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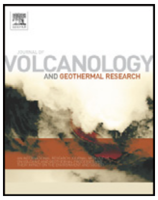

Observing silicic magma transport in dykes at depths of 8–19 km: Evidences from crustal xenoliths and numerical modelling

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ABSTRACT

Within the context of magma transport processes in a dyke, this paper integrates petrography and thermodynamic modelling together with fluid dynamics to model the melting of the wall rock in three magma dykes at crustal depths from 8 to 19 km. Using this combination we explore the interaction between thermal and mechanical processes during silicic magma ascent, and the implications for the relative abundance of different crustal xenoliths erupted at the surface. We utilize a two-dimensional thermal model of dacitic magma injection and flow in dykes of different thickness, lengths and depths and associated partial melting of the wall rock, and compare the results with field examples from the Neogene Volcanic Province, SE Spain.

The modelling results open the possibility to relate the range of observed xenoliths information (microstructures, size, distribution at the surface, P–T evolution) to their position in a transient thermal regime in the wall-rock of a magma conduit, and to the time spent immersed in magma. In addition, the effects of the modelled stress in the wall rock during magma ascent by the presence or absence of planar features in the xenoliths reveal that the stress patterns are independent of the dyke length and thickness.

1. Introduction

On a crustal scale, a magma plumbing system is the place where magmas reside, exsolve their gases, crystallize, mix, differentiate, melt and incorporate the wall rock (e.g. Vigneresse et al. (1996); Kavanagh et al. (2006); Gudmundsson (2011b)). Because direct observation of magmatic plumbing systems is not easy (except for local remnants in deeply eroded extinct volcanoes, including shallow chambers, Gudmundsson (2012a); or in ophiolites and eroded parts of the continental crust), our understanding of processes that occur at depth comes from indirect evidence such as observation of erupted volcanic rocks and gases, as well as geophysical data. As a result, numerous aspects of magma plumbing systems are currently unclear and a matter of intensive research, e.g., processes occurring during magma ascent (Karlstrom et al., 2009); and explosive fragmentation (Fowler and Spera,2010). Attempts to understand volcano behaviour and subsurface processes follow different approaches that are seldomly integrated: numerical simulations (e.g. Bruce and Huppert (1990); Mastin (2002); Costa et al. (2011)), petrology, thermodynamics, and geochemistry (e.g. Spera and Bohrson (2004); Castro and Dingwell (2009); Álvarez-Valero and Waters (2010)); stress and fracture-propagation modelling (Gudmundsson, 2006).

A widely accepted point is that the wide diversity in eruption style cannot be solely explained by fluid mechanical aspects such as conduit/dyke geometry and flow rate (e.g. Melnik and Sparks (1999); Spera and Bohrson (2004); Gudmundsson (2012b, 2014)). Instead, the processes within the conduit/dyke seem to partly determine eruption dynamics, whereas the overpressure evolution depends on magma chamber behaviour (Gudmundsson, 2012a, 2014). Numerical models of conduit and dyke dynamics are based on either direct measurements (Geshi et al. (2010); Galindo and Gudmundsson (2012); Becerril et al. (2013)), or on assumptions related to geometries, temperature distributions, and magma rheology in the magma plumbing system. Therefore the later needs input from petrological and geological studies. Likewise, the complete interpretation of any petrological dataset requires key numerical parameters. This study aims at bridging the gap between different approaches by using key parameters, obtained from natural rocks, for the numerical simulations.

Most of the recent contributions on eruption dynamics and styles (e.g. explosive versus effusive) focus on processes within the conduit, and studies on silicic systems focus on fragmentation processes (e.g. Gonnermann and Manga (2003); Polacci et al. (2004)), mechanical behaviour of the volcano (e.g. Novelo-Casanova et al. (2007); Gudmundsson (2012a); Becerril et al. (2013)), gas content and related

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pressure within magma and conduit (e.g. Sparks (1997); Massol and Jaupart (1999)), viscosity (e.g. Giordano et al. (2008)), heat transfer and Biot number (e.g. Carrigan (1988)), and isotopic studies (e.g. Watts et al. (2010)). Here we combine (at a greater depth than usually considered for conduits) a recent thermodynamic modelling of anatexis at a wall-rock/magma dyke interface (Álvarez-Valero and Waters, 2010) and thermomechanical models of fluid dynamics in the magma dyke itself. Our results in the extinct Neogene volcano of El Hoyazo have direct implications for models of eruption patterns and may help to evaluate eruption styles, because the petrologic observations of the crustal xenoliths (foliation, equilibrium mineral assemblages, mineral ages, size, abundance and distribution), considered as erupted solid materials, record processes within the volcanic dyke through which magma rises from the chamber (see also, Hodge and Jellinek (2012)).

1.1. Geological setting — summary of previous petrological results

Three main metapelitic xenolith-bearing volcanic suites are exposed within the Neogene Volcanic Province (hereafter NVP) in the Betic Cordillera (SE Spain), from SW to NE: El Hoyazo, Mazarrón and Mar Menor (Fig. 1). The xenoliths occur within a high-K calc-alkaline and shoshonitic lava series and are medium to coarse-grained granulite-facies rocks (e.g. Zeck (1970)). There is a striking co-existence of different xenolith types and sizes within each particular volcanic suite (Table 1, Figs. 1, 2). Microstructures and age relationships indicate that a first stage of migmatization and melt extraction produced rhyolite that mixed with an underplating basalt to form the host dacites (Duggen et al., 2005; Álvarez-Valero and Kriegsman, 2007), which was followed by a sequence of melt-bearing reaction microstructures in the xenoliths (Álvarez-Valero and Waters, 2010). At El Hoyazo and Mazarrón, for example, the larger, foliated and more abundant garnet–biotite–sillimanite (Grt–Bt–Sil) xenoliths (c. 60% abundance, up to 50 cm diameter) are restites after a migmatization process (Fig. 2a), whereas smaller, both foliated and non-foliated spinel–cordierite (Spl–Crd) xenoliths (c. 30% abundance, up to 15 cm diameter), are not related to the migmatization event (Fig. 2c, d, see also e.g. Álvarez-Valero et al. (2005, 2007)). The Mar Menor locality shows a similar distinction in xenolith size and amounts between foliated Spl–Crd samples with orthopyroxene (Opx) and non-foliated samples with andalusite (And) (Álvarez-Valero and Kriegsman, 2008; Álvarez-Valero and Waters, 2010).

Microstructures of the xenoliths in the NVP volcanic suites show several grades of foliation mainly marked by fibrolite aggregates and favoured by melt escape through extraction channels (e.g. Cesare et al. (1997); Álvarez-Valero et al. (2005, 2007); Álvarez-Valero and Waters (2010)). Foliations also wrap around phases like plagioclase, andalusite, and garnet porphyroblasts that contain melt inclusions (Cesare et al., 2003; Álvarez-Valero et al., 2005; Álvarez-Valero and Waters, 2010), suggesting a syn-anatectic process.

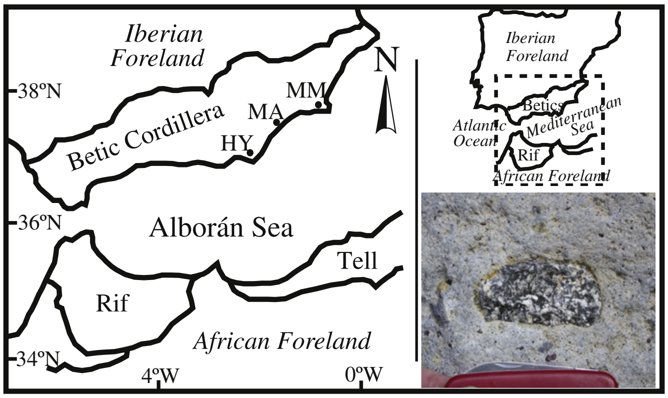

Fig. 1. Geographical location and tectonic sketch map of the Betic Cordillera and Rif (HY = El Hoyazo; MA = Mazarrón; MM = Mar Menor), and field aspect of a Grt–Bt–Sil main xenolith type in the dacitic lava of El Hoyazo.

Álvarez-Valero and Waters (2010) estimated the P–T conditions of the melting processes by a thermodynamic modelling approach. This took into account thermodynamic properties of phases involved in anatectic conditions such as silicate-glass and oxides (spinel and ilmenite), which were not available in previous estimates (same samples) through classical geothermobarometry (e.g. Cesare et al. (1997, 2003); Álvarez-Valero et al. (2005, 2007); Álvarez-Valero and Kriegsman (2007, 2008); Lavina et al. (2009)). Therefore we utilize for the numerical computation the P–T results of Álvarez-Valero and Waters (2010), despite of the previous, diverse and accurate P–T estimates. The calculations show that in two volcanic suites, Grt–Bt–Sil xenoliths contain distinctive fibrolite-melt intergrowths that formed over the range of 700–770 °C, at a pressure of 5–6 kbar in El Hoyazo (Fig. 2a) and 4–4.5 kbar in Mazarrón. These textures were overprinted by (i) newly elongated garnet–spinel-melt assemblages at 800–840 °C and 5–6 kbar in foliated samples (Fig. 2b, Table 1, see also Álvarez-Valero et al. (2005); Álvarez-Valero and Kriegsman (2007)); (ii) newly-grown spinel with melt haloes at 835 °C and 5.8 kbar in foliated samples; and (iii) coronas around garnet containing Spl–Crd-melt and alkali feldspar at 775 °C, 4.8 kbar in poorly to non-foliated samples (Fig. 2c). At Mar Menor, xenoliths show garnet replaced by Opx, Crd, Spl and melt at 810–840 °C, 2–2.5 kbar in foliated samples, and aluminous nodules containing And that is partly replaced by Spl + Crd under the same conditions in non-foliated samples. In summary, the results of the phase diagram modelling described successive stages of the mineralogical assemblage with increasing temperature, from Sil-melt intergrowths, via Spl–Grt-melt and Spl–Crd-melt coronas on Grt, to Opx-bearing coronas, with an increasing proportion of melt, quenched *in situ* as glass, and different grades of deformation (foliation) in each case. The xenoliths also record different pressures related to their geographical location (progressively lower P from SW to NE, i.e. from El Hoyazo to Mar Menor) that were interpreted as progressively shallower levels of magma emplacement at the base of the crust (Álvarez-Valero and Kriegsman, 2007).

Álvarez-Valero and Waters (2010) explained the P–T distribution, size and relative abundance of xenolith types by the formation of the melt-bearing assemblages in a transiently heated wall-rock profile adjacent to a magma dyke, followed by collapse and brief residence as xenoliths in dacitic magma at c. 850 °C. They estimated xenolith residence time in the magma as no more than a few days.

This study focuses a step further on the anatexis and magma flow at depth: i.e., the interaction between the different crustal xenolith types and the thermal and mechanical behaviour of the magma hosting them. In this paper we aim to understand: (i) the processes of magma-wall rock interaction and xenolith incorporation; (ii) the variation of xenolith types both at discrete locations and across the NVP; (iii) behaviour of the ascending magma as a function of its rheology; (iv) the relationship between transient heat transfer and melting of the wall rock; and (v) the effects of deformation in the wall rock during magma ascent by the presence or absence of planar features in the xenoliths. The method described here, i.e. integrating models of magma dynamics and information from crustal xenoliths, can be compared with petrologic and geophysical studies in general flow of magma in dykes in stratovolcanoes and felsic calderas worldwide.

2. Model setup

2.1. Governing equations (steady state)

The NVP xenolith assemblages record a range of P–T conditions and states of reaction development that reflect their position in a transient thermal profile in the wall rock of a volcanic dyke. The NVP volcanism pertains to an intraplate volcanic setting where basaltic intrusions supplied the heat necessary for migmatization, crustal melting and