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Mount Etna volcano (Italy). Just a giant hot spring!

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ABSTRACT

It is usually believed that volcanoes explicate their activity erupting magma, in which volatiles (mostly H_2O) are dissolved in modest quantities. At Mount Etna, the maximum H_2O found in olivine melt inclusions is 3.5 wt%, which would correspond to a moles H_2O/mol basalt ratio of 0.14. A reappraisal of published data is proposed here, and a comparison is made between the gas flux and the volume of erupted lavas. The results are surprising: the moles H_2O/mol basalt ratio is 1.41, which means that Mount Etna erupts 10 times the maximum H_2O that could be dissolved in magma and 40% more moles of gas (H_2O, CO_2 and S) than moles of basalt. By calculating the molar volume of the basaltic melt components (silicate tetrahedra and metallic cations) and of the gas phase at a pressure of 250 MPa, it is possible to envisage the magma within the deep plumbing system as a solution made of ~70% continuum gas phase (mostly H_2O) at a supercritical state (density 360 kg/m^3) and 30% basaltic melt components. The transition from this low-density (1140 kg/m^3) water melt solution (WMS) to the high-density (2800 kg/m^3) basalt, usually erupted (defined as a continuous melt phase, CMP), occurs in the last 2 km and marks the boundary between a deep and a shallow plumbing system. The depth of this boundary varies with time, being driven by the rate at which the gas escapes the WMS to feed the persistent gas plume at the summit craters, leaving the CMP, which accumulates within the shallow plumbing system, until erupted. The overpressure of the gas phase in the WMS, acting like a piston cylinder, is fundamental in driving the eruption. In this work, the thermal contribution provided to the CMP by the large gas flux has also been considered, proving that it can supply the heat necessary to maintain the CMP. The volcano is here considered a dynamic system in which the eruptive activity is ruled by discontinuities in the flux of gas and heat. Negative fluctuations in the gas flux would decrease the heat supply, promote viscosity and trigger eruptions. Moreover, this view of the volcanic system, subverting the common paradigm in which the gas emitted is associated with an equivalent amount of degassing magma, explains the phenomenon, known as the 'excess degassing problem', which affects volcanoes of basaltic and andesitic nature worldwide.

1. Introduction

Studies on volcanic gas on Mount Etna have chiefly focused on monitoring the eruptive activity to achieve short to mid-term eruption predictions based on the supposed relationship between gas flux and the supply of fresh magma. This approach stems from the 'mainstream belief' that volatile elements, by large, originate together with the basalt during the partial melting of the upper mantle. The molten phase would keep the volatiles dissolved until the pressure reduction, changing solubility conditions, drives gas exsolution, boiling and, finally, eruption (cf. Oppenheimer, 2003). One of the key points of this paradigm is that each gas species in the magma has its own solubility depth; mass ratios of different gas species (in particular CO_2/SO_2 - Aiuppa et al., 2007) should therefore indicate the rise of fresh magma that is potentially able to erupt. However, this paradigm has proven to be elusive in forecasting eruptions; only considering since the last decade, many explosive outbursts or long-lasting lava effusions have occurred on Mount Etna, and no successful predictions have been made irrespective of gas ratios. Such lack of 'experimental results', although significant, is not the main fault of such a paradigm. Most critical is the 'excess degassing' problem, i.e. in a given period of time, a volcano emits a greater quantity of gas than the amount that could be dissolved into the molten phase that effectively erupted through the same period (Andres et al., 1991; Keppler, 1999; Sharma et al., 2004). To resolve such an incongruence, observed in many volcanoes worldwide, both of basaltic and andesitic compositions, some authors have envisaged a continuous flux of fresh magma that rises almost to the surface and then degasses and sinks down to form dense plutonic bodies beneath the volcano ('magma convective degassing paradigm' Kazahaya et al., 1994; Shinohara, 2008).

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Fig. 1. Photo of the rim of Mount Etna Summit Craters. In contrast to the common belief, most of the gas in the persistent plume is not released by the free surface of magma but is instead emitted by a pervasive network of fractures diffused on the craters' walls and terraces.

1.1. Excess degassing problem on Mount Etna

Mount Etna is an open-conduit volcano that does not escape the fate of excess degassing. Located on the eastern coast of Sicily, for most of its bulk (~370 km^3 - Catalano et al., 2004), the volcano is composed of Na-rich basaltic hawaiites (Corsaro and Cristofolini, 1996; Tanguy et al., 1997), erupting at times trachybasalts (Schiano et al., 2001; Ferlito and Lanzafame, 2010). The summit craters are the culmination of the open-conduit feeding system, which is partitioned into four, permanently active, craters (Voragine, VOR; Bocca Nuova, BN; North East Crater, NEC and South east Crater SEC), usually characterised by three types of activity:

a) Non-eruptive emission of the gas plume through the free surface of lava within the conduits or through fumaroles spotting the inner walls of the craters (Fig. 1). This is a persistent and by far the most significant emitting activity of the Etnean volcano; the gaseous release is impressive, with SO_2 flux between 840 and 21,000 tons/day (t/d) (average 5000 t/d during non-eruptive periods) (Allard et al., 1991) (Fig. 2).
b) Effusive eruptions with low emission rate (typically < 4 m^3/s), scarce or null explosiveness, and long duration (months/years), generally occurring on short fractures at the base of SEC and NEC (Fig. 3).
c) Violent explosive eruptions (paroxysms) occurring on the main vents of all craters, with lava fountains of up to 1 km high, fast lava flows, high emission rate ($\gg$100 m^3/s) and short duration (hours), (Fig. 4).

On Mount Etna, the problem of excess degassing can be highlighted through a valuable record of data on SO_2 flux in the persistent gas plume through the summit craters collected for almost 30 years during eruptive and non-eruptive periods. As an example, between 1987 and 2000, the average flux of SO_2 not associated with any eruption was ~5450 t/d (> 20,000 t/d during eruptive paroxysms) (D'Alessandro et al., 1997; Bruno et al., 1999; Caltabiano et al., 2004). SO_2 is only part of the volatiles emitted; SO_2 is ~60% of CO_2 and only 10% of H_2O (Aiuppa et al., 2008); similar results are obtained from melt inclusions (MI) in olivines, which also show that Cl is present in amounts comparable with SO_2, whilst F is present at about half the amount of Cl (Métrich et al., 2004; Spilliaert et al., 2006).

Now, if we consider this gas flux as associated to equivalent amounts of magma as in the 'magma convective degassing paradigm' (Kazahaya et al., 1994; Shinohara, 2008), the continuous SO_2 flux in the gas plume would be produced by the exsolution of the S present in the magma. According to Allard et al. (2006), to produce the observed SO_2 emission (~5450 t/d during non-eruptive periods), a continuous flux of 3.7 m^3/s of non-erupted magma is needed. This flux of magma (~10,000 kg/s, considering a magma density of 2.8 t/m^3) should rise through the crust and the volcanic edifice well above the gas exsolution depth (6–7 km for H_2O; 3–4 km for SO_2, < 1 km for Cl and F - Métrich et al., 2004); climbing at high speed (~10 km/h, for meter size conduit), it should approach the summit of the volcano (3340 a.s.l.), lose its entire gas content, increase in density, sink and leave its place to another amount of ~10,000 kg of fresh magma in just 1 s. The sinking basalt would solidify at a depth, contributing to the growth of a subvolcanic plutonic complex (Hirn et al., 1991; Laigle et al., 2000). However, this theory is not at all convincing, and some of its weak points are summarised as follows:

a) It is practically impossible to extract all the volatiles from 10,000 kg of magma in 1 s within ~meter-wide conduits in non-eruptive/magma-disruptive conditions (Gonnermann and Manga, 2012).
b) The undercooling induced by volatiles' loss would promote massive crystal nucleation, increasing yield strength and viscosity, hindering magma recycling and causing the closure of the open-conduit in a short time (cf. Ferlito et al., 2009a, 2009b).
c) To sustain an SO_2 flux of ~5450 t/day (considering an average S content dissolved in magma of ~0.2 wt% - Métrich et al., 2004; Spilliaert et al., 2006), it is required that each day, a volume > 100,000 m^3 of basalt is transferred from depth to be stored cold and dense, once degassed, within the volcano edifice or right beneath it. This would imply a continuous and impressive inflation of the volcano, far larger than what is effectively measured (Bruno et al., 2012).
d) Furthermore, in the convective paradigm, the degassing of magma is considered complete, which is unlikely: it is a frequent occurrence when analysing the chemical composition of samples from lava flows that have been degassing for hours before solidification to measure loss on ignition, up to 1.0 wt%; considering that the highest H_2O found in melt inclusions (MI) is 3.5 wt% (Métrich et al., 2004), a large fraction of it is unable to exsolve, remaining trapped in the melt. This means that the flux of magma (3.7 m^3/s) envisaged by Allard et al. (2006) to sustain the measured gas flux is