Physics of the Earth and Planetary Interiors 256 (2016) 13–25

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

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

Two-dimensional magmons with damage and the transition to magma-fracturing

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A R T I C L E I N F O

Article history:
Received 24 February 2015
Received in revised form 3 March 2016
Accepted 9 March 2016
Available online 26 March 2016

Keywords:
Magma migration
Porosity waves
Two-phase flow
Damage
Magma-fracturing

A B S T R A C T

Magma-fracturing during melt migration is associated with the propagation of a pore-generating damage front ahead of high-pressure fluid injection, which facilitates the transport of melt in the asthenosphere and initiates dike propagation in the lithosphere. We examine the propagation of porous flow in a damageable matrix by applying the two-phase theory for compaction and damage proposed by Bercovici et al. (2001a) and Bercovici and Ricard (2003) in 2-D. Damage (void generation and microcracking) is treated by considering the generation of interfacial surface energy by deformational work. We examine the stability of 1-D solitary waves to 2-D perturbations, and study the formation of finite-amplitude, two-dimensional solitary waves with and without solenoidal (rotational) flow of the matrix. We show that the wavelength and growth rate of the most unstable perturbations are dependent on both background porosity and the presence of solenoidal flow field. The effect of damage on finite amplitude 2-D solitary waves is then examined with numerical experiments. Stably propagating circular waves become flattened (elongated perpendicular to gravity) for small porosity, or elongated (parallel to gravity) for large porosity with increased damage. We show that the weakening of the matrix due to damage leads to these changes in wave geometry, which indicates a transition from magmatic porous flow to dike-like or sill-like magma-fracturing as magma passes through a semi-brittle/semi-ductile zone in the lithosphere.

1. Introduction

Magma migration and extraction after melt generation is of importance for the physics of volcanism and the formation of the crust and the lithosphere. In the viscous asthenosphere, as partial melting occurs along grain boundaries, it migrates through porous flow initially. Previous studies have demonstrated the existence of magmatic solitary waves during melt migration both theoretically and numerically (Scott and Stevenson, 1986; Barcilon and Lovera, 1989; Spiegelman, 1993; Wiggins and Spiegelman, 1995). However, in the cold lithosphere and the crust, porous flow is prone to thermally and chemically equilibrate with host rock and is unlikely to reach the surface (Johnson et al., 1990; Kelemen et al., 1995b), in which case, other transport mechanisms like dike propagation become dominant (Lister and Kerr, 1991; Roper and Lister, 2005).

However, little attention has been paid to the transition from porous flow to fracturing and diking, and most studies treat the two mechanisms separately. In particular, a critical melt fraction (to drive an overpressure), or flux during deeper ductile porous transport is needed to initiate dike propagation (Spence and Turcotte, 1990; Lister and Kerr, 1991; Katz, 2010). Field evidence also suggests that dikes form in magma source regions (Nicolas, 1986), and the two-phase system can undergo both fracture and flow in the porous medium (Rubin, 1993b). Attempts that integrate mechanisms in both melt source region and dike propagation have been made recently (Havlin et al., 2013; Keller et al., 2013), but the physical mechanism for initiating micro-cracks in the porous medium is still unclear. Hewitt and Fowler (2008) suggest that, at the top of the partial melt, the fluid pressure becomes large enough for matrix fracturing, and oscillations of the pressure may initiate fracturing deeper in the partial melt. Connolly and Podladchikov (2007) propose a different approach by assuming an anisotropic bulk viscosity due to decompaction weakening, where percolating flow becomes channelized due to the viscosity variation.

The partitioning of deformational work between a dissipative and a stored component has been noted in studies of ductile void growth, dilatant plasticity, and metal composites (Farren and Taylor, 1925; Chrysochoos and Martin, 1989; Lemonds and Needleman, 1986). In our previous work on 1-D magma-fracturing

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http://dx.doi.org/10.1016/j.pepi.2016.03.002
0031-9201/

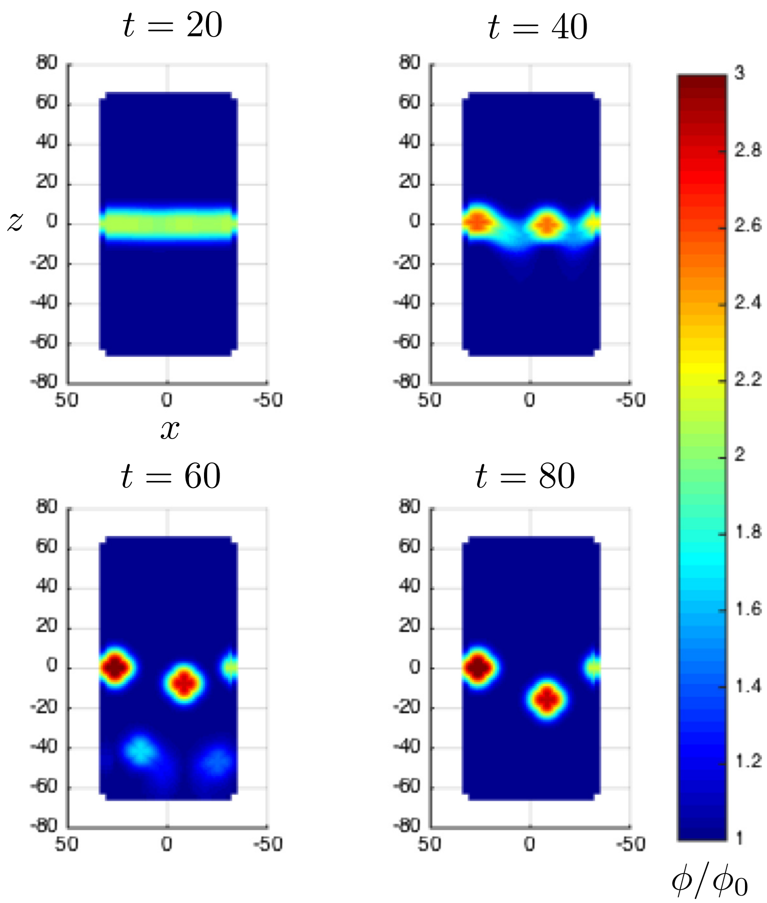

Fig. 1. The porosity field shows that two-dimensional solitary waves develop from small perturbation of 1-D solitary wave without solenoidal flow. The color bar represents ϕ/ϕ_0. Background porosity is $\phi_0 = 0.01$. The initial amplitude is $A_{1D} = \phi_m/\phi_0 = 2$. The grids scroll upward with the fastest growing wave pulse. Horizontal boundaries are periodic. z and x are in units of the porosity-dependent compaction length δ_c and t is in units of $\tau_c = \delta_c/w_0$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Cai and Bercovici, 2013), we have adapted the damage theory proposed previously (Bercovici et al., 2001a,b; Ricard et al., 2001; Bercovici and Ricard, 2003), which employs two-phase physics and interface thermodynamics to describe void/microcrack formation in porous flow. Part of the deformational work is stored as surface energy on the interface between phases, and is thus associated with microcrack and void generation. Therefore the transition from porous flow to fracturing is described by a nonequilibrium relation between interfacial surface energy, pressure and viscous deformation. In particular, a fraction of deformational work goes to reversible stored surface energy while the remaining part goes to irreversible dissipative heating. To describe a dike- or sill-like structure, in this work we extend our 1-D model into two dimensional space, with consideration of finite-amplitude porosity and the solenoidal flow field, which have been assumed small for numerical studies (Scott and Stevenson, 1986; Barcilon and Lovera, 1989; Spiegelman, 1993; Wiggins and Spiegelman, 1995). In the following analysis, two-dimensional results are benchmarked with those of Scott and Stevenson (1986) by perturbing a 1-D solitary wave in 2-D in the small-porosity limit and assuming irrotational matrix flow. Then we study the effect of finite porosity and solenoidal flow on the development of 2-D waves, and examine the effect of pore-generating damage on the propagation of 2-D porosity waves. We show that damage in 2-D leads to an effectively anisotropic bulk viscosity in the mixture, which thus changes the geometry of the 2-D circular wave into either flattened (elongated perpendicular to gravity) or elongated (parallel to gravity) porosity structures, depending on the melt fraction of the wave. The change in wave geometry due to damage influences the over-pressure driving diking at shallower depths; this provides a self-weakening mechanism of the brittle–ductile transition, from porous to diking transport of melt, in the lithosphere.

2. Two-phase viscous flow with damage: 2-D model

Since Bercovici et al. (2001a) and Bercovici and Ricard (2003) derived the original two-phase damage theory, and we previously presented a 1-D damage model for magma-fracturing (Cai and Bercovici, 2013), here we only review the governing equations briefly for the purpose of referencing. We assume both phases are viscous.

2.1. Mass conservation

We assume there is no mass exchange between phases, thus we do not consider melting, dissolution or chemical reaction. There are two equations involving transport of the fluid and matrix phases:

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\phi \boldsymbol{v_f}) = 0 \quad (1)$$

$$\frac{\partial (1-\phi)}{\partial t} + \nabla \cdot [(1-\phi)\boldsymbol{v_m}] = 0 \quad (2)$$