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Magma degassing and its impact on Earth's atmosphere: from magma oceans to lava lakes

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Foreword

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Magma degassing and its impact on Earth's atmosphere: from magma oceans to lava lakes

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Photo: The persistent lava lake lying at the bottom of the crater of Ambrym volcano in Vanuatu, and the plume of gases and aerosol discharged by the convecting magma column sustaining the lava lake (credit: C. Oppenheimer).

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Magmas contain significant quantities of volatile compounds, including water (H₂O), carbon dioxide (CO₂), sulphur, and halogen species, particularly at high pressures. Their separation through degassing is a critical process in planetary differentiation and plays a central role in shaping planetary atmospheres and climates. Key questions remain regarding the initial volatile inventory within planetary interiors and the mechanisms by which these volatiles are re-distributed across the various layers of a planet.

In planets like the Earth, large-scale convection serves to erase pre-existing temperature or density gradients, often leading to partial melting of solid rocks, such as during adiabatic upwelling. These partial melts act as powerful sinks for most volatiles. As a result, magmas are among the primary conduits for volatile redistribution within planetary interiors. When magmas reach the surface, their degassing can impact atmospheric conditions over a range of temporal and spatial scales. This includes secular degassing, which has gradually contributed to the formation of present-day atmospheres, as well as the ephemeral effects of individual volcanic episodes, which can modify atmospheric chemistry and turbidity with resultant climatic change. Volcanic eruptions also have immediate local and regional impacts on surface environments and on society. As a result, scientists are continuously refining monitoring strategies to improve forecasting of the timing and progression of eruptions.

This special issue highlights several ongoing efforts to understand the behaviour of volatiles in magmatic systems. It opens with a contribution from Labrosse *et al.*, who explore the behaviour of a magma ocean at the base of the mantle. The authors develop a new set of equations to model the coupling between a crystallizing basal magma ocean and an overlying convecting mantle, as well as its interaction with the core. Although the role of volatiles is not

directly addressed in this study, it lays the groundwork for future investigations by considering the case of a magma ocean deficient in volatiles (e.g., water or CO₂). Their results reveal large-scale geochemical heterogeneities that may help explain seismic observations of low-velocity zones at the core-mantle boundary.

In a separate study, Sanloup *et al.* investigate the behaviour of iodine in basaltic magmas under mantle pressures, particularly its speciation, using in situ X-ray measurements at high pressures and temperatures. Although iodine is a heavy halogen present in trace amounts in magmas (typically less than 1 ppm), it plays important roles in atmospheric chemistry, particularly in ozone depletion during explosive eruptions. The authors challenge previous assumptions by showing that, at high pressures, iodine binds to oxygen in the melt rather than to network-modifying cations (as is the case with chlorine). This finding suggests that oxidized iodine species may have been overlooked in past studies and could play a role in the degassing of water-poor magmas. This work highlights the need for further research into the speciation of iodine and other halogens in natural silicate melts.

Vetere *et al.* explore the effects of varying H₂O and CO₂ contents on phase equilibria in a shoshonite basaltic magma sampled from Vulcano, an active volcano in the Aeolian Arc. Phase equilibria experiments are a powerful tool for constraining the effects of volatiles on magma behaviour and identify the storage conditions of magmas beneath active volcanoes. While H₂O is well-known to depress the melting temperature of silicates, CO₂ was traditionally thought to have little such effect due to its lower solubility in silicate melts. However, Vetere *et al.* show that this is not the case for alkali-rich and water-poor melts, where high CO₂ concentrations decrease crystal fraction, potentially reflecting speciation effects linked to alkali elements. This finding underscores the need for further investigation into the effects of volatiles on such melts.

Daffos *et al.* examine how crystal content and strain influence the degassing behaviour of magmas during ascent in volcanic conduits. The loss or retention of volatiles during ascent dictates eruptive style at the surface. Magmas that retain most of their volatiles until approaching the surface tend to produce explosive eruptions, particularly in arc settings

where magmas are rich in water. Conversely, any factor that promotes volatile loss during ascent will act to reduce explosivity, often leading to lava or dome-forming eruptions. Daffos *et al.* demonstrate, through high-pressure experiments with bubble- and crystal-bearing magmas, that even moderate deformation at relatively low crystal fractions significantly enhances bubble connectivity, thereby facilitating gas loss during magma ascent. This has implications for understanding the dynamics of explosive eruptions, such as the infamous 1902 eruption of Montagne Pelée.

Moussallam *et al.* revisit geochemical gas data from several volcanic regions to identify signals of changes in deep magmatic processes, with a focus on temperature and oxygen fugacity (fO_2). Gas monitoring is a key method for forecasting volcanic activity, as the composition and flux of gases escaping from magmatic reservoirs can indicate magma migration, recharge, hydrothermal interaction and pressurization. Using data from three well-monitored active volcanoes in Japan, the authors show that variations in temperature and fO_2 can occur during the course of an eruption, with changes also observable through other petrological proxies. They propose that thermodynamic processing of routinely collected gas compositions could yield real-time insights into ongoing magmatic processes, thereby supporting hazard assessment.

In another study, Aiuppa and Moussallam examine global volcanic gas data to estimate fluxes of

hydrogen (H_2) and hydrogen sulphide (H_2S). These gases play a crucial role in the Earth's atmosphere, contributing to the balance of oxidized and reduced species, yet their global fluxes remain poorly constrained. The low concentrations of these gases and their rapid oxidation in the atmosphere make them difficult to measure accurately. The authors discuss the factors affecting H_2 and H_2S concentrations in volcanic gases, such as cooling and rock interactions, and provide new insights into their global fluxes.

Finally, Scaillet *et al.* aim to quantify the sulphur yield from eruptions of alkali-rich and evolved magmas, such as phonolites and trachytes. These magmas have been associated with several major eruptions, including the 1815 eruption of Tambora, which had a significant impact on global climate and is associated with "the year without a summer" of 1816. While the atmospheric and climatic impact of the Tambora eruption has been widely studied, the potential climatic effects of other such events, like the 13 kyr calBP Laacher See eruption, remain uncertain. Scaillet *et al.* use thermodynamic calculations to show that the sulphur yield from alkali-rich magmas is not higher than that of their calc-alkaline counterparts, which dominate explosive eruptions. They suggest that the Laacher See eruption likely did not have a strong global climate impact, highlighting the importance of accurately assessing sulphur content under pre-eruptive conditions on a case-by-case basis.