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INTRODUCTION

The biminerallie xenolith JYG41 is striking for its high-alumina clinopyroxene crystals showing garnet exsolution lamellae. It has been described previously with respect to aspects of mineral chemistry by Harte and Gurney (1975) and with respect to the orientations of garnet lamellae within clinopyroxene by Desnoyers (1972). A model of development was considered (Harte and Gurney 1975) in which exsolution occurred over a range of temperatures as a result of a slow cooling from solidus (1400°C-35 Kbar) towards the normal mantle geotherm temperature at constant depth. The purpose of the present paper is to consider the possibility of an alternative model in which exsolution occurred isothermally and use this model to estimate the approximate value of Al diffusion coefficient in clinopyroxene.

RESUME OF TEXTURAL AND CHEMICAL DATA

On the {001} clinopyroxene plane, garnet lamellae show various size (1000 μ to 10 μ), shapes (discontinuous to continuous layers), spacing and orientations ($\{110\}$, $\{010\}$, $\{130\}$). Big lamellae (1000 μ across) occurring parallel to $\{010\}$ form widely spaced (up to 1 cm), discontinuous layers. Medium to small lamellae (100 μ to 10 μ across) and parallel to $\{110\}$, $\{130\}$, closely spaced (100 μ to 10 μ) and form continuous lamellae. Simultaneous exsolution in $\{130\}$ and $\{110\}$ orientations is shown by single lamellae which pass from one orientation to the other.

At scale of individual grains (included lamellae) garnet is homogeneous. However the grossular content of garnet grains is correlated with the size of garnet grains (1000 μ across lamellae: Pyrope 33; Almandine 18; Grossular 44; 10 μ across lamellae: Pyrope 26, Almandine 13; Grossular 60). Clinopyroxene shows strong compositional zoning, the main feature of which being a decrease of Al (and minor Fe) as Si and Mg increase towards garnet contacts (Fig. 1). The composition profiles are related to the size of garnet lamellae with gradients in Si and Al up to 100 μ wide adjacent to 80 μ thick garnet lamellae, and up to 10 μ wide adjacent to 8 μ thick garnet lamellae. Note that beyond these distances, original Al and Si compositions appear to be preserved (Fig. 1). Ca, unlike most of the elements, shows very flat profiles in the clinopyroxene. At all the interfaces Si and Al, which are stoichiometrically controlled in garnet, have also a fixed concentration in the pyroxene. Ca, Mg, Fe vary in such way in clinopyroxene and garnet that they are not related by crossed tie lines for these elements (Fig. 2). At the same time the $K_{\text{Fe-Mg}}^{\text{Py-Grt}}$ maintains closely similar values at all interfaces. The interface Fe/Mg values give Grt. Cpx exchange temperature of c.a. 1050°C (Ganguly 1979) but are uncertain because of the large grossular component in the garnets.

REACTION MECHANISMS

Zoning in clinopyroxene is a result of unequal partitioning of Si/Al, Al/Mg during garnet growth depicted by the classical net transfer reaction 2 diopside + Al₂Mg-1 Si-1 = 2 grossular, 1 pyrope. Profiles within clinopyroxene whereas garnet are homogeneous

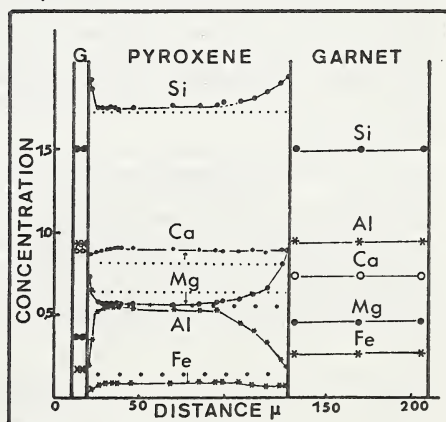


Fig. 1: Diffusion profiles in clinopyroxene adjacent to 8 μ , 80 μ thick garnets, parallel to $\{110\}$.
Formulae calculated on the basis of 6 Oxy.
.....: primary unexsolved pyroxene composition (Harte and Gurney 1975.)

REACTION MECHANISMS

Zoning in clinopyroxene is a result of unequal partitioning of Si/Al, Al/Mg during garnet growth depicted by the classical net transfer reaction $2 \text{ diopside} + \text{Al}_2\text{Mg} = 1 \text{ Si} = 2 \text{ grossular} + 1 \text{ pyrope}$. Profiles within clinopyroxene whereas garnet are homogeneous show that $D_{\text{Al}}^{\text{Px}} > D_{\text{Si}}^{\text{Px}} < D_{\text{Mg}}^{\text{Px}} < D_{\text{Ca}}^{\text{Px}}$.

Partitioning at the interface defines a state of local equilibrium consistent with diffusion controlled process. As we are concerned with multicomponent diffusion (Al₂Si-1) the slowest species will be rate limiting. Homogenisation experiments (at high T and P; Sautter 1986) show clearly that garnet dissolution is possible because of an inward Si diffusion from clinopyroxene whilst Al does not move outwards. Therefore D_{Al} will be rate limiting.

Although there is a correlation of the grossular content and size of garnet grains, there is no textural evidence to show a chronology of development of these lamellae. The correlation may indicate a relative chronology over a temperature range (Harte and Gurney 1975) but it is also possible that all lamellae nucleated simultaneously at one temperature, but showed varying nucleation density and amounts of subsequent growth partly as a function of clinopyroxene crystallography.

KINETICS MODELLING

The data of Richardson et Al. (1984) and Boyd et Al. (1985) indicate that the nodule may have formed in Archean times in a mantle with geotherm similar to present day shield areas. If we assume this and crystallisation of clinopyroxene from a magma initially at 1400°C, then the cooling interval of the clinopyroxene yielding garnet exsolution could be c.a. 400°C over a 3b.y. given kimberlite eruption at 100 M.y. For 1 km magmatic sheet at 1400°C, intruded into peridotite at 1050°C, the equation $T = T_0 + \frac{10^{-13}}{2} \text{erf} \frac{a}{2\sqrt{Xt}}$ (a = half layer thickness; X = thermal diffusivity = $0.83 \times 10^2 \text{ km}^2/\text{s}$) gives a cooling duration of 0.005 M.y. By comparison with likely diffusion coefficients (from 10^{-10} to $10^{-22} \text{ cm}^2/\text{s}$) this cooling duration is effectively instantaneous. Therefore, as an alternative to the progressive cooling model, we shall consider a model in which all the exsolution has occurred at 1050°C after a big overstep (400°C).

An internal kinetic model for exsolution reaction, where both diffusion and moving grain boundaries are involved, had been made to find the solution C(x,t) of 2 Fick's law. Al diffusion in clinopyroxene being the rate limiting step, Al is the component used in the following calculations. Garnet symmetrical axis is chosen as the fixed system of reference (Fig. 2a: X=0) and we just consider a semi-infinite medium (clinopyroxene) next to half a garnet lamellae (Fig. 2b). In these cartesian coordinates, the flux of Al across clinopyroxene garnet interface (X=X') (Fig. 2b) is chosen parallel to {110}. The boundary (X=X') conditions are as follows: $t=0 \text{ } X>0 \text{ } C=C_0$; $t>0 \text{ } x=x' \text{ } C=C_e$. The mass transfer problem is defined by interface velocity (v: Fig 2b) which decreases as garnet growths and Al diffusion distance which is proportional to garnet thickness (Fig. 1). This is equivalent to a heat transfer problem by conduction involving solidification of a liquid (-Stephan Problem: Ice crystallisation at the top of a lake). A transposition to our mass transfer problem gives a solution (Fig. 2c), obtained by scaling Al penetration depth and the width of garnet lamellae. Equation (Fig. 2c) contains two unknowns $D_{\text{Al}}^{\text{Px}}$ and t. As equilibrium (flat profile) had not been reached in JJG41, the time stay of almost 2.9 b.y. at 1050°C, constrains $D_{\text{Al}}^{\text{Px}}$ to an approximate value of $10^{-22} \text{ cm}^2/\text{s}$. With such a value, estimation of the time of development for various thickness of garnet lamellae had been done from the diffusion profiles in clinopyroxene (6.5 M.y. for 3u thick garnet; 50 M.y. for 80 u thick garnet).

An isothermal exsolution model is consistent with the diffusion profile for Al (Si,Mg) in clinopyroxene as well as being consistent with temperature of equilibration at garnet - clinopyroxene interface of a 1050°C. The constant composition of garnet lamellae is presumed to reflect the fact that diffusion rate, at least for 2⁺ cations are fast enough to maintain equilibrium across the garnet. If the model provides no simple explanation for the correlation of lamellae thickness with grossular content it is nevertheless the most coherent way to justify textural relationships of these lamellae related to anisotropic properties of clinopyroxene.

Fig. 2

Ca, Mg, Fe diagramme

- : garnets
- : pyroxenes

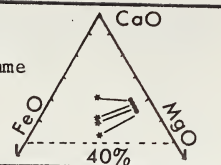
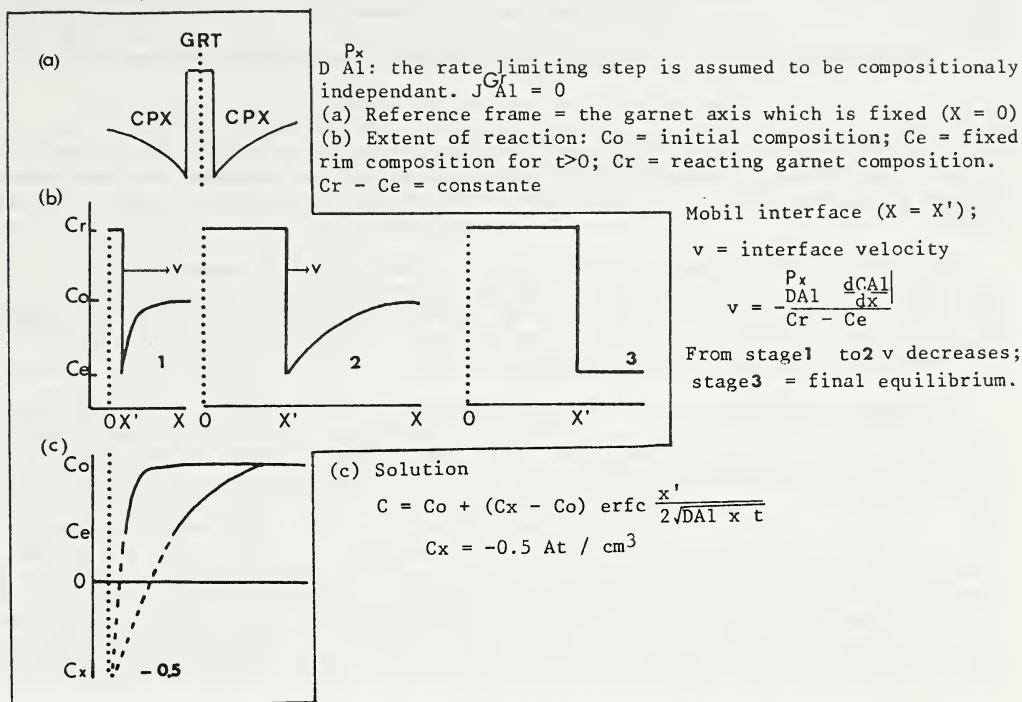


Fig. 3: Kinetics model (diffusion profiles C Al- X)



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