Earth and Planetary Science Letters 400 (2014) 123–129

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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Pore-space distribution and transport properties of an andesitic intrusion

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ARTICLE INFO

Article history:
Received 31 January 2014
Received in revised form 14 May 2014
Accepted 23 May 2014
Available online 6 June 2014
Editor: J. Brodholt

Keywords:
andesite
pore space distribution
power law scaling
transport properties
weathering reactions

ABSTRACT

The pore structure of magmatic rocks records processes operating during magma solidification and cooling. It has first order effects on the petrophysical properties of the magmatic rocks, and also influences mass transfer and mineral reactions during subsequent metamorphism or weathering. Here, the pore space characteristics of an andesitic sill intrusion were determined by multiscale resolution computed X-ray microtomography (μ-CT), and the 3D structure was used for transport modeling.

Unaltered andesite has a power law distribution of pore volumes over a range of five orders of magnitude. The probability distribution function (PDF) scales with the inverse square of the pore volume (V), PDF $\propto V^{-2}$. This scaling behavior is attributed to the coalescence of pores at crystal–melt boundaries. Large pores are concentrated on the outer margins of amphibole and plagioclase phenocrystals. Incipient weathering of the andesite is associated with preferential growth of weathering products in the largest pores. This can be explained by a model in which diffusion of external components into the porous andesite is controlled by a random network of grain boundaries and/or microfractures. This network preferentially links the larger pores to the system boundaries and it is the major fluid transport pathway, confining incipient weathering into a small fraction of the rock volume only.

1. Introduction

The porosity and pore space distribution in rocks provide first order controls on several petrophysical properties, including elastic moduli, diffusivity and permeability (e.g. Guéguen and Palciauskas, 1994). A broad pore size distribution may also drive internal redistribution of mass due to curvature effects on chemical potentials (Emmanuel and Berkowitz, 2007). This may furthermore control the extent to which crystallization processes in the pores of rocks or porous building materials cause fracturing due to growth related stress generation (Scherer, 2004). It is likely that the rate and progress of any fluid infiltration driven volatilization process in porous rocks, including weathering of igneous and metamorphic rocks, serpentinization of oceanic lithosphere, and carbon sequestration by *in situ* mineral carbonation, is to a large extent affected by the spatial distribution of the pore space as well as by the total porosity.

Recent advances in technology that enable 3D pore structure characterization over a large range of length scales (X-ray tomography, focused ion beam – scanning electron microscopy, neutron scattering, etc.) have dramatically increased our ability to study rock porosity and its effects on rock properties (cf. Zhu et al., 2011; Baker et al., 2012a; Renard, 2012; Keller et al., 2013).

In igneous rocks, porosity is generated when a low-density fluid exsolves from the host magma upon cooling and/or decompression. Bubble formation in rising magmas is a key element in many volcanic processes and has been studied extensively – both experimentally and theoretically (e.g. Sparks et al., 1994; Blower et al., 2002; Yamada et al., 2005; Gonnermann and Manga, 2007; Baker et al., 2012b). Porosity formation during the comparatively slow cooling and crystallization of intrusive rocks has received less attention (see, however Simakin et al., 1999), although it is likely to have a major effect on the petrophysical properties of the magmatic rocks as well as on post magmatic metamorphic or weathering related alteration process.

Here we present a 3D pore space characterization of an andesitic sill intrusion from the Neuquén Basin in Argentina obtained by computed X-ray microtomography. We then analyze the

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http://dx.doi.org/10.1016/j.epsl.2014.05.042

transport properties of a system in which diffusion takes place through a non-percolating pore space, and a matrix in which diffusion is controlled by 2D planar objects such as microfractures and grain boundaries. Our analysis shows that large pores have a higher probability of being part of the transport network than small pores, and thus that large pores will be preferential sites of reaction during post magmatic alteration. This provides a new explanation of why weathering reactions is localized onto only a fraction of the porosity, and why the pore space does not get clogged after incipient reaction.

2. The rock

The 8–10 m thick sill intrusion investigated here is andesitic to dacitic in composition (62–65 wt% SiO_2) and it was sampled near Cuesta del Chihuido in southern Mendoza, Argentina. The intrusion is hosted in the Vaca Muerta Formation of the Medoza Group, a marine limestone-shale unit of Upper Jurassic to Lower Cretaceous age (Leanza and Hugo, 1978). Field relations were described by Jamtveit et al. (2011).

Mineral analysis was performed using the Cameca SX100 electron microprobe at the Department of Geosciences, University of Oslo (see Jamtveit et al., 2011 for details). The magmatic mineralogy is dominated by euhedral plagioclase, amphibole, ilmenite, and apatite with interstitial quartz, albite and K-feldspar (Fig. 1). Plagioclase crystals commonly display oscillatory zoning with a range in composition from An_{30-40} to An_{40-50}. Grain sizes range from about 50 µm to ≈5 mm. Amphiboles are dominated by pargasites and pargasitic hornblende. Even in the best preserved rocks, chlorite occurs among the interstitial minerals and it is presumably formed by deuteric alteration during the late stages of cooling of the magmatic rocks. During spheroidal weathering, the magmatic minerals undergo hydrolysis and oxidation to produce ferrihydrite and carbonates as the main weathering products (Jamtveit et al., 2011).

The total porosity of fresh magmatic rocks measured by He porosimetry was 7.5–7.8%. The He-porosity is consistent with density measurements which indicate a total porosity in the 7–9% range (Jamtveit et al., 2011).

Fig. 1 shows back scattered electron (BSE) images of a fresh andesite. A large number of isolated small pores can be observed both within the plagioclase phenocrysts and within the grains comprising the fine grained groundmass (Fig. 1b). However, the largest pores (>100 µm) are concentrated near the phenocryst-groundmass interface. They often contain chlorite crystals interpreted to have formed at the expense of the original magmatic minerals during the cooling of the magmatic body.

3. The pore space

Two samples of unweathered homogeneous andesite were characterized by multiscale X-ray computed micro-tomography (µCT). Three datasets were obtained at different spatial resolutions. Low resolution data were obtained using a Nikon Metrology model XT H 225 LC industrial type µCT scanner at the Norwegian Geotechnical Institute with a voxel size of 6.6 µm for a 6 mm sized cubic sample. Two additional data sets from a single sample were obtained at spatial resolutions of 0.56 and 2.8 µm on beamline ID19 at the European Synchrotron Radiation Facility (Grenoble, France).

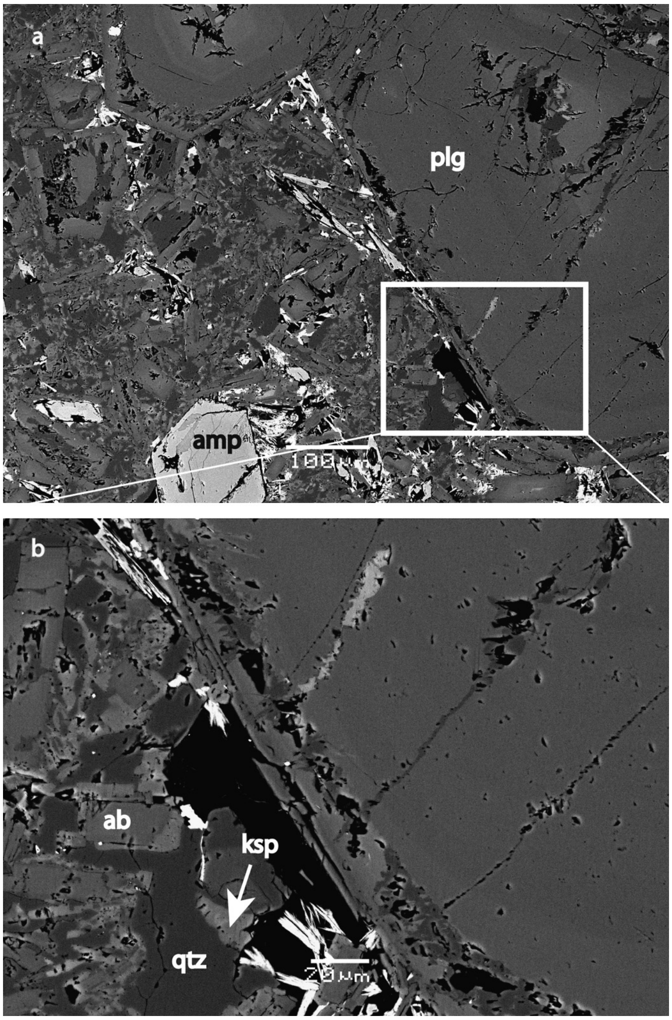

Fig. 1. Back scattered electron (BSE) images of a fresh andesite. (a) Amphibole (amp) and oscillatory zoned plagioclase (plg) crystals are embedded in a groundmass of albite (ab), K-feldspar (ksp) and quartz (qz). (b) Chlorite crystals (brightest color) are observed growing into the largest pores (black). Linear arrangements of small pores within the plagioclase phenocrysts are interpreted as partly healed micro-cracks formed by thermal contraction of the magmatic rock.

For the synchrotron runs, a cylindrical sample of 7 mm diameter and 7 mm height was scanned, and a set of 1500 to 3000 radiographs was reconstructed using a filtered back-projection algorithm into 32-bit gray-level volumes, and then rescaled to 8-bit volumes consisting of 1900 × 1900 × 1000 voxels. A multi-resolution technique was applied allowing imaging of the sample with a large field of view (5.7 mm wide and 2.8 mm high with a voxel size of 2.8 µm) and high resolution imaging of a smaller region near the center of the sample (1.1 mm wide and 0.56 mm high with a voxel size of 0.56 µm). An automatic change of X-ray optical system allowed the position of the sample to remain fixed during these two scans. Having the same reference frame facilitated later comparison and analysis of pore structure at two magnifications.

The software package AvizoFire© was used for data analysis and image processing. The following segmentation procedure was performed to analyze the tomography data. A mask was applied in order to remove the background, and a 3D Gaussian median filter was applied to the original gray-level images to reduce the noise. Then filtered gray images (Fig. 2a,b) were thresholded into binary form. Finally, additional filtering and morphological closing was applied to the binary images before they were segmented into clusters of connected components (pores). Fig. 2c shows the distribution of connected porosity in a ∼300 µm thick slice, where each connected pore cluster is marked by a different color. The 3D volumes of connected pore clusters were measured and used to plot the pore size distribution shown in Fig. 3.

The three data sets were used to analyze the pore size distribution in the andesite. For each data set an upper and lower cut