ARTICLE IN PRESS

EPSL:14128

Earth and Planetary Science Letters ••• (••••) •••–•••

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Giant magmatic water reservoirs at mid-crustal depth inferred from electrical conductivity and the growth of the continental crust

Mickael Laumonier [a,b,c,d,*], Fabrice Gaillard [b,c,d], Duncan Muir [e,f], Jon Blundy [e], Martyn Unsworth [g]

[a] *Bayerisches Geoinstitut, University of Bayreuth, 95440 Bayreuth, Germany*
[b] *Université d'Orléans, ISTO, UMR 7327, 45071, Orléans, France*
[c] *CNRS/INSU, ISTO, UMR 7327, 45071, France*
[d] *BRGM, ISTO, UMR 7327, BP36009, 45060 Orléans, France*
[e] *School of Earth Sciences, University of Bristol, Bristol BS8 1RJ, United Kingdom*
[f] *School of Earth and Ocean Sciences, Cardiff University, Cardiff CF10 3AT, United Kingdom*
[g] *Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada*

ARTICLE INFO

Article history:
Received 21 July 2016
Received in revised form 27 September 2016
Accepted 12 October 2016
Available online xxxx
Editor: J. Brodholt

Keywords:
electrical conductivity
water
andesite
continental crust growth
arc magmas

ABSTRACT

The formation of the continental crust at subduction zones involves the differentiation of hydrous mantle-derived magmas through a combination of crystallization and crustal melting. However, understanding the mechanisms by which differentiation occurs at depth is hampered by the inaccessibility of the deep crust in active continental arcs. Here we report new high-pressure electrical conductivity and petrological experiments on hydrated andesitic melt from Uturuncu volcano on the Bolivian Altiplano. By applying our results to regional magnetotelluric data, we show that giant conductive anomalies at mid-crustal levels in several arcs are characterized by relatively low amounts of intergranular andesitic partial melts with unusually high dissolved water contents (≥8 wt.% H_2O). Below Uturuncu, the Altiplano-Puna Magma Body (APMB) displays an electrical conductivity that requires high water content (up to 10 wt.%) dissolved in the melt based on crystal-liquid equilibria and melt H_2O solubility experiments. Such a super-hydrous andesitic melt must constitute about 10% of the APMB, the remaining 90% being a combination of magmatic cumulates and older crustal rocks. The crustal ponding level of these andesites at around 6 kbar pressure implies that on ascent through the crust hydrous magmas reach their water saturation pressure in the mid-crust, resulting in decompression-induced crystallization that increases magma viscosity and in turn leads to preferential stalling and differentiation. Similar high conductivity features are observed beneath the Cascades volcanic arc and Taupo Volcanic Zone. This suggests that large amounts of water in super-hydrous andesitic magmas could be a common feature of active continental arcs and may illustrate a key step in the structure and growth of the continental crust.

One Sentence Summary: Geophysical, laboratory conductivity and petrological experiments reveal that deep electrical conductivity anomalies beneath the Central Andes, Cascades and Taupo Volcanic Zone image the ponding of super-hydrous andesitic melts which contributes to the growth of continental crust.

1. Introduction

Convergent plate boundaries (subduction zones) are the loci of voluminous magmatism triggered by the release of volatiles, predominantly water, from the subducted plate into the overlying mantle and crust (Grove et al., 2012). Arc magmatism is widely considered to be the primary mechanism of continental crust formation, whereby mantle-derived magmas with basaltic to high-Mg andesitic compositions differentiate within the crust to produce more evolved, silica-rich magmas (e.g. Annen et al., 2006; Castro et al., 2013; Andújar et al., 2015). However, within this conceptual petrological framework, ongoing uncertainty remains about many of the key details, hampering our understanding of the mechanisms of magmatic differentiation, crustal growth and water recycling through subduction zones. For example, although Earth's continental crust has an overall andesitic composition (Rudnick, 1995), it is unclear whether andesite is truly the most abun-

* Corresponding author at: University B. Pascal, Laboratoire Magmas et Volcans, 6 avenue B. Pascal, 63178 AUBIERE Cedex, France.

E-mail addresses: mickael.laumonier@gmail.com (M. Laumonier), fabrice.gaillard@cnrs-orleans.fr (F. Gaillard), MuirD1@cardiff.ac.uk (D. Muir), gljdb@bristol.ac.uk (J. Blundy), unsworth@ualberta.ca (M. Unsworth).

http://dx.doi.org/10.1016/j.epsl.2016.10.023
0012-821X/

Table 1
Chemical compositions of the starting material and experimental glasses from electrical conductivity measurements. Standard deviations are indicated in the italic font below.

	SiO_2	TiO_2	Al_2O_3	FeO	MgO	MnO	CaO	Na_2O	K_2O	Total
GSM13N (Muir et al., 2015)	56.5	1.3	16.3	7.7	5.8	nd	7.9	2.4	1.9	99.8
UTU5 (Sparks et al., 2008)	59.85	1.17	17.26	7.14	3.38	0.11	5.83	2.27	2.99	99.62
Dry starting glass	60.93	1.14	17.20	6.60	3.20	0.12	5.54	2.09	3.17	98.47
	0.27	*0.09*	*0.14*	*0.28*	*0.16*	*0.08*	*0.10*	*0.05*	*0.07*	*0.38*
Exp. UTU5-15kb-0	61.46	1.15	17.10	6.37	3.27	0.01	5.51	2.10	3.02	98.34
	0.20	*0.08*	*0.14*	*0.20*	*0.06*	*0.02*	*0.06*	*0.03*	*0.04*	*0.19*
Exp. UTU5-15kb-1.8	61.37	1.18	17.79	5.82	3.31	0.03	5.31	2.17	3.03	96.65
	0.67	*0.08*	*0.53*	*0.20*	*0.17*	*0.03*	*0.14*	*0.09*	*0.10*	*0.34*
Exp. UTU5-15kb-5.9	61.08	1.17	17.21	6.27	3.40	0.09	5.48	2.11	3.19	92.78
	0.46	*0.12*	*0.30*	*0.46*	*0.60*	*0.11*	*0.19*	*0.07*	*0.10*	*0.24*
Exp. UTU5-15kb-7.2	61.75	1.23	18.38	4.89	3.30	0.01	5.37	2.03	3.03	91.19
	0.77	*0.09*	*0.66*	*0.16*	*0.10*	*0.01*	*0.14*	*0.03*	*0.06*	*0.34*

dant melt composition above subduction zones (Carmichael, 2002; Castro et al., 2013), or whether magma mixing and crustal melting play an important role in producing the observed compositional spectrum (Reubi and Blundy, 2009; Lee and Bachmann, 2014; Laumonier et al., 2014; Keller et al., 2015). Similarly, there is uncertainty over the dissolved magmatic water and carbon dioxide contents of arc magmas and the role that they play in triggering volatile saturation (Blundy et al., 2010), driving compositional diversity (Melekhova et al., 2013) and controlling the depths at which magmas stall and differentiate (Annen et al., 2006; Blatter el al., 2013). Water contents up to 10 wt.% have been measured in andesite melt inclusions (Grove et al., 2012) and inferred from mineral chemistry (Edmonds et al., 2014), whereas most arc basalts appear to contain approximately 4 wt.% H_2O (Plank et al., 2013). Although differentiation of hydrous basalts will tend to increase dissolved H_2O contents, this is only possible at elevated pressures because of the depth-dependent solubility of volatiles. It is unclear whether very high water contents are representative of arc magmas or simply local anomalies resulting, for example, from relatively high-pressure differentiation.

The study of exhumed rocks can elucidate many ancient magmatic processes occurring close to the surface, although the effects of melt solidification and modification during exhumation can confer complications. To image magmatic processes in real time, or at greater depth, geophysical exploration, such as seismic or magnetotelluric (MT) surveys are required. By measuring the crustal-scale conductivity and seismic wave velocity, geophysical exploration has produced 3D images of subduction zone magmatic systems (Comeau et al., 2015; Hill et al., 2009; Ward et al., 2014; Heise et al., 2010). In principle, conductivity and seismic images are able to detect silicate melts in the process of solidification to form plutonic rocks. Such images are not, however, unambiguous in their interpretation as a variety of interwoven factors can produce anomalies in velocity or conductivity. For example, electrical conductivity is sensitive to both the amount and the composition of the melt, including its dissolved water content, and also to pressure and temperature (Gaillard, 2004; Laumonier et al., 2015). The interpretation of MT data must be informed by laboratory studies of the electrical conductivity of melts at relevant pressure and temperature. To minimize ambiguity this interpretation must be placed in a petrological and geological context that includes the composition (and water content) of melt reservoirs and their distribution within the crust. In this study, we characterize the effects of temperature, pressure, dissolved water content and melt fraction to develop a model of electrical conductivity that can be used to interpret crustal conductivity anomalies due to andesitic partial melt. By combining our results with petrological experiments we are able to reveal the presence of large amounts of water dissolved in partial melts in mid crustal reservoirs formed by ponding of melts at their water-saturation depth.

2. Methods

2.1. Starting materials and hydration of samples

Samples for the electrical conductivity measurements were prepared from an andesitic inclusion (UTU5; Table 1) from Cerro Uturuncu, a Pleistocene volcano on the Bolivian Altiplano (Sparks et al., 2008). The andesite inclusions are hosted by dacite lava flows, which are the dominant eruptive product from Uturuncu. The andesites represent quenched intermediate magmas mixed into the dacites shortly before eruption (Sparks et al., 2008). A similar Uturuncu andesite sample was used in the phase equilibrium experiments (Table 1). The natural rock was crushed to powder and fused twice at atmospheric pressure to produce a homogeneous, volatile-free glass. This glass was used for both dry experiments and as the starting material for the hydration syntheses in a piston cylinder and internally heated pressure vessel as described in Laumonier et al. (2015).

The water content in the glass was measured before and after the experiments with infra-red spectroscopy at ISTO (Microscope IR Continuμm coupled with a Nicolet 6700 spectrometer and a MCT detector, Orleans, France) and BGI (Bruker IFS 120HR FTIR spectrometer, Bayreuth, Germany) using a KBr beam splitter. At least 128 scans with a resolution of 4 cm^{-1} were carried out for each spectrum. Each sample was analyzed through 7 to 25 spots to check for homogeneity of the water concentration. We used a linear baseline correction to determine the peak height absorbance, and calculated the water concentration by the Beer–Lambert law, using extinction coefficients for dacite with similar composition (Ohlhorst et al., 2001). The thickness of the sample was measured by a Mitutoyo digital micrometre and checked by the calibrated stage of the microscope. To minimize the uncertainty, samples were kept as thick as possible but transparent for IR rays (thickness <200 μm). Depending on the water content, the sample thickness and transparency, either the fundamental H_2O-stretching vibration (3530 cm^{-1}) or the molecular water (5200 cm^{-1}) and OH- (4500 cm^{-1}) stretching vibrations were used. The propagated uncertainty takes into account the accuracy of (i) the thickness, (ii) the absorbance peak height, (iii) glass density and (iv) extinction coefficient, resulting in a typical error in [H_2O] of 0.5 wt.%. After experiments, the samples were inspected to verify that the chemical composition of the glasses closely matched the starting material (Table 1) and the water content measured after experiments ranges between 1.7 and 9.0 wt.% (Fig. 1).