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The influence of edifice slope and substrata on volcano spreading

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ABSTRACT

Gravitational volcano spreading is caused by flow of weak substrata due to volcanic loading, and is now a process known to affect many edifices. The process produces extension in the upper edifice, evidenced by gräben and normal faults, and compression at the base, seen in strike–slip faults and thrusts. Where spreading is identified, host volcanoes have a range of fault densities, variable rift and gräben shapes, and different degrees of structural asymmetry. Previous studies have suggested a link between edifice shape and structure and the proportion of brittle to ductile material in the substrata or lower edifice. We study this link using refined sand cone analogue models standing on a brittle–ductile/sand–silicone substrata. Two scenarios have been investigated, the first mainly represents oceanic volcanoes with a ductile layer within the edifice (type I), where there is an outer ductile free surface. The second represents most continental volcanoes that have ductile substrata (type II). We apply the model results to natural examples and develop quantitative relationships between slope, brittle–ductile ratio fault density, spreading rate and structural style. Displacement fields calculated from stereophotogrammetry show significant differences between different slope models. We find that more faults are produced when the cone is initially steeper, or when the brittle substratum is thinner. However, the effect of the brittle layer dominates over that of slope. The strike–slip movements are found to be an essential feature in the spreading mechanism and the gräben are in fact transtensional features. Strike–slip and graben faults make a conjugate flower pattern. The structures produced are well-organised for type II edifices, but they are poorly organised for type I models. Type I models represent good analogues for oceanic volcanoes that are commonly affected by large slumps bounded by an extensional zone and lack of well-formed sector gräben. The well-observed connection between oceanic volcano rifts and large landslide-slumps is confirmed to be a consequence of spreading.

1. Introduction

Volcano spreading is a becoming a well accepted theory and has been studied both in the field (Van Bemmelen, 1949; Borgia and Van Wyk de Vries, 2003) and in the laboratory using numerical and analogue modelling (Borgia, 1994; Merle and Borgia, 1996; Van Wyk de Vries and Matela, 1998; Walter et al., 2006, Morgan, 2006). Spreading is linked to the presence of ductile substrata (for example sediments), which deform under the load of the overlying volcanic edifice (Van Bemmelen, 1949; Borgia, 1994; Merle and Borgia, 1996). Spreading can be triggered in the volcano itself especially in oceanic situations, if there are low strength layers (LSL) that can be composed, for example, of hydrothermally altered levels, weak sediments and mass slumping products (Oehler et al., 2005).

Summit gräben and basal thrusts are typical spreading structures (Merle and Borgia, 1996), but strike–slip faults are also closely associated with spreading (Borgia and Van Wyk de Vries, 2003). The main features are well displayed on small continental arc volcanoes, such as Concepción (Fig. 1), and other Nicaraguan volcanoes such as Mombacho, Nicaragua (Van Wyk de Vries and Borgia, 1996; Van Wyk de Vries and Francis, 1997; Borgia and Van Wyk de Vries, 2003; Shea et al., 2008). These volcanoes spread laterally on thick lacustrine and ignimbrite layers, and have either intensive fracturing of a young edifice, as at Concepción, or well developed graben faults, as on Maderas, or faults and large sector collapses associated with spreading, as at Mombacho. The relationship between sector collapse and gravity spreading was established by Van Wyk de Vries and Francis (1997), radial spreading tends to stabilise the edifice (Van Wyk de Vries and Borgia, 1996; Oehler et al., 2005), while spreading on one side can generate collapse (Wooller et al., 2004). Larger arc edifices also show spreading features, such as Poas, Costa Rica (Borgia et al., 1990), where the huge Alejuela fault forms a compressional feature below the edifice, while an axial graben cuts the

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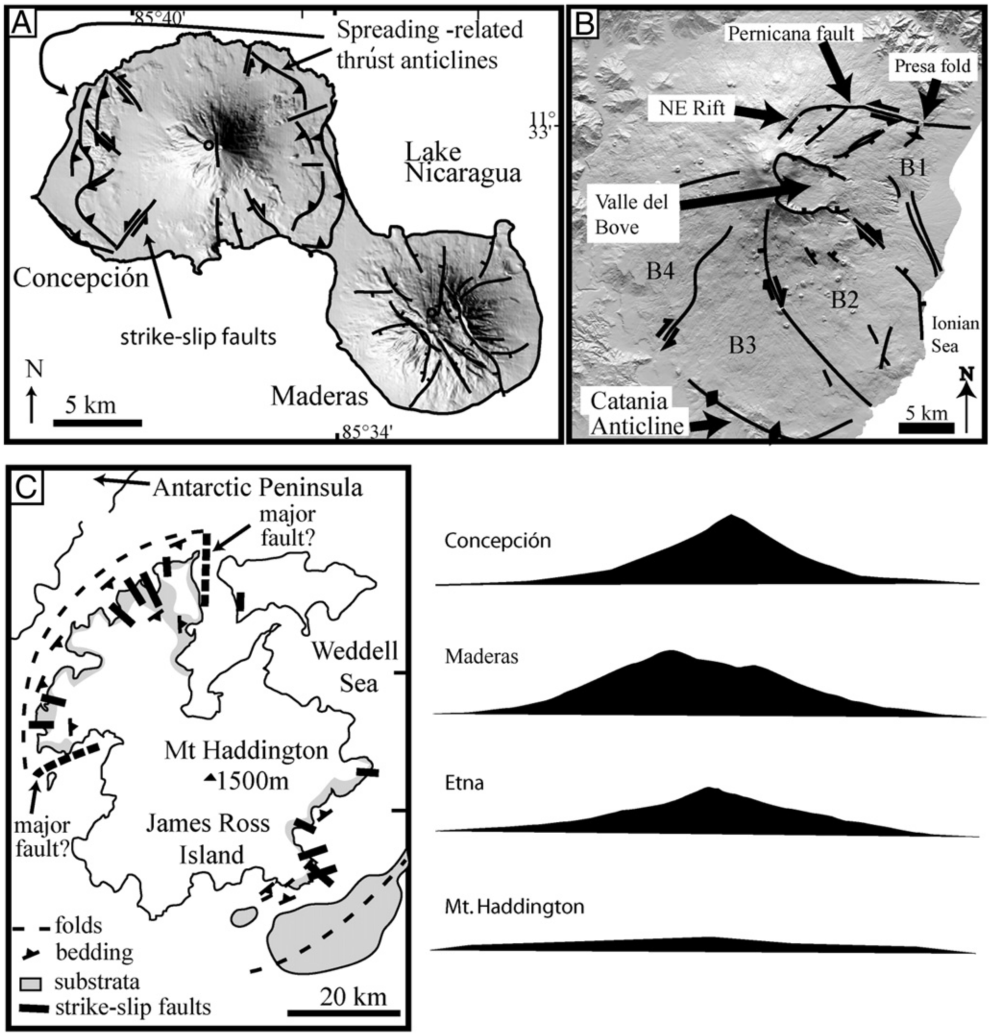

Fig. 1. Shaded relief images of Maderas and Concepción (A), Etna (B), and structural map of Mount Haddington (C) volcanoes, plus topographic profiles for each volcano. Morphology is different for each edifice. A: For Concepción, most of the edifice structures are buried by recent activity, but folds and strike–slip faults appear at the base; on Maderas clear gräben structures appear (Borgia and Van Wyk de Vries, 2003). These two volcanoes are steep (around 30°) although the summit of Maderas is now flattened. B: Mount Etna, whose slope is less than 20°, is cut by some faults which show strike–slip movement. The NE and SE rifts define a spreading sector. C: Mount Haddington is a less than 10° slope volcano and with no discernable spreading-related structures on the edifice, even though considerable deformation is seen in the substrata.

edifice. Etna is similar in size to Poas and displays well developed spreading-related gräben, as well as strike–slip and compressional structures at its base (Fig. 1). In the case of Poas the volcano may spread on altered volcanic and sediments, while Etna probably spreads on a lower clay layer, and possibly at a deeper level in association with the growth of a major intrusive complex.

Many Indonesian volcanoes were described as spreading by Van Bemmelen (1949). While spreading has been described for large oceanic volcanoes, such as Kilauea on Hawaii (Nakamura, 1980; Borgia, 1994; Morgan, 2006), the Canary Islands (Walter et al., 2006), and La Réunion (Oehler et al., 2005). On oceanic islands the main deformation décollement is thought to be the pelagic underlying sediments, but may also include within-edifice layers, such as hydrothermally altered rock (Merle and Lénat, 2003), or detrital and brecciated material such layers have been termed Low Strength Layers (Oehler et al., 2005).

There is a considerable variation in the geometry and density of spreading-related faults seen on volcanoes. For example, Maderas has a dense fault cover, while Etna has just a few large faults, and Mt Haddington none at all (Fig. 1). Also, the characteristic sector gräben on such volcanoes as Maderas, or Etna are not well represented on oceanic volcanoes, even though these have manifestly the highest spreading rates.

The volcanoes cited have very different edifice shapes (Fig. 1) and also stand on variable substrata. Thus, it is obvious that both edifice morphology and substrata have an important control on the structures produced. Merle and Borgia (1996) have already shown that edifice shape and the ratio of brittle to ductile rock in the substrata affects the propensity to spread and the rate of spreading. We take this study further by investigating the link between: 1, volcano initial morphology (taken as the slope), 2, substrata constituents, modelled as variations as the brittle and ductile substrata layers, and the observed spreading-related structures (gräben and thrusts). From the modelling we highlight empirical relationships between volcano geometrical parameters and observed structures, such as gräben geometry, number of faults and their orientation.

2. Modelling

2.1. Experimental set up

We consider two model types. The first (type I) is the analogue for oceanic volcanoes first used by Oehler et al. (2005) where the ductile layer, or low strength layer (LSL) is within the edifice and represents