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The impact of strike-slip, transtensional and transpressional fault zones on volcanoes. Part 1: Scaled experiments

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ABSTRACT

The activity of a regional strike-slip fault can affect or channel magma migration, can deform a volcano and can destabilise the edifice flanks. The aim of this study is to determine the location, strike, dip and slip of structures that develop in a stable or gravitationally spreading volcanic cone located in the vicinity of a fault with a strike-slip component. This problem is addressed with brittle and brittle-ductile analogue models. The one hundred and twenty three models were deformed by pure strike-slip, transtensional or transpressional fault displacements. The deformation was organized around an uplift in transpressional and strike-slip experiments and around a subsiding area in transtensional experiments. Most displacements are accommodated by a curved fault called Sigmoid-I structure, which is a steep transpressional to transtensional fault. This fault projects the regional fault into the cone and delimits a summit graben that is parallel to the main horizontal stress. The systematic measurements of faults strike and slip in the experiments indicate that extension along the faults in the cone increases with the extensional component of the regional fault and the thickness of the substratum ductile layer. The distribution of the fastest horizontal movements of the analogue cone flanks, which vary depending on the regional fault characteristics and on the composition of the substratum, correspond to the distribution of instabilities in nature. Natural examples of volcanoes sited in strike-slip contexts are described and interpreted in the light of the analogue results in the second article

1. Introduction

Many volcanoes are associated with faults that facilitate the transport of magma in the crust. Active faults interact with the volcano as it grows or/and as it becomes eroded. Volcanoes are also deformed by local processes such as gravitational spreading, which has been observed worldwide (van Bemmelen, 1953; Merle and Borgia, 1996; Borgia et al., 2000). This paper examines the structure of stable and spreading conical edifices interacting with faults that have a strike-slip component of movement.

There are three types of strike-slip faults: pure strike-slip, transtensional and transpressional. They are found in every geodynamic context and are the most common fault type associated with volcanic activity. Lithospheric strike-slip faults have an average slip of 1 mm to 1 cm per year (Dusquenoy et al., 1994; Bourne et al., 1998; Groppelli and Tibaldi, 1999; Corpuz et al., 2004) and fault planes are rapidly hidden by volcanic output and fast erosion of the accumulated volcanic deposits. A volcanic edifice can be internally deformed by a strike-slip fault movement even if no structures are visible at the surface (Norini and Lagmay, 2005) or may repair itself (dyke sealing fractures, etc.) between episodes of faulting (Belousov et al., 2005).

The fault kinematics and geometries considered here have been studied by previous authors. In theory, if a cone is added on top of a flat substratum above a strike-slip fault, its load will deflect the stress field (e.g. related to regional or far-field movement). A graben parallel to the regional sigma 1 and bordered by subsidiary synthetic shear fractures, i.e. Riedel (R) shears oriented at 15° and Y shears parallel to the principal displacement zone (e.g. Sylvester, 1988), initially form at the summit of the cone (van Wyk de Vries and Merle, 1998). During the experiment, the graben extends and converts to reverse faults down the cone flanks to form curved, synthetic R shears, referred to as a Sigmoid-I structure (Lagmay et al., 2000; Norini and Lagmay, 2005). A second set of synthetic shears, i.e. P shear, develops around the summit. The P shears are named Sigmoid-II structures (Lagmay et al., 2000) and border a fast moving summit area (Andrade, 2009; e.g. Fig. 1-b). In addition to these

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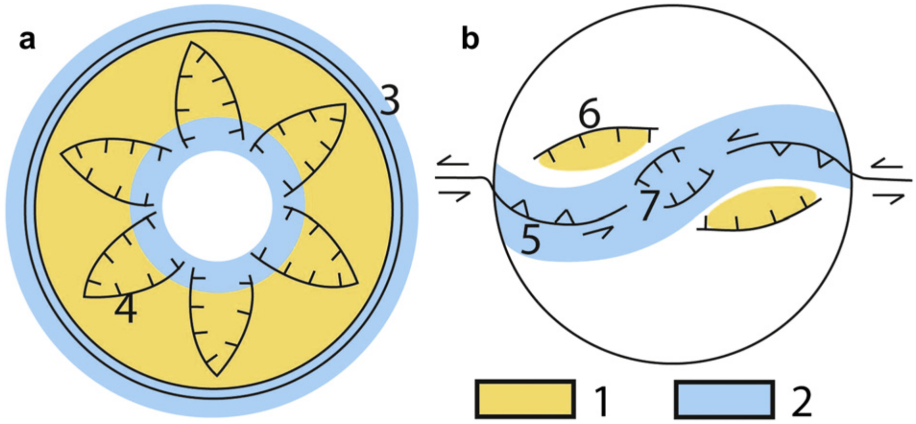

Fig. 1. Sketch of the main structures that form in an experimental cone located (a) above a ductile substratum (after Merle and Borgia, 1996) or (b) above a strike-slip fault (after Lagmay et al., 2000). The slowest and fastest horizontal movements are drawn after Delcamp et al. (2008) (a) and Andrade (2009) (b); (1) fastest and (2) slowest horizontal movements, (3) basal fold or reverse fault, (4) radial half-grabens or flower structures, (5) Sigmoid-I, (6) Sigmoid-II, (7) summit graben.

structures, folds are observed in the substratum, at the tip of Sigmoid-I faults (van Wyk de Vries and Merle, 1998). The aim of the previously published analogue modelling work was to explore the basic principles of strike-slip faults and volcanoes interaction (van Wyk de Vries and Merle, 1998) and to establish a link between regional strike-slip faults and the frequent sector collapses that affect cone-shaped volcanic edifices (Lagmay et al., 2000; Norini et al., 2008; Wooller et al., 2009). The aim of this study is to fully document the orientation, kinematics and slip rate of the Sigmoid structures. We make detailed observations on fault and fracture patterns by using a fine ignimbrite-derived powder for the modelling and we couple structural maps of the models with displacement maps to further explore the deformation of the volcanic cone's flanks.

Cones interacting with transtensional and transpressional fault planes located 10° and 20° from their strike-slip component of movement have been modelled by Andrade (2009). In these models, Sigmoid-II is a wide fracture zone in the mid-upper cone, which becomes part of the summit graben (transtension) and connects with Sigmoid-I at the cone base (transtension) or at the summit (transpression). The summit graben subsides the least and is the narrowest in transpressional experiments. The artificial North of Andrade's (2009) models is normal to the strike-slip component of movement, which strikes 090°. In these models, the summit graben strikes 040°–050° (sinistral transtension) and 060°–070° (sinistral transpression) and corresponds to the maximum rotation. The models presented in this paper build up on Andrade's (2009) pioneer study. We increase the extensional and compressional components of our faults and we quantify precisely the kinematics of each observed structure in order to better characterise the mechanisms of cone flank rotation.

Other studies have tested the volcano spreading mechanisms, which is a relevant process that controls the slow-rate and long-term structural and magmatic evolution of a volcano (e.g. Borgia, 1994). Spreading occurs at volcanoes which are underlain by a substratum containing a low-viscosity layer. The excess load (volcano) drives outward spreading movements, which form concentric thrusts and folds or sub-radial strike-slip faults in the substratum around the edifice (Merle and Borgia, 1996). The volcano is in turn affected by radial stretching and displays radial intersecting grabens, named flower grabens, and a fractured summit area (Fig. 1-b). The basic interaction between strike-slip faults and volcano spreading was described by van Wyk de Vries and Merle (1998). These authors predicted, that through theoretical considerations, the geometry of spreading-related structures (flower grabens) was expected to be disturbed by the strike-slip faulting. From this basic work, we use the analogue models to quantify the interaction between the spreading structures and a range of transtensional to transpressional fault movements, and we describe the resulting deformation fields.

The study is presented in a two-part paper. This article (part 1) employs analogue experiments to investigate the geometry of structures related to strike-slip movements in volcanic cones. Scaled analogue models are particularly useful, as the key parameters that influence the structural development can be determined by varying the experimental boundary conditions, which is not feasible in field studies. Both stable cones (Brittle substratum experiments) and spreading cones (Ductile substratum experiements) are modeled in this paper. The models were carried out in the Laboratoire de Magmas et Volcans, Blaise-Pascal University, Clermont-Ferrand, France. Part 2 investigates natural examples and compares them with the analogue models (Mathieu et al., 2011).

2. Experimental device, material and scaling

2.1. Material used

The substratum and the volcanic cone were modeled by a granular material. A first set of 112 experiments was carried out with fine-grained ignimbrite powder and 11 experiments were made with sand. Ignimbrite powder allows the development of a large number of faults and has enabled the quantification of fault kinematics, including slip and strike. This is because the ignimbrite powder preserves very clearly the fine-scale features, giving a much finer detail than sand (cf. Fig. 2). The powder is composed of sieved Grande Nappe Ignimbrite, from the Mont Dore volcano, France, consisting of angular glass and quartz grains less than 250 μm in diameter. The ignimbrite powder has an angle of internal friction of 38° and is more cohesive (100–230 Pa; Table 1) than sand (0–10 Pa) because the smallest grains (about 1 μm in size) block the pore spaces in the powder, and the grains are more angular. The sieved ignimbrite is similar to other analogue model granular materials as it fails in tension when unconfined and, when confined, fails with shear band formation. Sand is used in 11 experiments because it is easy to dye and is permeable, so, in contrast to ignimbrite, can be wet and sliced at the end of experiments to provide cross sections. The silicone Polydimethylsiloxan (PDMS), a linear viscous polymer (e.g. ten Grotenhuis et al., 2002) is used as a ductile substratum horizon in 51 experiments (cf. Table 2).