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Dynamic plumbing system beneath volcanoes revealed by kinetic modeling, and the connection to monitoring data: An example from Mt. Etna

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ABSTRACT

Our ability to monitor volcanoes (using seismic signals, ground deformation, gas fluxes, or other ground and satellite based observations) as well as our understanding of melt reservoirs that feed eruptions have evolved tremendously in recent years. The complex plumbing systems that are thought to feed eruptions are, however, difficult to relate to the monitoring signals. Here we show that the record preserved in compositional zoning of erupted minerals may be used to reconstruct sections of the plumbing system. Kinetic modeling of such zoning can yield information on the residence time of magma in different segments of the plumbing systems. This allows a more nuanced evaluation of the link between observed monitoring signals or eruption styles and the magmatic processes and movement of batches of melts at depth. The approach is illustrated through a study of the compositional zoning recorded in olivine crystals from the 1991–1993 SE-flank eruption products of Mt. Etna (Sicily). The zoning patterns in crystals reveal that the plumbing system of the volcano consisted of at least three different magmatic environments between which magma was transported and mixed in the year or two preceding the start of eruption. Quantification of this history indicates that two main pathways of melt migration and three timescales dominated the dynamics of the system. Combination of this information with the timing of observation of various monitoring signals allows a reconstruction of the dynamic evolution of this section of the plumbing system during the early stages of the 1991–1993 eruption. It is seen, for example, how the migration of melt through the same sections of the plumbing system can cause pre-eruptive triggering, enhance Strombolian activity, and through the ensuing eruption cleanse and flush the plumbing system. Different kinds of mixing occur simultaneously at different sections of the plumbing system on different timescales (a few days up to two years).

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1. Introduction

Our understanding of volcanic processes has increased tremendously in the last couple of decades due to improvements in geophysical and geochemical tools, and through the comprehensive installation of real time monitoring networks (microgravity changes, high resolution seismic and radar observations; e.g. Scarpa and Tilling, 1996). The ability to map changes of a volcanic edifice before, during, and after an eruption has also altered the classical view of magma storage in a simple, single 'magma chamber'. A dynamic plumbing system of interconnected melt reservoirs that define an extended molten region or 'magma mush zone' (e.g., Marsh, 2006) is probably more realistic, particularly in very active volcanic systems. This poses a new challenge for relating the various monitoring signals to movement of melt through a complex network.

Compositional zoning in magmatic crystals may record a series of processes that occur as magma progresses through such complex crystal-melt networks. The use of compositionally zoned minerals, including plagioclase (Ginibre et al., 2002; Milch, 1905; Pearce and Kolisnik, 1990; Vance, 1962, 1965), olivine (Clark et al., 1986; Kohn et al., 1989) and clinopyroxene (Clark et al., 1986; Downes, 1974; Streck et al., 2002) to unravel the sequence of events that occurred in a magmatic system is well established (Anderson, 1984; Ginibre et al., 2007; Helz, 1987; Hibbard, 1981; Humphreys et al., 2006; Singer et al., 1995; Streck, 2008; Wallace & Bergantz, 2002, 2004, 2005). Moreover, kinetic modeling of the diffusive modification of such zonings provides information on the timescale of melt transfer through the plumbing system. Diffusion modeling has been increasingly used to obtain timescales of individual magmatic processes (e.g. Costa et al., 2003; Costa et al., 2008, 2010; Morgan et al., 2004; Morgan and Blake, 2006; Nakamura, 1995; Zellmer et al., 1999).

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Here we show that the record preserved in compositionally zoned crystals can be used to map the history of passage of melts through complex plumbing networks, and that kinetic modeling of such zoning provides information on the timescale of such melt movement. The geophysical and geochemical monitoring tools applied to active volcanoes provide us a variety of information that needs to be interpreted as magma movement and/or interaction of magma with surrounding host rocks. However, it is difficult to uniquely relate these monitoring data to specific magma batches or magmatic processes occurring at depth. On the other hand, it is the chemistry of magmas (melts and crystals) that record the intensive thermodynamic variables (e.g. pressure, temperature, volatile content and composition) and the processes relevant for the evolution of a magmatic system. It is a highly desirable goal to be able to relate the time series information from various monitoring tools to specific variations of thermodynamic parameters and magmatic processes, and this manuscript aims at taking an important step toward achieving this goal.

We illustrate the approach using olivine compositions from the eruptive products of the 1991–1993 SE-flank eruption of Mt. Etna (Sicily), one of the best-monitored volcanoes on Earth. Numerous changes in geophysical (e.g. ground deformation, seismicity, microgravity), and geochemical (CO_2 and SO_2 gas emissions) signals were recorded prior to, during, and after this eruption. Olivine was chosen because of its diverse but systematic zoning patterns, and because diffusion coefficients of multiple elements are well known in this mineral. We have inferred a possible plumbing system, and a chronology of magmatic events preceding the eruption that can be related to specific surface monitoring signals. Extension of our observations to interpret the monitoring signals being observed during the current eruptive period (Bonforte et al., 2008) at Mt. Etna or at other well monitored volcanoes should enable us to obtain more realistic inversions of these data and better predict the course of future eruptions.

2. Sequence of events leading to and during the 1991–1993 eruption

The volcanic edifice of Mt. Etna towers about 3330 m a.s.l. on the eastern coast of Sicily and covers a basal area of ~1250 km^2 (Fig. 1). The 1991–1993 SE-flank eruption was preceded by a minor flank eruption in (September–October) 1989 and a series of paroxysmal episodes in early 1990 (Table 1). The flank activity resumed at Mt. Etna in the early hours of December 14, 1991 after a brief repose and was accompanied by a major seismic swarm (~250 events; Patanè et al., 1994). This event occurred after 23 months of quiet summit activity (Falsaperla et al., 1994). A new fracture system with two branches developed and propagated NE and SSE from the base of the Southeast crater (Fig. 1). The NE-branch was mainly characterized by ash and bomb fall and lasted a couple of hours. The SSE-branch propagated downslope to an elevation of 2700 m almost parallel to the 1989 fracture zone (Barberi et al., 1993; Calvari et al., 1994). During the night of 14th of December the eruptive activity continued from the western wall of the Valle del Bove (VdB) (Fig. 1) from eruptive vents between 2400 and 2200 m a.s.l. (Barberi et al., 1993; Calvari et al., 1994; Stevens et al., 1997). Finally, these vents became the source for a persistent effusive activity for the following 473 days. In March 1993 the activity ceased after producing a compound lava flow field of $240 \pm 29 \times 10^6$ m^3 (Calvari et al., 1994; Stevens et al., 1997). The samples studied are from three temporally separated trachybasaltic lava flows that erupted between December 1991 and March 1992 (hereafter the samples are referred as: 14-December-1991, 03-January-1992 and 14-March-1992).

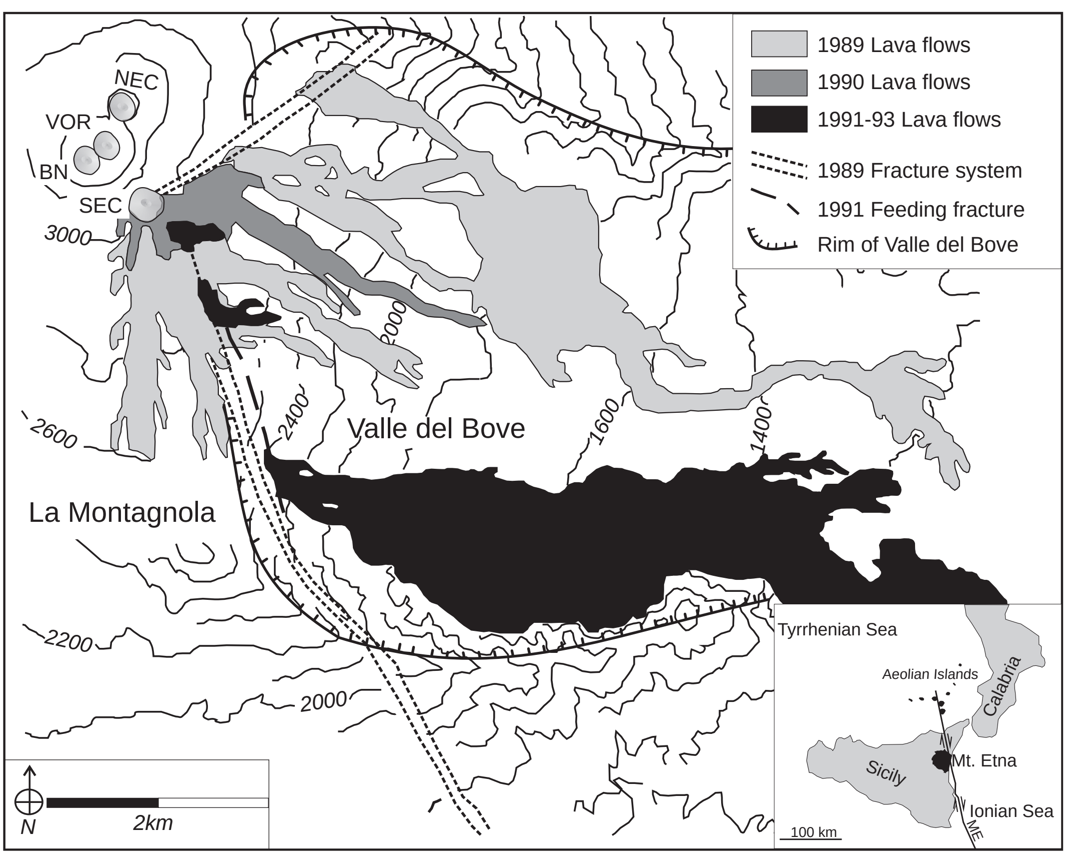

Fig. 1. 1991–1993 lava flow field map: Map of the SE-flank of Mt. Etna (Sicily) depicting the compound lava flow field of the major 1991–1993 flank eruption (black) and its predecessors in 1989 (light gray) and 1990 (dark gray). Figure modified from Barberi and Villari, 1994.

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