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Volcanic eruption triggers: A hierarchical classification

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ABSTRACT

Assessing the relative importance of various triggers of volcanic eruptions has been hampered because of the lack of a general model that allows a quantitative comparison in an unbiased form. In this paper the most important triggers of volcanic eruptions are examined using a general reference framework that visualizes volcanic eruptions as the final event on a chain of causality. Based on this general framework, a hierarchical classification of triggers is proposed. First and second order triggers are defined as processes capable to initiate the rupture of the walls of a magma reservoir, regardless of whether the tapped magma can reach the surface or not. Third order triggers are those taking place only after the rupture of the walls of a magma reservoir has occurred, but are important in determining whether the tapped magma actually reaches the surface. A fundamental trigger is defined as any first order trigger that also can provide enough energy to feed a volcanic eruption even in the absence of third order triggers. The assessment of the relative importance of triggers is done by considering the whole range of depths from which a volcanic eruption is likely to have been fed, including magma reservoirs located deeper than 150 km, even when these eruptions might be relatively uncommon in the geological record.

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1. Introduction

One of the fundamental questions in volcanology is to understand why magmas generated by partial melting at depth erupt at the surface of a planet. A quantitative answer to this question is not trivial. Volcanic systems are complex and dynamical, and many processes are likely to take place simultaneously, or at least in fast succession, to provide the energy required to drive any given eruption. Many of those processes are commonly non-linear, the interaction among them is probably stochastic, and there are many uncertainties in the controlling parameters. Consequently, forecasting all aspects of volcanic eruptions (when, where, how big, of what type, and for how long) has been considered to be best done in terms of probabilities rather than in a deterministic form (Sparks, 2003; Marzocchi and Bebbington, 2012). Despite all of their complexity, however, volcanic eruptions are ultimately controlled by the laws of physics. Consequently, a better understanding of the general framework imposed by the physical laws controlling every part of the eruptive process is required to improve our forecasting capabilities.

Over the years, the list of triggers of volcanic eruptions has expanded to include processes as diverse as magma buoyancy, volatile exsolution, magma injection in a pre-existing reservoir, thermal expansion of magma, earthquakes, rainfall, glacier retreat, sea-level changes, earth tides and even magma chamber geometry and meteorite impact (e. g., Ronca, 1966; Weertman, 1971; Mauk and Johnston, 1973; Sparks et al, 1977; Blake, 1981, 1984; Jull and McKenzie, 1996; McGuire et al., 1997; Woods and Pyle, 1997; Linde and Sacks, 1998; Neuberg, 2000; Violette et al., 2001; Matthews et al., 2002; Jellinek et al., 2004; Manga and Brodsky, 2006; Fowler and Spera, 2008; Pagli and Sigmundsson, 2008). Unfortunately, as noted by Schmincke (2004), while the potential of some of those triggers has been extensively studied, others have been identified only in a rather speculative form. Consequently, it is only fair to say that at present, our knowledge of volcanic eruption triggers remains fragmented and incomplete, therefore contributing to the uncertainties associated with volcanic eruption forecasting.

To reduce such uncertainties, it would be essential to devise a general framework that can be used to quantitatively compare a wide range of processes deemed to trigger eruptive events. The ideal situation would be to devise such a framework taking every possible aspect of volcanic activity into consideration, allowing us to make an accurate description of every possible scenario even in the minutest detail. Realistically, such an ideal framework is unlikely to be achieved in the near future due to the extreme complexity of volcanic systems. Nevertheless, it is possible to achieve a good approximation by focusing attention on the most fundamental aspects of volcanic activity.

In this paper a first attempt is made to establish a general framework capable to provide quantitative information concerning the relative importance of the various processes identified over the years as potential triggers of volcanic eruptions. To achieve this end, some simplifications and generalizations have to be made. In particular, eruptions are conceived as the last event of a chain of causality events that initiates with the rupture of the solid rock overlying a region where molten material exists. Processes of magma transport such as diapiric ascent, percolation through a permeable medium, assimilation or ductility of the surrounding rock are not considered here, even when it is recognized that those processes might provide pathways for magma ascent in some cases (e.g., Green and Gueguen, 1974; Fowler, 1990; de Silva and Gosnold, 2007). Such exclusions are justified because very often a new pathway opened by the brittle fracture of a solid rock must be formed for a magma body to migrate to the surface before an eruption takes place (Smith and Kilburn, 2010). This includes the reopening of a conduit because a solid seal has to be broken to allow the new activity to take place. Also, even if the ductile behavior of the surrounding crust favors the accumulation of large quantities of melt, there is the need for the brittle failure of the uppermost layers of the crust to initiate large tapping events (Gottsmann et al., 2009). Consequently, fracturing can be considered to be an ubiquitous process of many, if not all, volcanic eruptions (Kilburn, 2003; Benson et al., 2012). Other issues that are not considered in this paper include aspects related to the form in which any process modifies the behavior of an already ongoing eruptive event, and the dynamic coupling between magma ascent and rock fracturing. Although it is recognized that such processes are important in controlling the evolution of an eruption, disregarding them in the present context is justified because the main interest resides not so much in providing a complete description of specific eruptions, but in establishing a general framework that can be used to achieve a hierarchical classification of eruption triggers.

Since attention is focused on fundamental physical concepts that are valid in a general context, the analysis completed in this work is illustrative enough to help us appreciate the reasons why an eruption might take place without the previous occurrence of predefined precursory patterns, or why is it that sometimes a well defined precursory pattern might end up with no eruption at all. Furthermore, the hierarchy proposed here can serve as a quantitative tool that can be used to assign specific weights to particular processes that might be incorporated in more general tools of eruption forecasting (e.g., Marzocchi and Bebbington, 2012), thus rendering those probabilistic models more accurate than they are until now. Consequently, the approach followed here rapidly moves from the purely heuristic to provide a quantitative tool that albeit approximate, can be used to yield quantitative information about eruptive processes that is not possible to obtain by focusing attention in individual triggers on a case by case basis.

The paper starts by establishing a minimum of basic nomenclature that is required to avoid vague statements often associated to the occurrence of volcanic eruptions. Although for some readers Section 2 might seem to deal with semantic issues that provide unnecessary definitions, it provides the common ground that can be used as a reference to reconcile the often contradictory perspectives that many workers might have about the nature of volcanic eruptions, and that became evident when reading the comments made by various reviewers to previous versions of this work. In particular, while some reviewers considered entirely unnecessary to provide explicit definitions of some terms, others requested more punctual definitions of terminology. Consequently, the section is retained for the benefit of the readers willing to have an explicit definition of key terms, while the reader with more familiarity with those terms might want to skip this section. Sections 3 and 4 provide, respectively, the qualitative and quantitative aspects of a general framework in which the most common triggers of volcanic eruptions can be compared to each other. The second half of the paper starts in Section 5 by