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Magma reservoir failure on the terrestrial planets: Assessing the importance of gravitational loading in simple elastic models

Eric B. Grosfils *

Geology Department, Pomona College, 185 E. Sixth Street, Claremont, CA 91711, United States

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Abstract

Results from a finite element model characterizing tensile rupture of an internally pressurized ellipsoidal magma reservoir within an axisymmetric elastic half space illustrate that gravity plays a critical role in this process. Failure to incorporate gravitational loading correctly, which is the case for most published models, affects for example: (a) application of corrections designed to account for the presence of the free surface in analytical models; (b) inferences about the internal pressure that a reservoir can sustain prior to rupture; (c) conclusions about the importance of neutral buoyancy, i.e. the relative host rock and magma density structures; and, (d) predictions about the location at which rupture of the reservoir wall will occur and the style of intrusion which will be favored. Analyses that reduce magma reservoirs to a cavity within an unloaded elastic medium, inflated by only an excess pressure component, sacrifice important information and should not be used to interpret reservoir activity or to calibrate more advanced models of volcanic regions and phenomena; an exception to this rule occurs, however, when constraining the pressure that can be inferred from surface displacements for a reservoir of known geometry. In a gravitationally loaded model, the characteristics of the failure process are insensitive to geologically plausible variations in the tensile strength, shear modulus, density structure and gravitational acceleration. As a result the half-space analysis presented here, which will benefit from future expansion to include topography and other factors, can yield insight into not only magma reservoirs on Earth but those thought to have formed within the crusts of Mars, Venus and other solar system bodies as well.

Keywords: magma reservoir; inflation; rupture location; finite element modeling; gravity; gravitational loading; free surface effect; surface displacement; intrusion geometry; neutral buoyancy; planetary volcanism

1. Introduction

Magma reservoirs fed by periodic injections of fresh material ascending from below are a commonly described component of shallow volcanic systems. Repeated infusion of magma into a pre-existing reservoir is one mechanism capable of generating pressures which can induce inflation and eventual fracturing of the surrounding host rock, triggering an intrusive or extrusive volcanic event. Evidence of this process is observed in modern and ancient volcanic systems studied on Earth, for example through inflation and seismicity at Hawaii (Klein et al., 1987), cyclic layering in ancient reservoirs (Turner and Campbell, 1986), laterally extensive dikes composed of multiple injection pulses (Greenough and Hodych, 1990), and radial dike patterns focused on volcanic centers (Muller and Pollard, 1977). In addition, an abundance of intrusive and extrusive volcanic features of probable reservoir origin has been identified on

* Tel.: +1 909 621 8673; fax: +1 909 621 8552.
E-mail address: egrosfils@pomona.edu.

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Venus (e.g., Head and Wilson, 1992) and Mars (e.g., Wilson and Head, 1994). Attempts to understand the mechanical evolution of magma reservoirs and the factors which govern their failure can therefore provide important insight into how a wide variety of volcanic systems develop and grow on the terrestrial planets.

Complementing field-based research, both analytical and numerical models of pressurized ellipsoidal magma reservoirs have been used extensively to gain insight into magma plumbing systems, surface displacements, eruption styles, and the formation of structural features (e.g., Anderson, 1936; Mogi, 1958; Dieterich and Decker, 1975; Bianchi et al., 1984; Bonafede et al., 1986; Bianchi et al., 1987; McTigue, 1987; Chevallier and Verwoerd, 1988; Gudmundsson, 1988; Dragoni and Magnanensi, 1989; Tait et al., 1989; Bonafede, 1990; Chevallier and Verwoerd, 1990; Quareni, 1990; Sartoris et al., 1990; Parfitt et al., 1993; Chadwick and Dieterich, 1995; Maeda, 2000; Newman et al., 2001; Saunders, 2001; Gudmundsson, 2002; Jellinek and DePaolo, 2003; Trasatti et al., 2003; Lungarini et al., 2005; Trasatti et al., 2005). The majority of the modeling studies performed to date assume an elastic rheology, in some instances adopting it for tractability or convenience and in other cases justifying it on physical grounds. In spite of the seeming simplicity of the elastic approach, however, existing models often identify different parameters as important or unimportant, for instance proximity of the free surface, and thus they incorporate or ignore different factors. As a consequence published modeling results can yield insights that are strongly contradictory (e.g., Sartoris et al., 1990; Parfitt et al., 1993). This is particularly troubling for two reasons. First, modeling of active magmatic systems plays an important role in volcanic hazard identification and assessment. While elastic models clearly can't duplicate the full complexity evident at volcanoes, the potential for gaining critical first-order insights rapidly using elastic models is compromised until existing contradictions between simple elastic models are identified, understood and resolved. Second, as more complex numerical models employing alternate rheologies (e.g., Bonafede et al., 1986; Dragoni and Magnanensi, 1989; Maeda, 2000; Newman et al., 2001; Trasatti et al., 2003, 2005) or other factors are developed to enhance our ability to investigate complex volcanic systems, simple elastic model results are often used for their calibration, with the result that existing problems with simpler models can inadvertently get propagated into more advanced ones. Caution is particularly needed when seeking to understand magma reservoirs on other planets, where model design and evaluation can't be guided by the plethora of datasets (e.g., gravity, seismicity, heat flow, surface tilt) often available to researchers studying active magma systems on Earth.

The goal of the current paper is to provide a framework within which several key differences between existing elastic magma reservoir model results can be explored, compared, and better understood. The main focus is to understand magma reservoir failure and characterize where and under what conditions rupture of the wall will occur. The analysis begins with development and component by component testing of an isotropic and homogeneous half-space model which incorporates all major geological and geometrical factors identified by previous authors. This model is then used to characterize the extent to which magma reservoir failure is sensitive to different geological and geometrical parameters. Finally, based on this analysis, several key issues are assessed, including (a) implementation of depth-dependent host rock stress states, (b) failure location and intrusion style, (c) vertical displacement at the surface and inferences about subsurface magma pressures, (d) the magma pressure required to initiate rupture, (e) uniaxial strain conditions, and (f) the formation of radiating dike swarms. Throughout this paper the focus is on reservoirs subjected to physical conditions appropriate for Earth and Mars, but the latter is explored only to the extent necessary to elucidate fundamental behaviors. It is important to note that the current framework is intended as neither an endorsement of elastic model suitability for modeling magma reservoir processes nor a rejection of such an approach. Elastic models have value in some circumstances, for instance when rapid or first order insight into a magma plumbing system is required on the basis of limited observational data (e.g., Bianchi et al., 1984), and not in others, for instance investigation of long-lived systems better characterized by viscoelastic behavior or another rheological response (e.g., Newman et al., 2001). However, to the extent that a magma reservoir can be characterized as an internally pressurized ellipsoid subject to tensile failure within an elastic host, the model results presented here can be used to gain direct insight into failure conditions and related phenomena.

2. Computational model

2.1. Model formulation

COMSOL Multiphysics software (http://www.comsol.com/) is used to develop axisymmetric finite element models (FEMs) which treat the reservoir as an internally pressurized ellipsoid within an elastic host in the absence