C. R. Geoscience 342 (2010) 701–709

Contents lists available at ScienceDirect

Comptes Rendus Geoscience

www.sciencedirect.com

Petrology, geochemistry

Bimodal distribution of the solid products in a magmatic chamber: Modelling by fractional crystallization and coupling of the chemical exchanges with the differential melt/solid transport

Répartition bimodale des produits solides d'une chambre magmatique : modélisation par cristallisation fractionnée avec couplage des échanges chimiques et du transport différentiel magma/solide

Morad Lakhssassi [a], Bernard Guy [a,*], Eric Touboul [b], Jean-Yves Cottin [c]

[a] *Centre SPIN (sciences des processus industriels et naturels), École nationale supérieure des mines, UMR CNRS 6524 Magmas et volcans, 158, cours Fauriel, 42023 Saint-Étienne cedex 2, France*
[b] *Équipe Méthodes et modèles mathématiques pour l'industrie, centre G2I (génie industriel et informatique), École nationale supérieure des mines, 158, cours Fauriel, 42023 Saint-Étienne cedex 2, France*
[c] *LTL UMR CNRS 6524 Magmas et volcans, faculté des sciences, université Jean-Monnet-Saint-Étienne, rue du Docteur-P.-Michelon, 42023 Saint-Étienne cedex 2, France*

ARTICLE INFO

Article history:
Received 18 September 2008
Accepted after revision 12 April 2010
Available online 22 July 2010

Presented by Zdenek Johan

Keywords:
Fractional crystallization
Solidification
Chemical exchange
Sedimentation
Bimodal distribution
Discontinuity of composition
Magmatic chamber

Mots clés :
Cristallisation fractionnée
Solidification
Échange chimique
Sédimentation
Répartition bimodale
Discontinuité de composition
Chambre magmatique

ABSTRACT

Our aim is to explain the possible bimodality of the compositions of the magmatic rocks of the same province. In order to do so, we present a model for the crystallization of a magmatic chamber, coupling the three phenomena: solidification, sedimentation, chemical reactions between the solid and the liquid. These three phenomena make two independent dimensionless parameters appear: the ratios of the solidification rate to the transport velocity, and of the chemical kinetics to the transport velocity. The model is written for one independent chemical component. It is shown that, for certain values of the dimensionless parameters, the chemical composition of the chamber can present a bimodal distribution, starting from uniform initial conditions. This model shows that the coupling between three elementary phenomena is enough to explain the bimodality, or more generally the appearance of discontinuities of chemical compositions, without making any additional assumption.

RÉSUMÉ

Nous cherchons à rendre compte de la bimodalité possible des compositions des roches magmatiques d'une même province. Pour cela, nous présentons un modèle de cristallisation d'une chambre magmatique couplant les trois phénomènes : solidification, sédimentation, réactions chimiques entre le solide et le liquide. Ceux-ci font apparaître deux paramètres sans dimension indépendants, exprimant les rapports respectifs de la vitesse de solidification sur la vitesse du déplacement solide/liquide, et de la cinétique d'échange sur la vitesse de déplacement. Le modèle est écrit pour un constituant chimique

* Auteur correspondant.
E-mail address: guy@emse.fr (B. Guy).

1631-0713/$ – see front matter
doi:10.1016/j.crte.2010.04.007

indépendant. On montre que, pour certaines valeurs des paramètres sans dimension, la composition chimique de la chambre peut présenter une répartition bimodale, alors que les conditions initiales sont uniformes. Ce modèle montre que le couplage entre trois phénomènes élémentaires suffit à rendre compte de la bimodalité, ou plus généralement, de l'apparition de discontinuités de compositions, sans faire intervenir d'hypothèse additionnelle.

1. Introduction

Associated plutonic intrusions or volcanic emissions within the same province frequently show composition discontinuities (all compositions are not seen equally), on a local or a larger scale (see, for example, Halmlyn and Keays, 1979; Leblanc and Ceuleneer, 1992). One also very often observes bimodal distributions; for instance for the volcanic rocks, on one side the basaltic terms, and the other side the felsic terms (trachytes, phonolites) whereas the intermediate compositions (andesites) are very little represented (for the equivalent plutonic rocks: gabbroic rocks on one side, granitic rocks on the other, with the relative scarcity of intermediate rocks such as quartz bearing diorites or syenites) (Baker, 1968; Bonnefoi et al., 1995; Chayes, 1963; Clague, 1978; Daly, 1925; Gagnevin et al., 2003; Marsh, 2002)). One speaks of the Daly gap for the absence of intermediate terms in the volcanic series of oceanic islands, but the situation is similar in the continental series. In the present article, we wish to explain these features, and particularly the bimodality of the rock compositions, by way of simple models.

Many models have already been proposed for the first understanding of the variety of the plutonic and/or volcanic rock compositions of the same province. The fractional crystallization model is the best example. It suffers important limitations: in the models that are derived from it, nonlinear (composition dependent) chemical partition coefficients between the solid and the liquid are not taken into account (the models are adapted to trace rather than major elements); the relative displacement between the solid and the liquid, and the possible chemical exchanges along this displacement are not taken into account: there is no space variable. This model can be developed within larger models. For convenience, we will distinguish three classes of processes: processes of chemical exchanges between liquids and solids; processes of thermal transfer and solidification; processes of relative movement between the solid and the liquid (in relation to tectonics, or to the density differences between the solid and the liquid). Each one of these classes deserves more thorough development (see (Baker and Mcbirney, 1985; Bons et al., 2004; Godard et al., 1995; Jaupart and Tait, 1995; Jellinek and Kerr, 2001; Kuritani, 2004), for example).

However, the models remain generally specialized in each of the three classes of processes. Coupled models exist, but they only relate to partial aspects of the phenomena, their variety being so large. Also, in the end, the models do not allow a satisfactory answer to the above questions (appearance of bimodality and of composition discontinuities). Many explanations were proposed (see previous papers for example) and we will not discuss them in detail. They generally take us away from the elementary phenomena of fusion/solidification, relative displacement and chemical exchange between the solid and the liquid, and utilize some various additional phenomena (multiple injections, contamination in an open system etc.). In this work, we would like to go back to the elementary phenomena, deciding to consider them *together*. This can only be done at the price of a great simplification of each of them, but the result is a fertile overall picture. In particular, these three phenomena will reduce to two independent dimensionless parameters. These will enable us to discuss the important types of behaviour of the systems. We will take as an example that of the evolution of a closed magmatic chamber. This will be a vertical column containing the magma (with or without some solids) at time zero, along one space dimension, the vertical axis (Fig. 1). The other case of an open system is simpler, in that it corresponds to the subsystem of a larger system, and will also be discussed briefly. The three classes of phenomena are simplified as follows:

- *Solidification* is imposed by the thermal situation of the chamber, in particular the temperature gradient at the top. Without modelling all the heat transfers, we will

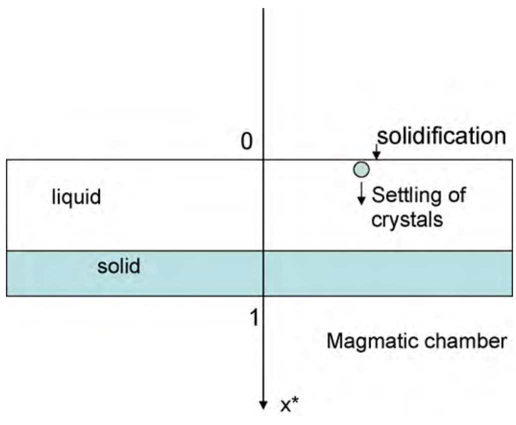

Fig. 1. Schematic view of a magmatic chamber: the vertical axis is the dimensionless *x*-axis used in the text (variation between 0 and 1; it corresponds to thicknesses of several hundreds of meters for natural chambers). The solidification may take place in the upper part of the chamber; the crystals formed subsequently settle and fill the bottom of the chamber (solid).

Fig. 1. Schéma d'une chambre magmatique. L'axe vertical représente la profondeur sans dimension figurée par la variable *x*, variant entre 0 et 1 (correspondant à des épaisseurs de quelques centaines de mètres pour des chambres naturelles). La solidification peut se faire dans la partie supérieure de la chambre ; les cristaux formés peuvent ensuite se sédimenter et remplir le bas de la colonne (partie solide).