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Review

Volcanoes and the environment: Lessons for understanding Earth's past and future from studies of present-day volcanic emissions

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ABSTRACT

Volcanism has affected the environment of our planet over a broad range of spatial (local to global) and temporal (<1 yr to 100s Myr) scales and will continue to do so. As well as examining the Earth's geological record and using computer modelling to understand these effects, much of our knowledge of these processes comes from studying volcanism on the present-day planet. Understanding the full spectrum of possible routes and mechanisms by which volcanism can affect the environment is key to developing a realistic appreciation of possible past and potential future volcanic impact scenarios. This review paper seeks to give a synoptic overview of these potential mechanisms, focussing on those that we can seek to understand over human timescales by studying current volcanic activity. These effects are wide ranging from well-documented planetary-scale impacts (e.g., cooling by stratospheric aerosol veils) to more subtle or localised processes like ash fertilisation of ocean biota and impacts on cloud properties, atmospheric oxidant levels and terrestrial ecosystems. There is still much to be gained by studying present-day volcanic emissions. This review highlights the need for further work in three example areas. Firstly, to understand regional and arc-scale volcanic emissions, especially cycling of elements through subduction zones, more volatile measurements are needed to contribute to a fundamental and systematic understanding of these processes throughout geological time. Secondly, there is still uncertainty surrounding whether stratospheric ozone depletion following volcanic eruptions results solely from activation of anthropogenic halogen species. We should be poised to study future eruptions into the stratosphere with regard to their impacts and halogen load and work to improve our models and understanding of the relevant underlying processes within the Earth and the atmosphere. Thirdly, we lack a systematic understanding of trace metal volatility from magmas, which is of importance in terms of understanding their geochemical cycling and use as tracers in environmental archives and of igneous processes on Earth and more broadly on silicate planetary bodies. Measurements of volcanic rock suites and metals in volcanic plumes have an important part to play in moving towards this goal.

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1. Introduction

Volcanism is a key planetary process transferring heat and matter between the Earth's interior and its surface reservoirs. The balance between these fluxes and other planetary scale processes has been implicated in the development of Earth's atmosphere and in maintaining long-term stability of the surface environment and thus habitability (e.g., Kasting and Catling, 2003). Changes in both short- and long-term rates of planetary outgassing and/or its composition have been connected with a range of perturbations to the global environment (e.g., Table 1). These range from the short-lived effects of individual eruptions (Robock, 2000), to the more prolonged proposed consequences of clusters or periods of enhanced volcanism occurring both by chance (Miller et al., 2012) and due to silicic 'flare ups' (de Silva and Gosnold, 2007) or large igneous province (LIP) volcanism (Self et al., 2014a). Other mechanisms linking volcanism to global change include more subtle feedbacks between the Earth's surface and rates of long-term volcanism or the mean composition of the gases emitted, for example, in response to deglaciation or resulting from the subduction of carbonate-rich sediments (Table 1).

Given the rarity or long-term nature of many of these effects, which both maintain and perturb Earth's surface environment, much of our evidence for their characteristics and effects must come from proxy records. For example, much can be learnt by combining volatile emissions estimates gleaned from melt inclusions in rock samples scaled by deposit volume/mass (Scaillet et al., 2003) with environmental proxies in archives such as tree rings (e.g., Briffa et al., 1998; D'Arrigo et al., 2013), ice cores (e.g., Zielinski et al., 1994; Bay et al., 2004; Lavigne et al., 2013; Sun et al., 2014) or sedimentary sections (e.g., Sanei et al., 2012; Percival et al., 2015). Considerable advances have also been made via modelling studies both of individual past eruptions (e.g., Timmreck et al., 2010; English et al., 2013) and extended events such as fissure eruptions (e.g., Stevenson et al., 2003; Highwood and Stevenson, 2003; Oman et al., 2006; Schmidt et al., 2010) or LIPs (e.g., Caldeira and Rampino, 1990; Beerling et al., 2007; Iacono-Marziano et al., 2012; Black et al., 2013; summarised in Self et al. (2014a)). Comparing similar classes of past events that have varying degrees of global environmental impacts is also a powerful approach (e.g., Ganino and Arndt, 2009; Jones et al., 2015). However if we are to develop a process understanding of planetary outgassing and its effects on the Earth's environment it is important to consider what we can learn from present-day measurements of volcanic emissions and their impacts. It is also timely to consider how future advances in our analytical and measurement capabilities might open the way for a broader understanding in this area.

This review seeks to give a brief overview of what we have learnt to date about the potential effects of volcanism on our planet's surface environment over its geological past by studying present-day volcanism (Section 2). This section is intended to be synoptic and to act as a guide towards the relevant literature to facilitate deeper study of the many research areas covered. I then highlight 3 example areas where the scene is set to make substantial progress over the coming years. Section 3 covers the area of global, regional and arc-scale volatile budgets. Section 4 discusses the impacts of volcanism on stratospheric ozone levels and the challenges of understanding the consequences of past volcanism given the uncertainties associated with volcanic plume processes and present-day anthropogenically perturbed stratospheric chemistry. Section 5 examines our understanding of the behaviour of trace metals in volcanic systems and considers how we might further systematise this understanding in the future.

2. Studies of the present-day environmental effects of volcanism: a brief synoptic overview

Present-day active volcanism has a range of chemical and physical impacts on the local to regional and global surface environment and atmosphere of our planet. These effects are largely mediated by the transfer of significant quantities of different materials from the Earth's interior to its surface reservoirs, although volcanic heat has also been suggested to play a role (e.g., Mather, 2008). The actual emissions themselves are studied, in the case of the major volatile gas, aerosol species and ash by satellite-based or ground-based remote sensing or in situ direct measurements. In the case of ash emissions such measurements are complemented by mapping and sampling the products left behind on the Earth's surface by volcanic activity. Melt inclusion and other petrological/geochemical studies of these products can also yield key insights into volatile loss during volcanism. Current techniques applied to the measurement of volcanic gas and aerosol are summarised in Table 2.

Similarly a mixture of remote sensing, field studies and experiments are used to study the environmental consequences of volcanism. Fig. 1 and Table 3 summarise the different environmental effects of volcanism suggested by present-day observations of volcanic events and continuous activity. Some of these effects, such as global cooling resulting from stratospheric sulphate aerosol veils following large explosive eruptions into the stratosphere, are relatively well documented. Others, such ash fall to marine and terrestrial ecosystems, the effects of volcanic aerosol on cloud properties and levels of atmospheric oxidants, are more subtle and less well understood. On geological timescales, other mechanisms have also been suggested. These include: (i) significant and prolonged volcanic CO_2 emissions associated with LIP volcanism leading to global warming (Chenet et al., 2008; Sobolev et al., 2011; Joachimski et al., 2012) and ocean acidification (e.g., Payne and Clapham, 2012); (ii) long-term increased uptake of atmospheric CO_2 due to increased weathering resulting from fresh volcanic rock on the Earth's surface following extended periods of enhanced volcanism (e.g., Schaller et al., 2012; Dessert et al., 2001); (iii) continental ash blankets increasing planetary albedo (Jones et al., 2007). The primary association of these effects with very large-scale volcanism and their spatial and temporal scales can make testing their likely extent challenging using present-day field measurements. Nonetheless such observations have a clear role to play. Examples include efforts to improve our understanding of C partitioning during igneous processes (see Section 3) and studies of present-day weathering rates at active volcanoes (Jones et al., 2011).

The limitation of our direct observation of volcanism to the scale that has occurred in recent times is important to consider when seeking to understand the broader interactions of volcanic activity with the environment. Several studies have shown that 'scaling up' from present-day volcanism to larger-scale events or episodes is not straightforward with factors such as aerosol microphysics and oxidation agent depletion causing complications (e.g., Bekki et al., 1996; Oman et al., 2006; Schmidt et al., 2010; Timmreck et al., 2010; English et al., 2013). Feedbacks in terms of environmental and climatic impacts via changes in the levels of atmospheric oxidants induced by volcanic emissions (e.g., Iacono-Marziano et al., 2012) are also hard to explore, although there were suggestions of such effects in atmospheric records following the eruption of Pinatubo in 1991 (Manning et al., 2005; Telford et al., 2010). These and other uncertainties regarding the environmental effects of volcanism have recently been discussed with respect to LIPs (Self et al., 2014a).

The scientific efforts following the Pinatubo eruption in 1991 (the largest eruption to the stratosphere to date in the satellite era) yielded extensive new insights into numerous volcanic impacts on the environment. Historical records, such as those associated with the Laki fissure eruption in 1783 (the closest recent analogue to flood basalt volcanism) pose numerous further hypotheses about such impacts. With unprecedented arrays of satellite-borne and ground-based sensor networks the scientific community is now better positioned than ever to use current and future large-scale volcanism to test hypotheses about the response of climate, atmospheric dynamics and chemistry and feedbacks (e.g., via the response of vegetation, ocean fertilisation or oxidant levels). The recent response to the 6-month fissure eruption that took place at the Holuhraun lava field in Iceland between August 2014 and February 2015 is a good example (Gíslason et al., 2015; Schmidt et al.,