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Conceptual and numerical models of ring-fault formation

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Abstract

Most ring faults of collapse calderas are primarily shear fractures the initiation and development of which depends on the state of stress in the host rock. The state of stress in a volcano is controlled by the loading conditions, such as magma-chamber geometry and pressure, but also by the mechanical properties of its rock units and structures (such as existing contacts, faults, and joints). Ring-fault formation is thus essentially a problem in rock physics. Field observations show that some ring faults are dip–slip, whereas others are partly faults (shear fractures) and partly ring dykes (extension fractures). Although slip on existing ring faults is much more common in basaltic edifices (shield volcanoes) than in true composite volcanoes, in both types of volcanoes most caldera unrest periods do not result in ring-fault slip. Here I present new conceptual and numerical models of caldera formation in volcanoes with shallow spherical (circular) or oblate ellipsoidal (sill-like) magma chambers. In the layered models, the host rock above the chamber is composed of 30 comparatively thin layers with stiffnesses (Young's moduli) alternating between 1 GPa and 100 GPa. The chamber itself is located in a single, thick layer. The crustal segment hosting the chamber is either 20 km or 40 km wide but has a constant thickness of 20 km. The loading conditions considered are: (1) a crustal segment subject to 5 MPa tension; (2) crustal segment subject to excess magmatic pressure of 10 MPa at the bottom (doming of the volcanic field containing the chamber); (3) a combination of tension and doming; and (4) chamber subject to underpressure (negative excess pressure) of 5 MPa. The main results are as follows: (1) Excess pressure and underpressure in a chamber normally favour dyke injection rather than ring-fault formation. (2) For doming or tension, a spherical magma chamber favours dyke injection except when the layer hosting the chamber is very soft (10 GPa) or one with recent dyke injections, in which case the surface stress field favours ring-fault formation. (3) For a sill-like chamber in a 20-km wide crustal segment, a ring-fault can be generated by either tension or tension and doming; for a 40-km wide segment, doming alone is sufficient to generate a ring fault. (4) Since individual layers in a volcano may develop different local stresses, stress-field homogenisation through all the layers between the chamber and the surface is a necessary condition for ring-fault formation. (5) Because the mechanical properties of the layers that constitute basaltic edifices are more uniform than those that constitute true composite volcanoes, it follows that stress-field homogenisation, and thus ring-fault formation or slip, is more commonly reached in basaltic edifices than in composite volcanoes. (6) Both for basaltic edifices and composite volcanoes, the stress fields most likely to initiate ring faults are those generated around sill-like chambers subject to tension, doming, or both.

Keywords: collapse calderas; rock properties; magma chambers; crustal stresses; composite volcanoes; basaltic edifices

1. Introduction

Many caldera collapses are associated with violent, explosive eruptions which can devastate large and densely populated areas. Collapse-caldera formation,

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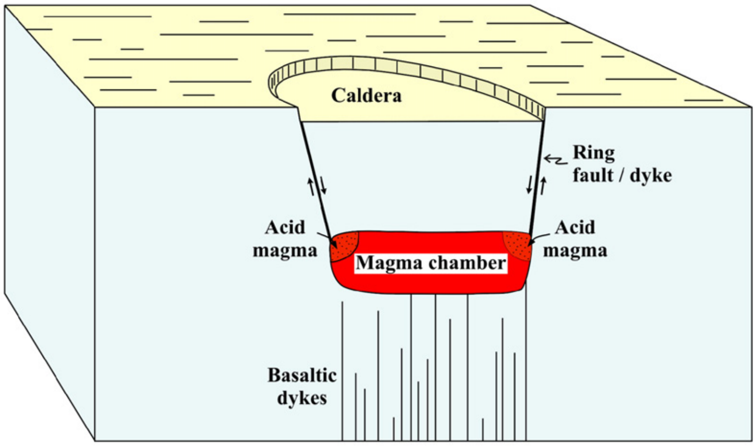

Fig. 1. The ring fault of a collapse caldera is normally associated with a shallow crustal magma chamber of a cross-sectional area similar to that of the caldera. Some ring faults are occupied by ring dykes, often injected from accumulations of acid magma in low-potential regions below ring faults. Most ring faults and ring dykes are close to vertical or dip steeply inward.

and slip on existing ring faults, is therefore not only of academic interest, but also of great concern to human society. Typical collapse calderas are commonly many kilometres in diameter and with a vertical displacement (subsidence) from several hundred metres to several kilometres (Fig. 1).

The ring faults of collapse calderas are rock fractures; the magma chambers from which most of them develop are rock cavities (Fig. 1). The initiation and development of any rock fracture depends on the state of stress in the host rock. The state of stress in a volcano is controlled by the material properties of its rock units and structures, such as existing contacts, faults, and joints, as well as by the loading conditions. In solid mechanics, “loading conditions” normally denote the forces, stresses, or pressures that are applied to a body and external to its material (Benham et al., 1996). Here, “loading conditions” refer to the fluid pressure in the shallow magma chamber, and the tectonic stress applied to the chamber and the associated volcano. The loading conditions thus depend on the tectonic environment and, in particular, the geometry and magma pressure of the chamber. The formation of a ring fault is thus essentially a problem in rock physics; it should not be confused with the separate problem of an ash-flow eruption, even if these are commonly associated.

While eruptions in collapse calderas are very common (Newhall and Dzurisin, 1988), formation of new ring faults or slip on existing ring faults are, in comparison, rare. This applies particularly to slip on ring faults in composite volcanoes (stratovolcanoes); in basaltic edifices or shield volcanoes such as in Hawaii and the Galapagos Islands, slip on existing calderas, often with very small or no eruptions, is more common.

To understand how and when a ring fault develops, and why an existing ring fault slips so infrequently, one must know the state of stress in the host volcano. This implies the knowledge of the rock properties and structures of the volcano. Furthermore, to forecast whether a ring fault is likely to form or slip during a particular unrest period, we must have a rough idea of the geometry of the associated magma chamber. Ring-fault formation and slip are mechanical processes that cannot be forecasted solely on the basis of empirical criteria; to develop viable models to assess the probability of ring-fault formation or slip these processes must be understood in mechanical terms.

This paper has three principal purposes. The first is to discuss the general structure and attitude of ring faults. The focus is on summarising field results and to provide a conceptual model of a typical ring fault. The second is to explain the general stress-field conditions for the formation of or slip on existing ring faults. Here the focus is on the results of field studies and numerical models of the stress fields that must be generated so as to trigger ring-fault formation. The third is to use the results of the numerical models to explain why ring-fault formation and slip on existing faults is much more common in basaltic edifices than in composite volcanoes.

2. Ring-fault structure

Traditionally, collapse calderas are defined as circular or moderately elliptical volcanic depressions (Fig. 1) with a diameter exceeding about 1 mile or 1.6 km (Macdonald, 1972). Using this definition, calderas on Earth are from 1.6 km to about 80 km in maximum diameter (Lipman, 2000). The lower limit makes it