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Volcanic hazards, magma chambers, local stresses, and eruptions

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During volcanic unrest periods, some of the fundamental questions facing scientist and civil authorities is if, and then where and when, an eruption is likely to occur. In order to answer these questions, the processes manifested at the surface (such as inflation, deflation, and changes in gas emission) must be understood in terms of realistic volcanotectonic models of the processes that take place inside a volcano during an unrest period. Here I argue that most volcanotectonic processes, to a large degree, depend on local stresses; stresses which may change abruptly from one mechanical layer in the volcano to another. Since the great majority of eruptions are supplied with magma through fractures (dykes and inclined sheets), it follows that viable eruption forecasting must be based on a thorough understanding of the local stress conditions that affect magma-driven fracture propagation.

More specifically, in order to assess the probability of a volcanic eruption during an unrest period we must understand magma-chamber rupture and dyke propagation to the surface or, alternatively, dyke arrest at depth in the volcano. These tectonic processes are strongly dependent on the local stresses in the individual layers which constitute a volcano which are determined by the loading conditions (tectonic stress, magmatic pressure, or displacement) and the mechanical properties of the layers. In the absence of stress monitoring of volcanoes, their local stresses must be inferred from models, either analytical or numerical.

Analytical models of magma chambers ignore different mechanical properties of the layers and their contacts, assume the volcano to behave as a homogeneous, isotropic, elastic half space or a semi-infinite plate, and are of two main types: nuclei of strain and cavities. The best-known nucleus of strain is the point-source Mogi model, used to explain surface deformation as a result of either increase or decrease in magma pressure in a chamber whose depth is also inferred from the surface data. The model explains stresses and displacements far away from the chamber, but neither the stress concentration around the chamber, which determines if and where chamber rupture and dyke injection take place, nor the shape, size, or likely tectonic evolution of the chamber.

In contrast to the Mogi model, a cavity or a (two-dimensional) hole model of a magma chamber has a finite size. Thus, the local stresses at, and away from, the boundary of a chamber can be calculated. For various loading conditions, a cavity model gives a crude indication of the local stresses in a volcano and its surface deformation. However, variation in mechanical properties and contacts between layers are ignored. A cavity model thus cannot be used for detailed analyses of the local stresses in a composite volcano.

Numerical model results presented here show that the local stresses in a volcano depend strongly on the properties of its layers which are often contrasting, particularly at shallow depths, and on the magma-chamber geometry. For example, lava flows, welded pyrolastic units, and intrusions may be very stiff (with a high Young's modulus), whereas young and non-welded pyroclastic and sedimentary units may be very soft (with a low Young's modulus). Consequently, the local stresses may change abruptly between adjacent layers so that, for example, while one layer favours dyke propagation an adjacent one favours dyke arrest. No dyke-fed eruption can occur if there is any layer where the stress field is unfavourable to dyke propagation along its potential pathway to the surface; if such a layer occurs, the dyke becomes arrested and an eruption is prevented. The present numerical results indicate that during unrest periods composite volcanoes commonly develop local stresses that arrest dykes and prevent eruptions, in agreement with field observations and underlining the need for in situ stress monitoring to assess the probability of dyke-fed eruptions.

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