studies of the charnockites from the MGB of the SGT have given evidences for the involvement of CO$_2$ fluid in charnockite making process no much study has been carried out to know the relation of CO$_2$ influx and the graphite mineralization in the area. Some of this graphite is found to be giving the signatures of fluid origin (see Chapter V). So a detailed study on the influence of CO$_2$ influx in graphite mineralization is of much importance. From the studies on the mineralogical characteristics of the graphite, it has been noticed that these graphites are having a crystallization temperature of 700±100°C (see Chapter V). So the present study is aimed at finding out the temperature of entrapment of the CO$_2$ inclusions in the graphite bearing rocks and to discuss the role of CO$_2$ in graphite genesis.

6.8.1 Sample locations

Fluid inclusions were studied from the charnockites of eleven localities in the southern part of the MGB (Fig 6.1). These localities are Valavoor (Sample Nos: G4, CK108), Punchavayal (Sample No: G5), Kannimala (Sample No: G6), Muvattupuzha (Sample No: CK6B), Mamala (Sample No: CK57G), Erumeli (Sample No: CK42), Kanjiramattom (Sample No: CK73), Manjamattom (Sample No: CK109), Supplapuram (Sample No: CT122) and Muthukudi (Sample No: CT125). Most of the samples selected for the study are graphite bearing. In some samples graphite is not visible.
Fig. 6.1 Sample locations of fluid inclusion studies
megascopically but it is found in the weathered equivalent of the rock (laterite) in the area. Details about the sample location and the rock types are given in table 6.2.

6.8.2 Fluid inclusion petrography

Fluid inclusions may occur in almost all minerals but in metamorphic rocks fluid inclusions are present mostly in quartz or calcite. More than 90% of fluid inclusion studies of metamorphic rocks were carried out in the inclusions from quartz since it is a principal phase of the peak metamorphic assemblage with high viability for heating freezing experiments. The absence of cleavage and the ability of easy re-crystallization make quartz to preserve the fluid inclusions and so the possibility of decrepitation of the inclusions at the time of the experiments is comparatively less (Van den Kerkhof and Hein, 2001; Van den Kerkhof and Thiery, 2001; Touret, 2001). Thus quartz rich samples were selected in this study. The fluid inclusion petrography of the samples is observed at a room temperature of 26-28°C. The most common type of fluid inclusions is monophase gas rich which are inferred to be of CO$_2$. These inclusions are found as solitary negative crystal type inclusions or in isolated groups, which can be considered of primary origin, compared to those occurring as arrays along healed or fresh fractures (pseudosecondary and secondary). Biphase liquid/gas rich and polyphase inclusions of vapour + liquid + halite are also noticed as pseudosecondary or secondary type. Some melt inclusions are also noticed in some of the samples. Brief description of the samples from the eleven localities studied and the nature of inclusions seen in them are given below.
**Table 6.2. Details of the location and the major rock types present there from which the samples for fluid inclusion studies are taken**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Location / Place Name</th>
<th>Rock types in the location</th>
</tr>
</thead>
<tbody>
<tr>
<td>G4</td>
<td>Uzhavoor (Kerala)</td>
<td>Massive charnockite, Garnet biotite gneiss</td>
</tr>
<tr>
<td>G5</td>
<td>Punchavayal (Kerala)</td>
<td>Massive charnockite</td>
</tr>
<tr>
<td>G6</td>
<td>Mundakayam (Kerala)</td>
<td>Massive charnockite</td>
</tr>
<tr>
<td>6B</td>
<td>Muvattupuzha (Kerala)</td>
<td>Mafic medium grained charnockite</td>
</tr>
<tr>
<td>57G</td>
<td>Mamala (Kerala)</td>
<td>Massive charnockite</td>
</tr>
<tr>
<td>42</td>
<td>Erumeli (Kerala)</td>
<td>Massive charnockite</td>
</tr>
<tr>
<td>73</td>
<td>Kanjiramattam (Kerala)</td>
<td>Massive charnockite</td>
</tr>
<tr>
<td>108</td>
<td>Valavoor (Kerala)</td>
<td>Massive charnockite</td>
</tr>
<tr>
<td>109</td>
<td>Manjamattom (Kerala)</td>
<td>Mafic massive charnockite</td>
</tr>
<tr>
<td>122</td>
<td>Supplapuram (Tamil Nadu)</td>
<td>Charnockite, Garnet biotite gneiss, Pegmatites</td>
</tr>
<tr>
<td>125</td>
<td>Muthukudi (Tamil Nadu)</td>
<td>Charnockite, Garnet biotite gneiss</td>
</tr>
</tbody>
</table>
Two samples are studied from the Valavoor due to the heterogeneity observed in the rock types from adjacent quarries. In the location at Valavoor-1 (V1), the major rock type present is massive charnockite, which has been retrogressed to form garnet-biotite gneiss at several places. The presence of pegmatitic veins intruded in zigzag manner all over the charnockites gives some evidence for the cause of the retrogression. Graphite is found syngenetic to the pegmatites and gneisses. The sample for the fluid inclusion study is taken from the charnockite-gneiss contact zone.

Monophase, biphase as well as polyphase inclusions are present in the sample G4B. Monophase inclusions of variable dimensions and cavity shapes are found in isolated groups or as single inclusions, which can be considered as older generation fluids. These are but comparatively less in number and measure up to 20 micron size (Plate 6.1a). Most of the biphase inclusions appear to be secondary or pseudosecondary. These are occurring as trails trapped in fractures that developed after the initial crystallization of the mineral grains in which they are found. Many of the trails occur entirely in the interior of the grains and do not extend to the grain boundaries. However fluid inclusion arrays crossing the grain boundaries are never noticed. The secondary/pseudosecondary biphase inclusions are found very much distorted and leaked indicating post inclusion deformations in the rock (Plate 6.1b).

Valavoor-2 (V2) is a massive charnockite quarry, which is near to V1, but the retrogressive character noticed at V1 is not found in this exposure. Graphite is also absent here. The fluid inclusion petrography also
PLATE 6.1a Monophase inclusions of variable dimensions and cavity shapes from sample G4B

PLATE 6.1b Pseudosecondary biphase inclusions from sample G4B showing leakage/distortion
shows noticeable difference. In the sample (CK108), isolated monophase inclusions, which can be considered as the first generation fluid inclusion is seen in very less amount but are, found post trapped to the melt inclusions. Monophase inclusions of pseudo secondary type i.e., found along arrays can be considered to be the next generation. Biphase inclusions are also found to be of this generation but are comparatively less in number.

Punchavayal location is massive charnockite quarry where specks of graphite are found as accessory mineral (Sample No. G5). The first generation fluid inclusions found here are the isolated negative crystal type monophase CO\textsubscript{2} rich inclusions, the composition of which is confirmed by microthermometry. The second-generation inclusions include both monophase as well as biphase. The biphase inclusions are of CO\textsubscript{2} + H\textsubscript{2}O components.

Kannimala is a roadside quarry in Mundakkayam-Erumeli road. The rock type is massive charnockite. Specks of graphite are found associated with biotites in the rock. Similar to the above said locations here also the monophase CO\textsubscript{2} bearing inclusions are found in isolated groups or as single negative crystals which forms the older generation, followed by arrays of monophase as well as biphase inclusions along healed micro fractures. Biphase inclusions alone found along some fresh fractures, and may be of a different generation.

From Muvattupuzha quarry, samples selected are from a migmatitic body associated with charnockite (CK6B). Large amount of biotites are found in the charnockite giving it a dark appearance. Migmatitic texture is within the charnockite characterised by alternating quartzo-feldspathic...
bands. Quartz veins of few centimetre widths are traversing all over the rock body.

The monophase fluid inclusions found are inferred to be of comparatively older whereas the biphase inclusions (CO$_2$ + H$_2$O) and (CO$_2$ gas + CO$_2$ liquid + H$_2$O) bearing polyphase inclusions are also noticed as younger generation.

Medium grained charnockite (CK42) collected from Erumeli for the fluid inclusion studies only bear rare amount of isolated monophase inclusions but rich in pseudosecondary/secondary biphase inclusions. Presence of polyphase inclusions or triple phase inclusions (liquid + gas + solid) is a peculiarity observed in the sample. The solid phase is identified as halite.

Mamala is an extensive charnockite hillock covering >1km$^2$ showing much heterogeneity in the mineral assemblage at its different parts. Generally speaking the charnockite is massive in nature affected by a series of E-W trending vertical faults. The fault plains are characterised with considerable amount of mylonites and pseudotachylites. The presence of garnet, cordierite and thin flakes of graphite are noticed in some parts of the rock. Fluid inclusion wafers prepared for analysis are from less deformed part (CK57G). Isolated monophase inclusions are rarely found in the samples, but those which noticed are of secondary/pseudosecondary origin which appeared like "rain droplets" (Plate 6.2).

Mafic charnockite (CK73) from Kanjiramattom is characterised with both monophase and biphase fluid inclusions. The first generation monophase inclusions (the isolated ones seen in other locations) are not
Plate 6.2 Array of monophase fluid inclusions from CK57G

Plate 6.3 Biphasic leaked inclusions from sample CK.73
visible in the sample. Pseudosecondary type monophase inclusions along linear arrays are seen. Biphase inclusions are also found to be of this generation, and most of them are CO$_2$ rich showing leakage of the second phase (Plate 6.3). This leaked phase is believed to be of H$_2$O composition.

Manjamattom, which is also a massive charnockite exposure (CK109) near to Kanjiramattom is characterised mostly by biphase pseudosecondary/secondary type fluid inclusions. Monophase inclusions are hardly seen.

Supplapuram and Muthukudi are two locations from Tamil Nadu. Major rock type found at Supplapuram is charnockite in contact with garnet-biotite gneiss. The gneiss is formed as a retrogressive counterpart of the charnockite. Flakes of graphite are very much visible along the foliation planes of the gneiss whereas in charnockite the graphites are found isolated or disseminated. Pegmatite veins of 5-10cm width have intruded the charnockite in a zigzag pattern. Fluid inclusions of the charnockite were studied (CT122). Primary monophase inclusions are rarely seen. Many arrays of secondary/pseudosecondary monophase inclusions are available. In this category biphase inclusions are less in number.

Muthukudi is a large hillock composed of garnet-biotite gneiss within which small patches of charnockite are seen. The charnockites developed, gives arrested nature (Incipient charnockite). The inclusions found in the sample CT125 are mostly CO$_2$ rich monophase and are found in quartz as well as garnets. CO$_2$ + H$_2$O biphase inclusions are also found common (Plate 6.8) and both appears to be pseudosecondary in nature of almost the same generation. This sample is also devoid of primary type inclusions.
6.8.3 Chronology of the fluid inclusions

From all the samples selected for the fluid inclusion analysis, a general chronology of fluid trapping can be traced out based on fluid inclusion petrography. Even though some generations of fluid inclusions are not visible in some of the samples, may be due to some localized petrological changes, the overall picture can be described as below which can be further substantiated with the help of microthermometric studies (See section 6.9).

Chronologically the fluid inclusions can be grouped into three major generations. They are:

i) Monophase carbonic inclusions with well-developed negative crystal shape seen isolated or in isolated groups in the samples. Based on fluid inclusion petrography this can be considered to be of primary origin (Plate 6.4) but since most of the host rocks are massive in nature and primarily grown minerals generally are not preserved (Van den Kerkhof and Hein, 2001) these inclusions can be termed 'early' or 'first generation'.

ii) Monophase carbonic inclusions of pseudosecondary type (occurring in arrays mostly along healed fractures) (Plate 6.5). This can be considered to be the modified first generation fluid inclusions. Sometimes biphase (CO₂ + H₂O) inclusions are also found as pseudosecondary type, which may be of the same generation due to some heterogeneous trapping, or of
Plate 6.4 First generation monophase inclusions
Plate 6.5 Second-generation pseudosecondary monophase/biphase inclusions
two different generations. Their relative chronology is not clear from the fluid inclusion petrography.

iii) Secondary type (occurring along fractures) biphase \((\text{CO}_2 + \text{H}_2\text{O})\) as well as polyphase \((\text{CO}_2 \text{ liquid} + \text{CO}_2 \text{ gas} + \text{H}_2\text{O} + \text{NaCl})\) inclusions that can be considered to be the last generation fluid inclusions (Plate 6.6).

Other than fluid inclusions rare presence of melt inclusions is noticed in some of the samples and chronologically it appears to be earlier than all the types of fluid inclusions, i.e., the first generation of fluid inclusion, were post entrapped to the melt inclusions.

6.8.4 Microthermometric Investigations

The microthermometric investigations of the samples were carried out on a Linkam TMSG-600 heating-freezing stage \((-196\,\degree\text{C} \text{ to } +600\,\degree\text{C})\) at IIT Bombay (Plate 6.7). The thermal lag of the instrument is noted as \(\pm 1.1\,\degree\text{C}\). Fluid inclusions in quartz alone were investigated. The data obtained from microthermometry, and occasionally volume fraction estimates of the fluid inclusions were evaluated using computer program package FLUIDS-1 (Bakker, 2003) in order to transform melting temperatures, homogenization temperatures and optical volume fraction estimates into bulk compositions and densities.

6.8.4a Freezing stage experiments

The freezing stage experiments conducted in almost all samples in which both monophase and biphase inclusions were studied. From the analysis the presence of \text{CO}_2 is confirmed by measuring the melting
Plate 6.6 Third generation secondary biphase inclusions
Linkam TMSG-600, Heating-Freezing stage attached to a Petrological Microscope

Fluid inclusion lab at IIT Bombay

Plate 6.7
temperature \((T_M)\) of the inclusions. In the given samples the \(T_M\) of CO\(_2\) inclusions ranges between \(-55.7^\circ\text{C}\) to \(-58.5^\circ\text{C}\) (Fig 6.2), which is having slight variation from the triple point temperature, \(-56.6^\circ\text{C}\) of pure CO\(_2\). This indicates that all the analysed monophase inclusions are of near pure CO\(_2\) composition with minor amounts of H\(_2\)O, which may be present wetting the walls of the inclusions. This may also be due to a slight variation in the density caused by some other additional components like CH\(_4\) or N\(_2\) (Touret, 1981). The formation and dissolution of minor amounts of clathrates in some of the inclusions in samples CK6, CK42, CK57G, CK108, CT122 and CT125 during the freezing-heating analysis supports this fact. It is also noted that \(T_M\) (CO\(_2\)) of these clathrate bearing inclusions falls exactly between \(-57.6^\circ\text{C}\) and \(-58.5^\circ\text{C}\). However this contamination is less significant because CO\(_2\) inclusions of \(T_M\) up to \(-58^\circ\text{C}\) contain less than 8 mole percent methane (Burruss, 1981). But there are earlier findings which points that, a very few inclusions are capable of preserving their original density since majority of inclusions re-equilibrate to the changes in P-T conditions during the time of uplift (Sterner and Bodnar, 1989; Hollister, 1988; Bakker and Jensen, 1991) and the lower density inclusions are trapped during the late stage of evolution (Vitik and Bodnar, 1995a).

**6.8.4b Heating stage experiments**

As a liquid CO\(_2\) fluid inclusion cools, a vapour bubble eventually appears and on reheating it will disappear called the temperature of homogenization \((T_H)\). It is generally taken to be the isochore for that inclusion intersects the liquid-vapour boundary curve. In the present
Fig. 6.2 Temperature of melting ($T_M$) of monophase CO$_2$ inclusions
samples the monophase CO\textsubscript{2} inclusions are homogenising within a range of +9.4°C to +20.1°C and the CO\textsubscript{2} in the mixed carbonic aqueous inclusions are homogenising into a liquid phase at comparatively higher temperature (+21.7°C to +31°C) obviously due to low density (Fig 6.3). An example for a mixed CO\textsubscript{2} Liquid+ CO\textsubscript{2} Vapour + H\textsubscript{2}O inclusion (from sample CK 73) while freezing from room temperature (26.8°C) to -184°C and then heating up to the complete homogenisation temperature of 349°C is illustrated in Plate 6.8. From the picture the T\textsubscript{M} (CO\textsubscript{2}) is found at -56.7°C and T\textsubscript{H} (CO\textsubscript{2}) vapour bubble at 31°C.

The behaviour of biphase/polyphase inclusions from the samples during the freezing-heating analysis is summarised as below.

**Samples G4B and G5:** The total homogenisation of biphase inclusions from both the samples is to liquid phase. For G4B the total homogenisation temperature (T\textsubscript{H (TOT)}) range between 200°C and 348°C in which majority of the inclusions homogenise between 343 -348°C (Fig 6.4a). Halite crystals are found in some of the inclusions, which are found dissolving at 210.6°C. In sample G5, the T\textsubscript{H (TOT)} is noticed at 380°C.

**Sample G6:** The biphase/polyphase inclusions from sample G6 show a striking peculiarity that they are found homogenising into gaseous state at very high temperature at 800 to 1000°C. Only one or two inclusions are showing the T\textsubscript{H (TOT)} at a nominal range between 340 -380°C (Fig 6.4b). Clathrates are found to be forming at (-15) to (-20)°C and its dissolution at 10 to 12°C.

**Sample CK68:** The T\textsubscript{H (TOT)} of the biphase inclusions from this sample lies between 227 and 289°C. In the case of some polyphase
Fig. 6.3 Temperature of homogenisation ($T_H$) of $CO_2$ in monophase and biphasic inclusions
Plate 6.8 Changes of a biphase inclusion from CK.73 while freezing and heating (see text for details)
inclusions, with halite crystals, the H₂O bubbles are getting homogenized between 289°C and 300°C but the complete homogenization is occurring after the halite dissolution at 400-412°C (Fig 6.4c).

**Sample CK42:** Polyphase inclusions with a solid (halite) phase show TH (H₂O) at 355°C-405°C (Fig 6.4d) homogenizing to both liquid as well as gas phase. The total homogenization is noted at 512 °C after the halite dissolution at 443°C. In some polyphase inclusions the Clathrates are found at (-16)°C and get dissolved at 10°C.

**Sample CK57G:** The biphase gas rich inclusions form this sample are getting totally homogenised after H₂O homogenization at 373 and 395 °C. But a majority of inclusions that are liquid rich in nature are getting homogenised between 147 and 165°C to both gas and liquid phases (Fig 6.4e). The presence of vapour-dominant and liquid-dominant inclusion pairs with similar homogenisation temperature is usually identified in geothermal waters at fluid boiling conditions (Norman et al., 1996, 2001, 2002). So in this sample also it is an evidence for the boiling condition at the time of trapping of the inclusions and the inclusions are suspected to be of geothermal origin. Presence of Clathrate is noticed in some inclusions at (-15)°C and its dissolution at 10.3°C.

**Sample CK108 and CK109:** These samples show almost same type of biphase inclusions. The TH (TOT) from both the locations is noted at a range of between 260 and 380°C (Fig 6.4f). In CK108 clathrate are formed at a temperature of (-18) to (-20)°C and its melting is noted at 8 - 16°C.

**Sample CTN122:** Polyphase inclusions from this sample is characterised by the presence of halite as well as clathrate. While heating,
Fig. 6.4 State of total homogenisation of the inclusions from different samples
clathrate dissolution is noticed at 10°C and halite dissolution at 564°C. The total homogenization is above 600°C.

Sample CTN125: The $T_{H\text{TOT}}$ of biphase inclusions from this sample is at 348-368°C. Clathrate melting temperature is found at 12°C. Halite was not present.

(The data obtained from heating freezing studies are given in Appendix III)

6.8.5 Density of CO$_2$ inclusions

Information on the pressure temperature conditions of formation of any inclusions can be inferred from the density of the fluid trapped. The density is determined by the P-T condition at which the inclusion becomes a closed constant volume system. Thus the density of the fluid can be calculated from the homogenising temperature of the fluid (Crawford and Hollister, 1986).

The density of the monophase CO$_2$ inclusions lies between 0.77g/cc and 0.87g/cc whereas the CO$_2$ in biphase/polyphase inclusions gives a density range of 0.58g/cc-0.75g/cc. The relationship between the homogenisation temperature of CO$_2$ and the density depending on the homogenisation state, put forward by Valakovich and Altunin (1968) as shown in the Fig. 6.5.

6.8.6 Salinity of H$_2$O inclusions

In H$_2$O-NaCl system the compositional difference in inclusions is based on the salinity. For salinities <23.2 wt% NaCl the composition is determined from the ice melting temperature. The H$_2$O containing NaCl up to the eutectic composition of 23.2wt% will show depression in the freezing
Fig. 6.5 Relationship between temperature of homogenisation and density of CO₂ bearing inclusions (after Valakovich and Altunin, 1968)
point. Based on this Bodnar (1993) postulated an equation for salinity calculation,

\[
\text{Salinity (wt\%)} = 0.00 + 1.78\theta - 0.0442\theta^2 + 0.000557\theta^3
\]

(eq: 6.1)

where \(\theta\) is the freezing point depression in degree Celsius. But in the inclusions containing >26.3 wt% NaCl it is very difficult to determine the ice melting temperature and is always confused with the hydrohalite dissolution and the method is rather erroneous. Presence of clathrates also plays a negative effect in deriving the salinity from the melting temperature of ice (Bodnar, 1983). In this case the halite crystal dissolution temperature is more accurate for the salinity calculations (Bodnar and Vityk, 1994). Sterner et al. (1988) determined the solubility of halite under vapour-saturated conditions, which in turn is used to describe the salinity.

i.e., Salinity (wt\%) = 26.242 + 0.4928 \(\Psi\) +1.42 \(\Psi^2\) + 0.223 \(\Psi^3\) + 0.04129 \(\Psi^4\) + 6.295 \times 10^{-3} \(\Psi^5\) - 1.967 \times 10^{-3} \(\Psi^6\) + 1.1112 \times 10^{-4} \(\Psi^7\) (eq:6.2)

where \(\Psi = T(\text{°C})/100\).

The equation is actually the solubility of NaCl in water from the peritectic temperature (0.1°C) to NaCl triple point (801°C). Based on this equation, a standard table of \(T_M\) (halite) vs Salinity (wt\%) has been prepared from which the salinity can be easily extrapolated (Table 6.3).

Theoretically the equation is valid where the homogenisation of the three phases occurs simultaneously (Bodnar and Vityk, 1994) but can also be in a case where the liquid-vapour homogenisation is slightly higher than halite dissolution temperature (Chou, 1987).
Table 6.3 Halite solubility in weight percent as a function of temperature calculated by Sterner et al. (1988)

<table>
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<th>$T_m$ (HALITE)</th>
<th>0</th>
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<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
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<td>26.8</td>
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<td>28.6</td>
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The samples G4B, CK6B, CK42 constitute of halite bearing inclusions. The respective salinity calculated for the inclusions are 32.4 wt%, 48.5 wt% and 52.0 wt%. The steps of halite dissolution in an inclusion from CK42 are illustrated in Plate 6.9.

6.9 INTERPRETATIONS FROM THE FLUID INCLUSION DATA

An interpretation of fluid inclusion data can only be done by comparison with independent P-T estimates derived from co-existing minerals and a precise knowledge on the chronology of inclusions (Touret, 2001). The composition of fluids trapped together with the density data obtained from homogenisation temperatures can be used to construct representative isochores in pressure-temperature space. An inclusion can be trapped anywhere along the isochore, and even high density fluid inclusions are some times trapped at the lower P-T region of the isochore (Fonerav et al., 2003; Santosh et al., 2004).

In the present fluid inclusion study all the samples selected are graphite bearing and the inclusions are compositionally CO$_2$, CO$_2$+H$_2$O,
PLATE 6.9 Dissolution of halite in an inclusion from CK42
CO₂+H₂O+ NaCl, with minor amounts of CH₄. The monophase CO₂ inclusions are considerably pure, sometimes showing decrease in T_M due to the presence of CH₄. The calculated density of the inclusions falls in a nominal range of 0.77-0.87 g/cc. Based on the P-T estimates of the MGB from the present study (see Chapter IV) and the available data from earlier works (Harris et al., 1982; Mohan and Windley, 1993; Ravindrakumar and Chacko, 1994; Mohan et al., 1996b; Prakash, 1999; John et al., 2005) the CO₂ isochores are plotted corresponding to the P-T space (Fig 6.6). The inclusion data evaluated in this study show that the isochores does not satisfy the conditions of synmetamorphic entrapment. The P-T from mineral equilibria can be generalised in such a way that the MGB metamorphism has taken place at temperature between 600°C to 900°C and pressure between 5kb to 9.5kb. Fluid inclusion studies on carbonic fluids in the massive charnockites of Kerala (in which some of the locations are near to the locations of present study) by Santosh (1998) has estimated almost similar P-T conditions for the fluid inclusion entrapment and density of the inclusions is found to be lying between 0.92g/cc -1.10g/cc. In comparison, in the present study it can be noted that density (0.77g/cc - 0.87g/cc) as well as the pressure (2.6kb-5.2kb) derived is considerably low. This type of situation is reported in many studies on CO₂ rich fluid inclusions in high-grade terrains with considerable explanations. For instance, Frezzotti et al. (2004) stated that the degree of preservation of inclusions formed at high P-T conditions (granulites, eclogites) could not always give the same P-T of the formation of host rock. The feeble presence of H₂O, ranging from 10mole% to 36mole% within these inclusions (usually difficult to detect
Fig. 6.6 P-T diagram showing CO$_2$ isochores and proposed fields of inclusions in the present study
optically) can mislead the isochors to higher pressures (Brown and Lamb, 1986; Touret and Hansteen, 1988; Lamb et al., 1991). To compensate this error an addition of 1 to 2 kb pressure can be applied to the calculated CO₂ pressure (Touret, 1987). The removal of water from inclusions by reactions involving hydrous daughter mineral like phlogopite (Touret and Hansteen, 1988) or preferential leaking of water through bulk diffusion or selective diffusion along twin boundaries and dislocations can also account for the above problem (Hall and Sterner, 1993). The effect of retrogressive metamorphism has also its own effect on the inclusions and there is no meaning in expecting the same density of trapping after some retrogressive changes (Vityk and Bodnar, 1995a).

Many such explanations can be attributed for the decrease in density and the calculated pressure of the inclusions in high-grade metamorphic rocks. But a special factor that is to be taken into consideration here is that the present samples are graphite bearing. The presence of graphite adds an important constraint on the thermodynamic behaviour of petrologic systems and indicates that in many cases metamorphic fluids are graphite saturated during both their generation and evolution, and at the times of their trapping as fluid inclusions (Cesare, 1995). The precipitation of graphite cause decrease in the fluid inclusion density and as a consequence the isochores extrapolated from the densities do not pass through the pressure temperature conditions at which the inclusion was trapped with pressure under estimates up to 2 kb (Cesare, 1995). For confirming this graphite forming mechanism further studies are needed using Raman spectroscopy to identify the graphite
precipitates within the fluid inclusion and characterizing them isotopically, because it is not visible under an optical microscope (Van den Kerkhof et al., 1991; Wilmart et al., 1991). However the limited range in the density of monophase inclusions and the very high temperature of homogenisation of some of the inclusions favour a model involving graphite precipitation accompanying peak metamorphism from carbonic fluids. This is in agreement with available graphite-crystallinity and stable isotope data on the MGB graphites, which is suggestive of the presence of fluid-derived as well as biogenic graphites in the terrain (see chapter 5). Further the MGB graphites are of high crystallinity indicative of their formation at high temperature (650-800 °C) (see chapter 5). The origin of graphite by any hydrothermal activity can be ruled out because these processes can only give low-crystalline graphite (Pasteris et al., 1986; Pasteris, 1998; Pasteris, 1999). So the graphites formed will be very much along the progressive metamorphism of the terrain along or before the first generation fluid entrapment from multiple sources.

The interpretation of the evolution of the pseudosecondary inclusions described in this study is a difficult issue. The occurrence of CO₂ rich inclusions in granulite was a subject of considerable debate for several decades. The theory of carbonic metamorphism put forward by Newton et al., (1980) is an almost accepted description on the source of CO₂ (Santosh, 1986a & b; Hansen et al., 1984). Several other elucidations were put forward by many workers suggesting a post-metamorphic entrapment, peak metamorphic fluid trapping etc. However the exact picture on the source of CO₂ rich fluids in high-grade metamorphic rocks still remains
controversial that its source is from an external mantle or lower crustal source, or derived internally by the oxidation of graphite or pore fluid release during uplift (Jackson et al., 1988 and the references there in). Cesare et al. (2005) has put forward the reaction producing CO$_2$ melt/fluid by the oxidation of graphite, from biotite bearing rocks during high temperature metamorphism. In the case of biotite bearing rocks where graphite is present the biotites are the only carriers of Fe$^{3+}$ will be get melted as temperature increases leading to iron reduction accompanied by the oxidation of carbon (graphite) producing CO$_2$. The reaction is

$$2\text{Fe}_2\text{O}_3^{(\text{Bi})} + \text{C}^{(\text{Gr})} \Rightarrow 4\text{FeO}^{(\text{Crd}, \text{Grt}, \text{lim}, \text{Opx})} + \text{CO}_2$$ (eq:6.3)

There is a general rule in the case of high grade metamorphic rocks that a partial retrogression of peak metamorphic minerals will correspond to the greatest number of inclusions (Touret, 2001) i.e., in the present study even if the mineral equilibria gives a peak metamorphic temperature around 800°C the most visible inclusions shows much lower temperature. As Touret (2001) states these inclusions do not indicate an external independent source of fluids but only corresponds to the local re-equilibration of fluids (Vry and Brown, 1991) already present even since the pre-metamorphic stage. Re-equilibration of fluid inclusions may occur when the internal pressure of the inclusion is different from the external pressure. This makes the density changes of the fluid within the inclusions due to leaking or the change in volume of the inclusions. The morphology of the inclusions re-equilibrated under conditions of decompression (internal overpressure) or compression (internal underpressure) always differ. Three dimensional array of numerous tiny inclusions and fractures
surrounding a central inclusion, referred to as 'imposition halos' are characteristic of re-equilibration by internal under pressure (Sterner and Bodnar, 1989), whereas the presence of oriented planar arrays of numerous tiny secondary inclusions, termed 'decrepitation clusters', surrounding a central inclusion refers to an internal overpressure re-equilibration (Vityk and Bodnar, 1995b). In the present studied samples the morphology of re-equilibrated inclusions points to internal overpressure experience. Star like appearance of aqueous inclusions are indicative of this (Plate 6.10). A fluid inclusion study on enderbitic granulites from Bamble, Norway by Van den Kerkhof et al. (1994) describes a similar situation in which different densities of carbonic inclusions were noted at different parts of apparently homogeneous rock, which is interpreted as a result of local re-equilibration. It is concluded that only one inclusion out of 800 randomly selected inclusions is possibly of granulite facies, whereas the others were modified during subsequent stages of uplift and retrogression (Vitik and Bodnar, 1995a; Van den Kerkhof and Hein, 2001).

The presence of melt-inclusions points to the role of certain magmatic activity in the evolution of the host rock. Since the melt inclusions are pre-genetic to the fluid inclusions, it can be concluded that the carbonic metamorphism has taken place later to the melt activity. The youngest generation biphase/polyphase inclusion identified in the samples illustrate a late stage hydrothermal activity and the CO$_2$ densities from these CO$_2$+H$_2$O inclusions are comparatively low (0.58 -0.75 g/cc) which reveal that it is originated at a lower temperature. In the field it is noted that the charnockites of the present study are seen retrogressed to
Plate 6.10 'Star' like appearance of aqueous inclusions indicating re-equilibration due to internal over pressure in the inclusions
biotite/hornblende-bearing gneisses at places controlled by fractures associated with pegmatitic veins and/or quartz veins. The presence of halites in this generation of inclusions points to an influx of some saline brine at the time of the retrogressive mechanism. Similarly the simultaneous occurrence of vapour-dominant and liquid-dominant inclusion pairs with similar homogenisation temperature denotes the fluid boiling conditions (Norman et al., 1996, 2001, 2002). So in this sample it is also evident that the inclusions are of geothermal origin. Presence clathrates and its dissolution have been identified in many samples like G6, CK42, 57G, CK108, CK109 and CTN125. The high salinity of these inclusions is confirmed and it is calculated as 32.4 wt% - 52.0 wt% NaCl equivalent. A wide range of salinity can be expected as the increase in metamorphic grade with the highest levels tracking halite saturation (Yardley and Graham, 2002). The high fluid salinities can some times result from retrograde dehydration reactions in fluid-starved crystalline rocks (Bennett and Barker 1992; Yardley and Valley 1997). Thus the very high values of salinity can be attributed to such process.

The interaction of brine fluids and graphite can produce CO$_2$-CH$_4$ rich fluids (Vapnik, et al. 2002). The immiscible nature of brine and carbonic fluids, which can persist together, even at very high magmatic temperatures (Shmulovich et al. 1994), gives the explanation for the coexistence of CO$_2$ inclusions and NaCl-CaCl$_2$-H$_2$O high salinity inclusions in same trails. However, as the source and chronology of the brine in relation to the host rock is not well established, it is difficult to discuss these aspects further.
6.10 CONCLUDING REMARKS

- The analysis of the fluid inclusions reveals the presence of three sets of fluid inclusions representing three important stages in the evolution of the terrain.
- The first generation is the monophase CO$_2$ inclusions the composition of which is confirmed by freezing studies.
- Since the mineral equilibria based P-T estimates are much higher and the isochores of inclusions from the present study do not represent such a high P-T it can be inferred that none of the inclusions represent the peak metamorphic regime.
- Though petrographically they may be considered as primary fluid inclusions they do not represent a peak metamorphic entrapment owing to their lower density compared to the synmetamorphic high-density inclusions recorded elsewhere from the granulite-facies rocks from the SGT.
- The decrease in the density observed and the lower pressure estimates are interpreted to be due to the graphite precipitation from the fluids.
- An intermediate generation of pseudosecondary type biphase/monophase inclusions are the result of re-equilibration or modification of the first generation fluids.
- The total homogenisation temperature of more than 1000°C and the presence of melt inclusions points to a magmatic affinity for at least some of the inclusions.
• The youngest generation of fluids that caused the retrogression is low temperature (homogenising around 350 °C) high saline brine that has interacted with graphite to release CO\textsubscript{2} and this appears to be geothermal fluid.