Lithos 132-133 (2012) 37–49

Contents lists available at SciVerse ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

The influence of crystal settling on the compositional zoning of a thin lamprophyre sill: A multi-method approach

Teresa Ubide *, Enrique Arranz, Marceliano Lago, Carlos Galé, Patricia Larrea

Earth Sciences Department, Faculty of Sciences, Universidad de Zaragoza, C/ Pedro Cerbuna 12, 50009 Zaragoza, Spain

ARTICLE INFO

Article history:
Received 9 May 2011
Accepted 15 November 2011
Available online 1 December 2011

Keywords:
Sill zonation
Crystal settling
Antecryst
Geochemical modelling
Principal component analysis
Camptonite

ABSTRACT

We have studied a visibly zoned, thin (<0.5 m) lamprophyre sill that crops out in the Catalonian Coastal Ranges (NE Spain). The sill is a camptonite composed of large abundant crystals, mainly of clinopyroxene and amphibole, set in a fine-grained groundmass. The mineral chemistry of the different crystal populations indicates that the large crystals are inherited antecrysts incorporated into the magma before emplacement. The major and trace element whole rock profiles are S-shaped, with the development of a marginal reversal in the lower chilled margin. These profiles cannot be explained by normal fractionation of the magma inwards. Instead, the whole rock zoning is controlled by the presence of antecrysts. This is proven: 1) quantitatively, through a trace element model which evaluates the contribution of the antecrysts to the overall composition of the rock, and 2) statistically, through a principal component analysis on the complete trace element data set. The mineral and groundmass compositions show rectilinear compositional profiles, indicating that the magma was emplaced in a single pulse. The accumulation of the antecrysts towards the bottom of the sill, together with the calculation of settling velocities for clinopyroxene and amphibole and cooling velocities for the magma, indicate that the settling of antecrysts during cooling is responsible for the varying proportions of antecrysts and therefore for the whole rock compositional zoning. This study proves that crystal settling is a significant process in triggering compositional zoning of igneous intrusions even at the cm-scale, provided that the magma carries large crystals upon emplacement.

1. Introduction

Compositional zoning is a common phenomenon in igneous intrusions, regardless of their age, geographical location, form, size, and bulk composition. Tabular intrusions (sills, dikes) are typically used to study compositional zonation, as they allow detailed observations and sampling across the intrusion, from one margin to the other, as well as recognition of gravitational settling mechanisms, where present. Thick sill-like bodies (>50 m) have traditionally been those most studied, due to their normally better developed zonation, with cumulate layers at the lower zones and pegmatoid facies towards the top (e.g., López-Moro et al., 2007). However, some studies have also been carried out on small bodies (Brouxel, 1991; Chistyakova and Latypov, 2009a, 2009b, 2010; Kretz et al., 1985). Several recent studies (Chistyakova and Latypov, 2009b, 2010) highlight the need for more data in cm-scale intrusions, where compositional variations can also be recognised but, where there is less diversity of processes. Small (<0.5 m thick) intrusions can therefore provide the key to a better understanding of the processes operating in more complex geological objects, such as mafic–ultramafic sills, large layered intrusions or crustal magma chambers.

Different explanations have been proposed for the origin of compositional zoning in sill-like bodies (e.g., Latypov, 2009), including single- or multi-pulse injection of crystal-free or -laden magmas, and several other hypotheses (see Chistyakova and Latypov, 2009a, 2009b). Specifically, mechanical processes like crystal settling are regarded as rather irrelevant in the formation of sill zonation by some authors (e.g., Gibb and Henderson, 1992; Latypov, 2003a), although this process has been called on by others to explain differentiation throughout thick intrusions (e.g., Marsh, 2000). In thin (cm-scale) intrusions, the significance of crystal settling is thought to be extremely unlikely in triggering internal compositional zoning (Chistyakova and Latypov, 2009a, 2009b).

Despite being used extensively in other fields of earth sciences, principal component analysis (PCA) is not commonly applied in igneous-mineralogical or -geochemical studies where generally, multivariate statistical methods are rarely used (e.g., Allègre et al., 1995; Cheng et al., 2011; Cortés et al., 2007; Forster et al., 1999; Janousek et al., 2004; Vogel et al., 2008). PCA reduces the dimensionality of a data set consisting of a large number of interrelated variables, retaining as much as possible of the variation present in the data set. This is achieved by transforming to a new set of variables, the principal components (PCs), which are uncorrelated, and ordered so that the first

* Corresponding author. Tel.: +34 976 762 474; fax: +34 976 761 106.
E-mail address: tubide@unizar.es (T. Ubide).

0024-4937/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.lithos.2011.11.012

few retain most of the variation present in all of the original variables (Joliffe, 2002). PCA is, therefore, a powerful tool for the treatment of large geochemical data sets. It permits grouping or, on the contrary, discriminating the compositions taking into account all the elemental contents. In consequence, PCA makes it possible to establish interpretations based on the whole analytical data set.

In this paper, we present a detailed petrological and compositional study of a thin (<0.5 m) alkaline lamprophyre intrusion that crops out in the Catalonian Coastal Ranges (NE Spain). It is a porphyritic zoned sill which contains large, abundant antecrysts. The relationships between mineral and whole rock compositions are tested by applying geochemical modelling and multivariate statistics (PCA); a combination of these methods will be used to unravel the origin of the compositional zoning of the sill, as being due to gravitational settling of the antecrysts after emplacement of a single pulse of magma.

2. Geological context and field observations

The Catalonian Coastal Ranges are a NE–SW trending orogen located in north-eastern Spain (Fig. 1A). Lamprophyric intrusions are quite common in the NE area of the orogen. They intrude both Variscan calc-alkaline granitoids and Paleozoic metasediments. The most common intrusions are late-Variscan in age (Losantos et al., 2000); they make up dense sub-vertical dike swarms that are easily recognisable all along the Costa Brava coast. There are also some late-Cretaceous single intrusions (Solé et al., 2003), which sometimes cut the late-Variscan dikes. These late-Cretaceous intrusions have been described as sills, given that they were emplaced following well-developed structures of the country-rock (sub-horizontal joints or, less commonly, sub-vertical fractures). They were emplaced during the late-Cretaceous crustal relaxation and thinning (Salas and Casas, 1993; Vergès et al., 2002) which allowed the ascent of alkaline magmas (Solé et al., 2003 and references therein).

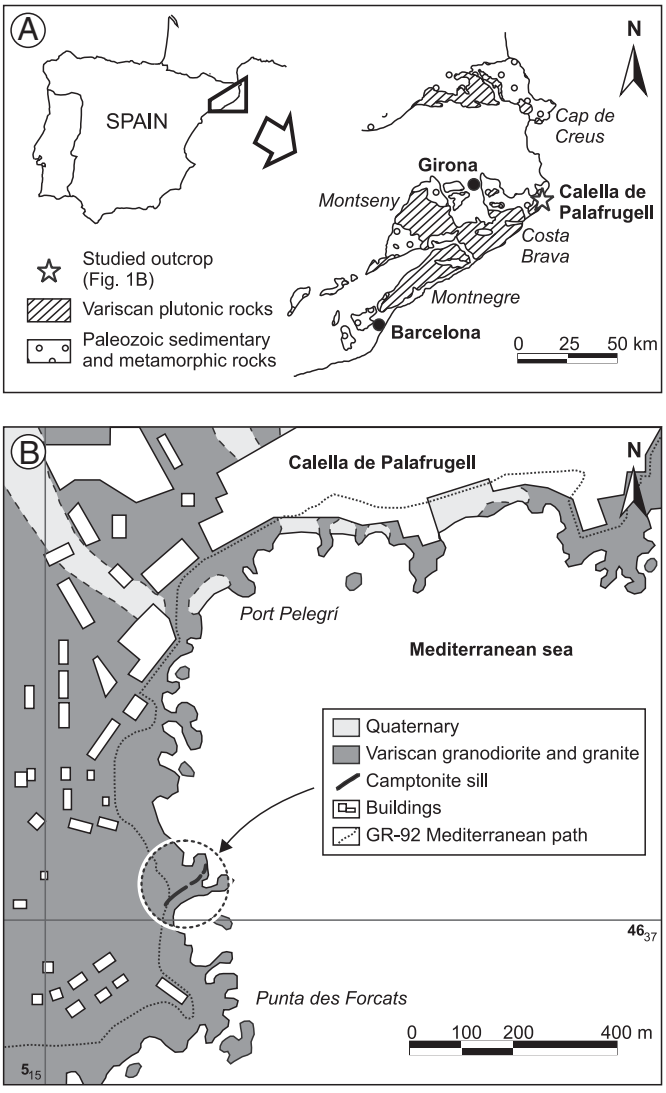

Fig. 1. Location of the studied sill, cross-cutting late-Variscan granitoids.
A) Modified from Enrique (1990). B) Modified from Losantos et al. (2004); UTM grid and coordinates.

Petrologically, neither of these two groups of lamprophyres has been studied in detail, although they are widely reported in papers on regional geology (Calderón et al., 1907; San Miguel Arribas, 1952; San Miguel de la Cámara, 1936; Velde and Tournon, 1970); few studies have dealt with the age of these lamprophyres (Chessex et al., 1965; Solé et al., 2003).

The present paper is focused on one of the late-Cretaceous sills, of particular interest because it is both thin and visibly zoned. It is an alkaline lamprophyre cropping out on the shoreline, near Calella de Palafrugell village (UTM: 31T 515127 4636865, Fig. 1B). The studied sill is a N065–N085 trending, 10–20° northward dipping intrusion, emplaced within late-Variscan granodiorites. It is easily recognisable, as its dark grey colour contrasts with the country-rock granitoid (Fig. 2A). It has sharp contacts and crops out for ca. 100 m. It is divided into sections by small-scale faults and is wedge-shaped, ranging from 15 to 40 cm of observed thickness. The extreme ends of the sill cannot be seen because quaternary debris deposits cover the SW part of the outcrop and the NE part of the sill disappears beneath the sea.

Fig. 2A–B shows the most representative section of the sill, located at the NE part of the outcrop. Wide aphyric chilled margins are developed at both contacts; the upper chilled margin is usually thicker (ca. 5 cm wide), while the lower one (ca. 4 cm wide) displays an incipient lamination. The central facies is ca. 25 cm wide. It exhibits an inequigranular texture resulting from the presence of large mafic crystals measuring up to 7 mm in diameter, which are therefore visible to the naked eye. According to their size, they can be classified as macrocrysts (Le Maitre, 2002). According to their mineralogical composition, these crystals did not crystallise from the magma in which they are now hosted, but rather represent a magma laced with a crystal cargo that has been inherited from other magmas related to the same magmatic system. Therefore, they are "antecrysts", as defined in several recent contributions (Charlier et al., 2005, 2007; Davidson et al., 2007; Gill et al., 2006; Hildreth and Wilson, 2007; Jerram and Martin, 2008). The antecrysts are concentrated at the bottom of the central facies and become progressively scarcer towards its top.

Vesicles are very common and reach 5 mm in diameter; their abundance suggests a shallow emplacement level which enabled the degassing of the magma, together with a fairly fast solidification. Vesicles are concentrated at three levels (Fig. 2A–B): i) the lower chilled margin, where small, irregular vesicles are scattered, ii) the contact between the upper chilled margin and the central facies and iii) the centre of the sill, where vesicles are most abundant. At levels ii and iii, the vesicles define sub-planar zones within the sill, related to its zonation during the cooling evolution of the magma at low pressure.

The particularly well developed vertical division of the studied sill, including wide chilled margins, vesicle alignments and varying proportions of mafic antecrysts, allows it to be divided into the following five zones (Fig. 2A–B): 1) lower chilled margin; 2) lower antecrystic central facies; 3) upper antecrystic central facies; 4) homogeneous central facies; 5) upper chilled margin.

3. Samples and methods

Due to the clear vertical structure of the studied sill and its low degree of alteration, its different zones were studied separately. The