Earth and Planetary Science Letters 486 (2018) 119–128

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Formation of magmatic brine lenses via focussed fluid-flow beneath volcanoes

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A R T I C L E I N F O

Article history:
Received 17 August 2017
Received in revised form 15 January 2018
Accepted 18 January 2018
Available online xxxx
Editor: T.A. Mather

Keywords:
magmatic fluid
ore deposit
transport in porous medium
brine lens
electrical resistivity

A B S T R A C T

Many active or dormant volcanoes show regions of high electrical conductivity at depths of a few kilometres beneath the edifice. We explore the possibility that these regions represent lenses of high-salinity brine separated from a single-phase magmatic fluid containing H_2O and NaCl. Since chloride-bearing fluids are highly conductive and have an exceptional capacity to transport metals, these regions can be an indication of an active hydrothermal ore-formation beneath volcanoes. To investigate this possibility we have performed hydrodynamic simulations of magma degassing into permeable rock. In our models the magma source is located at 7 km depth and the fluid salinity approximates that expected for fluids released from typical arc magmas. Our model differs from previous models of a similar process because it is (a) axisymmetric and (b) includes a static high-permeability pathway that links the magma source to the surface. This pathway simulates the presence of a volcanic conduit and/or plexus of feeder dykes that are typical of most volcanic systems. The presence of the conduit leads to a number of important hydrodynamic consequences, not observed in previous models. Importantly, we show that an annular brine lens capped by crystallised halite is likely to form above an actively degassing sub-volcanic magma body and can persist for more than 250 kyr after degassing ceases. Parametric analysis shows that brine lenses are more prevalent when the fluid is released at temperatures above the wet granite solidus, when magmatic fluid salinity is high, and when the high-permeability pathway is narrow. The calculated depth, form and electrical conductivity of our modelled system shares many features with published magnetotelluric images of volcano subsurfaces. The formation and persistence of sub-volcanic brine lenses has implications for geothermal systems and hydrothermal ore formation, although these features are not explored in the presented model.

1. Introduction

Magmatic systems beneath volcanoes not only produce magmas that can erupt at the surface, but also discharge hot magmatic fluids originally dissolved in silicate melts stored at depth (e.g. Edmonds and Wallace, 2017). Fluids are released as magma cools and solidifies or as it ascends and decompresses, due to a combination of the low volatile content of crystallising silicate minerals and the pressure-dependent solubility of volatile species in melts. Magmatic fluids comprise mixtures of, in order of decreasing abundance, H_2O, CO_2, sulphur species (SO_2, H_2S), halogen species (NaCl, KCl, HCl, HF), methane and hydrogen, together with a wide range of dissolved solutes, including ore metals (e.g. Pokrovski et al., 2013). Fluids may occur in a supercritical state or as mixtures of low density vapour (gas), higher density liquids (e.g. brines), and precipitated solutes depending on the pressure–temperature (P–T) conditions of fluid release and its initial chemical composition. Released magmatic fluids experience a variety of fates: they may be discharged co-eruptively with magma, escape passively during periods of volcano dormancy, or drive hydrothermal circulation, rock alteration and mineralisation.

A magmatic fluid undergoes chemical and physical changes in response to the temperature and pressure drop associated with release and ascent. Of particular interest in this regard are H_2O–NaCl fluids released from magmas emplaced in the shallow crust: phase relations in this system dictate that supercritical fluids released from magma stored at pressures of ∼120 MPa or more undergo phase separation as they ascend, forming a mixture of low-salinity vapour (steam), high-salinity liquid (brine) and solid (halite). Chloride-bearing fluids have an exceptional capacity to transport metals, due to the ligand-forming ability of Cl^- ions (Pokrovski et al., 2013), whereas low-salinity vapours have con-

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https://doi.org/10.1016/j.epsl.2018.01.013

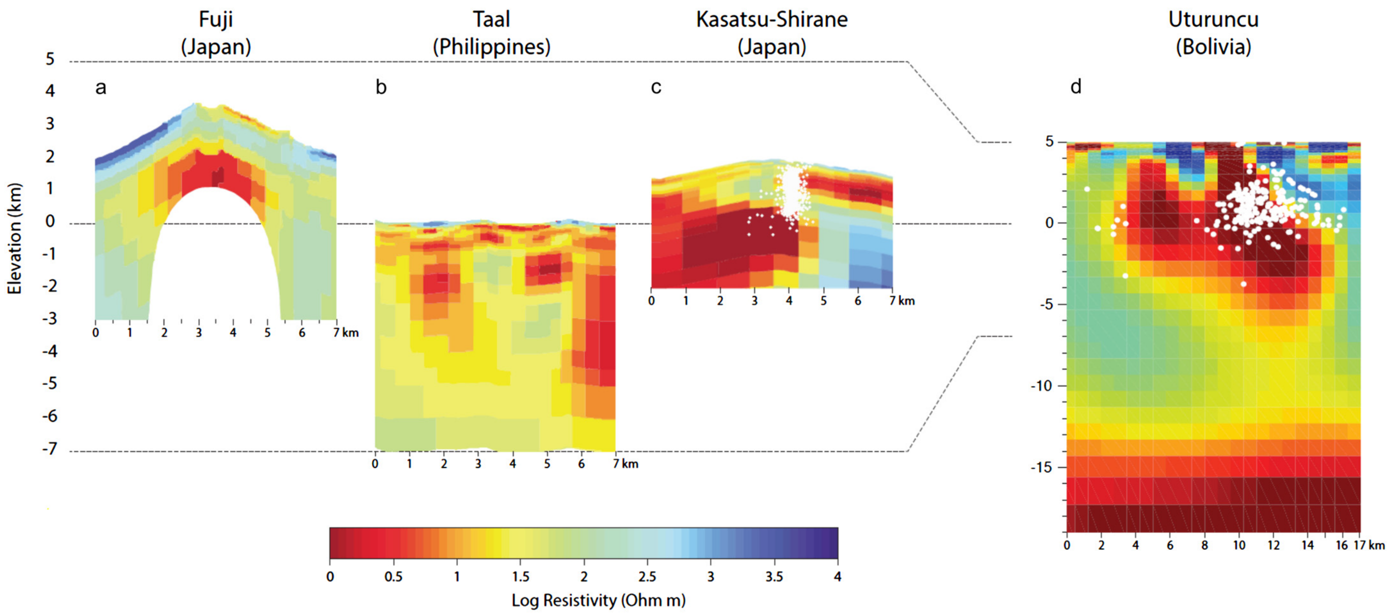

Fig. 1. Electrical conductivity images of four arc volcanoes as determined by magnetotelluric (MT) surveys. In each image the original, published figure has been redrafted to provide consistency in resistivity contours (coloured bar) and dimensions. (a) Mount Fuji (Japan) after Aizawa et al. (2005). (b) Taal (Philippines) after Yamaya et al. (2013). (c) Kusatsu–Shirane (Japan) after Nurhasan et al. (2006). (d) Uturuncu (Bolivia) after Comeau et al. (2015). Earthquake hypocentres in (c) and (d), as reported by the original authors, are shown as small white dots.

siderable heat-carrying capacity (Arnorsson et al., 2007). Thus, the fate of H_2O–NaCl fluids has relevance to both hydrothermal ore deposit formation and geothermal power generation. Their behaviour is a complex function of original fluid chemistry, the *P*–*T* path they follow during ascent, the physical characteristics (porosity, permeability) of the rocks through which they pass, and the extent of any chemical interactions with host rocks and meteoric water. In this study we use numerical modelling to explore the evolution of H_2O–NaCl fluids released from shallow crustal magma bodies beneath volcanoes. We compare our results to geophysical images, from magnetotelluric surveys, of the volcanic subsurface to assess the extent to which fluids are accumulated, dispersed or released to the surface. A focus here is the hypothesis that some features of the geophysical images can be explained by the accumulation of large volumes of brines exsolved from ascending magmatic fluids (e.g. Fournier, 1999).

2. Geophysical images of the volcanic subsurface

The subsurface chemistry and distribution of magmatic fluids beneath volcanoes can be sampled directly through drilling of boreholes or imaged by geophysical techniques, of which the most widely used are magnetotelluric surveys of electrical conductivity. Direct sampling is relatively limited spatially, due to the challenges of deep drilling into hot rocks and the difficulty of recovering pristine fluids. Deep boreholes drilled through geothermal reservoirs in Japan (Kakkonda; Kasai et al., 1998) and Italy (Lardarello; Cathelineau et al., 1994) have identified brines as an important component of the subsurface fluid inventory. However, in both cases the fluids are recovered at temperatures lower than those at which they would have been released from the parent magmas.

The high electrical conductivity of brines (e.g. Sinmyo and Keppler, 2017), compared to melts, rocks and vapours, makes them ideally suited to electrical conductivity surveys. Magnetotelluric (MT) images, obtained for several active and dormant volcanoes, testify to the potential presence of magmatic brines and provide clues to their distribution. Although the configurations and detailed interpretations of MT surveys vary from volcano to volcano, a number of common features emerge. In Fig. 1 we summarise these with respect to MT surveys at four active or dormant volcanoes, typical of magmatic arcs above subduction zones: Mount Fuji (Japan; Aizawa et al., 2005), Kusatsu–Shirane (Japan; Nurhasan et al., 2006), Taal (Philippines; Yamaya et al., 2013), and Uturuncu (Bolivia; Comeau et al., 2015). These volcanoes were chosen to span a wide range of eruption styles and magma compositions.

Mount Fuji is a dormant basaltic stratovolcano in central Honshu that last erupted from its flanks in 1707 (Yoshimoto et al., 2010); the last summit crater eruption was ∼2200 yr ago. Taal volcano, at the southwestern end of Luzon, Philippines, has erupted 33 times since 1572. The last major eruption from its main crater was in 1911; phreatic eruptions from the flanks occurred in 1965 to 1977. Taal has produced a wide spectrum of lava compositions from basalt to rhyolite (Castillo and Newhall, 2004). Kusatsu–Shirane is a Quaternary andesitic to dacitic stratovolcano 200 km north of Mount Fuji. It has experienced numerous phreatic eruptions since 1803, most recently in 1983 (Takano et al., 2008). Finally, Cerro Uturuncu is a 6000 m high dacitic lava-shield volcano in the Bolivian Altiplano (Sparks et al., 2008). It last erupted ∼250 kyr ago; current signs of activity are limited to sulphurous fumaroles near the summit. Uturuncu overlies the giant Altiplano–Puna geophysical anomaly, thought to represent a mid-crustal accumulation of water-rich andesitic melts (Laumonier et al., 2017).

Beneath each of these four volcanoes lie conductive, low resistivity (0.1 to 1 Ω·m) bodies at depths of 1–2 km or more below the surface, embedded within a less conductive medium (≥10 Ω·m). At Kusatsu–Shirane (Fig. 1c) the conductor is displaced laterally by about 1 km relative to the volcanic edifice. The shape of the conductive body varies from volcano to volcano, but typically has a horizontal dimension of 2–5 km. The vertical extent of the conductor is less well resolved, but may exceed several km, e.g. almost 10 km in the case of Uturuncu (Fig. 1d). Taal and Uturuncu (Figs. 1b and 1d) are underlain by a pair of conductive bodies partially separated by a less conductive vertical structure with a resistivity similar to that of the surrounding region. In those studies where earthquakes have been co-located with the resistivity image the hypocentres lie within the upper reaches of the conductor (Fig. 1c and 1d). At all four volcanoes another conductive body (0.1 to 1 Ω·m) lies at very shallow depths. This body is limited in