Dike propagation in volcanic edifices: Overview and possible developments

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1. Introduction

Understanding magma ascent and extrusion at volcanoes is a crucial step to minimizing hazards associated with volcanic unrest. Eruptions are often fed by dikes, as observed at numerous active volcanoes worldwide, for example, Afar (Sigmundsson, 2006), Cerro Negro (Nicaragua; La Femina et al., 2004), Miyakejima (Japan; Ueda et al., 2005), Iwate (Japan; Sato and Hamaguchi, 2006), Kiluaea (Hawaii; Desmarais and Segall, 2007), Montserrat (Lesser Antilles; Mattioli et al., 1998), Piton de la Fournaise (Reunion Island; Cayol and Cornet, 1998), Nyiragongo (Congo; Komorowski et al., 2002), Etna (Italy; Bouquet and LanzaFame, 2001), and Stromboli (Italy; Acocella et al., 2006a). In many of these episodes, dikes ruptured the surface close to urban areas, feeding eruptive vents and sometimes even causing landslides and tsunamis (Komorowski et al., 2002; Billi et al., 2003; Behnke et al., 2005; Calvari et al., 2005). These and other examples illustrate that to improve our understanding of magma transport and eruption, and associated consequences, it is fundamental to advance knowledge of dike propagation.

The mechanisms of dike propagation in the crust have been the subject of many theoretical studies in the past several decades (e.g., Anderson, 1936; Ode, 1957; Pollard, 1973; Pollard and Muller, 1976; Delaney et al., 1986). The orientation of a dike is controlled by the orientation of the principal stresses, with the dike orthogonal to the least compressive stress in the crust (e.g., Nakamura, 1977; Rubin and Pollard, 1988). This relation is best demonstrated in absence of prominent relief, as in flat rift zones along divergent plate boundaries (Iceland, Afar). In such locations dike propagation may be heavily influenced by stiffness contrasts within the host rock (Gudmundsson, 2006, and references therein).

The presence of a volcanic edifice, with some relief, complicates this simple dependence on the regional tectonic setting, introducing significant deviations from expected patterns. Loading by the edifice focuses the stresses above the center of a magma chamber, promoting the development of a central vent system (Pinel and Jaupart, 2003). In addition, dikes and/or fissure eruptions at many volcanic edifices show characteristic radial and/or circumferential patterns (e.g., Chadwick and Howard, 1991; Takada, 1997), suggesting control by a local stress field imposed by a pressurized magma reservoir and/or the load of the edifice. In particular, the latter effect becomes predominant with increasing volcano height (McGuire and Pullen, 1989). The location and orientation of the dikes may be also controlled by the shape of the edifice (Fiske and Jackson, 1972), or the presence of scarps along the volcano slopes, commonly produced by sector collapses (e.g., McGuire and Pullen, 1989; Tihaldi, 2003; Walter et al., 2005a). Therefore, while dike propagation in areas without prominent relief is usually controlled by regional tectonism, the propagation of dikes in volcanic edifices seems to depend upon the shape and topography of the edifice, as well as the stress conditions within shallow magma reservoirs.

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This study aims at producing an overview of the factors controlling the propagation of dikes within volcanic edifices. Because eruptive fissures and rift zones on volcanic edifices are dike-fed, we include data from such activity in our analysis. Largely based on published data, the types of dikes and eruptive fissures in volcanic edifices are discussed to derive general, semi-quantitative insights into dike behavior as a function of the edifice shape, topography, structural setting, and volcano composition.

2. Overview of dike patterns and propagation

2.1. Type of dikes within a volcanic edifice and related conditions of formation

The most common patterns of dikes (or eruptive fissures) in volcanic regions can be largely categorized as belonging to one of three classes: regional, circumferential and radial. While regional dikes result from the influence of a far-field (i.e. regional) stress, circumferential and radial dikes result from a near-field (or local) stress imposed by the presence of a pressurized magma reservoir and/or the load of the volcano. The main features of each of these configurations are summarized below.

2.1.1. Regional dikes

Regional dikes within volcanic edifices are aligned with the regional tectonic stress field, that is, perpendicular to the least compressive stress. Several volcanoes are characterized by a dike complex consistent with such a far-field stress. Most of these are located along the axis of extensional rift zones, in oceanic (Askja and Krafla, in Iceland; Gudmundsson and Nilsen, 2006, and references therein) and continental settings (ErtA Ale, Ale Bagu, Dabbahu and Gabho, in Afar, Nyiragongo and Nyamuragira, in Congo, Tongariro, in New Zealand, early stage of Etna, in Italy; Barberi and Varet, 1970; Nairn et al., 1998; Komorowski et al., 2002; Corsaro et al., 2002; Wright et al., 2006). Common features are the development of focused and clear rift zones, usually departing from the volcano summit and parallel to the regional extensional structures (Fig. 1a). The regional dikes within volcanic edifices in rift zones are usually subvertical to steeply dipping, several meters thick (Gudmundsson, 1998); at times, as Hawaii, dikes may constitute more of 50% of the rift zone (Walker, 1987, and references therein). The development of regionally-controlled rift zones is also common to arc stratovolcanoes in compressional settings, such as Reventador, Ecuador (Tibaldi, 2005); Izu-Oshima (Ida, 1995; Fig. 1b); Iwate and Chokai, Japan (Nakano and Tsuchiya, 1992; Ida, 1995; Sato and Hamaguchi, 2006); and Batur, Indonesia (Newhall and Dzurisin, 1988, and references therein). The main difference between regional dike patterns in volcanic edifices in extensional and compressional settings lies in the fact that the former may often propagate beyond the base of the volcano, reaching considerable distances along the rift. This is the case for regional dikes formed in volcanoes along the divergent plate boundaries in Iceland and the Afro-Arabian Rift (Gudmundsson, 1995; Ebinger and Casey, 2001; Sigmundsson, 2006).

Independent from their tectonic setting, regional dikes within volcanic edifices may undergo vertical (Sato and Hamaguchi, 2006) or lateral (Wright et al., 2006; Paquet et al., 2007, and references therein) propagation. Lateral propagation usually occurs when the magma reaches the level of neutral buoyancy within the host rock (Rubin and Pollard, 1987; Morita et al., 2006), which, for most magmas, occurs when the host rock density is between 2300 and 2700 kg/m³ (Pinel and Jaupart, 2000). The load of a volcanic edifice enhances lateral propagation of regional dikes beneath the volcano (Pinel and Jaupart, 2000), which may partly explain the occurrence of regional, laterally propagating dikes in central volcanoes and within related magmatic segments along the axis of oceanic (Gudmundsson, 1995) and continental (Ebinger and Casey, 2001; Wright et al., 2006; Sigmundsson, 2006) rifts.

2.1.2. Circumferential dikes

Circumferential dikes form arcuate patterns concentric to the volcanic edifice, especially at summit craters and calderas, where the dikes may be also associated with pre-existing faults or fractures.
Circumferential dikes have been mostly reported along the sides of several calderas, including Medicine Lake (California; Donnelly-Nolan, 1990) Kilauea (Hawaii; Neal and Lockwood, 2003), Suswa (Kenya; Skilling, 1993, and references therein) and Galápagos Islands (Ecuador; Chadwick and Howard, 1991). In particular, the best-known examples of circumferential dikes at active volcanoes are found around the calderas of shield volcanoes in the western Galápagos archipelago, especially Cerro Azul, Darwin, Fernandina, and Wolf (Fig. 2; Chadwick and Howard, 1991). Their development may be related to overpressure within a shallow diapiric magma reservoir, which also promotes radial dike formation on the lower flanks of the volcanoes (Chadwick and Dieterich, 1995). An additional factor for the development of circumferential dikes around summit calderas may be the topographic expression of the caldera, which may re-orient the least compressive stress radially (Munro and Rowland, 1996); a similar reorientation of the stress trajectories has been observed at volcanoes characterized by significant scarps, like those related to sector collapses (Fiske and Jackson, 1972; McGuire and Pullen, 1989; Acocella and Tibaldi, 2005).

At extinct caldera complexes there is widespread evidence for the presence of circumferential dikes lying at a deeper level within the volcanic edifice (Yoshida, 1984; Troll et al., 2000; Kennedy and Styx, 2007), even though the nature of some of these is debated (Driscoll et al., 2006, and references therein). These circumferential dikes usually form above the periphery of a shallow magma chamber, resulting from an increase (cone sheets) or decrease (ring dikes) in the magmatic pressure (Gudmundsson, 2006, and references therein).

2.1.3. Radial dikes

This group of dikes has a characteristic radial distribution with regard to the axis of the volcanic edifice. The radial pattern may be isotropic, with a similar frequency of dikes in every direction, or, more often, anisotropic, with clustering along preferred orientations. Examples of the first group include Fernandina, Galápagos (Chadwick and Dieterich, 1995); Summer Coon volcano, Colorado (Poland et al., 2004, 2008); Kluchevskoi, Kamchatka (Takada, 1997); as well as extra-terrestrial volcanoes (Krasilnikov and Head, 2003). Examples from the second group are more numerous, including Vesuvio, Etna, and Stromboli, Italy (Fig. 3; Acocella and Neri, 2003; Tibaldi, 2003; Acocella et al., 2006b); Spanish Peaks, Colorado (Ode, 1957); Hekla, Iceland (Gudmundsson et al., 1992, and references therein); Fuji and Sakurajima, Japan (Takada, 1997, and references therein; Takada et al., 2007); and Erta Ale, Ethiopia (Acocella, 2006). The rift zone passing through the summit of some of these volcanoes (Hekla, Erta Ale), even though associated to a regional stress field, resembles an end-member type of highly-clustered radial configuration of dikes (see also Section 3.1). The anisotropic distribution of radial dikes may result, in general, from the influence of a regional stress field which orients most dikes perpendicular to the least compressive stress (Nakamura, 1977). Anisotropic distributions of radial dikes are also found at volcanoes in intraplate settings, in absence of a dominant regional stress field. In such locations, the development of rift zones may be controlled by the stability of the flank of the volcano and/or the presence of nearby volcanoes (e.g. Fiske and Jackson, 1972; Walter et al., 2006). Examples include Kilauea and Mauna Loa, Hawai‘i (Decker, 1987), Fogo, Capo Verde (Day et al., 1999), and Piton the La Fournaise (Carter et al., 2007, and references therein). In the Canarian archipelago (Marinoni and Gudmundsson, 2000; Acosta et al., 2003, and references therein; Walter, 2003), radial dikes cluster in rift zones that form triple-arms spaced 120° apart and focused on the summit conduit. This configuration is interpreted to result from the shallow emplacement of magma below the volcano summit and/or the growth of nearby spreading volcanoes, promoting connecting rift zones (Walter, 2003, and references therein).

Two mechanisms favour the development of radial dikes in a volcano. The first is the distribution of the gravitational stresses due to the load of the edifice. This controls the trajectories of the maximum compressive stress, which becomes subparallel to the slope of the volcano (Dieterich, 1988), while the minimum compressive stress is tangential (Fig. 4a; Acocella and Tibaldi, 2005, and references therein). The larger and taller the volcano, therefore, the stronger is the maximum local stress (McGuire and Pullen, 1989). Locally, the propagation path of radial dikes may be controlled by the presence of significant scarps or other topographic irregularities on the volcano flanks. In this case, the trajectory of the maximum compressive stress at the scarp margin varies, becoming subparallel to the scarp; the minimum compressive stress becomes perpendicular to the direction of the scarp (Fig. 4b). As a result, dikes tend to propagate parallel to the major scarps on volcanoes, as at Stromboli and Etna, Italy (McGuire and Pullen, 1989; Ferrari et al., 1991; Tibaldi, 2003; Neri et al., 2004; Acocella and Tibaldi, 2005; Rust et al., 2005; Walter et al., 2005b; Neri and Acocella, 2006; Neri et al., 2007). Similarly, elongated volcanic edifices will be characterized by a maximum compressive stress oriented parallel to the major axis of the edifice, these conditions will result in the development of dikes oriented parallel to the elongation of the edifice (Fig. 4c; Fiske and Jackson, 1972). Notable examples of rift zones parallel to the major elongation of the edifice include Mauna Loa and Kilauea volcanoes, Hawai‘i (Decker, 1987), even though the shape of both volcanoes may be controlled by lateral instability. The second mechanism controlling the development of radial dikes is radially-oriented maximum compressive stress due to pressurization in a subsurface magma reservoir (Knopf, 1936; Ode, 1957). In this case, radial dikes form to accommodate the enlargement of the circumference of the edifice with relief, due to volcanic inflation (Acocella et al., 2001, and references therein).

Radial dikes may propagate vertically or laterally from the volcano's central conduit along the slope of the volcano. The mechanism of lateral propagation of dikes from the summit of a volcanic edifice remains poorly understood. Observational evidence suggests that propagation direction may depend in part on the closure/opening of the central conduit (Fig. 5; Acocella et al., 2006b). When the central conduit is closed or solidified, magma is emplaced in the edifice by means of vertically propagating dikes; in the upper part of the edifice, along the frozen conduit, these may follow gravitational stresses, becoming radial. Conversely, the lateral propagation of dikes is widespread, but not exclusive (Acocella and Neri, 2003; Lanzafame et al., 2003), in volcanoes characterized by an open summit conduit. Here, magma in the upper part of the conduit degasses and, becoming denser, intrudes laterally, propagating downslope. Notable examples of volcanoes with such a behaviour include Tenerife.
Fig. 3. Examples of radial eruptive fissures. 

- Etna, period 1900–2005; inset b) shows fissure orientation; inset c) shows the three main rift zones.
- Vesuvio, period 1631–1944; inset e) shows fissure orientation.
Estimates from Etna and Vesuvio suggest that the mean along-strike top surface of a laterally propagating dike has a moderate downslope dip, on the order of 10°–15° (Acocella et al., 2006c, and references therein). This mechanism of emplacement of radial dikes is usually limited to the upper part of the edifice, below its slope. Therefore, the specific conditions controlling it (i.e. opening/closure of the conduit) need not to be the same as those of the radial dikes propagating at the base of the volcanic edifice, as for example observed at Summer Coon Volcano (Poland et al., 2008).

2.2. What controls dike propagation in different volcanic edifices

The features discussed above establish general guidelines for dike propagation in volcanic edifices. The relations between these features (e.g., topography, regional vs. local stress field) and other factors (e.g., shape of the volcano, composition of magma) in the context of dike propagation has not yet been investigated in detail. Here, we aim to minimizing this gap, with a semi-quantitative analysis of the relations between various factors related to dike emplacement. We consider several features, listed in Table 1, related to dike emplacement at 25 active volcanic centers. Those features include: 1) height (H1) to the base of the edifice, including any submerged portion. 2) Aspect ratio (A) of the edifice (where $A = \text{height/width}$). 3) Eccentricity ($E$) of the edifice (where $E = \text{minimum elongation/maximum elongation}$). 4) Mean SiO$_2$ content of the erupted magmas, which is expected to approximate, to a first order, average magma viscosity. It is possible that dikes have far from average compositions, but this possibility has not been taken into account in this study. 5) Maximum length ($L$) reached by the dikes or, more commonly, the eruptive fissures in a volcano; in both cases, it is possible that the real length of the dike may be larger than that of its visible part, so this length has to be considered as minimum value. 6) Difference in height ($H_d$) between the highest and lowest part of the longest fissure or outcropping dike; this value refers to the subaerial part of the dike or fissure and thus may significantly differ from H1. 7) Frequency of...
The distribution of the RR values for the selected volcanoes shows a cluster at RR=0, where radial or circumferential systems are dominant and regional dikes are absent (Fig. 6a). These volcanoes are ocean island shields related to hot spot activity and away from plate boundaries with strong regional stress fields. Another at RR∼0.5 represents stratovolcanoes with similar proportions of local- and regional-controlled dikes or fissures. A third cluster of data, approaching RR=1, corresponds to volcanoes that are isolated and without regional stress. Therefore, for volcanoes that are isolated and without major flank slip, the data suggest that there may be a general correlation between the elongation of a volcano and the pattern of regionally-controlled dikes.

There is also an inverse correlation between the regional tectonic control on dike emplacement (RR) and the maximum height of a volcano above its base (H1; Fig. 6d). Volcanoes located in hot spot settings have not been considered in this diagram, as lacking of any regional extension, regional compression, hot spots). The general relations between these features are summarized in Fig. 6.

The distribution of RT values for the selected volcanoes shows a cluster at RT=0, where radial or circumferential systems are dominant and regional dikes are absent (Fig. 6a). These volcanoes have been selected based on availability of data (from previously published studies), variability of edifice type (e.g., calderas, shield volcanoes, composite volcanoes), and tectonic setting (e.g., regional extension, regional compression, hot spots). The general relations between these features are summarized in Fig. 6.
edifice is replaced by a local, topographic stress field (McGuire and Pullen, 1989).

The development of radial dikes was analysed as a function of $H_1$, $H_d$, $A$ and $SiO_2$. There is a direct proportion between the maximum length of an eruptive fissure or dike ($L$) and the total height of the volcano (Fig. 6e). The association of longer fissures or dikes with taller volcanoes suggests topographic control on dike propagation. Similar results are suggested by Fig. 6f, which indicates a direct proportionality between $L$ and the differential vertical height of the fissure or dike. The behaviour may be associated with dikes propagating laterally downslope, from the summit of an open conduit. In fact, it is expected that the shallower the dike separates from the central conduit, the higher its potential energy and propagation force will be; therefore the dike will propagate laterally a greater distance. There is

clear proof of such lateral propagation of dikes only at ∼30% of the considered volcanoes (Table 1), so further evidence is needed to generalize such behaviour.

The correlation between the maximum length of an eruptive fissure or dike (L) and the SiO2 content of the related magma (Fig. 6g) is poor, indicating that the composition and/or viscosity of the magma does not significantly limit dike propagation. This is in agreement with recent data from Stromboli, showing that the petrochemical features of the magma, including viscosity, have a very low influence on the geometry of dike propagation (Corazzato et al., 2008).

There is also no correlation between the maximum length of an eruptive fissure or dike (L) and the aspect ratio of the volcanic edifice (A; Fig. 6h). Apparently, the dip of the slope of the volcano, related to the aspect ratio of the edifice, does not influence dike propagation.

Finally, there is a direct proportionality between the aspect ratio of the volcanic edifice (A) and the sector of the edifice (Hd; Fig. 6i). The result implies that steeper volcanoes are also associated with eruptive fissures with larger difference in height; therefore, even though the length of the dike is not controlled by the steepness of the volcano (Fig. 6h), the drop in altitude of the dike may depend from the dip of the slope of the volcano.

3. Discussion

3.1. General features of dike propagation

The overview above indicates that the propagation path followed by dikes within a volcanic edifice is influenced by several factors. More than one of these factors may act simultaneously, producing complex dike patterns, and the role of each factor on dike propagation is summarized in Fig. 7. Below, we consider each factor independently, as end-member; however, corresponding examples are not always found in nature, given the complex interactions between the factors or the specificity of some conditions. Examples given (italic in Fig. 7) are supposed to provide the best available approximation, even though the dike patterns at those volcanoes may result from more than a single mechanism.

The most important first-order control on dike propagation within an edifice is topographic relief. Topography always introduces a local, gravitational stress field which is superimposed over other local (e.g., induced by a shallow magma reservoir) or regional stress field. The general consequence of significant topography is the development of a radial (more or less isotropic) dike pattern. The lack of topographic relief may lead to circumferential and/or regional dike patterns.

Edifices without significant relief may develop subparallel dike swarms consistent with the regional tectonic trend, as exemplified at Krafjla, Iceland. In absence of a regional stress field, the dike pattern may be controlled by the presence of topographic irregularities, such as calderas; circumferential dike systems may form at the periphery of the caldera. To our knowledge, there is not any particular example of active volcano with exposed circumferential dikes related to the lack of relief and regional stress field. Another possible control on dike propagation is that induced by a shallow magma reservoir; circumferential dikes are still mostly expected to form. Underpressure conditions within the reservoir will generate ring dikes, whereas overpressure conditions will generate cone sheets (Anderson, 1936; Phillips, 1974). Again, we are not aware of any clear dike pattern resulting from a magma chamber and the absence of topographic relief and a regional stress field in an active volcano. Therefore, these conditions, even though feasible, remain largely theoretical.

Edifices with topographic relief are characterized by a radial most compressive stress and will be dominated by radial dikes. Any departure...
from an isotropic radial pattern and clustering of the dikes along preferred orientations depends upon the shape of the edifice and, to a lesser extent, the regional stress field. If a sector collapse scar or other major scarps is present, radial dikes will partly focus around and parallel the relief, as observed at the Scia dei Fuoco flank collapse at Stromboli and the Valle del Bove at Etna (McGuire and Pullen, 1989; Acocella and Tibaldi, 2005).

In the case of subcircular or elongated edifices, the dike pattern will depend upon the presence or absence of a regional stress field. Without a regional stress field, dikes follow the major axis of the edifice, as at Kiluaea and Mauna Loa, or develop characteristic triple configurations at 120°, as at Tenerife. With a regional stress field, elongated volcanoes develop dikes focused along preferred regional orientations (as at Erta Ale, Afar, or Hekla, Iceland) or simply dike swarms that parallel the most compressive stress, as at Izu-Oshima (Fig. 1). The first situation can be interpreted as an end-member type represented by a highly asymmetric radial configuration of dikes, focused along a direction. The second situation, where the dikes are more dispersed, regards the emplacement of non-radial dike swarms. The development of one configuration (focused) or the other (dispersed) may depend from the intensity of the regional stress. At oceanic and continental divergent plate boundaries (exemplified by Erta Ale and Hekla), extensional stress focuses strain on the axis of the rift, where volcanoes are usually located. Extension is therefore restricted to a narrow axial zone passing through the volcano summit. Conversely, at arc or back-arc settings (for example, at Izu-Oshima; Takada, 1997), weaker tectonic extension results in more dispersed extensional structures, forming wider rift zones (Macdonald, 1998, and references therein). As a consequence, dike swarms may be found throughout the volcanic edifice and not restricted to the axial zone of the volcano.

Similar to elongated edifices, the dike pattern at subcircular edifices also depends upon the presence or absence of a regional stress field. Without any regional stress field, the dikes follow a radial path, as at Fogo (Capo Verde). With a regional stress field, the dike pattern may also depend upon the height of the edifice. Dike propagation at short volcanoes may be still partly influenced by a far-field stress, developing radial patterns with a clustering along directions parallel to the regional most compressive stress (for example, Nyamuragira, Nyiragongo, and Miyakejima). Dike propagation at taller volcanoes is less influenced by a regional stress field, displaying a more (though seldom fully) isotropic radial pattern (examples include Etna, Fuji and Kluchevskoi). The boundary that defines the relation between the height of a volcano and any anisotropy of the pattern of its radial dikes is not sharp, as several volcanoes (e.g., Vesuvio and Sakurajima), display intermediate values of H1 and RR.

The final dike pattern on a volcano may also depend upon the superimposition of different evolutionary stages of the edifice. In fact, the development of the main rift zones may be also due to lateral collapses or stress variations (Walter et al., 2005a; Tibaldi et al., 2006; Corazzato et al., 2008, and references therein).

The dike patterns described above may be more or less pronounced depending upon the length reached by the dikes. As introduced above, the most important parameter controlling the extent of dike propagation is probably the height of the edifice. Other factors, such as the composition of magma or the aspect ratio of the edifice, have moderate or negligible influence (Fig. 6). The comparison with known active cases (Hawaii, Tenerife, Etna, Vesuvio, Stromboli) suggests that these conditions may significantly apply to laterally propagating dikes. This common process of lateral dike propagation may be related to the opening of the central conduit, even though a more advanced study is needed (Acocella et al., 2006b).

3.2. Implications for hazard and future research

The factors above suggest that the emplacement of dikes in a given volcano may be predicted based on knowledge of the most important controlling parameters on dike propagation. Studies that account for dike emplacement and eruption are essential in any project concerning hazard mitigation at active volcanoes. In fact, many volcanic eruptions are fed by dikes, and dike-fed vents may develop at significant distances from the summit of a volcano. Therefore, understanding the controls on dike propagation is crucial to predict where a vent may develop and what hazards may result.

On these premises, we suggest that future research on dike emplacement should focus on the following points. 1) A better definition of the mechanical conditions for the lateral development of dikes originating from the central conduit of a volcanic edifice. Such dikes are a common feature in many types of volcano, regardless of tectonic setting. 2) The evaluation of the potential propagation paths of dikes at individual volcanoes. To the latter aim, the nature of the boundary conditions of individual volcanic systems need to be defined, including the opening or closure of the central conduit (e.g., Acocella et al., 2006b), the stress distribution within the volcanic edifice (e.g., Dieterich, 1988), as well as a function of its topography (Acocella et al., 2006a), the magmatic pressure in subsurface reservoirs (e.g., Gudmundsson, 2002, 2003), the presence of central or eccentric reservoirs (e.g. Neri et al., 2005, and references therein), the recent eruptive history (e.g. Behncke and Neri, 2003; Behncke et al., 2005; Allard et al., 2006), the occurrence of pre-eruptive earthquakes (Nostro et al., 1998; Walter et al., 2005b) and the presence of layers with different stiffness or mechanical properties (Gudmundsson, 2006, and references therein).

For example, investigations at Vesuvio, Stromboli and Etna suggest that most of the recent dikes propagate laterally from the central conduit, with a path largely controlled by the topography, as significant scarps (Neri et al., 2005, and references therein; Acocella et al., 2006a,b, c; Neri et al., 2008). These studies may constitute a starting point to try to evaluate with more precision the future propagation paths of the dikes as a function of different boundary conditions in these volcanoes. More in general, the propagation paths of dikes, as well as their likely lengths, may be estimated at a given volcano, allowing for the creation of hazard maps with the probability of dike-fed activity in different areas of the volcano. Such an approach may predict dike propagation at a volcano, considering not only the distribution of the most recent vents or fissures, but especially understanding why and under which conditions these dikes and fissures developed.

4. Conclusions

We describe the formation of three types of dikes (regional, circumferential and radial) in relation to several factors, including volcano topography (positive or negative relief, shape, height, sector collapses), tectonic setting (presence of a regional stress field) and mean composition (SiO2 content). Data from 25 volcanic edifices in different settings indicate that dike propagation depends, in order of importance, upon the presence of any relief, the shape of the edifice, and the presence of a regional stress field. Taller volcanoes develop longer dikes with radial orientations, with negligible effects of the composition of magma or the aspect ratio of the volcano. Our overview demonstrates that the style of dike emplacement may be predicted at given volcanoes. Future research and hazards assessments should evaluate the possible propagation paths of dikes at specific volcanoes, as well as the role of the boundary conditions of the system, including the opening or closure of conduit, the regional stress trajectories within an edifice, the magmatic pressure, the recent eruptive history, the occurrence of pre-eruptive earthquakes, and the presence of layers with different stiffness.

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