Journal of Volcanology and Geothermal Research 176 (2008) 291–301

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Contractional tectonics and magma paths in volcanoes

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ARTICLE INFO

Article history:
Received 22 November 2007
Accepted 7 April 2008
Available online 24 April 2008

Keywords:
compressional tectonics
reverse faults
volcanism
Trohunco
Los Cardos–Centinela
El Reventador

ABSTRACT

This study aims to contribute a possible explanation for magma migration within volcanoes located in contractional tectonic settings, based on field data and physically-scaled experiments. The data demonstrate the occurrence of large stratovolcanoes in areas of coeval reverse faulting, in spite of the widely accepted idea that volcanism can develop only in extensional/transcurrent tectonic settings. The experiments simulate the propagation of deformation from substrate reverse faults with different attitudes and locations into volcanoes. The substrate fault splits into two main shear zones within the volcano: A shallow-dipping one, with reverse motion, propagates towards the lower volcano flank, and a steeper-dipping one, with normal motion, propagates upwards. In plan view, the reverse fault zone is arcuate and convex outwards, whereas the normal fault zone is rectilinear. Structural field surveys at volcanoes located in contractional settings show similar features: The Plio–Quaternary Trohunco and Los Cardos–Centinela volcanic complexes (Argentina) lie above Plio–Quaternary reverse faults. The Late Pleistocene–Holocene El Reventador volcano (Ecuador) is also located in a coeval contractional tectonic belt. These volcanoes show curvilinear reverse faults along one flank and rectilinear extensional fracture zones across the crater area, consistent with the experiments. These data consistently suggest that magma migrates along the substrate reverse fault and is channelled along the normal fault zone across the volcano.

1. Introduction

For decades, volcanism and regional extensional tectonics have been thought to be tightly linked, as this stress state favours magma upwelling along vertical fractures perpendicular to the regional horizontal least principal stress (σ_3) (Anderson, 1951; Cas and Wright, 1987; Watanabe et al., 1999). For arc volcanism occurring at convergent margins, Nakamura (1977) states that the overall tectonics of the arcs should be strike–slip (with σ_3 and greatest principal stress, σ_1, both horizontal) instead of compressional reverse (σ_3 vertical). This would allow magma to ascend through vertical dykes parallel to the direction of σ_1 (Nakamura and Uyeda, 1980). This idea is consistent with the models of Hill (1977) and Shaw (1980) that suggest composite systems of tensional and shear fractures for dyke propagation as well as with field data (e.g. Tibaldi and Romero-Leon, 2000; Pasquarè and Tibaldi, 2003; Lara et al., 2006) and geophysical data (Roman et al., 2004). In other strike–slip settings, volcanism has been associated with local dilation occurring at releasing bends and pull-apart basins (Pasquarè et al., 1988; Petrinovic et al., 2006; Busby and Bassett, 2007).

By contrast, a true contractional tectonic environment, with reverse or transpressional faulting, is usually considered a highly unfavourable setting for volcanism (Glazner, 1991; Hamilton, 1995; Watanabe et al., 1999) where only intrusive emplacement is expected (Cas and Wright, 1987). More recently, based on field mapping of plutonic rocks, it has been suggested that transpressional tectonics can be an efficient mechanism for moving magma through the lithosphere (Saint Blanquat et al., 1998), although Marcotte et al. (2005) suggest that transpression can result in the movement of only a small volume of magma to the surface. To investigate how magma rises through the brittle upper crust in the context of contractional tectonics, Galland et al. (2003) have performed experiments on scaled physical models. These authors suggest that magma in orogenic belts can rise along thrust faults, but horizontal compression favours thick flat-lying intrusions, and prevents magma from reaching the surface. However, in a more recent paper Galland et al. (2007a) suggest that magma can reach the surface along thrust faults. Field geological and structural data do show correlation between volcanism and reverse and strike–slip faults in the Mojave Desert area (USA, Glazner and Bartley, 1994), whereas field and geophysical data demonstrate that the entire history of development of the El Reventador volcano (Ecuador) occurred within a contractional tectonic regime with reverse or reverse-oblique faulting (Tibaldi, 2005). In recent years it has also been recognized that some other volcanoes lie close to major thrust faults, such as Guagua Pichincha in Ecuador (Legrand et al., 2002), Tromen in Argentina (Marques and Cobbold, 2002; Galland et al., in press), and some volcanic edifices in the Calchaquì valley of Argentina (Guzman et al., 2006) as well as in northern Japan (Yoshida, 2001). A true regional contractional tectonic environment must be distinguished from local compressional deformation resulting from

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doi:10.1016/j.jvolgeores.2008.04.008

gravitational spreading of substrata below the volcano load, such as at Socompa in Chile (van Wyk de Vries et al., 2001). In some cases the temporal coincidence between contractional tectonics and volcanism has not been unequivocably determined (e.g. Taapaca in Chile, Clavero et al., 2004), whereas in other instances it has been shown that the volcanic loading can induce a strain partitioning involving deflection and flattening of regional compressive structures (Branquet and van Wyk de Vries, 2001).

Understanding whether magma can reach the surface in the presence of regional contractional tectonics is not only a "leading edge" matter of scientific debate, but also has major implications in terms of natural hazards mitigation and natural resource exploitation. The evaluation of volcanic and seismic hazards involves the reconstruction of the structural architecture and the stress state of the volcano and the surrounding basement. Moreover, when conducting hydrogeologic and geothermical studies in volcanic areas, it is crucial to be able to correctly identify the tectonic framework.

This paper presents some field examples of clear correlations between major volcanism and coeval regional contractional deformation. Furthermore, results of experiments on scaled physical models, aimed at investigating how magma moves at shallower crustal depths across volcanic cones in a contractional strain field, are presented. These new experiments complete the work started by Vidal and Merle (2000) and Merle et al. (2001), who simulated deformation in volcanoes above vertical faults. The data presented here lead to a proposed mechanical model that explains: i) how volcanoes deform above moving reverse faults, ii) how magma can ascend across volcanoes under a regional compressional stress state, and iii) why classical morphometric analyses of volcano–tectonic relationships can be misleading in this tectonic environment. These observations cast some doubt on models of extensional magmatism that claim only crustal extension facilitates the transport of magma to the surface. Moreover, these data suggest the presence of volcanic edifices or extensional structures on volcanoes in a given area does not necessarily indicate regional extension.

2. Field examples

Three examples are described here using a combination of new observations and published data. These are the El Reventador stratovolcano (Ecuador), toghether with the Trohunco and Los Cardos–Centinela volcanic complexes (Argentina).

2.1. El Reventador

El Reventador is a late Quaternary active stratovolcano located in the Ecuadorian jungle of the sub-Andean zone near the Colombian border (Fig. 1) (Hantke and Parodi, 1966; Pichler et al., 1976; Hall, 1977). It has an average diameter of 14 km, a height of 3562 m a.s.l., and its substrate crops out at an altitude of 1800 m. Its lavas are basaltic andesites, andesites, dacites and rhyolites, which belong to a medium to high-K calcalkaline suite with an adakitic affinity (Barragan and Baby, 1999). Its oldest rocks have been dated to 0.34 Ma (INECEL, 1988). The volcano has a series of satellite volcanic domes and has produced two sector collapses towards the east (Fig. 2) (INECEL, 1988; Tibaldi, 2005). Its substrate is represented by a NNE–SSW-trending deformed belt made of early Palaeozoic–early Mesozoic crystalline rocks that were thrust onto the Sub-Andean zone in the Tertiary (Pasquarè et al., 1990). Around El Reventador, a series of N–S to NNE-striking faults, mostly west-dipping, have been active in Plio–Quaternary times with reverse and right-lateral reverse motion (Tibaldi, 2005). The largest of these faults crops out around the western part of the volcano and also affects the edifice (Fig. 2). Neotectonic field data and seismic data indicate that contractional tectonics have been active here during the Holocene and remain active at present, highlighting the coexistence of reverse and reverse-oblique faulting and volcanism (Tibaldi, 2005).

Based on new field observations, the volcano succession has here been divided into three main units: the Late Pleistocene deposits (Coca Synthem), the Middle–late Pleistocene deposits (Malo Synthem), and

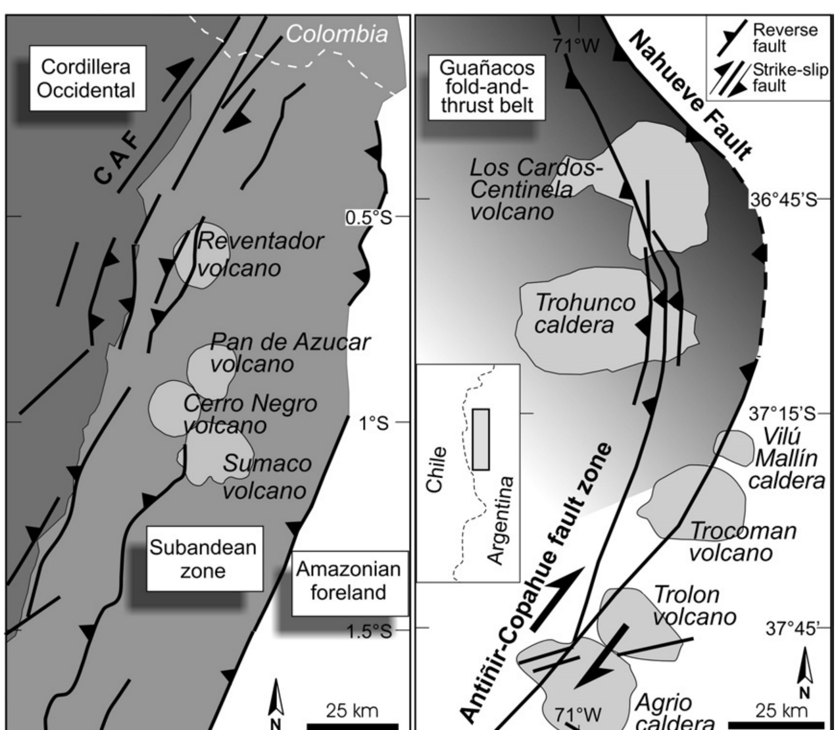

Fig. 1. Location of the studied field examples and their structural settings. The structures shown are the main faults of Quaternary age, based on Tibaldi (2005), Folguera et al. (2006) and Miranda et al. (2006). The different shading represent the various geological–physiographic domains, passing from the high Andean range to the West, to the Amazonian foreland to the East. Note the presence of other large Plio–Quaternary volcanoes aligned along the Andean frontal thrust zone both in Ecuador and in Argentina. CAF = Cayambe–Afiladores Fault.