Mechanical models for correlation of ring-fracture eruptions at Pantelleria, Strait of Sicily, with glacial sea-level drawdown

Peter C Wallmann¹, Gail A Mahood¹, and David D Pollard¹,²

¹ Department of Geology, Stanford University, Stanford CA 94305
² Department of Applied Earth Science, Stanford University, Stanford CA 94305

Abstract. Recent K-Ar dating of eruptions at Pantelleria, a peralkaline volcanic island in the Strait of Sicily, shows a correlation between eruption of pantellerite lavas from caldera ring fractures and low stands of sea level as determined from δ¹⁸O stratigraphy. Post-caldera pantellerite lavas associated with an ~114-ky-old caldera erupted along the ring-fracture zone during a major low stand of sea level at about 67 Ka. The most recent episode of lava-flow emplacement began about 20 ky ago during the last glacial maximum. Magma vented along the ring fault of a 45-ky-old caldera, from fractures radial to the caldera, and along faults formed by intracaldera trapdoor uplift. Two mechanical models based on elasticity theory are presented to explain the correlation of post-caldera ring-fracture eruptions at Pantelleria with lowering of sea level. A simple analysis of a bending circular plate of thickness, \( T \), and radius, \( R \), representing the magma-chamber roof block, shows that tensile stress is concentrated by a factor of \( 0.75R^2/T^2 \) at the lower perimeter of the plate when sea level drops. Stress changes may be even greater if \( T \) is effectively less than the stratigraphic thickness due to layering of rocks in the roof block. Calculated stress changes due to a 100-m drawdown of sea level are similar in magnitude to stresses associated with dike propagation. More realistic model geometries, including different chamber shapes, a conical volcanic edifice, and sea-level drawdown beyond the surface projection of the magma chamber, were tested using the boundary-element method. Lowering sea level generates a horizontal tensile stress above the chamber, even when sea water is removed outboard of the magma chamber. For some chamber geometries the magnitude of the tensile stress maximum is greater than the ~1 MPa pressure of the 100 m of removed water and is of the right order of magnitude for dike propagation. Dikes initiated by the change of the stress field may originate and propagate along fractures inboard of the chamber margin. The magnitudes of tensile maxima along the top of the chamber decrease as original sea level is moved outboard of the chamber margin and as the chamber thickness decreases. When the depth to the top of the magma chamber reaches a critical value, dependent on chamber geometry, the propagation of dikes to the surface is inhibited.

Introduction

Many authors have used theoretical calculations and empirical data to show that major volcanic eruptions can cause global cooling trends (Kennett and Watkins 1970; Lamb 1970, 1971; Kennett and Thunell 1975; Pollack et al. 1976; Bray 1977; Self et al. 1981; Rampino and Self 1984; Jakosky 1986). Some researchers, however, have suggested that the explosive eruptions associated with cooling trends actually occurred after the onset of global cooling (Rampino et al. 1979). Mechanisms that could explain why eruptions might follow global cooling include stress changes due to perturbation of the Earth's rotational parameters by glacial loading (Anderson 1974; Rampino et al. 1979), stress gradients associated with mantle flow in response to increased glaciation (Rampino et al. 1979), and unloading of ocean basins promoting upward movement of basaltic magma (Matthews 1969), which may itself serve as an eruption trigger (Sparks et al. 1977; Eichelberger 1978). Recent geological and geochronological
work on the island of Pantelleria (Mahood and Hildreth 1986), a peralkaline volcanic center in the Strait of Sicily, shows a temporal correlation between the two most recent glacially induced low stands of sea level and the onset of voluminous post-caldera ring-fracture volcanism. This correlation suggests that unloading of a magma chamber by glacially induced lowering of sea level could trigger eruptions.

Two elastic models for host-rock deformation over the Pantelleria magma chamber are developed in this paper to explain the apparent relation between sea-level drawdown and eruption of ring-fracture lavas. Elasticity theory has been used by numerous authors to explain geologic features related to igneous intrusions. Anderson (1936) used solutions for the displacements and stresses in a semi-infinite body resulting from a center of dilatation and a point-force in an attempt to explain the formation of cone sheets and ring dikes. Two subsequent studies (Robson and Barr 1964; Roberts 1970) used two-dimensional elastic solutions for pressurized cavities in a remote stress field to examine the same problem. Koide and Bhattacharji (1975) examined the pattern of ore-bearing fractures around magma bodies using elasticity theory. Elastic modeling has also been used by Odé (1957) and Muller and Pollard (1977) to analyse the pattern of dikes and stress state at the time of dike formation in the Spanish Peaks region, Colorado.

Geology of Pantelleria

Pantelleria is a small island located within the drowned continental rift in the Strait of Sicily between Sicily and Tunisia. The long dimension of the 13-by-8-km island is parallel to the rift edge (Fig. 1, inset). This still-active rift system began to develop in late Miocene or early Pliocene time (Finetti and Morelli 1973). Lack of continuous magnetic anomalies like those found along oceanic spreading centers indicates the absence of

---

Fig. 1. Simplified geologic map for Pantelleria (after Mahood and Hildreth 1986). Solid triangles, eruptive vents; open triangles, vents mantled by Green Tuff. CD and LV identify Cinque Denti and La Vecchia caldera fault scarps. Location of summit of Monte Gibele cone shown by large cross.