

# Physical approach to the problem of origin of charnockitic rocks of southern India: Mechanisms of crustal heating and transfer of carbon dioxide

A. O. Gliko

Institute of Physics of the Earth, Academy of Sciences of Russia, Moscow, Russia

R. N. Singh and P. S. Swathi

Center for Mathematical Modeling and Computer Simulation, Bangalore, India

## 1. Introduction

Origin of charnockites/granulites is one of the most fashionable and important problems in Earth's sciences. It has a key significance for understanding the nature of the lower continental crust and creates one of the most active fields of present day research. Really, the deep continental crust all over the world includes within it a close association of charnockitic granulites and metasediments of Archean – Proterozoic age. As a result of extensive uplift and erosion, parts of the former deep crust are exposed now in some places on old cratons (such as granulite terranes of Canadian, Baltic and Guyana shields). But only in the southern India and nowhere else a continuous cross-section through the middle to the lower crust is available for studying the processes operating over the full thickness of the continental crust. The practical importance of this problem is determined by the fact of close association of gold mineralization with fluid transport during formation of charnockites, and really, many gold-rich bearings are found in charnockitic terranes. Although there is a long history of studies and a large number of publication on this subject, including several outstanding monographs and reviews, the problem of origin of charnockitic rocks is still far from the solution and different points of view on their origin are discussed by petrologists. In our opinion, the verifying of these hypotheses based on the petrological and geochemical data could be done only by studying of physical aspects of charnockites formation (modelling of the thermal processes in the crust and mechanisms of fluid heat and mass transfer during the charnockitization). Here we make a first step in such a testing, based on the best and most comprehensive set

of data available now only for the charnockites of the southern India and using the mathematical modelling as a main research instrument.

## 2. Petrological Constraints and Qualitative Hypotheses.

The charnockite assemblages include orthopyroxene, orthoclase (the characteristic mineral association for this type of rocks), clinopyroxene and some of the following minerals – plagioclase, hornblende, quartz, garnet, biotite and other accessory minerals such as ilmenite, magnetite, zircon. The chemical composition of charnockites can be represented by the following system of oxides:  $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-FeO-MgO-K}_2\text{O-Na}_2\text{O-Ti}_2\text{O-H}_2\text{O}$ .

Charnockite/granulite belt of the Southern India being one of the largest granulitic provinces in the world occupies the extended parts of Karnataka, Tamil-Nadu and Kerala, bounding from the south the gneisses and metasediments of the oldest tectonic unit of the Indian shield – the Dharwar craton. In accordance to the isotopic dating, most of the charnockites from this region were formed in the late Archaen time 2500–2700 Ma. Only charnockites of Kerala are interpreted to be younger and correspondingly cover the time span 1930–540 Ma, according to U-Pd data [*Srikantappa et al.*, 1985]. It is important that the age determinations obtained by the use of different isotope methods are very close. For instance, the age of charnockites from the area near Chennai is determined as  $2555 \pm 140$  Ma by use of Sm-Nd method and as  $2563 \pm 65$  by use of Rb-Sr isotopes ratio [*Bernard-Griffiths et al.*, 1987].

*Pichamuthu* [1954] was the first who proposed the formation of earlier group of charnockites by regional metamorphism of pre-existing Peninsular gneisses and Dharwar schists. Now the metamorphic nature of charnockites is widely recognised on the base of strong geochemical and petrological evidences. The particular signif-

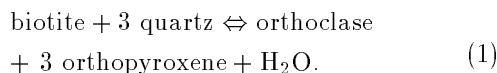
---

©1999 Russian Journal of Earth Sciences.

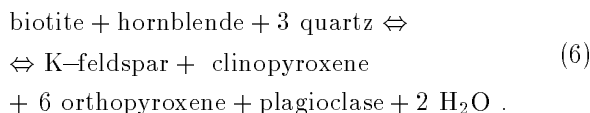
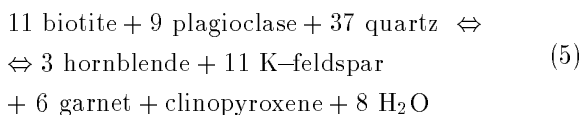
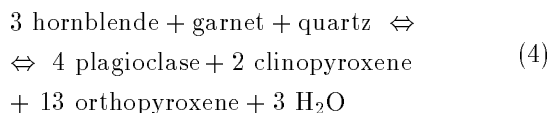
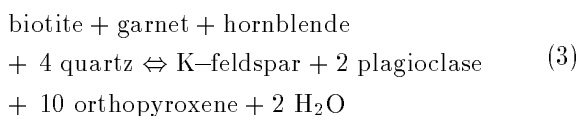
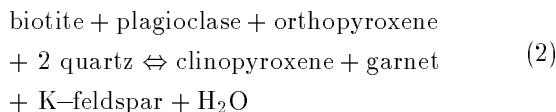
Paper No. TJE99019.

Online version of this paper was published on August 20, 1999.  
URL: <http://eos.wdcb.rssi.ru/tjes/TJE99019/TJE99019.htm>

icance has the fact of near identical chemical composition of charnockites and the old grey gneisses of the Dharwar craton [Ravindra Kumar *et al.*, 1993]. The formations of the Dharwar and more broadly of almost all the Central cratonic region including gneisses, granites as well as large sequences of metasedimentary and metavolcanic rocks are metamorphosed in the greenschist – lower amphibolite facies. The transitional zone between the craton and charnockite/granulite province is of 30–60 km wide and is characterised by the progressive increase of metamorphic grade approximately from the north to the south up to the granulite facies. This spectacular geological phenomenon provides a possibility to study “the arrested charnockites formation” – continuous transition from incipient to massive charnockites [Hansen *et al.*, 1987; Newton, 1988]. The mineral reactions leading to the formation of charnockites are these creating orthopyroxene and/or orthoclase (K-rich feldspar) instead of biotite, hornblende and quartz. The most important reaction creating both the characteristic minerals of charnockites – orthopyroxene and orthoclase and called the “charnockite reaction” is



Other reactions which could be involved in the formation of charnockites are the following [Mueller and Saxena, 1977]



From these five reactions the last one is the most important because it includes as the reactants only miner-

als certainly presented in the original rock of amphibolite grade (biotite, hornblende and quartz) and produces the minerals which are the most common in charnockites (two pyroxenes, K-feldspar and plagioclase). Reactions (2–4) include as the reactants such minerals as garnet and orthopyroxene. The parent gneisses contain low concentrations of garnet and do not contain orthopyroxene at all. So, these reactions can be considered only as auxiliary. The reaction (5) occurs at the P–T conditions of the upper amphibolite facies ( $T < 700^\circ\text{C}$ ) and has no direct relation to the charnockitization. The peak conditions of metamorphism estimated by use of different kind of geothermometers and geobarometers available for the granulite facies (see for review, for instance, [Mahabaleswar, 1993] are in the range of 700–800°C and 5–8 kbars, but in some places a pressure as high as 10 kbar (Nilgiri Hills) and temperature up to 850°C have been attained (Eastern Ghats). The main problem in the genesis of charnockites is related to very high temperatures attained during their formation. This temperature range is far beyond the melting temperatures of the appropriate silicate systems in the presence of water (600–650°C). The large amount of water certainly had to release during the charnockitization (we see from equation (1) that that formation of 1 mole of orthopyroxene is accompanied by the releasing of 1 mole of H<sub>2</sub>O) would led to the extensive melting and migmatization. However, any traces of such migmatization were found in rocks. Nor incipient charnockites of the transitional zone nor the massive charnockites are associated with migmatites. This fact is the most intriguing and its explanation is the key point of the “charnockite problem”. Another problem concerns the thermal regime of the crust during the formation of charnockites – temperatures as high as 800°C were attained at the depth of 20–30 km (which correspond to the estimated pressures) inside a very broad region of lateral dimension of an order of thousand kilometres. So, if the first question which is addressed is:

- how the high temperatures of the formation of charnockitic rocks can be reconciled with the fact of absence of anatexic melts?,

the second question is:

- how such a high temperatures could be reached at the relatively shallow depths?

The modern view on the first problem is based on the results of experimental studies of mineral reactions and processes of melting in the presence of fluid phase. It is well established that the increasing of the mole fraction of carbon dioxide in the H<sub>2</sub>O–CO<sub>2</sub> fluid suppress the activity of water, increases the melting temperature of silicate system under the given pressure and expands the

stability field of the orthopyroxene-bearing assemblage being in equilibrium with the fluid into the higher temperatures [Philpotts, 1990]. This theoretical suggestion is supported by data on the composition of fluid inclusions in charnockites [Mohan *et al.*, 1996; Santosh, 1988; Santosh *et al.*, 1991; Srikantappa *et al.*, 1992; Touret, 1988] which are very rich in CO<sub>2</sub>. It is remarkable that the CO<sub>2</sub> – isochores for the high density inclusions yield a pressure and temperature range which is in accordance with the estimation from mineralogical thermobarometry. The dominantly carbonic composition of fluids during metamorphism of the charnockitic terranes is recognised now as a fact, although the origin of CO<sub>2</sub>-rich fluid is under discussion. There are several comprehensive reviews of viewpoints on this subject and consequently on the origin of charnockites [Newton, 1988; Radhakrishna, 1993; Radhakrishna *et al.*, 1990]. These views may be classified into the following four groups:

1. CO<sub>2</sub>-rich fluid are considered as a products of decarbonation of crustal limestones and dolomites [Glassley, 1983],
2. CO<sub>2</sub>-rich fluid is proposed to be a deep crustal fluid trapped in the inclusions and released by deformation associated with the metamorphic event [Stahle *et al.*, 1987],
3. the origin of the carbon-dioxide is considered to be related to the processes of exsolution from crystallising deep-crustal or intermediate mafic magma bodies [Touret, 1988] or from low-SiO<sub>2</sub> granites [Srikantappa, 1993],
4. the appearance of CO<sub>2</sub>-rich fluids in the deep and middle crust is attributed to the intensive carbon-dioxide flux from the mantle [Harris *et al.*, 1982; Newton, 1988, 1983; Newton *et al.*, 1980], and CO<sub>2</sub> is considered to be of a mantle origin.

It is remarkable that any of the above hypothesis does not preclude a priori the scenario at which two different mechanisms could interfere. For instance, carbon-dioxide of mantle origin could be transported by alkaline basaltic magmas and exsolved from the crystallising intrusion at the deep-middle crustal level, still carrying its mantle isotopic signature. Only the first hypothesis is no more considered as a reasonable one. Its straightforward version proposing the involving of large masses of crustal limestones or dolomites contrasts with geological observations – nowhere, except granulite terranes of the Sri Lanka, even the traces of such carbonates have been found. The more sophisticated and ingenious variant [Raith *et al.*, 1983] deals with the secondary carbonates originated from the interaction of presumably andesitic or dacitic protoliths with the seawater

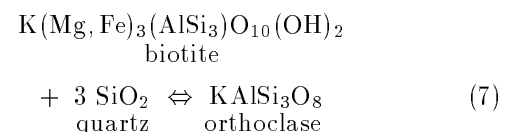
and later undergone progressive decarbonatization during the consequent high-grade metamorphic event. Although such a scenario is not seemed to be impossible one from the physical point of view – certainly if we mean not the infiltration of seawater to the depth of an order of 20–30 km but the shallow subduction of already carbonated rocks – it contradicts the data on oxygen and carbon isotope composition of the fluid inclusions from charnockites [Jackson *et al.*, 1988; Jiang *et al.*, 1988; Stahle *et al.*, 1987] which point out a mantle rather than crustal source of carbon dioxide. This conclusion is strongly supported by the studies of the helium isotope ratio <sup>3</sup>He/<sup>4</sup>He for the high-density carbonic fluid inclusions, which shows the mantle signature [Dunai and Touret, 1993]. Besides this, the amount of carbon dioxide needed for formation of charnockites is far beyond all the reasonable upper limits of productivity of carbonated volcanic rocks.

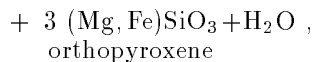
According to our estimate (see below), the minimal amount of CO<sub>2</sub>, required for the formation of charnockites, is approximately 4.98–3.88 wt % for a given metamorphic pile. Interaction of the sea water with andesitic or felsic rocks at the P–T range corresponding to the greenschist metamorphic facies (pressure up to 5 kbar and temperature T – 350–550°C) could lead to the formation of calcite. Decarbonation of 100 g calcite/aragonite (CaCO<sub>3</sub>) which would occur during the higher grade metamorphism at the later stage produces 44 g of CO<sub>2</sub> and 56 g of CaO. Thus, 2–4 wt % of CO<sub>2</sub> could be produced from a pre-metamorphic pile containing 4.4–5.2 wt % of calcite. But the real content of calcite in gneisses, originated from the volcanic rocks of andesitic or felsic composition, does not exceed 0.5 wt % [Dobretsov, 1977], which corresponds to only 0.22 wt % of CO<sub>2</sub>. But even such a rate of sea water alteration is unreasonable to propose for a pile of parent gneisses as thick as 10–20 km.

So, the main conclusion came from the petrological studies is the mantle origin of the carbon dioxide involved in the formation of charnockitic rocks. Now we have a basis for the discussion of the required amount of CO<sub>2</sub> and mechanisms of its transfer to the lower and middle crust.

### 3. Estimation of Required Amount of Carbon Dioxide and Possible Mechanisms of its Transfer in the Lithosphere

We start from the main “charnockite reaction” (1)





producing one mole of water and three mole of orthopyroxene instead of one mole of biotite and 3 mole of quartz. This relationship between mole fractions of orthopyroxene and water can be used for estimation of amount of water released during the formation of charnockite rock of a given composition if it could be argued that most of orthopyroxene has been appeared as a product of reaction (7). Because orthopyroxene could be formed also by reactions (3), (4) and (6), a retrospective analysis is required, and not in any case such an analysis could be done definitely. But upper limit for the amount of the released  $\text{H}_2\text{O}$  can be easily estimated on the base of reaction (7), because it provides the highest mole fraction of water with respect to orthopyroxene –1:3 as well as the reaction (6), when the other reactions give 1:4 and 1:5 (reaction (4) and (3), respectively). The composition of rocks from the St. Thomas Mount, Madras and of similar charnockites from Kerala probably is of the best choose for evaluating the amount of metamorphic water. These rocks contain from 5 to 10% of orthopyroxene as well as 2–15% of hornblende, 2–8% of clinopyroxene, 10–40% of plagioclase, but only a little of quartz and do not bear a primary biotite which is scarce and has the secondary origin [Srikantappa *et al.*, 1985]. The practical absence of biotite and quartz indicates the genetic relationship to the reaction (7). In this case the estimated upper bound for the amount of water released during the high-grade metamorphism would be very close to its real value. From the equation (7) we see that this reaction produces 18 g of water per 332 g of orthopyroxene. Thus, for the metamorphosed rock containing 5–10% of orthopyroxene, the amount of water released in the process of dehydration of parent gneisses would be in the range 0.27–0.54 wt %.

Now we are able to evaluate the minimum amount of  $\text{CO}_2$  required for the formation of charnockites by use the available data on the composition of  $\text{CO}_2$ – $\text{H}_2\text{O}$  fluid phase during metamorphism. In accordance with estimates of *Touret et al.* [1997], the mole fraction of  $\text{H}_2\text{O}$  in the metamorphic fluid have must be lower than 0.3:

$$\frac{X_{\text{H}_2\text{O}}}{X_{\text{H}_2\text{O}} + X_{\text{CO}_2}} \leq 0.3 . \quad (8)$$

It follows from here that the required amount of  $\text{CO}_2$  (in wt % with respect to the bulk of the rock) can be evaluated as  $m = 7.32 p$ , where  $p$  is the amount of water released during the dehydration reaction. It gives  $m = 1.98$ – $3.88$  wt %. So, finally we obtain the following limits for the minimum amount of  $\text{CO}_2$  – 0.99–1.94 wt % , for the charnockite containing consequently, 5 and 10% of orthopyroxene. This is a minimal amount providing

the required decrease of the activity of water, but the larger amounts are not precluded.

The recognising of the mantle origin of  $\text{CO}_2$ -rich fluid involved in the formation of granulites (and in particular charnockites) poses a question of the form in which the carbon dioxide could be stored in the mantle and the problem of its transport to the lower and middle crustal level. The data of experimental petrology show that carbonates such as dolomite and magnesite would be stable phases at the deep mantle conditions although would rarely survive transport to crustal levels [Canil, 1990; Egger, 1976]. Such a survival requires extremely high rates of decompression and sufficiently coarse original aggregates [Ganguly *et al.*, 1995; Ionov *et al.*, 1993]. Thermal disturbances in the mantle associated with the convective instabilities and formation of plumes led to the decomposition of carbonates and creation of carbonate-rich magmas, which under rapid uprising give rise to the nephelinitic volcanism and under some special conditions to carbonatitic lavas flow [Le Bas, 1977]. But retaining in equilibrium with mantle, they can react, crystallise and release  $\text{CO}_2$  vapour at pressures 25–27 kbar, which corresponds to the depth  $\sim 70$  km [Lee and Wyllie, 1998; Wyllie and Huang, 1976]. Some evidences for such a process have been obtained from the study of kimberlites [see Jones and Wyllie, 1985]. There are reasons to propose much more intensive generation and transport of carbonated melts in the Precambrian resulting in the formation of large kimberlitic bodies in the lower lithosphere as it was argued by P. Wyllie. Another indirect evidence comes from the fact that most of the large alkaline complexes are of Proterozoic age. From the other hand, the role and scale of volcanic processes comparing to the igneous activity at the crustal levels was certainly much higher in the Archean time than during the subsequent periods. Beginning from this point we should discriminate two possibilities of carbon dioxide transfer through the lithosphere in the Archean time – first is the transport of  $\text{CO}_2$  in the form of a separate fluid phase (probably mixture of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  with predominance of  $\text{CO}_2$ ), and the second – transport of  $\text{CO}_2$  by uprising nephelinitic or alkaline basaltic magmas partly in the form of solution and partly in the form of inclusions (the solubility of  $\text{CO}_2$  in silicate melts decreases strongly with decreasing of pressure and becomes practically zero at  $P \approx 15$  kbar).

The first variant could be viewed a priori as a buoyancy driven flow in the rigid, elastic or viscous matrix, depending on the rheology of the lithosphere. Ganguly *et al.* [1995] assumed the rock matrix to be rigid and carbon dioxide to be transported in accordance with the D'Arcy theory of filtration. They were able to derive an analytical solution for that model and study quantitatively the possible role of  $\text{CO}_2$  as an agent heating the middle crust up to temperatures corresponding to

the conditions of granulite facies. They showed that the flux of CO<sub>2</sub> required for rising of temperature up to 800°C would be no less than 112.5–180 mol/m<sup>2</sup>·year under condition that such a high flux values are sustained during the period of no less than, correspondingly 35 and 10 Ma. They compared these flux values with the available estimates of the present carbon dioxide outflow from the mantle and in the Archean time with the conclusion that 0.01–2% of the total CO<sub>2</sub> outgassed during the Archean had to be focused through southern India. No attempts have been made on the way to consider the transport of carbon dioxide in the framework of models with elastic or viscous rock matrix although the appropriate mathematical methods are successively used in the modelling of volcanic gases emanation induced by the inflation of magma chamber and also in the study of melts transport in the mantle and metamorphic fluids in the crust (we refer here only to some publications – [Bonafede, 1990; Khodakovskii et al., 1998; McKenzie, 1984; Natale et al., 1998; Spiegelman, 1993a; Wiggins and Spiegelman, 1995]). The models of this kind are free from the difficulties which are related to the variants of magma underplating and give a simple explanation for the observed strong heating of the crust and at the same time the lack of intrusions in the most of the charnockite province of the South India. But the total amount of carbon dioxide required for the rise of temperature up to the granulite facies range, estimated by Ganguly et al. [1995] as  $18 \times 10^{18}$  kg or  $4 \times 10^{20}$  mol for the territory occupied by the south Indian granulites seems to be too high. But the main difficulty of this model comes from the assuming the rigid matrix. Because the driving force for the flows is the buoyancy related to the density difference between the rocks and the carbon dioxide, the pressure in the rock matrix and in the fluid CO<sub>2</sub> phase would be different. The application of the model with the rigid rock matrix is restricted by the requirement that the stresses arising in the matrix are small comparing to the strength of the rocks and the deformations of the matrix are also small enough. But in the case of carbon dioxide transport from the depth of 70 km the pressure difference in the rock matrix and in the fluid phase could be higher than the real strength of rocks. This difference in pressure  $\Delta P$  can be estimated as  $\Delta P = \Delta p g (h_2 - h_1)$ , where  $\Delta p$  is the mean density difference between the rock and CO<sub>2</sub>, and  $h_1$  and  $h_2$  correspond to the crustal level and to the depth from which carbon dioxide start to move as a separate phase. For  $\Delta p \sim 2000$  kg/m<sup>3</sup>,  $h_1 = 20$  km and  $h_2 = 70$  km, we get  $\Delta P \sim 10$  kbar. It means that the model assuming the transport of CO<sub>2</sub> as a separate phase should take into account the rheology of the rock matrix.

The second variant was proposed by several authors, but only on the way of purely qualitative speculation [Harris et al., 1982; Hopgood and Bowes, 1990]. This

scenario is attractive as it provides a simple and natural explanation for the thermal event, but could be not so easy in explaining the lacking of volcanic products contemporary with the charnockites. Another question arises when we look at the possible traces of the magma underplating in the structure of the crust – mantle interface which could be revealed by geophysical methods. The teleseismic tomography infers the relatively low velocity in the crust and upper mantle which is in contrast to the general expectations for higher seismic velocities for the models with underplated layer of basic magma. This is a question of great interest, and we shall discuss it in the end of this paper.

#### 4. Steady-State Thermal Models for the Archean Crust, Pre-Metamorphic Temperature Profiles and Possible Sources of Heating

There are numerous publications concerning the study-state thermal models of the continental crust and especially of the old Precambrian shields [Jessop and Lewis, 1978; Mareschal and West, 1980; Singh and Negi., 1980; West and Mareschal, 1979]. These very simple models predict the temperature distribution in the stable continental crust due to the heat generation in the uppermost felsic crustal layer highly enriched in radiogenic elements and heat flow supplied to the base of the crust from the mantle. The basic equation for such models is

$$\kappa \Delta u + H(x, y, z) = 0. \quad (9)$$

Here  $u(x, y, z)$  is temperature distribution in the crust,  $H(x, y, z)$  – the heat generation by radioactive elements per unit volume. The elementary solution for a one-dimensional problem (this model is good enough in most of the applications, because the lateral variations of radiogenic elements concentrations in the stable crust are small comparing with the vertical trend) looks as

$$u(z) = \frac{q_0}{\kappa} z - \frac{1}{\kappa} \int_0^z \int_0^\beta H(\alpha) d\alpha d\beta. \quad (10)$$

Here  $q_0$  is the surface heat flow density and  $\kappa$  – the thermal conductivity. The surface heat flow density is related to the value of mantle heat flow  $q_m$  by the following expression

$$q_0 = q_m + \int_0^h H(\alpha) d\alpha. \quad (11)$$

Here  $h$  is the thickness of the “radiogenic” layer in the upper crust.

Two types of function  $H(z)$  are usually considered in geothermal applications. The simplest one is equal to constant  $H = H_0 > 0$  at  $z < h$  and zero at larger depths. Another one is the exponential model with the heat generation function  $H(z) = H_0(\exp(-z/D))$ . The last model has the advantage to be more consisted with the ideas of upward concentration of radioactive elements came from the geochemistry. It also provides the validity of the linear relationship between the heat generation of near surface rocks and the heat flow density even during the erosion processes. Under given parameters  $q_m$  and  $H_0$  for the first type of model and  $q_m$ ,  $H_0$  and  $D$  for the last, temperatures at the Moho and at the depths of 30 km represented by the studied charnockites can be easily estimated on the base of (10) and (11). According to *Jessop and Lewis* [1978] and also to *West and Mareschal* [1979] we assume the value  $35 \text{ mW/m}^2$ ; for the mantle heat flow at time 2.5 Ga. Heat production data for the rocks of the Indian shield [*Gupta et al.*, 1991] give the average value  $H = 2.22 \text{ } \mu\text{W/m}^3$  which could be at least as twice as much at the time - 2.5 Ga. *West and Mareschal* [1979] pointed out that really the average heat generation in the high radioactive upper layer at that period could reach even as a high values as  $12 \text{ } \mu\text{W/m}^3$ . In fact, not a value of the heat production of near surface rocks but the integral heat production of the whole high-radioactive layer is important - integral (11) or the product of  $H_0 \cdot h$  for the simplest model. We calculated temperature at the depth 30 km  $T_{in}$ , which is of present interest, for the model with constant heat production in the upper high radioactive layer assuming the thickness of this layer to be equal to 10 km. The value  $2.4 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$  has been taken for the thermal conductivity of crustal rocks. The following values of temperature  $T_{in}$  have been obtained -  $474^\circ\text{C}$  for  $H_0 = 4.2 \text{ } \mu\text{W/m}^3$ ,  $498^\circ\text{C}$  for  $H_0 = 5.8 \text{ } \mu\text{W/m}^3$  and  $544^\circ\text{C}$  for  $H_0 = 8 \text{ } \mu\text{W/m}^3$ . These estimates may be considered as upper bounds because the corresponding temperatures at the Moho (the available geological data and geophysical reasons point out the thickness of the late Archean crust not to differ significantly from the present average 40 km) -  $598^\circ\text{C}$ ,  $623^\circ\text{C}$  and  $669^\circ\text{C}$  - would be very close or even a little higher than the solidus temperature of felsic rocks in the presence of water. For the model with exponential distribution of radiogenic elements, the same values of  $H_0$  and reasonable values of  $D$  the conclusion is the same - the crust at the levels of charnockitization must be heated at least for a  $300^\circ\text{C}$  or even more. Taking into account the width of the charnockitization zones (many kilometers), we can not believe that such a heating could be provided by shear heating. The only reasonable cause in view of recent data can be related to underplating of hot material.

## 5. Mechanism of Viscous Consolidation and Transport of Carbon Dioxide by Non-Linear Porosity Waves

We assume here the viscous rheology for the rock matrix which seems to be a reasonable approximation for the hot subcrustal mantle. A theory of viscous consolidation takes into account flow of the matrix which occurs under the stresses arising from the density difference between the rock matrix and the fluid phase creating an interconnected network. This theory predicts the spreading of non-linear porosity waves transporting the fluid phase to the upper horizons. The geophysical applications of the viscous consolidation theory originated from papers of *McKenzie* [1984], *Richter and McKenzie* [1984] and *Scott and Stevenson* [1984] allow to understand many aspects of magmatism and metamorphism (such as melt uprising and focusing beneath the Mid-Ocean ridges, transport of fluids in metamorphic environment). It is important to keep in mind that this theory does not necessarily infer the mass transfer at the scale of mineral grain which is usually called the pervasive flow, but can be valid in describing the mass transfer at much larger scale. The main requirement is that the spacing between the fluid conduits must be small comparing to the characteristic dimension of the considered domain, so the averaging of equation governing the flow of fluid and matrix could be done. In this sense the consolidation theory might be applied to the study of fluid transfer in the large system with spacing of cracks, say of an order of 10 or 100 m. But at the scale of the distance between the neighbouring conduits, the fluid transport would be seen as a channelized one. The theory of viscous consolidation assumes the rock massif having some initial permeability  $K_0$  (and this is a controversial point in this theory), which changes in the process of consolidation, including the rapid transport of fluid with respect of the much more viscous rock matrix as well as the viscous deformation of matrix itself. As some anomalous region of high porosity arises in the rock massif, it is not able to resist the stresses, and deformation of the matrix spreads upward in form of non-linear porosity waves. In the approximation of a small porosity the dimensionless equations of viscous consolidation theory reduce to the following equation for the porosity or volume concentration of fluid ( $\text{CO}_2$  + some additional species like KCl, NaCl)  $\Phi(x, y, z, t)$

$$\text{div} \left( \Phi^3 \nabla \frac{\partial \Phi}{\partial t} \right) + \frac{\partial \Phi}{\partial t} - \frac{\partial \Phi^3}{\partial z} = 0. \quad (12)$$

The scales for time  $\tau_0$ , length  $l_0$  and hydrodynamic flow velocity  $v_0$  are

$$\tau_0 = \left( \frac{\mu \eta}{K_0} \right)^{1/2} \frac{\Phi_0}{\Delta \rho g}, \quad l_0 = \left( \frac{K \eta}{\mu} \right)^{1/2}, \quad v_0 = \frac{K_0 \Delta \rho g}{\Phi_0 \mu}.$$

Here  $K_0$  is the initial permeability of rock massif,  $\Phi_0$  – the initial permeability,  $\Delta\rho$  – the density difference between the rock and fluid (in our case  $\text{CO}_2$ ),  $g$  – the acceleration of gravity,  $\mu$  – the viscosity of fluid and  $\eta = \eta_s + 4\xi/3$  is the effective viscosity of matrix, where  $\eta_s$  is viscosity of matrix and  $\xi$  – the bulk viscosity responsible for the changing of porosity. This equation has been intensively studied and there are many papers on this subject followed the first publications of *Barcilon and Richter* [1986], *Richter and McKenzie* [1984], and *Scott and Stevenson* [1984, 1986] (for a more comprehensive view we refer to *Spiegelman* [1993a, 1993b]). It predicts the spreading of solitary porosity waves or wave trains depending on the initial conditions. The simplest 1-D non-linear solitary wave solution [*Barcilon and Lovera*, 1989] has the implicit form  $\pm\zeta = F(f, A)$

$$\pm\zeta = \left( A + \frac{1}{2} \right) \left[ -2(A-f)^{1/2} + \frac{1}{(A-1)^{1/2}} \ln \frac{(A-1)^{1/2} - (A-f)^{1/2}}{(A-1)^{1/2} + (A-f)^{1/2}} \right]. \quad (13)$$

Here  $f = \Phi/\Phi_0 = f(\zeta)$  is the normalized distribution of porosity (concentration of  $\text{CO}_2$ ),  $\zeta = z - ct$ , and  $c$  is the wave velocity which is simply related to the amplitude  $A$  of non-linear wave  $c = 2A + l$ . Although it was shown [*Barcilon and Lovera*, 1989; *Khodakovskii et al.*, 1998; *Wiggins and Spiegelman*, 1995] that such a 1-D wave became unstable after some time and evolves to a group of 2- or 3-D wave disturbances, we think that this solution can be used for an estimation of the amount of  $\text{CO}_2$  and rate of its transfer to the base of the crust as well as the related heat effects. The solitary wave arises and spreads upward if the initial distribution of porosity (concentration of  $\text{CO}_2$ ) corresponds to the function

$$\pm z = F(f_0).$$

The fluid flow velocity (the hydrodynamic velocity, not the D'Arcy one) is determined easily in the approximation of low porosity  $\Phi \ll 1$ . From the equation of continuity for a fluid

$$\frac{\partial\Phi}{\partial t} + \frac{\partial}{\partial z}(\Phi v) = 0 \quad (14)$$

we get for  $\Phi = \Phi_0 F(\zeta)$  and  $v = v_0 h(\zeta)$  a simple equation  $-cf' + (fh)' = 0$ . Under condition that  $f \rightarrow 1$  at  $\zeta \rightarrow \infty$  (porosity must approach the undisturbed value  $f = 1$ ) and  $h \rightarrow 1$  (the fluid flow velocity  $v$  must come to the value  $v_0$ , corresponding to the filtration through the matrix with the initial porosity  $\Phi_0$ ) we obtain

$$hf = c(f - 1) + 1, \quad (15)$$

which in dimensional form is seen as

$$c\Phi_0(f - 1) + \Phi_0 = v_0\Phi_0 f v. \quad (16)$$

Now we can estimate the amount of carbon dioxide transported by a solitary wave by the integration

$$M = \int_{-\infty}^{+\infty} [f(\zeta) - 1] d\zeta \quad (17)$$

$M$  is just the excess porosity. Notice that  $M$  could be calculated as  $M = 2|I|$ , where

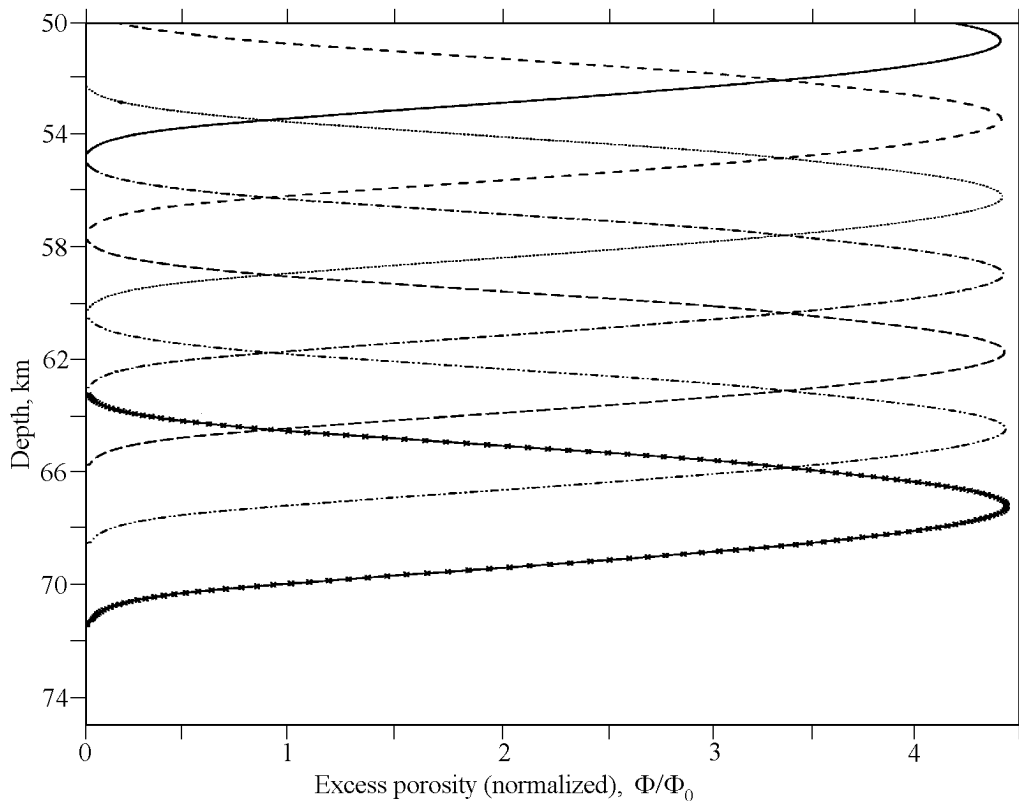
$$I = \int_1^A \zeta^+(f) df \quad (18)$$

and integration is performed on the  $f$ -domain. This integral is easily calculated and the results is written as

$$M = \frac{2}{3}(2A + 1)^2(A - 1)^{1/2}. \quad (19)$$

Going to calculation of the amount of carbon dioxide which can be transported by a non-linear solitary wave we should discuss the choosing the values of the relevant physical parameters. The data on the density of carbon dioxide under the elevated temperature and pressure were taken from the paper of *Bottinga and Richet* [1981]. For the temperature range 700–1300°C and corresponding range of pressure 7–27 kbar density of carbon dioxide changes in the limits – 1000–1530 kg/m<sup>3</sup>. For the crude estimates the average value of about 1200 kg/m<sup>3</sup> might be used. Viscosity of  $\text{CO}_2$  fluid according to *Walther and Orville* [1982] lies in the range 1.0–1.5 × 10<sup>-5</sup> Pa·s, and we used the lower value although a changing the viscosity in a one and half times does not influence the result. The initial permeability  $K_0$  has been taken as low as 10<sup>-19</sup> m<sup>2</sup>. The more disputable are the values of effective viscosity of the matrix  $\eta$  and the normal volume concentration of  $\text{CO}_2$ . We consider the value 10<sup>18</sup> Pa·s a good approximation to the viscosity of the hot sub-crustal Archean mantle, especially if the underplating has taken place just before the main metamorphic event. The value 0.01 has been taken for  $\Phi_0$ , which corresponds approximately to 0.003 wt % of  $\text{CO}_2$ . The characteristic scales under the parameters given above would be  $l_0 \cong 100$  m,  $\tau_0 \cong 150$  yr and  $v_0 \cong 0.67$  m/yr. The amplitude  $A$  could be different depending on the initial condition. Spreading of a solitary compaction wave is illustrated by Figure 1 where profiles of porosity for the case  $A = 5.4$  are shown for subsequent moments of time with time interval  $\Delta t = 2.5\tau_0$ . It is easy to see that the wave passes the first 20 km only for 17.5 × 150 yr = 2625 yr.

The volume of  $\text{CO}_2$  stored in the pile with the cross section of 1 m<sup>2</sup> and transported by a solitary wave is estimated according to  $V = M\Phi_0 l_0 S_0$ . For  $\Phi_0 = 10^{-2}$ ,  $l_0 = 100$  m and  $A = 5$  ( $S_0 = 1$  m<sup>2</sup>), we get  $V = 161$  m<sup>3</sup>. For an area of  $S \sim 1.5 \times 10^5$  km<sup>2</sup>, the total mass of



**Figure 1.** Subsequent profiles of non-linear solitary porosity wave (explanations are given in text).

CO<sub>2</sub>, transported by a solitary wave is estimated as  $2.4 \times 10^{13}(\text{m}^3) \times \rho_{\text{CO}_2} \cong 2.6 \times 10^{16}$  kg. It should be compared with the amount required from the viewpoint of geochemistry. We estimated above this amount as 0.97–1.93 wt %. It means that for a pile of 1 m<sup>2</sup> cross-section and height of 10 km the required amount of CO<sub>2</sub> would be  $\sim 10^6$  kg and for an area with the surface of  $S \sim 1.5 \times 10^5$  km<sup>2</sup> it results in  $1.2 \times 10^{17}$  kg. This mass of CO<sub>2</sub> could be transported by only 6 subsequent solitary waves related to 6 pulses of fluid activity.

## 6. Thermal Effects Related to the Transport of CO<sub>2</sub> by Non-Linear Porosity Waves

The thermal effects related to the propagation of non-linear porosity waves are described by the energy conservation equation written in the co-ordinate system fixed in the matrix. It should be written in this system because we are interested in the evaluation of temperature rise at some level coupled with the matrix. Neglecting the effect of the non-homogeneous deformation of the matrix which is of the second order in  $\Phi_0$ , the equation

of heat transport in dimensional form is written as

$$\frac{\partial u}{\partial t} + \frac{\rho_f c_f}{(\rho c)_{av}} [c(f-1) + 1] \Phi_0 \frac{\partial u}{\partial z} = a^2 \frac{\partial^2 u}{\partial z^2}. \quad (20)$$

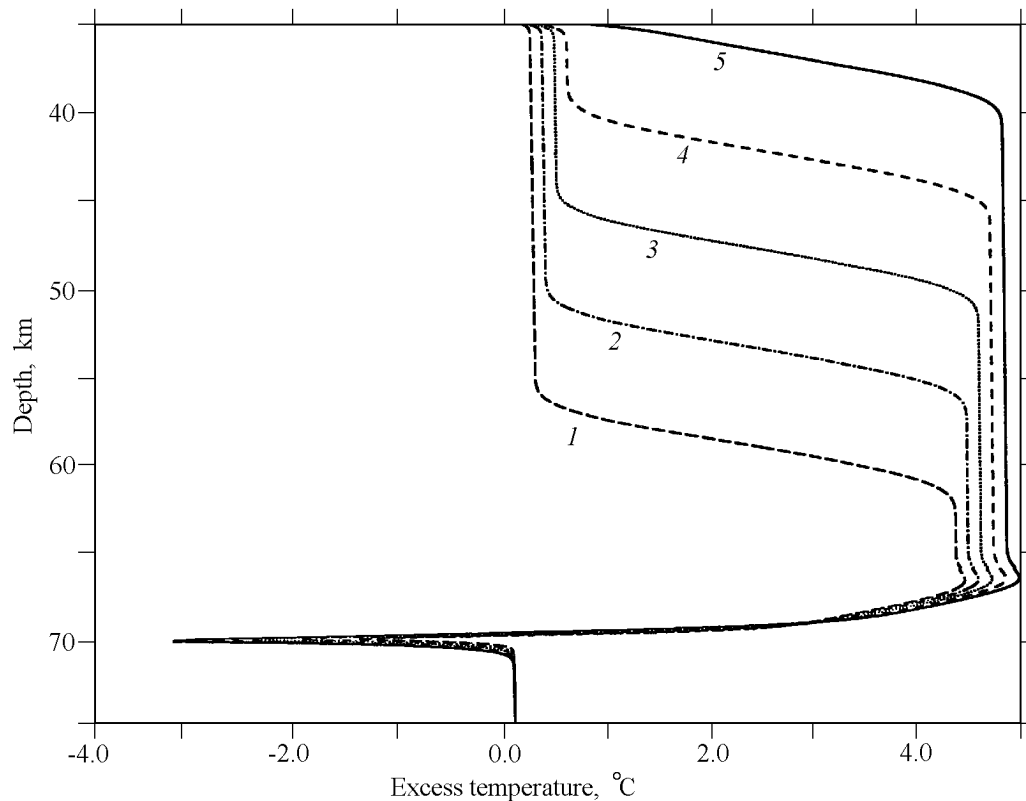
In non-dimensional form more convenient for numerical study it is seen as

$$\frac{\partial u}{\partial t} + \frac{\rho_f c_f}{(\rho c)_{av}} [c(f-1) + 1] \Phi_0 \frac{\partial u}{\partial z} = Ba \frac{\partial^2 u}{\partial z^2}. \quad (21)$$

Here  $Ba$  is the non-dimensional parameter  $Ba = a^2 \tau_0 / l_0^2 = a^2 \mu^{3/2} (K_0^{3/2} \eta^{1/2} \Delta \rho g)^{-1}$  and  $(\rho c)_{av}$  – the average value of the product of density and heat capacity for the rock-fluid system, which it is very near to  $\rho_m c_m$  due to a small values of porosity. The last equation has been solved numerically for the following set of parameters  $A = 5$ ,  $c = 11$ ,  $\Phi_0 = 10^{-2}$ ,  $Ba = 0.455$ . The initial temperature distribution has been chosen as linear one at the depths shallower than 70 km and reaching 1300°C at this depth. We also proposed temperature at the lower horizons to be equal to 1300°C at the initial moment.

The heat transfer equation has been solved by a finite-difference method, and the results of calculation





**Figure 2.** Heating effect (subsequent excess temperature profiles) of  $\text{CO}_2$  – transport by a non-linear solitary wave.

are demonstrated at Figure 2. The lowermost curve 1 depicts the excess temperature profile at moment  $t_1 = 10 \times \tau_0 = 1500$  yr. Other curves illustrate the progressive heating of the lithosphere and represent the excess temperature profiles for the subsequent moments of time with interval  $\Delta t = 5\tau_0$  beginning from the moment  $t = t_1$ . Curve 5 at Figure 2 corresponds to the moment  $t = 30\tau_0 = 4500$  yr. The maximum thermal perturbation which could be achieved at the base of the crust is around  $5^\circ\text{C}$  (see curve 1 at Figure 3, corresponding to the moment  $t = 60\tau_0 = 9000$  yr), and such a signal comes from the depth of 70 km for the time  $\sim 10^4$  yr. For comparison, the thermal effect from the wave of larger amplitude ( $A=10$ ) is illustrated by curve 2.

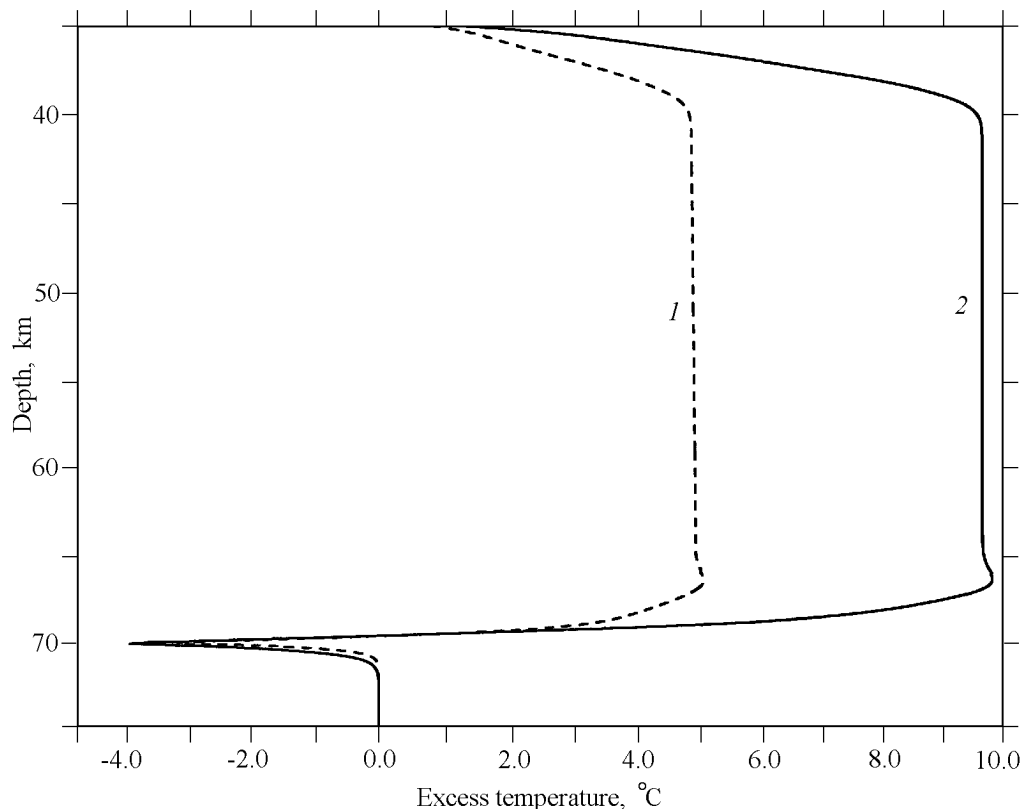
Returning to the point where we estimated the mass of  $\text{CO}_2$  required for transformation of parental gneisses into charnockites ( $\sim 1.2 \times 10^{17}$  kg for a 10 km thick charnockitic layer occupying the area  $S \sim 1.5 \times 10^5 \text{ km}^2$ ) and conclusion that such a mass of  $\text{CO}_2$  could be transported by the sequence of only 6 solitary waves, we see that such a sequence would provide the temperature rise no more than  $25^\circ\text{C}$ . This result is quite clear from the physical point of view – as it was shown by *Ganguly et al.* [1995], the mass of  $\text{CO}_2$  needed to heat the crust un-

der the area of the same surface ( $S \sim 1.5 \times 10^5 \text{ km}^2$ ) up to the conditions of the granulite facies should be around  $18 \times 10^{18}$  kg, which is almost two order less than the mass transported by the considered sequence of waves.

So, the mechanism of  $\text{CO}_2$  transport by non-linear porosity waves could be responsible for the transport of  $\text{CO}_2$  from the mantle depths to the crustal levels, but the heating of the crust probably is not related to the direct effect of fluid transfer.

## 7. Conclusive Discussion: Source of the Carbon Dioxide, Magma Underplating and Exsolution of $\text{CO}_2$

Although there are different points of view for a possible source of carbon dioxide providing the necessary condition for the formation of charnockites, we believe the most natural explanation is related to the experimental data on the melting of the carbonated peridotites [Eggler, 1976; Lee and Wyllie, 1998; Wyllie and Huang, 1976]. These experiments predict the releasing of  $\text{CO}_2$ -rich fluid phase at the depth  $\sim 70$  km, corresponding to pressure of about 27 kbar. At larger depths  $\text{CO}_2$  can not exist in the form of a separate phase and is ab-



**Figure 3.** Maximal thermal effect induced by a non-linear wave transport of  $\text{CO}_2$ .

sorbed by a partial melt or reacts with the silicate rocks to form dolomite being a stable carbonate phase below the solidus at pressures more than 27 kbar. Rising up to the level of 70 km in the mantle the partial melts associated with mantle plumes should release  $\text{CO}_2$ -rich fluid phase near this level. There are indications for a much more intensive generation and transport of carbonated melts in the Precambrian resulting in the formation of large kimberlite bodies in the lower lithosphere as it was proposed by P. Wyllie. Another indirect evidence comes from the fact that most of the large alkaline complexes are of Proterozoic age. Finally, the recent data (*Janardhan, personal communication*) show that many granitic bodies found in charnockite environment and previously interpreted of being much younger than charnockites, really have the same age. Our final conclusion is in favour of the following scenario:  $\text{CO}_2$  is released from the mantle melts at the depth near 70 km and transported by the non-linear porosity waves to the base of the crust and further to the level where charnockitization would start. The heat needed for temperature uprising is supplied by the magma underplating. Uprising of low-viscosity partially melted material could, in turn, create the real conduits for the non-linear waves.

Such a situation realises in the case of plume uprising through a relatively cold lower lithosphere. In this case  $\text{CO}_2$ -rich fluid rapidly transported upwards by a porosity waves in the low viscosity plume material, would create the carbon dioxide-rich head of the plume. Flux of  $\text{CO}_2$  would come to the crust almost contemporarily with the heating. In the case when the lower lithosphere is hot enough to have a viscosity of an order of  $10^{18}$  Pa·s, carbon dioxide could be transported by non-linear porosity waves independently from the motion of the partially melted material. The signature of underplating of hot material could not be necessarily result in high seismic velocities in the lower crust and subcrustal mantle. So, the petrological interpretation of DSS data for the crust of the charnockitic province in the southern India based probably on papers of *Sobolev* [1998 and some earlier publications] could be very fruitful. Concerning the transport of  $\text{CO}_2$  phase at the higher levels in the brittle crust we can propose an active role of hydrofracturing and poroelastic waves.

**Acknowledgement.** This work was done under ILTP program of Indo-Russian collaboration. A.O.G. is grateful to Department of Science and Technology, India, for provid-

ing a fellowship to visit C-MMACS and to Prof. V. K. Gaur, Earth Sciences Area Co-ordinator from the Indian side, for the support of this project. A.O.G. is indebted to Prof. T. S. Prahlad, director of NAL and also all the staff of C-MMACS for their help and support during his staying in Bangalore. The authors would like to thank Prof. A. S. Janardhan for fruitful discussions.

## References

- Barcion V. and Lovera O., Solitary waves in magma dynamics, *J. Fluid Mech.*, *204*, 121–133, 1989.
- Barcion V. and Richter F. M., Non-linear waves in compacting media, *J. Fluid Mech.*, *164*, 429–448, 1986.
- Bernard-Griffiths J., Jahn B. M. and Sen S. K., Sm-Nd isotopes and REE geochemistry of Madras granulites, India: An Introductory statement, *Precamb. Res.*, *37*, 343–353, 1987.
- Bonafede M., Axisymmetric deformation of a thermo-elastic half-space: inflation of a magma chamber, *Geophys. J. Inter.*, *103*, (2), 289–299, 1990.
- Bottinga Y. and Richet P., High pressure and temperature equation of state and calculation of the thermodynamic properties of gaseous carbon dioxide, *American J. Sci.*, *281*, 615–660, 1981.
- Canil D., Experimental study bearing on the absence of carbonate in mantle-derived xenoliths, *Geology*, *18*, 1011–1013, 1990.
- Connolly J. A. D., Devolatilization-generated fluid pressure and deformation-propagated fluid flow during prograde regional metamorphism, *J. Geophys. Res.*, *102*, (B8), 18,149–18,173, 1997.
- Crawford M. L. and Hollister L. S., Metamorphic fluids: the evidence from fluid inclusions. In: *Fluid-Rock Interactions during Metamorphism*, J. V. Walther and J. V. Wood (Eds.), pp. 1–35, Springer-Verlag, 1986.
- Dobretsov N. L., *The global petrology*, 277 p., Nauka, Moscow, 1977, (in Russian).
- Dunai T. J. and Touret J. L. R., A noble gas study of a granulite sample from Nilgiri Hills, southern India: implications for granulite formation, *Earth and Planet. Sci. Lett.*, *119*, 271–281, 1993.
- Eggler D. H., *Composition of the partial melt of carbonated peridotite in the system CaO-MgO-SiO<sub>2</sub>-CO<sub>2</sub>*, v. 75, pp. 623–626, Carnegie Inst. Washington Yearbook, 1976.
- Ganguly J., Singh R. N. and Ramana D. V., Thermal perturbation during charnockitization and granulite facies metamorphism in southern India, *J. Metamorphic Geol.*, *13*, 419–430, 1995.
- Glassley W. E., Deep crustal carbonates as CO<sub>2</sub> fluid sources: evidence from metasomatic reaction zones, *Contrib. Min. Petr.*, *84*, 15–24, 1983.
- Gupta M. L., Sunder A. and Sharma S. R., Heat flow and heat generation in the Archean Dharwar cratons and implications for the Southern Indian Shield geotherm and lithospheric thickness, *Tectonophysics*, *194*, (1/2), 107–122, 1991.
- Hansen E. G., Janardhan A. S., Newton R. C., Frame W. K. B. N. and Ravindra Kumar G. R., Arrested charnockite formation in southern India and Sri Lanka, *Contrib. Min. Petrol.*, *96*, 225–244, 1987.
- Harris N. B. W., Holt R. W. and Drury S. A., Geobarometry, geothermometry and late Archean geotherms from the granulite facies terrain of South India, *J. Geol.*, *90*, 509–528, 1982.
- Hopgood A. M. and Bowes D. R., Contrasting structural features in the granulite-gneiss-charnockite complex, Lake Baikal, U.S.S.R.: evidence of diverse geotectonic regimes in early Proterozoic times, *Tectonophysics*, *174*, 279–299, 1990.
- Ionov D. A., Dupuy C., O'Reilly S. Y., Kopylova M. G. and Genshaft Y. S., Carbonated peridotite xenoliths from Spitsbergen: implications of trace element signature of mantle carbonate metasomatism, *Earth Planet. Sci. Letters*, *119*, 283–297, 1993.
- Jackson D. H., Matthey D. P. and Harris N. B. W., Carbon isotope compositions of fluid inclusions in charnockites from the southern India, *Nature*, *333*, 167–170, 1988.
- Janardhan A. S., Newton R. C. and Smith J. V., Ancient crustal metamorphism of low P<sub>H<sub>2</sub>O</sub> charnockite formation of Kabbaldurga, South India, *Nature*, *278*, 511–514, 1979.
- Janardhan A. S., Newton R. C. and Hansen E. C., The transformation of amphibole facies gneiss to charnockite in southern Karnataka and northern Tamil Nadu, India, *Contrib. Min. Petrol.*, *79*, 130–149, 1982.
- Jessop A. M. and Lewis T., Heat flow and heat generation in the Superior Province of the Canadian Shield, *Tectonophysics*, *5*, 55–77, 1978.
- Jiang J., Clayton R. N. and Newton R. C., Fluids in granulite metamorphism: a comparative oxygen isotope study of the south India and Adirondack high-grade terranes, *J. Geol.*, *96*, 517–533, 1988.
- Jones A. P. and Wyllie P. J., Paragenetic trends of oxide minerals in carbonate-rich kimberlites with new analysis from the Benfontein sill, South Africa, *J. Petrol.*, *26*, 210–222, 1985.
- Khodakovskii G., Rabinowicz M., Genthon P. and Celulener G., 2D Modeling of melt percolation in the mantle: the role of a melt dependent mush viscosity, *Geophys. Res. Lett.*, *25*, 683–686, 1998.
- Kreulen R. and Schuiling R. D., Are thermal domes heated by CO<sub>2</sub>-rich fluids from the mantle?, *Earth and Planet. Sci. Lett.*, *43*, 298–302, 1979.
- Kreulen R. and Schuiling R. D., N<sub>2</sub>CH<sub>4</sub>-CO<sub>2</sub> fluids during formation of the Dome De L'Agout, France, *Geochim. Cosmoch. Acta*, *46*, 193–203, 1982.
- Le Bas M. J., *Carbonatite-Nephelinite Volcanism*, 395 pp., London, John Wiley, 1977.
- Lee W.-J. and Wyllie P. J., Petrogenesis of carbonatite magmas from mantle to crust, constrained by the system CaO-(MgO + FeO\*)-(Na<sub>2</sub>O + K<sub>2</sub>O)-(SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> + TiO<sub>2</sub>)-CO<sub>2</sub>, *J. Petrol.*, *39*, 495–517, 1998.
- Mahabaleswar B., Geothermobarometry along the North – South Transect – a review. In: *Continental crust of South India*, B. P. Radhakrishna (Ed.), pp. 303–312, Geol. Soc., India, Bangalore, 1993.
- Mahadevan T. M., *Deep Continental Structure of India: A*

- Review, 562 pp., Geol. Soc., India, Bangalore, 1994.
- Mareschal J.-C. and West G. F., A model for Archean tectonism, Part 2, Numerical models of vertical tectonism in greenstone belts, *Canadian J. Earth Sci.*, 17, 60–71, 1980.
- McKenzie D., The generation and compaction of partially molten rock, *J. Petrol.*, 25, part 3, 713–765, 1984.
- Mohan A., Prakash D. and Sachan H. K., Fluid inclusions in charnockites from Kodaikanal massif (South India): P–T record and implications for crustal uplift history, *Min. and Petrol.*, 57, 167–184, 1996.
- Mueller R. F. and Saxena S. K., *Chemical Petrology*, 378 pp., Springer-Verlag, 1977.
- Natale G., Salusti E. and Troisi A., Rock deformation and fracturing processes due to nonlinear shock waves propagating in hyperthermal fluid pressurized domain, *J. Geophys. Res.*, 103, (B7), 15,325–15,338, 1998.
- Newton R. C., Nature and origin of fluids in granulite facies metamorphism, *J. Geol. Soc. India*, 31, 1003–1012, 1983.
- Newton R. C., Metamorphic fluids in deep crust, *Ann. Rev. Earth Planet. Sci.*, 17, 385–412, 1988.
- Newton R. C., Smith J. V. and Windley B. F., Carbonic metamorphism, granulites and crustal growth, *Nature*, 288, 45–50, 1980.
- Philpotts A. R., *Principles of igneous and metamorphic petrology*, 484 pp., Prentice-Hall Intern. Inc., Englewood Cliffs, 1990.
- Pichamuthu C. S., The charnockites of South India, *Proc. Pan. Indian Ocean Sci. Cong.*, pp. 50–51, Perth, Sec. C-C, 1954.
- Radhakrishna B. P., Ramakrishnan M. and Mahabaleswar B. (Eds.), *Granulites of South India, Puchamuthu volume*, 502 pp., Geol. Soc. India, Bangalore, 1990.
- Radhakrishna B. P., (Ed.), *Continental crust of South India*, 497 pp., Geol. Soc. India, Bangalore, 1993.
- Raith M., Raase P., Ackermann D. and Lal R. K., Regional geothermobarometry in the granulite facies terrane of south India, *Trans. R. Soc. Edinburgh, Earth Sci.*, 73, 221–244, 1983.
- Ravindra Kumar G. R., Srikantappa C. and Hanson E., Charnockite formation at Pohmudi in Southern India, In: *Continental crust of South India*, pp. 251–256, B. P. Radhakrishna (Ed.), Geol. Soc. India, Bangalore, 1993.
- Richter F. and McKenzie D., Dynamical models for melt segregation from a deformable matrix, *J. Geol.*, 92, 729–740, 1984.
- Santosh M., Fluid inclusions palaeopressures and source of carbonic fluids in the massive charnockites of Kerala, South India, *Mem. Geol. Soc. India*, 11, 91–99, 1988.
- Santosh M., Jackson D.H., Harris N. B. W. and Matthey D. P., Carbonic fluid inclusions in south Indian granulites: evidence for entrapment during charnockite formation, *Contrib. Min. Petrol.*, 108, 318–330, 1991.
- Scott D. and Stevenson D., Magma solitons, *Geophys. Res. Lett.*, 11, 1161–1164, 1984.
- Scott D. and Stevenson D., Magma ascent by porous flow, *J. Geophys. Res.*, 91, 9283–9296, 1986.
- Singh R. N. and Negi J. G., On the estimation of vertical distribution of radiogenic heat production in the crust, *Geophys. J.*, 62, (1), 221–224, 1980.
- Sobolev S. V., 3-D mantle temperature and dynamics of the French Massif Central from integrated interpretation of seismic tomography, mantle xenoliths and surface heat flow, *Annales Geophys.*, 16, (S1), p. 90, 1998.
- Spiegelman M., Flow in deformable porous media, Part 1, Simple analysis, *J. Fluid Mech.*, 247, 17–38, 1993a.
- Spiegelman M., Flow in deformable porous media, Part 2, Numerical analysis – the relationship between shock waves and solitary waves, *J. Fluid Mech.*, 247, 39–63, 1993b.
- Srikantappa C., High pressure charnockites of the Nilgiri Hills, Southern India, In: *Continental crust of South India*, B. P. Radhakrishna (Ed.), pp. 95–112, Geol. Soc. India, Bangalore, 1993.
- Srikantappa C., Reith M. and Spierling B., Progressive charnockitization of a leptynite – khondalite suite in southern Kerala, India – Evidence for formation of charnockites through decrease in fluid pressure, *J. Geol. Soc. India*, 26, 849–872, 1985.
- Srikantappa C., Reith M. and Touret J. L. R., Synmetamorphic high-density carbonic fluids in the lower crust: evidence from the Nilgiri granulites, southern India, *J. Petrol.*, 4, 733–760, 1992.
- Stahle H. J., Raith M., Hoernes S. and Delfs A., Element mobility during incipient granulite formation at Kabbaldurga, southern India, *J. Petrol.*, 28, 803–834, 1987.
- Touret J. L. R., Nature and interpretation of fluid inclusions in granulites, *J. Geol. Soc. India*, 31, (1), 158–160, 1988.
- Touret J. L. R., Vladaar N. M. and Weerhoten P., Role of CO<sub>2</sub> – bearing fluids in granulite formation, *Acta Geophysicae*, 51, 99 pp., 1997.
- Walther I. V. and Orville P. M., Volatile production and transport in regional metamorphism, *Contrib. Miner. Petr.*, 79, 252–257, 1982.
- West G. F. and Mareschal J.-C., A model for Archean tectonism, Part I, The thermal conditions, *Canadian J. Earth Sci.*, 16, 1942–1950, 1979.
- Wiggins Ch. and Spiegelman M., Magma migration and magmatic solitary waves in 3-D, *Geophys. Res. Lett.*, 22, 1289–1292, 1995.
- Wyllie P. J. and Huang W. L., Carbonation and melting reactions in the system CaO–MgO–SiO<sub>2</sub>–CO<sub>2</sub> at mantle pressures with geophysical and petrological applications, *Contrib. Min. Petrol.*, 54, 79–107, 1976.

(Received June 15, 1999.)

### Физические аспекты происхождения чарнокитов Южной Индии: Механизмы разогрева коры и переноса двуокиси углерода.

А. О. Глико, Р. Н. Сингх, П. С. Свати

#### Аннотация

Рассмотрена модель формирования чарнокитовых пород Южной Индии, базирующаяся на известной идее о роли флюидной фазы, богатой двуокисью углерода.

Присутствие  $\text{CO}_2$  в достаточных количествах понижает активность воды, повышает температуру солидуса и расширяет поле устойчивости двуокисно-ассоциации в области высоких температур. При этом возникают вопросы о механизме разогрева коры, источнике углекислоты и механизме ее транспортировки. В принятой модели источник углекислоты связывается с выделением  $\text{CO}_2$ -содержащей фазы из карбонатитовых расплавов, происходящим на глубинах около 70 км. Даны оценки необходимых для образования наиболее характерных чарнокитов г. Сен-Томас (Мадрас) количества углекислоты, которые используются в качестве исходных данных. Неустойчивость слоя обогащенного углекислотой реализуется в виде вязкой консолидации и рас-

пространения вверх нелинейных волн пористости. Выполнены расчеты динамики таких волн. Перенос углекислоты такими волнами оказывается очень эффективным - дистанцию в 30 км (т.е. до подошвы коры) волна проходит за время чуть большее 2500 лет. Показано, что шести импульсов флюидной активности вполне достаточно для транспортировки количества углекислоты, необходимого для образования 10-километровой толщи чарнокитовых пород (0,97–1,93 масс.%). Приведены результаты расчета теплового эффекта таких волн. Показано, что реальный разогрев нижней коры до температур порядка 750–850°С может быть связан только с подъемом горячих глубинных масс и размещением их в достаточной близости к подошве коры (underplating).