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Natural equivalents of thermal gradient experiments

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ABSTRACT

Crystallization experiments using the intrinsic thermal gradient in 10 mm length capsules loaded in piston-cylinder assemblies were used to investigate silicic magma crystallization. The application of experimental results to natural environments requires the scaling of physical parameters of petrological interest. Therefore, we propose here a comparative study between thermal gradients and numerical simulations of natural magma chambers. We use the Finite Element method to calculate thermal profiles across a cooling silicic magma chamber. These numerical profiles are compared with the intrinsic thermal structure of half-inch, piston-cylinder assemblies at 500 MPa. It is concluded that a set of varied magma chamber geometries and/or distinct stages of their cooling history can approach the intrinsic thermal structure of laboratory experiments. Once the thermal properties for magma and its host rock are fixed, the experimental–numerical approach is mostly dependent on the volume and aspect ratio of the magma chamber. Our results indicate, for instance, that a 10 mm length capsule with a thermal gradient of 40 °C/mm (from 1100 to 700 °C) may represent a 150–1100 m wide portion of a cooling magma chamber of 10–20 km diameter and 2–10 km height, emplaced at a depth of 18 km. Additional possible scenarios are represented by larger magma chambers, up to 30 km diameter, in which the experimental thermal gradient can represent a 150–3700 m-thin-section of the large igneous bodies.

1. Introduction

Experimental petrology apparatus, like the piston-cylinder (Boyd and England, 1960), were designed to simulate natural conditions in small capsules in which temperature (and pressure) is constant over their entire volume; a requirement to reproduce phase compositions in the laboratory through the control of intensive variables. However, outside a restricted area (*hotspot*) of about 5 mm diameter, strong thermal (intrinsic) gradients develop in piston-cylinder assemblies (Watson et al., 2002; Lundstrom et al., 2005; Huang et al., 2009). The thermal gradient is controlled by a number of factors such as capsule length, assembly design, pressure transmitting solid media, and the pressure and temperature used (Schilling and Wunder, 2004).

Thermal gradient measurements in piston-cylinder are firstly affected by the large conductivity of the metal capsule that buffers the thermal difference across the assembly. Thus, the thermal structure of a piston-cylinder will also depend on the length, diameter and the metal composition of the capsule. The use of different materials in the solid pressure transmitting media can affect thermal gradient depending on its thermal conductivity. Moreover, temperature and pressure conditions can affect the thermal conductivity of solid pressure media. Previous experimental works (Pickering et al., 1998; Watson et al., 2002) and numerical modeling (Schilling and Wunder, 2004) were performed to constrain thermal profiles in experimental assemblies with marked differences with respect to our design. Hence, new experiments are required to better constrain the thermal gradient in half-inch assemblies loaded with the longer capsules.

The point of interest is that in using long capsules (>5 mm length), it is possible to take advantage of the intrinsic thermal gradient in order to simulate the crystallization of shallow magma chambers, which cool from their walls to the innermost part (Huang et al., 2009; Masotta et al., 2012; Mollo and Masotta, 2014). Preliminary results are of great value to gain intuition on processes in magma chambers; however the transfer of experimental results to km-sized magma bodies is not a straightforward process. Here we present the scale of application to km-sized magma bodies in nature. With this purpose, we have compared intrinsic thermal gradients in piston-cylinder experiments and magma chamber gradients inferred by means of thermomechanic numerical modeling.

Experimental thermal profiles are compared with those resulting from numerical simulations reproducing natural magma chambers at different stages of their cooling history. In both capsules and selected magma chambers, the whole temperature range that encompasses *liquidus* to *solidus* conditions (Fig. 1) of intermediate andesitic systems ($SiO_2 \approx 60$ wt.%) has been reproduced. The relevant issue for the scaling is to infer what the conditions are in terms of magma chamber geometry, size and evolutionary stage, for which the experimental–natural comparison is relevant. The geometry of the gradient curve

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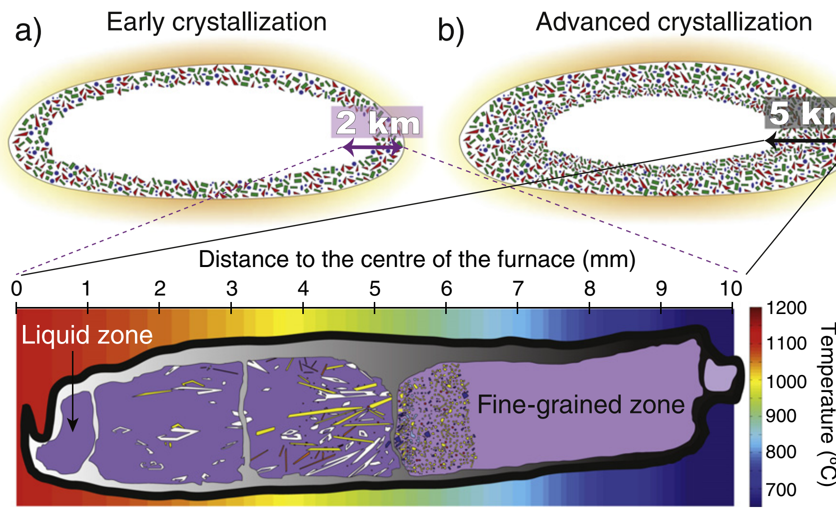

Fig. 1. Sketch illustrating thermal gradient experiments that may represent varied evolutionary stages of the same magma chamber. (a) The experimental thermal gradient may correspond to early stages of cooling, representing just a distance of 2 km from the boundary with the host rock. (b) In a more evolved magmatic system, the thermal gradient imposed to the experiments can be equivalent to a distance of 5 km from the walls of the magma chamber (red zone).

from *liquidus* to *solidus* depends on magma chamber parameters such as the diameter, depth of emplacement and cooling time period. Our results indicate that intrinsic experimental gradients can fit only a limited set of natural conditions. Hence, caution must be exercised for the application of thermal gradient experiments to settings outside those recommended here.

2. Rationale

It is known from experiments and thermal modeling of piston-cylinder assemblies (Pickering et al., 1998; Watson et al., 2002; Schilling and Wunder, 2004; Huang et al., 2009; Masotta et al., 2012) that large thermal gradients occur inside the graphite furnace. Temperature is constant over a short distance of about 5 mm from the center of the furnace and drops suddenly to much lower values towards the bottom and the top. Interestingly, the *liquidus–solidus* interval can be covered by this intrinsic thermal gradient, opening new possibilities to study magma differentiation processes.

The scaling of this intrinsic experimental thermal gradient may be performed by direct comparison of the thermal structure within the graphite furnace with that of a km-sized magma chamber. By contrast, the kinetic processes responsible for the experimental results cannot be scaled only through the thermal properties of piston-cylinder apparatus. The results from the laboratory experiments shed light to specific phenomena constrained to limited portions of a magma chamber. The aim of this work is to delimit the equivalence of this portion in nature by means of the thermal structure imposed in these experiments. To do so, we present a new approach to scale thermal gradient experiments to natural systems. On the one hand, the intrinsic thermal gradient is directly measured by using special assemblies equipped with double thermocouples. On the other hand, natural gradients of km-sized magma chambers are calculated by means of numerical modeling. The latter consists of a time-dependent thermal model that simulates the cooling process of a closed magmatic system embedded in a colder and homogeneous host rock. To achieve this comparison, we extrapolate the entire capsule length to natural cases (Fig. 1).

We use as an example of application the experimental thermal profile in which the hotspot is constrained to the *liquidus* of a given standard andesitic composition. In any case, this process can be repeated for different magma compositions or experimental thermal setups. It must be noted that it is not possible to explore all possible combinations of the mentioned parameters in the current paper and that it may be addressed in future works.

The intrinsic thermal gradient is directly measured by using special assemblies equipped with double thermocouples. The natural gradients of km-sized magma chambers are calculated by means of numerical modeling. Shedding some light on the natural equivalence of the experimental thermal gradient allows a better understanding of the experimental results as pertaining to magma chambers of different sizes and evolutionary stages, and/or to different portions of magma chambers. It is worth noting that the thermal gradient can be correlated either to the initial cooling representative of a small fraction (Fig. 1a) of the chamber near the wall rocks, or to more advanced stages of cooling associated to higher degrees of crystallization (Fig. 1b). The results obtained here indicate that the thermal gradient, imposed over the entire capsule length, allows us to simulate various evolutionary stages of the same magma chamber and/or different magma chambers within a wide range of sizes and geometries.

3. Calibration experiments of thermal gradients in piston-cylinder apparatus

3.1. Experimental techniques

The experiments were designed to calibrate the thermal gradient operating in the capsule. Runs were carried out using a double thermocouple setup in order to measure the temperature gradient. The thermocouples measured temperatures from 900 to 1200 °C over a constant pressure of 500 MPa. Calibration experiments were performed in a Boyd–England type piston-cylinder apparatus installed at the University of Huelva (Spain). The two thermocouples are positioned in a “special periclase assembly”. This assembly is made up of a 12.5 mm (half inch) diameter, talc–Pyrex–periclase cell, Au–Pd capsule and drilled periclase. Gold–palladium ($Au_{70}Pd_{30}$) capsules of 3 mm diameter, 10 mm length, and 0.15 mm wall were filled with drilled periclase that serves (1) to simulate the sample effects on the gradient and (2) to ensure that the thermocouple is at the desired position with respect to the center of the furnace (Fig. 2). Then, the capsules were introduced into MgO pressure containers.

The temperature was measured and controlled with two Pt_{100}–$Pt_{87}Rh_{13}$ thermocouples connected to Eurotherm 808 controllers, with estimated uncertainties of ± 1 °C. The first thermocouple is