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Review

Structure of volcano plumbing systems: A review of multi-parametric effects

Alessandro Tibaldi

Department of Earth and Environmental Sciences, University of Milan-Bicocca, Piazza della Scienza 4, 20126 Milan, Italy

A R T I C L E I N F O

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A B S T R A C T

Magma is transported and stored in the crust mostly through networks of planar structures (intrusive sheets), ranging from vertical dykes to inclined sheets and horizontal sills, and magma chambers, which make up the plumbing system of volcanoes. This study presents an overview of plumbing systems imaged at different depths and geodynamic settings, in order to contribute to assessing the factors that control their geometry. Data were derived from personal field surveys and through the analysis of publications; observations include local lithology and tectonics of the host rock with special reference to local fault kinematics and related stress tensor, regional tectonics (general kinematics and far-field stress tensors), geology and shape of the volcano, topographic settings, and structural and petrochemical characteristics of the plumbing system. Information from active volcanoes and eroded extinct volcanoes is discussed; the shallow plumbing system of active volcanoes has been reconstructed by combining available geophysical data with field information derived from outcropping sheets, morphometric analyses of pyroclastic cones, and the orientation and location of eruptive fissures. The study of eroded volcanoes enabled to assess the plumbing system geometry at deeper levels in the core of the edifice or underneath the volcano-substratum interface. Key sites are presented in extensional, transcurrent and contractional tectonic settings from North and South-America, Iceland, the Southern Tyrrhenian Sea and Africa. The types of sheet arrangements illustrated include swarms of parallel dykes, diverging rift patterns, centrally-inclined sheets, ring and radial dykes, circum-lateral collapse sheets, sills, and mixed members. This review shows that intrusive sheet emplacement at a volcano depends upon the combination of several local and regional factors, some of which are difficult to be constrained. While much progress has been made, it is still very challenging to forecast the likely paths and geometry of sheet propagation and emplacement during volcanic unrest events.

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1. Introduction

This paper addresses the fast-growing field of studies on the structure of magma plumbing systems below and inside volcanoes, the sites where processes like magma transfer, storage and evolution occur. A magma plumbing system can be defined as a network of conduits along which magma moves, interconnected with chambers where magma accumulates. A plumbing system may be connected to the surface, at least during transient times, to which magma is transported producing eruptions. During transfer from the deep fluid source and subsequent storage in the crust, magmas are subject to a series of processes that lead to their differentiation. From the shallow chambers to the surface, magmas are subject to further processes that eventually dictate the type, intensity and duration of eruption. All these processes are influenced by a series of parameters that include, for example, depths of differentiation, amount of wall-rock assimilation, rates and timescales of magma generation, and times of storage (Annen and Zellmer, 2008). Magma storage and ascent are above all tightly linked to the structure and state of stress of the crust (Chaussard and Amelung, 2014), but in turn magma intrusions might control plate boundary evolution (Acocella, 2014). As a consequence, the reconstruction of the structure and geometry of the plumbing system is of paramount importance for understanding how the subvolcanic engine works.

The assessment of volcanic hazard is also dependant on the comprehension of the structure of magma plumbing systems. Processes acting at open conduit volcanoes, and leading to paroxistic explosions, have been recently addressed taking into consideration the structure of the shallower conduits. Chouet et al. (1997), for example, studied the wave fields of tremors and explosions at Stromboli Volcano, Italy, demonstrating that the source of this phenomenon is localised beneath the summit crater in the shallower part of the plumbing system at depths < 200 m. The model for degassing and explosion occurrence is consistent with a vertical, NE–SW-striking crack-like conduit. This geometry fully coincides with the field observations carried out at Stromboli's plumbing system, which crops out in the more dissected parts of the volcano (Pasquarè et al., 1993; Tibaldi, 1996, 2001). Later, more detailed geophysical studies on the active conduit (Chouet et al., 2008) and field data on Holocene conduits (Tibaldi, 2003; Corazzato et al., 2008) put further constraints on conduit geometry suggesting a dip towards NE.

Also the evaluation of the areas most prone to the opening of new vents and eruptive fissures is intimately linked to the understanding of the structure of plumbing systems, especially at volcano-tectonic rift zones on volcano slopes (e.g. Bonali et al., 2011). Mafic magma, in fact, is normally supplied to the surface along planar and mostly steeply-dipping intrusive sheets that may group to form dyke swarms (Dieterich, 1988; Carracedo, 1994; Moore et al., 1994; Walter and Schmincke, 2002), and eventually volcano-tectonic rift zones formed by hundreds of such parallel dykes (Fiske and Jackson, 1972; Walker, 1999). These rift zones can be studied at the surface by analysing the orientation and location of eruptive fissures, vents and the morphometric characteristics of pyroclastic cones (Tibaldi, 1995), as well as by interferometric methods (Massonnet and Sigmundsson, 2000). At the same time, much information can be obtained by studying in the field the eroded parts of the rift zones where sheet intrusions are exposed. Field studies of thousands of sheet intrusions also show that most sheets become arrested on their way to the surface, and that unrest commonly does not lead to an eruption (Fig. 1) (Gudmundsson and Brenner, 2005). The comprehension of this phenomenon depends on a better understanding of the physical conditions for the injection of sheet intrusions from the source magma chamber and their propagation to the surface, which again requires knowledge of the structure of the plumbing system and of the host rock.

Classically, studies of plumbing systems focused on igneous processes that are elucidated by sampling of exposed rocks and laboratory analyses, more recently integrated with experimental approaches. The new field of studies of "volcanotectonics" devoted to reconstructing the structure of plumbing systems uses field data, analogue modelling and numerical modelling. The experimental approaches are rapidly growing in number and quality, but it is fundamental to anchor and validate their results with field truth. In recent years, exposed plumbing systems have been studied in sufficient detail with modern techniques of structural geology in order to get information aimed at a better understanding of the entire process from crustal magma storage to eruption at the surface.

The present paper contributes to the knowledge of magma plumbing systems by reviewing the most relevant literature and integrating it with field data mostly collected by the author. The focus is on the analysis of the structure of plumbing systems in the uppermost crust and inside volcanoes, where more data obtained from field evidence and geophysics are available. This is integrated with a summary of the literature on the deeper part of plumbing system above the melt generation zone. These data provide a backdrop for understanding the entire magma plumbing system and the processes that take place within it. Through a series of examples, from deeply eroded volcanoes to the surface of active volcanoes, I describe the various parameters that control the geometry of plumbing systems; these in fact are sensitive to multiple factors that frequently work together to dictate the final configuration of the conduit array. Intact cones and volcanoes that experienced lateral failure or caldera collapse are taken into consideration.

One of the most complex conditioning factors is represented by the tectonic settings; the tectonic influence on magma migration and volcanism has received a lot of attention recently, but several issues are still open and controversial. As an example, for decades volcanism and regional extensional tectonics have been thought to be tightly linked, as

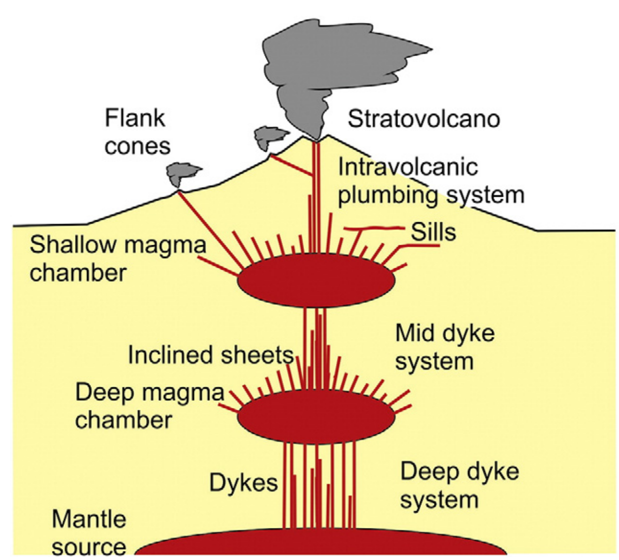

Fig. 1. A magma plumbing system is represented as a network of vertical, inclined and horizontal conduits that channel magma towards the surface, and a series of chambers where magma can be stored. Main nomenclature is shown. Not to scale.