AN EVALUATION OF THE RESIDENCE DURATION OF MEGACRYSTS IN ALKALINE MAGMA CHAMBERS

A. Ibhi *, H. Nachit *, D. Khatib **, El H. Abia * and M. Berrahma ***

ABSTRACT

The integration of the differential equation of the second law of Fick applied to the diffusion of chemical elements in a semi-infinite solid made it easier to estimate the time of stay of olivine megacrysts horted into alkaline lava. The results of this research show the existence of two groups of olivine. The first remained in contact with the magmatic liquid during 30 to 34 days, while the second remained so during only 4 to 7 days only. This distinction is correlative to that based on the qualitative observation.

Key words: Atomic diffusion, residence time, olivine megacrysts, alkaline lavas, Anti-Atlas Morocco, Canary Islands.

RESUMEN

La integración de la ecuación diferencial de la segunda ley de Fick aplicada a la difusión en un sólido semiinfinito, permitió estimar el tiempo de la residencia de los megacristales de olivino incluidos en lavas alcalinas. Los resultados muestran que existen dos grupos de olivino: el primero persiste entre 30 a 34 días, en contacto con el líquido magmático, mientras que, el segundo, solamente lo hace entre 4 a 7 días. Esta distinción está de acuerdo con la observación petrográfica.

Palabras clave: Difusión atómica, tiempo de residencia, megacristales de olivino, lavas alcalinas, Islas Canarias, Anti-Atlas marroquí.

Introduction

Megacryst-sized olivine crystals are common in alkaline lavas (Irving and Frey, 1984; Liotard et al., 1988). Olivine megacrysts studied here are from Saghro mountain (Anti-Atlas, Morocco) (Ibhi, 1997) and from La Palma alkaline lavas (Canary Islands) (Dautria and Girod, 1987). The origin of the olivine crystals is still debatable; however, most authors have divided them into two groups, according to their genetic relationship with the host lava (Irving, 1984; Long et al., 1993):

1. Most olivine megacrysts appear in approximate from equilibrium with the host lava (OlE).
2. Others are in disequilibrium with the host lava (OlD).

Different cationic exchange models between megacrysts and host lava give the diffusion profiles upon which Fick’s law is applied. The latter enables to calculate minerals period of stay in magmatic liquid.

Material and chemical analyses

Megacrysts are defined here as discrete crystals that have a dimension greater than 2 cm. They have subspherical shape or are angular fragments. The destabilisation of olivine in the host lava, produces coronitic pseudomorphs. These structures are narrow.

Megacrysts were analysed by automated microprobe, Camebax Sx 50 of CAMPARIS, by using routine analytical conditions: 15 kV acceleration voltage, 20 nA beam current, 30 s count time, and tracor Northern ZAF matrix correction with natural mineral standards. Analytical errors are ± 0.5 %-2 % for major elements and 10 %-20 % for minor elements.

Representative electron microprobe analyses of olivine megacrysts (OlD, OlE) are given in table 1; and host rock chemical analyses are given in table 2.
Table 1.—Representative electron microprobe analyses of olivine megacrysts (Ol$_{h}$, Ol$_{e}$)

<table>
<thead>
<tr>
<th></th>
<th>Ol$_{h1}$</th>
<th>rim</th>
<th>Ol$_{h2}$</th>
<th>rim</th>
<th>Ol$_{e1}$</th>
<th>rim</th>
<th>Ol$_{e2}$</th>
<th>rim</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>40.10</td>
<td>37.76</td>
<td>40.22</td>
<td>38.24</td>
<td>39.36</td>
<td>38.68</td>
<td>38.58</td>
<td>37.83</td>
</tr>
<tr>
<td>MgO</td>
<td>45.80</td>
<td>37.07</td>
<td>45.83</td>
<td>34.61</td>
<td>41.52</td>
<td>36.86</td>
<td>41.23</td>
<td>36.98</td>
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<tr>
<td>CaO</td>
<td>0.25</td>
<td>0.42</td>
<td>0.17</td>
<td>0.39</td>
<td>0.25</td>
<td>0.27</td>
<td>0.18</td>
<td>0.33</td>
</tr>
<tr>
<td>MnO</td>
<td>0.14</td>
<td>0.07</td>
<td>0.16</td>
<td>0.67</td>
<td>0.31</td>
<td>0.20</td>
<td>0.33</td>
<td>0.43</td>
</tr>
<tr>
<td>NiO</td>
<td>0.19</td>
<td>0.07</td>
<td>0.25</td>
<td>0.05</td>
<td>0.09</td>
<td>0.03</td>
<td>0.11</td>
<td>0.02</td>
</tr>
<tr>
<td>Cr$_2$O$_3$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>100.10</td>
<td>100.40</td>
<td>100.60</td>
<td>100.70</td>
<td>100.50</td>
<td>100.90</td>
<td>100.80</td>
<td>99.70</td>
</tr>
</tbody>
</table>

C$_{Fe}$ 14.4 27.7 14.6 30.7 20.0 27.7 22.3 27.2

Structural formulae calculated on the basis of 4 oxygens ($C_{Fe}$ is the mole % fayalite content of the olivine).

**Diffusion equations**

The analysis of the olivine megacrysts using electron microprobe, revealed diffusion profiles of Fe and Mg (diagrams a1, b1, c1 and d1 of figures 1, 2, 3 and 4). It is known that diffusion depends on crystallographic direction, oxygen pressure, chemical composition, pression and temperature (Buening and Buseck, 1973; Jurewiez and Watson, 1988; Nakamura and Schmalzried, 1984; Morioka and Nagazawa, 1991; Jaoul et al., 1995, and Chakraborty, 1997).

**Crystallographic control**

Olivine is orthorhombic (a ≠ b ≠ c) and diffusion is anisotropic ($D_{[100]} ≠ D_{[010]} ≠ D_{[001]}$). At 1100° C, the interdiffusion coefficient ($D_{Fe-Mg}$) in olivine is 10 times greater for the c-axis than for the a and b axes (Buening and Buseck, 1973; Misener, 1974; Jurewiez and Watson, 1988).

**Oxygen pressure**

Dislocations and plasticity of natural olivine have been extensively investigated essentially by means of creep test experiments (Jaoul et al., 1979; Gueguen and Darot, 1982, and Poumellec and Jaoul, 1984). They depend on oxygen pressure and water pressure (Poumellec and Jaoul, 1984). These mechanical properties are controlled by the diffusion rate of the slowest species $D_{Si}$, but with an important enhancement due to the presence of the most abundant and mobile defects, the octahedral vacancies, $V_{Me}$, with concentration $[V_{Me}]$, which are "pulling" the slow silicons (Jaoul, 1990). In olivine, iron is found in considerable concentration in the two valency states ($Fe^{2+}$ and $Fe^{3+}$). The $Si$ concentration is related to oxygen fugacity (Morioka and Nagazawa, 1991) by:

$$\frac{1}{2}O_2(gas) + 3Fe_{Me} \rightleftharpoons 2Fe_{Me}^* + V_{Me} + FeO_{(solidsolution)} \quad [1]$$

$$K = a_{FeO} \frac{[V_{Me}]}{[Fe_{Me}]} \cdot \frac{[Fe_{Me}]}{[Fe_{Me}]} \quad [2]$$

where $K$ is the equilibrium constant at T, $pO_2$ is the oxygen partial pressure around the sample and $a_{FeO}$ represents FeO activity. $Fe_{Me}^*$ is atomic fraction of iron in octahedral sites, $Fe_{Me}$ stands for the $Fe^{3+}$ concentration in $Fe^{2+}$ site and $V_{Me}$ represents vacant octahedral sites.

Electronic neutrality $2(V_{Me}) = (Fe_{Me}^*)$ yields:

$$D_{Fe/Mg}a(V_{Me})a_{O_2}^{1/6} \quad [3]$$

The $Fe/Mg$ interdiffusion coefficient ($D_{Fe/Mg}$) depends on $pO_2$ roughly as $(pO_2)^{1/6}$. The relationship has been verified experimentally by Buening and Buseck (1973) and Nakamura and Schmalzried (1983) (the latter found a 1/5.5 exponent in their study).
Table 2.—Host-rock chemical analyses [1: % oxide weight; 2: % atom weight = (% oxide weight × atomic weight)/molecular weight].

<table>
<thead>
<tr>
<th>Host-rock</th>
<th>(Olp3, Olp2 and Olp2)</th>
<th>Host-rock</th>
<th>(Olq1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(1)</td>
</tr>
<tr>
<td>SiO₂</td>
<td>40.43</td>
<td>Si</td>
<td>18.896</td>
</tr>
<tr>
<td>FeO</td>
<td>10.98</td>
<td>Fe</td>
<td>8.534</td>
</tr>
<tr>
<td>MgO</td>
<td>10.73</td>
<td>Mg</td>
<td>6.471</td>
</tr>
<tr>
<td>CaO</td>
<td>15.35</td>
<td>Ca</td>
<td>10.969</td>
</tr>
<tr>
<td>MnO</td>
<td>0.20</td>
<td>Mn</td>
<td>0.154</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>11.76</td>
<td>Al</td>
<td>6.223</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.78</td>
<td>Ti</td>
<td>1.666</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.36</td>
<td>Na</td>
<td>2.492</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.80</td>
<td>K</td>
<td>1.494</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>1.07</td>
<td>P</td>
<td>0.467</td>
</tr>
<tr>
<td>PF</td>
<td>2.19</td>
<td>PF</td>
<td>1.32</td>
</tr>
<tr>
<td>Total</td>
<td>100.60</td>
<td>Total</td>
<td></td>
</tr>
</tbody>
</table>

Host lava oxygen fugacity has been determined from ilmenite-magnetite couple (temperature/oxygen fugacity curves; Buddington and Lindsay, 1964). At 1,100° C ± 40° C, this fugacity is of 10⁻¹⁰.⁴±0.⁶ atm.

**Diffusion coefficient**

Following Nakamura and Schmalzried (1983), we have considered that $D_{Fe-Mg}$ varies exponentially with $X_{Fe}$ so that we have

$$D_{Fe-Mg}^{O} = D_{Fe-Mg}^{O_0} \exp(\epsilon X_{Fe})$$

[4]

where $X_{Fe}$ is the Fe/(Fe + Mg) content of the olivine, $D_{Fe-Mg}^{O_0}$ is the Fe-Mg interdiffusion coefficient in an olivine of forsterite (symbol Fo) composition, and $\epsilon$ is a factor empirically evaluated. Nakamura and Schmalzried have verified this relationship at higher temperatures ($1,050° < T < 1,280°$ C) by treating their data with the Boltzmann-Matano approach. For each experimental temperature they determined a value of $\epsilon$, with $\epsilon$ increasing from 4.14 at 1,050° C to 6.38 at 1,280° C.

The expression for $D_{Fe-Mg}$ determined by Buening and Buseck (1973) at a temperature below 1125° C is given by the expression:

$$D_{Fe-Mg} = 10^2 (FO\text{O}_2)^{1/6} \exp(-0.0501C_{Fe} - 14.03) \exp([-31.66 + 0.2191C_{Fe}/RT])$$

[5]

where $D_{Fe-Mg}$ is in units cm² s⁻¹, $C_{Fe}$ is the mole % fayalite content of the olivine, $R$ is the gas constant and $T$ is the absolute temperature. This is the expression that we used for our calculations.

**Temperature - Pressure estimates**

In alkaline basalt, the olivine appears at liquidus. The host lava temperature is calculated by using Leeman and Schridegger thermometric equations (1977). This was done by supposing that the equilibrium is realised between the rock and the most magnesic olivine phenocrysts.

Regression formulas are the following:

$$\ln D_{Fe^{2+}} = 9016/T - 5.46$$

and

$$\ln D_{Mg} = 8916/T - 4.29$$

[6]

Obtained temperatures are 1,100° C ± 40° C.

Pressure estimation have been indirectly performed from previously calculated temperatures, by using the geotherm established by Mercier and Carter (1975). They are 2.9 GPa ± 0.1 GPa.

**Numerical application**

The crystal surface is supposed plane. That means its irregularities are small compared to the depth of the concentration gradient. The diffusion coefficient is supposed constant in all points of the system, because the variations of the temperature, of oxygen fugacity and those of chemical compositions are slow in the magmatic chamber.

The solution to the diffusion problem is the following, according to the boundary conditions:

$$C(x,t) = C_t + (C_0 - C_t)\text{erf}\left(\frac{x}{2\sqrt{Dt}}\right) = C_t + (C_0 - C_t)\text{erf}(ax)$$

[7]

where

$$a = \left(\frac{1}{2\sqrt{Dt}}\right)$$
In equation [7], $C_1$ is olivine superficial concentration and $C_0$ the initial concentration in the crystal (the concentration at the crystal core). $x$ is the diffusion distance, $D$ is the diffusion coefficient, and $t$ the diffusion duration; erf is the error function.

The application of the Fick’s law on cationic diffusion profiles made it possible for us to calculate the time spent by these crystals in the lava. The different olivine crystals residence duration is calculated and reported in Table 3. The results show the existence of two olivine populations. The first was in contact with the magmatic liquid from 30 to 34 days for olivine in equilibrium with host lava (Ol$_E$), while the second was only for 4 to 7 days, regrouping crystals in disequilibrium (Ol$_D$).

Megacrysts in disequilibrium remained in contact with host lava for just the period reminding that of cropping up of a xenolith having a diameter of 10 cm in volcanic chimney calculated from Stockes law, for a 50 km distance (Kushiro et al., 1976). The origin of these megacrysts can be looked for in the desegregation of Cr-diopside suite xenoliths. This goes side by side with Johnson’s chemical studies (1989).

Nakamura (1995) estimated the residence time of olivine phenocrysts in magma that erupted from the
EVALUATION OF THE RESIDENCE DURATION OF MEGACRYSTES IN ALKALINE MAGMA CHAMBERS

Table 3.—Olivine megacrysts period of stay calculation in alkaline lavas (T = 1,100° C).

<table>
<thead>
<tr>
<th>Group A</th>
<th>Axis</th>
<th>C Fe</th>
<th>D(µm²/s)</th>
<th>1</th>
<th>t (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OIₐ₁</td>
<td>Mg</td>
<td>14.4 ± 0.2</td>
<td>3.27 × 10⁻³ [18]</td>
<td>0.0122 ± 0.003</td>
<td>142 ± 84</td>
</tr>
<tr>
<td></td>
<td>Fe</td>
<td>14.4 ± 0.3</td>
<td>3.27 × 10⁻³ [20]</td>
<td>0.0115 ± 0.004</td>
<td>160 ± 127</td>
</tr>
<tr>
<td>OIₐ₂</td>
<td>Mg</td>
<td>14.6 ± 0.2</td>
<td>3.18 × 10⁻³ [18]</td>
<td>0.0146 ± 0.003</td>
<td>102 ± 49</td>
</tr>
<tr>
<td></td>
<td>Fe</td>
<td>14.6 ± 0.3</td>
<td>3.18 × 10⁻³ [20]</td>
<td>0.0153 ± 0.002</td>
<td>93 ± 31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group B</th>
<th>Axis</th>
<th>C Fe</th>
<th>D(µm²/s)</th>
<th>1</th>
<th>t (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OIₕ₁</td>
<td>Mg</td>
<td>20.0 ± 0.3</td>
<td>1.71 × 10⁻³ [20]</td>
<td>0.0076 ± 0.003</td>
<td>700 ± 430</td>
</tr>
<tr>
<td></td>
<td>Fe</td>
<td>20.0 ± 0.4</td>
<td>1.71 × 10⁻³ [22]</td>
<td>0.0074 ± 0.003</td>
<td>738 ± 434</td>
</tr>
<tr>
<td>OIₕ₂</td>
<td>Mg</td>
<td>22.3 ± 0.3</td>
<td>1.34 × 10⁻⁴ [25]</td>
<td>0.0257 ± 0.005</td>
<td>798 ± 440</td>
</tr>
<tr>
<td></td>
<td>Fe</td>
<td>22.3 ± 0.4</td>
<td>1.34 × 10⁻⁴ [27]</td>
<td>0.0255 ± 0.006</td>
<td>811 ± 480</td>
</tr>
</tbody>
</table>

D is calculated from equation [5] (* values in brackets are percent error).

northern Yatsugatake volcanoes in Japan using compositional zoning. Just from the results of modelling the Fe/Mg compositional profiles; he concluded that the residence times of olivines was between 10 days and 1 year.

We think, based on these results, that it becomes possible to talk about the notion of the period of stay of olivine megacrysts once the distinction between the form more or less in equilibrium and those in disequilibrium with host liquid is established.

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References


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