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The diverging volcanic rift system

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A B S T R A C T

Eruptions and volcano internal growth are mostly fed by dykes. The comprehension of the control factors on dyke paths is fundamental for the assessment of areas prone to vent formation and to the general understanding of how volcanoes work. We analyse an understudied magma path system; field data of nine volcanoes show they have a rectilinear rift zone in the central part passing into fan-arranged dykes at the two opposite volcano flanks. The geological, geomorphological and structural characteristics of these volcanoes and their substrate suggest that the formation of these "diverging rifts" is not specifically linked to substrate lithology and mechanical behaviour. The studied volcanoes have elongation <0.88 and $V > 10$ km^3 (mostly >300 km^3). Eight volcanoes have the central rift that is normal to the regional tectonic least principal stress (σ_{3reg}) and in one case it is sub-perpendicular. Field data have been combined with scaled analogue modelling, suggesting that if the σ_{3reg} is oblique to the volcano elongation axis, dyke geometry in the edifice axial zone is controlled by elongation and thus by local gravity σ_3, but dyke strike becomes perpendicular to σ_{3reg} when dykes intrude the more external areas of the volcano. If a dyke is injected under the volcano flanks with slope inclination >50°, it attains a geometry parallel to the slope. At lower slope inclinations at the edifice terminations, magma paths diverge outwards and crosscut slopes at high angle. Our data are in agreement with the assumption that regional tectonic stresses can affect large volcanoes up to the summit area guiding the development of a rectilinear thoroughgoing rift, both in extensional and transtensional regimes. The diverging pattern takes place due to reorientation of the local stress field guided by topography only when dyke inception localizes laterally respect to the edifice axis.
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1. Introduction

Volcanic rift zones are widespread on shield and stratovolcanoes and are expressed, at the surface, by aligned pyroclastic cones, vents and parallel fissures and faults, overlying swarms of parallel, steeply inclined intrusive sheets defined as dykes (Fiske and Jackson, 1972; Walker, 1999). These dyke swarms may contribute to the endogenous growth of volcanoes by up to 13% or more (Annen et al., 2001; Walter and Schmincke, 2002). Dyke arrangement can be more complicate, with steep dykes replaced by concentric swarms of tabular magmatic intrusions dipping inwards and converging at a focal zone, commonly known as cone sheets (Fig. 1) (Bailey et al., 1924). Intrusive sheets can also be diverging and dipping outwards to form ring dykes (Anderson, 1936). Finally, radial dykes can also be widespread in central volcanoes. Dykes and inclined sheets thus represent the magma paths feeding eruptions and the internal growth of volcanic edifices.

Although in general intrusive sheets tend to propagate along a plane normal to the least principal stress (σ_3) (e.g. Nakamura, 1977), the forces responsible for the orientation and magnitude of the stress can have different sources, spanning from remote tectonic forces to gravity forces linked to the basement geometry, to the general shape and load of the volcano and to the very local topography, to magma forces linked to expansion and inflation of magma chambers and to dyke propagation, and to barrier forces linked to discontinuities and rheological changes in the rock succession (Acocella and Tibaldi, 2005; Clemens and Mawer, 1992; Gretener, 1969; Gudmundsson, 1986, 1990, 2003; Gudmundsson and Philipp, 2006; Kavanagh et al., 2006; Kervyn et al., 2009; Lissenberg et al., 2004; Tibaldi, 2003). The orientation and magnitude of stresses, which depend upon the origin of the forces and the geological/geomorphological characteristics of the volcano and its substrate, dictate the final configuration of the magma paths.

The general sheet geometry is commonly used to infer the orientation of the stresses and their origin; for example circumferential (ring dykes and cone sheets) and radial dykes are normally considered the expression of magma stresses dominating over remote tectonic stresses (Bistacchi et al., 2012, and references therein), whereas parallel steep dykes can be controlled by dominant tectonic stresses (Fig. 1) (Acocella and Neri, 2009, and references therein). In very large volcanoes like the Hawaii islands, it has also been proposed that gravity forces can control the orientation of rectilinear dyke swarms (Fiske and Jackson, 1972), once space for dyking is provided by slip of the volcano flank on deep faults (Dieterich, 1988). It is thus very important to correctly comprehend the geometry and possible origin of the magma paths and stresses in a volcano, since this knowledge is also relevant for volcanic hazard assessment of possible new vent opening, as well as to the understanding of the structure of a volcano, its general

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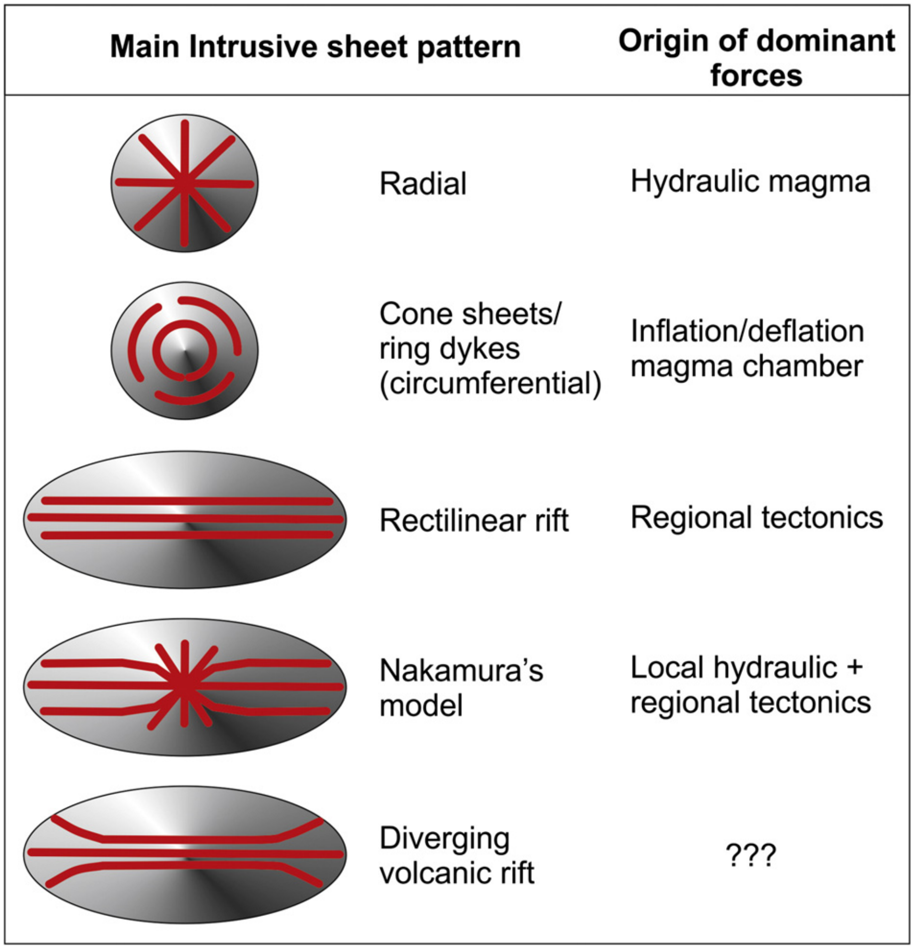

Fig. 1. Sketch of the main configurations of intrusive sheets at volcanoes and indication of the dominant forces guiding the geometry of magma paths. Nakamura's model after Nakamura (1977).

behaviour, and possible lateral instability (Tibaldi et al., 2010, and references therein).

In the present paper we analyse a magma path pattern that has received poor attention in the literature; it is represented by a central rectilinear volcanic rift zone passing outwards into fan-shaped dyke systems at the two opposite volcano flanks (Fig. 1). In their pioneering analogue experiments, Fiske and Jackson (1972) suggested that this geometry might be linked to the elongated shape of a volcano. Anyway, their analogue model needs improvements since the scaling procedure was not complete and the claimed major controlling factor on dyke emplacement – i.e. topography – was exaggerated due to a width/height ratio of the cone with much steeper slopes than reality. Moreover, their experiments and successive numerical calculations mimicked volcanoes with a simplified triangular section. We instead propose a multidisciplinary approach to better understand the development of this magma path pattern. For the first time it is presented a review of field data of volcanoes that have the diverging rift pattern; we describe nine volcanoes that have been chosen based on the clear expression of the rift geometry, and analyse the geological, geomorphological and structural characteristics of each of these volcanoes and their substrate. We then combine these results with a series of scaled analogue models that were designed on purpose and developed in order to contribute to understanding the various parameters that might control the formation of the diverging rift structure. The analogue volcanoes have scaled dimensions and shapes strongly based on field data. We want to focus on interesting questions like: 1) Why don't all elongated volcanoes develop this pattern? 2) Is there any relationship with regional tectonics? 3) Is there any control of the substrate lithology and structure? And 4) How much slope inclination might have influence? These data complete and integrate previous findings on magma paths, contributing also towards a better assessment of volcanic hazards.

2. Examples of diverging volcanic rift systems

2.1. Morphostructural analysis to reconstruct magma paths and define volcanic rifts

In this paper with the term "magma paths" we refer to the location and geometry of intrusive sheets that may constitute the magma plumbing system of a volcano, regardless they fed an eruption or not. Several (generally tens to hundreds) magma paths forming swarms of close and parallel sheets are referred to as "volcanic rift zones". On the eroded parts of the studied volcanoes, we thus recognized the rift orientation and location by the presence and geometry of swarms of parallel dykes (e.g. Fig. 2A and F). At un-eroded volcanoes, we inferred the main magma paths near the surface by analysing the geometry of eruptive fissures (Fig. 2B) combined with the distribution and geometry of faults, vents and pyroclastic cones. In fact, the formation of fissures/faults associated with volcanic activity has been interpreted as being due to the emplacement of a fracture-parallel dyke (Bousquet and Lanzafame, 2001; Pollard and Muller, 1976, and references therein), although it may be complicated by the presence of a layering with different mechanical properties (Gudmundsson, 2002, and references therein). In the areas where field data on eruptive fissures/faults and dykes were not available, to locate the rift zone we analysed the distribution and geometry of vents (mostly associated to pyroclastic cones) because they

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