Dike propagation within active central volcanic edifices: constraints from Somma-Vesuvius, Etna and analogue models

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Abstract

Dikes within stratovolcanoes are commonly expected to have radial patterns. However, other patterns may also be found, due to regional stresses, magmatic reservoirs, topographic variations. Here we investigate dike patterns within volcanic edifices, by studying dike and fissure complexes at Somma-Vesuvius and Etna (Italy) and using analogue models. At the surface, the dikes and fissures show a radial configuration. At depths of tens to several hundreds of m, in areas exposed by erosion, tangential and oblique dikes are also present. Analogue models indicate that dikes approaching the flanks of cones, regardless of their initial orientation, reorient to become radial (parallel to the maximum gravitational stress). This reorientation is a significant process in shallow magma migration and may also control the emplacement of dike-fed fissures reaching the lower slopes of the volcano.

1 - Introduction

Volcanic eruptions are often fed by dikes, as observed at recently erupting volcanoes worldwide (e.g. Gudmundsson, 2006, and references therein). In stratovolcanoes, dike patterns are expected to be radial, as suggested by examples in nature (Poland et al., 2008, and references therein) and analogue models (e.g. Walter and Troll, 2003). At the surface of active volcanic edifices, the majority of dikes and eruptive fissures have a radial configuration, and tangential and oblique dikes or fissures are rare (as on the shields of the western Galapagos, as shown by Chadwick and Howard, 1991). However, within many eroded volcanic edifices, dikes and dike-fed eruptive fissures commonly have more complex patterns (e.g. Takada, 1997; Gudmundsson, 2006, and references therein), resulting from regional stresses, magmatic reservoirs, anisotropies or variations in topography. The surface dominance of radial dikes and fissures suggests that radial dikes are the most common way to transfer magma to the surface of a volcanic edifice, where they feed eruptions, independently of their source. Here we investigate this hypothesis, using data from dike and fissure patterns at the active volcanoes of Somma-Vesuvius and Etna (Italy) and analogue models.

2 – Dike and dike-fed fissure complexes at Somma-Vesuvius and Etna

Somma-Vesuvius is a stratovolcano, 1225 m in elevation, which formed over the last ~39 ka (Santacroce and Sbrana, 2003). The active cone (Vesuvius) is partly bordered by the remnants of the older Somma edifice, which forms an arcuate scarp (Fig. 1a), that is interpreted as a multi-stage caldera developed between ~22 ka BP and 79 AD. The scarp exposes the older deposits of Somma-Vesuvius, emplaced during ~39-22 ka (Cioni et al., 1999). Vesuvius formed in the last ~1.5 ka, with the most recent phase of activity occurring between 1631-1944 (Cioni et al., 1999). Data on dike emplacement at Somma-Vesuvius was gathered from three areas. The first is along the Mt. Somma scarp, where the dikes emplaced, between 39-22 ka, at depths ~100 to ~400 m, as suggested by reconstructing the Somma edifice (Cioni et al., 1999). Most of these dikes arrested and did not reach the surface, whereas propagation paths are both vertical and lateral (Porreca et al., 2006). Additional data were obtained from dike-fed eruptive fissures that outcrop on the Somma edifice, which were emplaced between 39-22 ka and reconstructed from mapping and the recognition of aligned and/or elongated spatter cones (Santacroce and Sbrana, 2003). Finally, we used dike-fed eruptive fissures on the Vesuvius cone, which had a lateral downslope propagation direction and were emplaced between 1631-1944 (Acocella et al., 2006).

The Somma-Vesuvius dikes and eruptive fissures can be used to investigate magma transport within a volcanic edifice over time. Its dike distribution (reported as a function of the angle δ, with $\delta=0°$ for radial dikes and $\delta=90°$ for tangential dikes) indicates that dike-fed fissures on the surface of the Mt. Somma and Vesuvius cones are radial or sub-radial (Fig. 1b). Conversely, dikes emplaced at a deeper level within the Somma edifice that have been exposed by erosion have a more dispersed orientation, with a significant (~40%) population that are oblique and tangential to the to the location of the older Somma edifice (Cioni et al., 1999).

Mt. Etna is a 3329 m high stratovolcano. The central edifice, formed during the last 220-120 ka, is characterized by a central conduit that feeds four summit craters immediately to the west of the Valle del Bove (VDB) depression (Fig. 1c; Bousquet and Lanzafame, 2001, and references therein). The VDB is the result of a sector collapse at 15-5 ka (Calvari et al., 1998, and references therein). Several hundreds dikes outcrop on the walls of VDB; most of these dikes formed between 85-10 ka and were emplaced at depths of several tens to hundreds of metres (Ferrari et al., 1993). The orientation of the dikes emplaced during the last ~2000 years was obtained from the distribution of eruptive fissures and aligned or elongated cones. These features, usually fed by dikes propagating laterally from the summit craters, largely focus along rift zones radial to the summit; these are preferred sites for intrusions, also of eccentric dikes (Bousquet and Lanzafame, 2001; Behncke and Neri, 2003, and references therein). The distribution of dikes as a function of δ at Etna indicates that dikes which outcrop on the present edifice are radial or sub-radial (Fig. 1d), with a few curved paths (here δ was obtained considering the mean strike of the dike). Dikes emplaced at deeper levels and exposed in the VDB walls, younger than ~45 ka (period in which the location of the summit of Etna has been stable; Ferrari et al., 1991) have a significant presence (~45% of data) of oblique and tangential orientations (Figure 1d).

The data from both volcanoes highlight a general trend of increasing proportion of dikes oriented parallel to the slope of the edifice (which is generally radial) with decreasing depth, suggesting reorientation during emplacement. This occurs regardless of the location and type of the magmatic source, which may consist of a central conduit, or a central or eccentric reservoir. We investigate the mechanism behind this observation with analogue experiments.

3 – Analogue models of dike emplacement in a cone

Analogue experiments of dike emplacement within a cone (height ~10 cm and diameter ~30 cm), having a slope of ~35°, were used to gain insights into dike propagation within a central stratovolcano. Similar to previous experiments (e.g.: Fiske and Jackson, 1972; McGuire and Pullen, 1989; Walter and Troll, 2003), gelatin and water were used to simulate the volcanic edifice and magma respectively. These experiments, even though belonging to the same experimental set as those of Acocella and Tibaldi (2005), have not been previously described, as being without lateral collapses. A detailed scaling is discussed in Acocella and Tibaldi (2005) and only general information is provided here. The density of the gelatin (200 bloom) was increased by adding salt, to achieve a gelatine/water density ratio ~1.07, similar to that of host rock/magma. Gelatin is a brittle viscoelastic solid; its Young's modulus (~10^4 Pa), Poisson's ratio (0.5) and cohesion (10^3 Pa) have been evaluated through rheometer tests. The imposed scaling ratios (Acocella and Tibaldi, 2005) show that 1 cm in our experiments corresponds to ~50 m in nature. Coloured water was injected (1 ml/sec) from a basal syringe-pipe at different locations beneath the cone. As these experiments were devoted at understanding the geometrical features of the dikes, kinematic behavior (as the velocity of injection or propagation), not perfectly scaled, was not considered (Acocella and Tibaldi, 2005).

Thirty-one injections were made at random locations beneath the center and periphery of the base of the cone, to simulate the wide range of possible propagations of dikes below volcanoes. Injections were made into different cones or in distant parts of a same cone, keeping the distance between injection points greater than the length of the dikes, to avoid any interaction. The initial orientation of the dikes was random, with uniformly distributed values of radial, oblique and tangential dikes (Fig. 2a). After injection, dike propagation was generally lateral towards the outer portion of the cone and, to a much lesser extent, towards its top. When approaching the surface, 97% of the dikes were radial or sub-radial (Fig. 2b), independent of the injection point. Dike re-orientation occurred during both lateral and vertical propagation.

An example of map-view reorientation of a laterally propagating dike is shown in Fig. 2c-d. Upon injection, the dike had an almost tangential orientation. While propagating laterally, the dike curved to become sub-radial as it approached the sloping surface. Vertically propagating dikes also reoriented to become radial with decreasing depths, Fig. 2e-g. In this case, to better appreciate any variation in the orientation of the dike along the vertical, we maximized the density contrast with the gelatin, enhancing the vertical rise of the dike by injecting air instead of water (e.g. Takada, 1994). The initial dike had an oblique orientation in map view. Dike propagation was mostly vertical and subordinately lateral; any lateral propagation occurred on the side of the nearest slope. The change in dike orientation during vertical propagation is summarized in Fig. 2g (inset), which shows the strike of the upper tip of the dike at three different times.

4 – Discussion and conclusions

The dike (and fissure) complexes at Etna and Somma-Vesuvius demonstrate that, while radial dikes dominate at the surface, a significant number of oblique and tangential dikes are present at depths of tens to hundreds of m. Analogue models suggest that dikes with initially random orientations reorient to become radial or sub-radial during lateral and/or vertical propagation. Similar behaviour has been observed in other analog experiments (e.g. Walter and Troll, 2003).

In map view, the maximum and minimum horizontal stress due to gravity in a cone are always radial and tangential, respectively (Acocella and Tibaldi, 2005, and references therein). In cross section, the maximum stress due to gravity in a cone is, immediately below the surface, subparallel to the slope, becoming subvertical with increasing depth towards the base of the edifice (Dieterich, 1988). Such a stress distribution may explain the observed reorientation of the dikes at Etna and Somma-Vesuvius and in our analogue modelling. Dikes, whatever their initial orientation, while moving to shallower levels (either rising vertically towards the surface or propagating horizontally beneath a sloping surface), become parallel to the radially-oriented maximum horizontal stress (local $\sigma 1$) and perpendicular to the tangentially-oriented minimum horizontal stress (local $\sigma 2$; Fig. 3). The stress regime due to the load of the cone has therefore an effect on dike propagation near the surface. Other mechanisms of shallow reorientation were recognized, as en-echelon dikes propagating from a parent dike (e.g. Delaney and Pollard, 1981).

Within a volcanic edifice, the random orientation of dikes upon injection, as seen in the analogue models, has several possible explanations. The propagation path of the dikes at depth may become progressively (with increasing length) more dependent upon stresses induced by magma reservoirs, regional tectonics or topographic variations (Gudmundsson, 2006, and references therein). Pre-existing discontinuities (such as buried caldera faults, sector collapse structures, layering or other dikes) or different central conduits in overlapping edifices may similarly alter the propagation path of dikes at the base of a volcano (Gudmundsson, 2006; Takada, 1994). These factors may induce significant deviations from the expected radial pattern of dikes within stratovolcanoes (e.g. Poland et al., 2008), explaining the more complex patterns observed in the eroded portions of Etna and Somma-Vesuvius.

The results from field observations and analogue modelling indicate that a dike propagating within a volcanic edifice may be reoriented to a radial direction at shallow levels (Fig. 3). This occurs regardless of the location and type of the source, as a central conduit, a central or eccentric reservoir. The critical depth, above which such a re-orientation is observed, is tens to a few hundred meters in volcanoes that are in the order of 1000 m high (Etna and Somma-Vesuvius). In our analogue experiments, reorientation during vertical dike propagation (Fig. 2e-g) occurs in the upper ~30% of the thickness of the volcano at the point where the dike is located.

The proposed model, independent of the size or the height of the edifice, can readily be applied to Etna and Somma-Vesuvius, where ~95% of the most recent phase of non-summit activity has involved the emplacement of radial dikes feeding eruptive fissures and vents. At Etna, this includes the last ~2000 years (Behncke and Neri, 2003) and at Vesuvius the 1631-1944 period (Acocella et al., 2006). At the surface of these volcanoes, the absence of non-radial dike patterns either suggests that (a) a dike reorients towards the surface or (b) that the shallowest propagation of a non-radial dike is hindered by the configuration of the stresses towards the surface (Fig. 3). While (a) may explain the radial orientation of the vertically propagating dikes, (b) may indirectly explain the predominance of laterally propagating radial dikes which do not appear to have experienced shallow re-orientation, whose development is commonly expected in stratovolcanoes (e.g. Odè, 1957; Poland et al., 2008).

The Somma edifice lacks of evidence for dike emplacement after the development of the caldera, which occurred in the last 19 ka (Cioni et al., 1999), as also observed at Kliuchevskoi (Takada, 1997). A possible explanation for this condition is that the radial dikes emplaced on the volcano's slopes were largely fed by a magma body beneath the central part of the volcano. When the continuity with the central feeding system was interrupted (during formation of the caldera), the magma supply to the periphery of the volcano was cut off and radial dikes did not develop. If this scenario is true, our model may only be applied to those portions of a volcanic edifice that are not topographically or structurally isolated from the main magmatic system area.

Because the general re-orientation of dikes appears largely driven by gravity and is imposed by the presence of an edifice with some relief, we propose that our model is generally applicable to stratovolcanoes with a conical or subconical shape. At such volcanoes, dike-fed eruptions are therefore expected to occur from radial fissures. These, unlike tangential or oblique fissures, tend to vary in length between 10^2 and 10^4 m and may easily reach the base of the edifice, where any human presence is likely to be greatest.

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Figure captions

Fig. 1 – Digital Elevation Models showing the topography of Somma-Vesuvius (a) and Etna (c); VDB=Valle del Bove. The eruptive fissures and dikes, not shown for simplicity, are measured on the surface of the edifices; boxes highlight major scarps where dikes emplaced at depths of tens to hundreds of meters have been exposed by erosion. For details on the dike and fissure patterns see Ferrari et al. (1991), Behncke and Neri (2003), Santacroce and Sbrana (2003), Acocella et al. (2006) and Porreca et al. (2006). The distribution of the dikes at the surface and along major scarps (boxes in a and c) at Somma-Vesuvius (b) and Etna (d); the angle δ is 0° for radial dikes and 90° for tangential dikes.

Fig. 2 – Orientations of analogue model dikes in a gelatine cone during initial injection (a) and final emplacement (b), as a function of δ (see Figure 1). The evolution of a laterally propagating dike from tangential to radial is shown in parts c (initial injection) and d (final orientation). Evolution of a vertically propagating dike is shown in parts e (initial injection), f (intermediate

stage) and g (final orientation). Inset in part g shows the variation in the strike of the upper tip of the dike in the various stages, becoming radial on approaching the surface.

Fig. 3 - Schematic representation of dike reorientation upon approaching the surface of a cone, in map and section view. At the base of the cone, the attitude of the dike depends upon the remote stress field, characterized by a maximum (σM) and minimum (σm) principal stress, as shown by the insets. At the surface, the load of the cone re-orients the dike, in accordance with the three principal gravitational stresses (local σ1, σ2 and σ3), as shown in the insets.

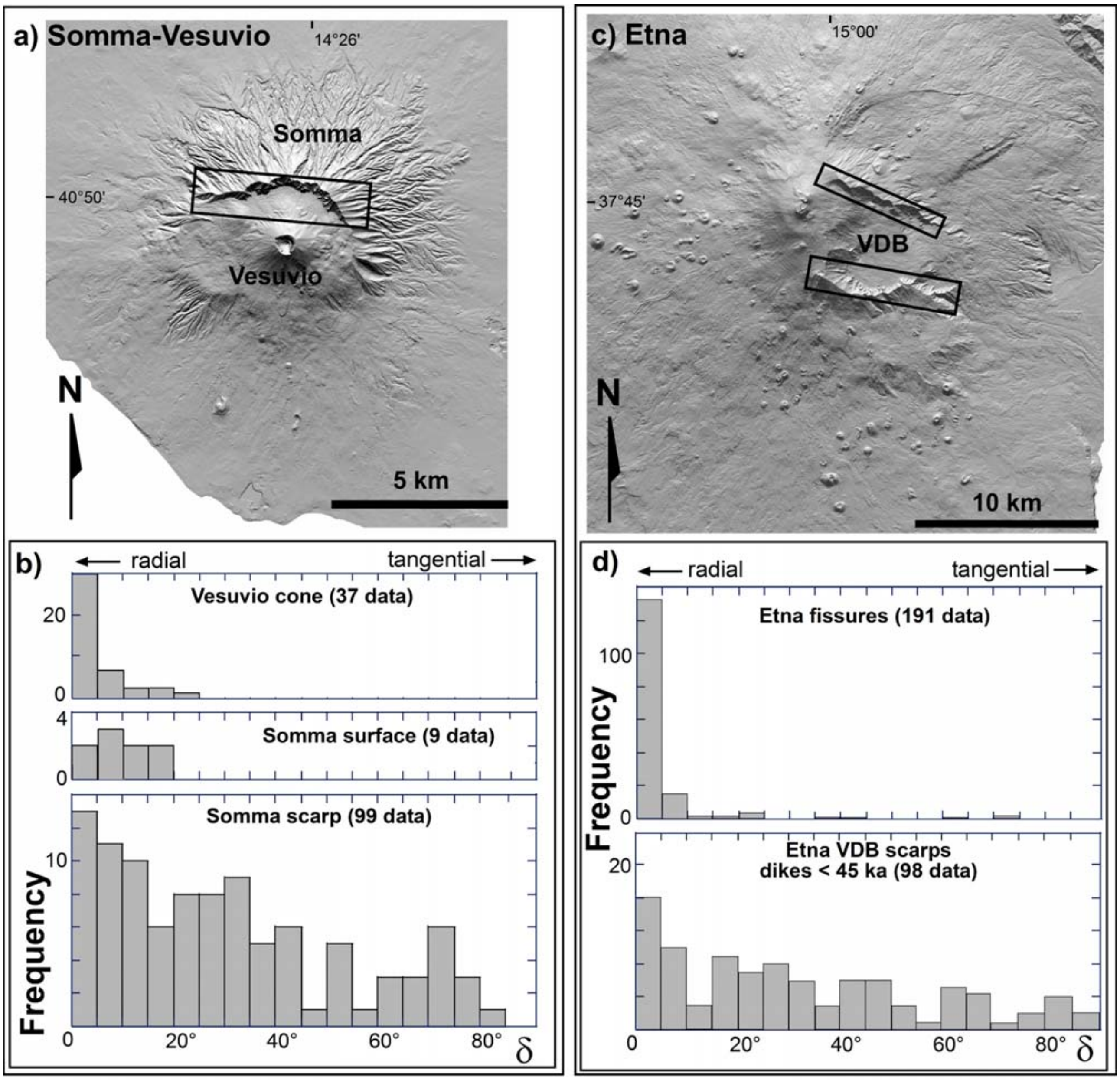
a) Somma-Vesuvio
14°26'
Somma
40°50'
Vesuvio
N
5 km
c) Etna
15°00'
37°45'
VDB
N
10 km
b)
radial
tangential
Vesuvio cone (37 data)
20
0
4
Somma surface (9 data)
0
Somma scarp (99 data)
10
Frequency
0
20°
40°
60°
80°
δ
d)
radial
tangential
Etna fissures (191 data)
100
0
Frequency
Etna VDB scarps
dikes < 45 ka (98 data)
20
0
20°
40°
60°
80°
δ

Fig 1

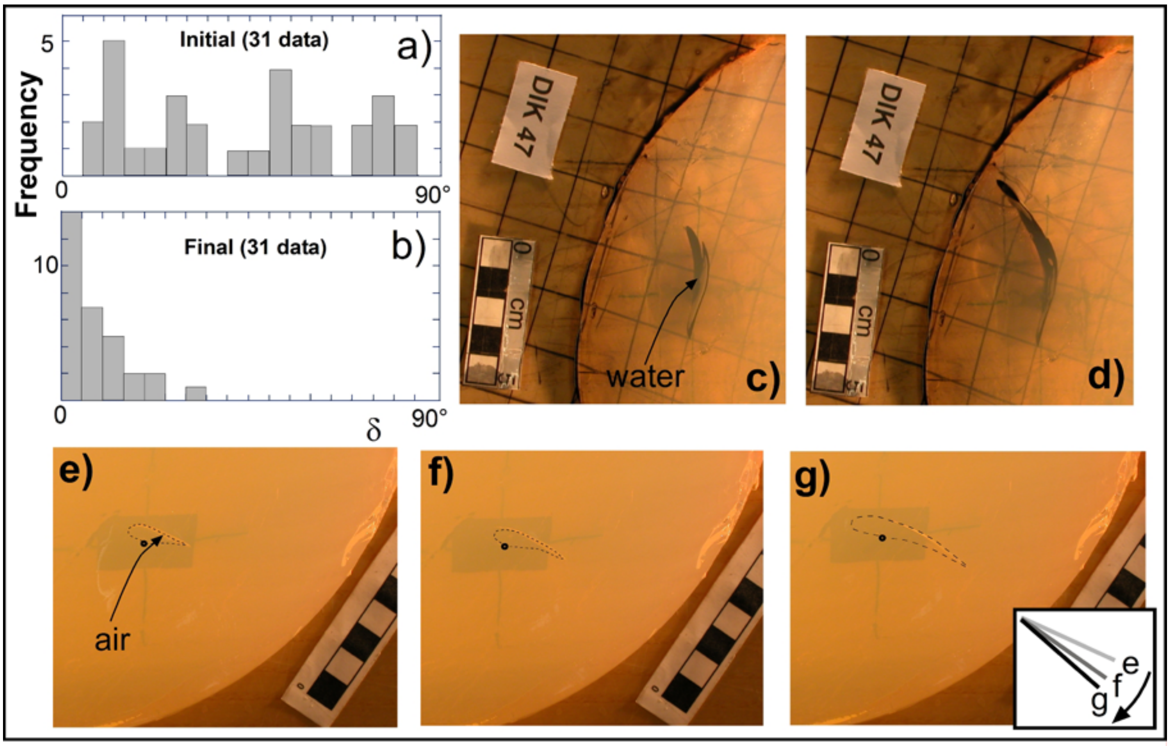
a)
Initial (31 data)
Frequency
5
0
90°
b)
Final (31 data)
10
0
δ
90°
c)
DIK 47
0
cm
water
d)
DIK 47
0
cm
e)
air
f)
g)
e
f
g

Fig. 2

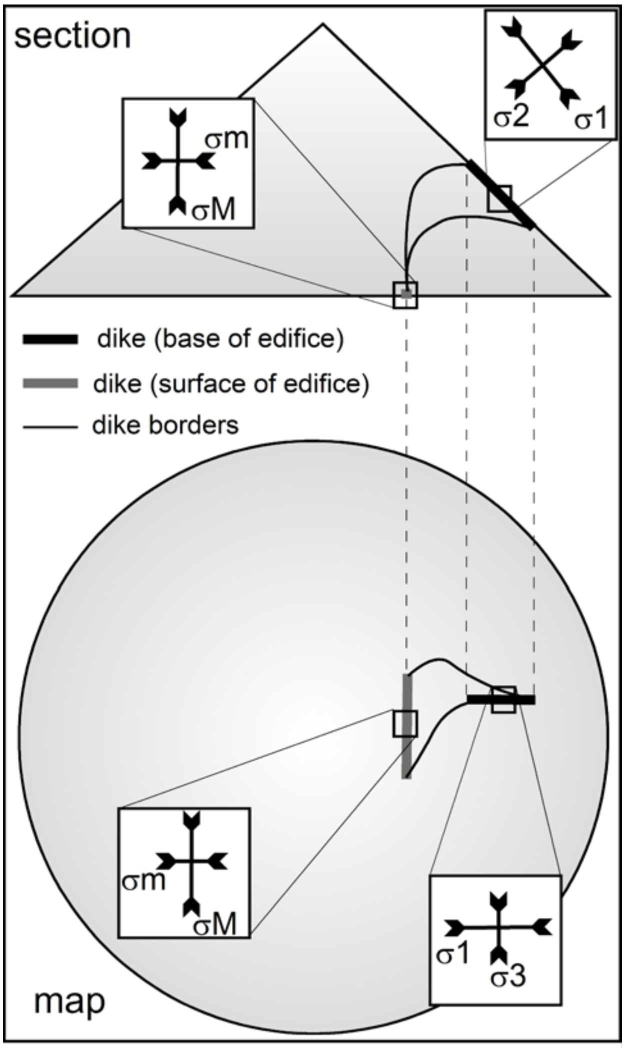
section
σm
σM
σ2
σ1
dike (base of edifice)
dike (surface of edifice)
dike borders
σm
σM
σ1
σ3
map

Fig. 3