Open-vent volcanoes: a preface to the special issue

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Open-vent volcanoes are special systems where the dynamics of sustained magmatic processes can be thoroughly investigated and where new monitoring tools can be tested and applied. They provide a window into the plumbing system and hence play a crucial role in increasing our understanding of fundamental physical and chemical processes below the surface. However, open-vent volcanoes remain puzzling in various aspects and forecasting their behaviour is still challenging. Some of these volcanoes have a clear bimodal eruptive pattern with well-established surface activity, interrupted at times by paroxysms, as has been noted for Stromboli (Italy; Bertagnini et al. 2011; Rose et al. 2013; Métrich et al. 2021) and Villarica (Chile; Johnson and Palma 2015; Aiuppa et al. 2017). Such paroxysmal eruptions and hazardous fissure-type eruptions that can drain persistent lava lakes resident in summit craters, as at Ambrym for example (Németh and Cronin 2011; Shreve et al. 2019), represent one of the major hazards at open-vent volcanoes. This can pose a high-risk problem to nearby population and tourists. This special issue thus brings together a series of papers that aim at a better understanding of such volcanic systems and their associated hazards.

Open-vent volcanoes can be active in various geodynamic contexts. As reviewed by Rose et al. (2013), their erupted lavas span a wide range of chemical compositions from basalts to nephelinite or trachy-andesite and phonolite. Besides bulk chemistry and volatile content, magma viscosity is strongly influenced by temperature (Giordano and Dingwell 2003; Lelosh et al. 2015). Low-viscosity systems are characterised by permanent plumes and gas emissions,

persistent explosive activity and/or frequent emissions of lava flows, whereas high-viscosity magma may be able to retain gas for longer and promote lava dome growth. These systems may remain continuously active over time periods spanning decades to millennia, whereas changes in activity style and intensity can occur over short (hours–days), medium (weeks–months) and long (years–decades) time scales.

The definition of open-vent systems, although seemingly simple to understand at first glance, is not straightforward (Rose et al. 2013; Vergnolle and Métrich [this issue](#)). An open-vent system exists when the same eruptive pattern lasts for a long period. The duration of the Pu'u'O'o eruption of Kilauea, Hawaii (> 30 years) clearly places this eruption into the category of open-vent systems, even though Kilauea volcano behaves mostly as a closed-vent system (Patrick et al. 2020). The definition of open-vent systems becomes even more complicated when the magma-free surface is not well exposed. Some volcanoes may have debris-covered vents, the thickness of the debris layer being variable and mostly unconstrainable. For example, some explosions at Stromboli (Italy) are produced from debris-covered vents (Patrick et al. 2007). However, these explosions, which have different explosion characteristics (Schmid et al. 2021), do not disturb the steady pattern characteristic of Stromboli, making it one of the best examples of an open-vent system. Another aspect to consider is degassing at the vent. Volcanoes with a large gas flux at the surface may be considered as belonging to the open-vent systems category, such as Popocatepetl (Mexico), even though its current activity only started 15 years ago (Quezada-Reyes et al. 2013; Gómez-Vázquez et al. 2016; Campion et al. 2018). The quasi-steady eruptive pattern at Santiaguito (Guatemala), which has been ongoing for almost a century, is another example of an open-vent system, despite its weak degassing (Rose 1973, 1987; Harris et al. 2003; Bluth and Rose 2004; Holland et al. 2011; Rose et al. 2013; Lamb et al. 2019).

Two main types of surface activity characterise open-vent systems: exposed magma columns and lava lakes. While they both have exposed magma/lava at the surface,

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the distinction between the two types is important, as additional processes may develop in the lava lake which can partially hinder and/or influence the processes occurring in the underlying conduit. The exposed surface of the magma varies greatly in size between small, if contained in the conduit or just attaining the level of the vent, to large at lava lakes where lava fills a larger pit at the head of the conduit. In this respect, Erebus (Antarctica), classically described as a lava lake (Lev et al. 2019), should in fact be classified as the top of a magma column due to its small diameter being similar to that of the conduit (Bouche et al. 2010). Other classic and well-studied examples of exposed magma columns are represented by Stromboli, as well as Yasur (Vanuatu; Vergnolle and Métrich, this issue). At the time of writing (March 2021), there have been active lava lakes at Erta Ale (Ethiopia, since 1967), Villarica (Chile, since 1985), Masaya (Nicaragua, intermittent since 1858–1859 and re-emergent in 2015–2016) and Nyiragongo (Democratic Republic of Congo, since 1928) (e.g. Tazieff 1968, 1977; Aiuppa et al. 2018).

The surface activity at lava lakes, whose diameter is larger than the conduit, is very well quantified in terms of magma motion at the surface (Lev et al. 2019). Long and short time series exist for the level of the lava lakes at Erta Ale using satellites-derived measurements (Oppenheimer and Francis 1997; Vergnolle and Bouche 2016), Kilauea using continuously operating cameras at the crater rim (Patrick et al. 2015; 2019), and Nyiragongo using sporadic visual observations for the period 1948–2020 (Poucllet and Bram 2021) and INSAR data (Wauthier et al. 2012). The recent disappearance of lava lakes at Ambrym, Vanuatu (up to 5), which had been persistent for several decades, resulted in magma drainage ($> 0.4 \text{ km}^3$) into the rift zone to feed a submarine eruption (Shreve et al. 2019). This dramatic event poses the question: how do open-vent systems suddenly change, with a well-established surface behaviour suddenly stopping. The final stage of the long-lasting eruption of Pu 'u 'O 'o at Kilauea (Patrick et al. 2020) provides another impressive example of a well-documented drainage process (Neal et al. 2019). Instead, variations in magma level are more difficult to quantify at open-vent systems without lava lakes, but small variations involving a few tens of meters are known to occur from the time delay between event onsets recorded in infrasonic and thermal data (Ripepe et al. 2002).

A key question has been how do such systems remain active and open for such long periods? One way to maintain hot magma at the surface is by quasi-permanent degassing (Giberti et al. 1992). The degassing has tended to be associated with magma convection in the conduit and a persistent gas flux (Kazahaya et al. 1994; Stevenson and Blake 1998; Witham and Llewellyn 2006; Witham et al. 2006; Palma et al. 2011). Surface gas emissions are mainly composed of H_2O , CO_2 and SO_2 in variable proportions (Symonds

et al. 1994; Shinohara 2008). All volatiles start to exsolve at depth but carbon dioxide exsolution begins earlier than most other volatiles as it becomes oversaturated at greater pressure. This results from the pressure dependence of its solubility in magma (Shishkina et al. 2014). As a result, recording the CO_2 flux is a key constraint for degassing processes (e.g. Baubron et al. 1990; Gerlach and Taylor 1990; Gerlach et al. 2002). However, CO_2 flux is rarely monitored in a continuous manner, but can be derived from CO_2/SO_2 ratios and remotely sensed SO_2 fluxes (Aiuppa et al. 2017). Therefore, one has to rely to the SO_2 flux to assess shallow degassing; an assessment which is complicated by its complex behaviour in the plumbing system and at the vent which results from its multi-valence states and dependence on parameters such as $f\text{O}_2$, $f\text{S}_2$, pressure and magma composition (Wallace and Edmonds 2011; Métrich 2021). However, the use of satellites has led to improved quantification of SO_2 fluxes worldwide while also revealing new degassing sites in remote areas where passive SO_2 emissions were previously unknown (Carn et al. 2017). Retrieved SO_2 fluxes vary greatly, between a few tens to hundreds of tons per day, as at Erta Ale (Oppenheimer et al. 2004; Sawyer et al. 2008; de Moor et al. 2013), to hundreds of thousands of tons per day as recorded at the Ambrym lava lakes (Allard et al. 2016). There is a broad consensus that the amount of gas released is positively correlated with the volume of degassing magma (e.g. Andres et al. 1991; Francis et al. 1993; Allard 1997; Harris and Stevenson 1997a, b). The very large SO_2 flux at Ambrym, for example, must be related to an equally large volume of degassed basaltic magma, whereas the lower flux at Erta Ale must in turn be related to a smaller volume (Oppenheimer and Francis 1997; Vergnolle and Gaudemer 2012).

Open-vent systems emit more gas than magma, this being the so-called excess degassing phenomenon (e.g. Andres et al. 1991; Francis et al. 1993; Kazahaya et al. 1994, Shinohara 2008). The pioneering work of Stevenson and Blake (1998) reconciled this apparent paradox by invoking the existence of conduit convection. In this model, the co-existence of gas-rich magma and partially outgassed magma in the conduit (Gurioli et al. 2014) corresponds to a bi-directional flow in the conduit (Kazahaya et al. 1994). One model involves a central rising core of gas-rich magma superimposed on the downward annular flow of degassed magma (Burton et al. 2007). This model assumes that the volume flux in the central flow is maximal. However, a few experimental studies (Huppert and Hallworth 2007; Beckett et al. 2011; 2014) have shown that the net ascending flux of the less dense, less viscous, magma cannot be determined so simply. In addition, the effect of the angle of the conduit (inclined or vertical) likely plays a role on the convective pattern (Palma et al. 2011), although this is largely unknown at present. Therefore, further constraints are needed from

geological, geochemical and geophysical studies, which is one of the aims of this special issue.

At the other end of the spectrum of open-vent volcanoes are relatively viscous, siliceous cases that form lava domes, but which can also maintain persistent activity for years to decades. For example, Popocatepètl in Central Mexico is known for its passive degassing, puffing activity, and high SO₂ fluxes despite the presence of a lava dome (Gómez-Vazquez et al. 2016; Campion et al. 2018). Santiaguito is another siliceous system that has maintained quasi-steady eruptive activity for almost a century, accompanied by weak but continuous degassing, 30–80 tons per day (Rose 1973, 1987; Bluth and Rose 2004; Holland et al. 2011; Lamb et al. 2019). Santiaguito eruptive behaviour is however completely different from that of Popocatepètl with, for example, differing magma temperatures, degassing rates, extrusion rates and time-scales of “open-vent” behaviour. These more siliceous systems will also be discussed in this special issue to provide a framework for the definition of the full range of open-vent systems in all geodynamic and petrological settings.

Overall, the key questions that this special issue aims to address are:

1. What are the specific conditions leading to the existence or disappearance of open-vent volcanoes?
2. Why are some systems short-lived while others are long-lived?
3. Why do some systems produce lava lakes while others do not?
4. How can open-vent systems develop in various tectonic settings and for different magmatic properties (composition, viscosity, temperature, dissolved volatiles ...)?
5. What are their characteristics, similarities and differences, and their dynamic conditions?
6. Do they result from specific conditions in their magma feeding system (ascent rate, geometry, depth of reservoir)?
7. Which are the respective roles of the underlying crust and of the compressibility of the magma reservoir?
8. What can continuous monitoring of open-vent volcanoes teach us?
9. What are the specific environmental and societal impacts of open-vent volcano activity?

This volume brings together a series of papers that cover many of these aspects. Most of the papers are focused on the studies of lava lakes, such as those active at Masaya, Villarica, Nyiragongo, either through a geological or geophysical approach or by combining elements of both approaches. A few of the studies are aimed at a better understanding of the paroxysmal eruptive phase, which punctuates the persistent “normal” activity at these open-vent systems, such as

at Ambrym, Villarica and Stromboli. A strong emphasis is also placed on persistent degassing elements through measurements, involving ground and satellites measurements of SO₂ flux, vesicularity profiles in the lava lakes, modelling in the conduit, and the role of the gas flux in transitioning between different eruptive regimes and its link to magma reservoirs. Long time series of seismic and satellite sensor-derived data are also included here for the constraints that they can provide on the long-term temporal evolution of open-vent systems.

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