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Modeling frictional melt injection to constrain coseismic physical conditions

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ABSTRACT

Pseudotachylyte, a fault rock formed through coseismic frictional melting, provides an important record of coseismic mechanics. In particular, injection veins formed at a high angle to the fault surface have been used to estimate rupture directivity, velocity, pulse length, stress drop, as well as slip weakening distance and wall rock stiffness. These studies have generally treated injection vein formation as a purely elastic process and have assumed that processes of melt generation, transport, and solidification have little influence on the final vein geometry. Using a pressurized crack model, an analytical approximation of injection vein formation based on dike intrusion, we find that the timescales of quenching and flow propagation may be similar for a subset of injection veins compiled from the Asbestos Mountain Fault, USA, Gole Larghe Fault Zone, Italy, and the Fort Foster Brittle Zone, USA under minimum melt temperature conditions. 34% of the veins are found to be flow limited, with a final geometry that may reflect cooling of the vein before it reaches an elastic equilibrium with the wall rock. Formation of these veins is a dynamic process whose behavior is not fully captured by the analytical approach. To assess the applicability of simplifying assumptions of the pressurized crack we employ a time-dependent finite-element model of injection vein formation that couples elastic deformation of the wall rock with the fluid dynamics and heat transfer of the frictional melt. This finite element model reveals that two basic assumptions of the pressurized crack model, self-similar growth and a uniform pressure gradient, are false. The pressurized crack model thus underestimates flow propagation time by 2–3 orders of magnitude. Flow limiting may therefore occur under a wider range of conditions than previously thought. Flow-limited veins may be recognizable in the field where veins have tapered profiles or smaller aspect ratios than expected. The occurrence and shape of injection veins can be coupled with modeling to provide an independent estimate of minimum melt temperature. Finally, the large aspect ratio observed for all three populations of injection veins may be best explained by a large reduction in stiffness associated with coseismic damage, as injection vein growth is likely to far exceed the lifetime of dynamic stresses at any location along a fault.

1. Introduction

Earthquakes occur when a fault patch suddenly slips (ruptures), releasing high frequency (>∼0.1 Hz) seismic waves. Though a defining characteristic of earthquakes, radiated seismic waves contain only a small portion of the total earthquake energy, and provide an incomplete view of the earthquake source region (Beeler, 2006). Much of the energy released is absorbed by physicochemical processes (Shipton et al., 2006) driven by slip-induced changes in stress and temperature within the fault zone (Reches and Dewers, 2005; Sibson, 1973). By integrating theoretical and experimental modeling and field studies we can obtain a more complete view of the active physicochemical processes, parameters, and physics at the earthquake source (Niemeijer et al., 2012).

Studies of pseudotachylyte injection veins (Fig. 1), opening-mode fractures originating from a fault surface filled with solidified frictional melt (Sibson, 1975), have been particularly successful at recovering earthquake source parameters from exhumed fault zones. In order to form frictional melt, slip rates at seismogenic depth must exceed $\sim 10^{-2}$ m/s (Sibson, 1973, 1975), within the range of rates that is unique to earthquakes (Cowan, 1999; Rowe and Griffith, 2015). The rapid quench times of these thin melt veins, ∼100 s or less (Rowe et al., 2012; Sibson, 1975), is on the order of the source duration for moderate to large earthquakes (Kanamori and Brodsky, 2004), suggesting that they solidify during seismic slip or soon after slip ceases. Pseudotachylyte injec-

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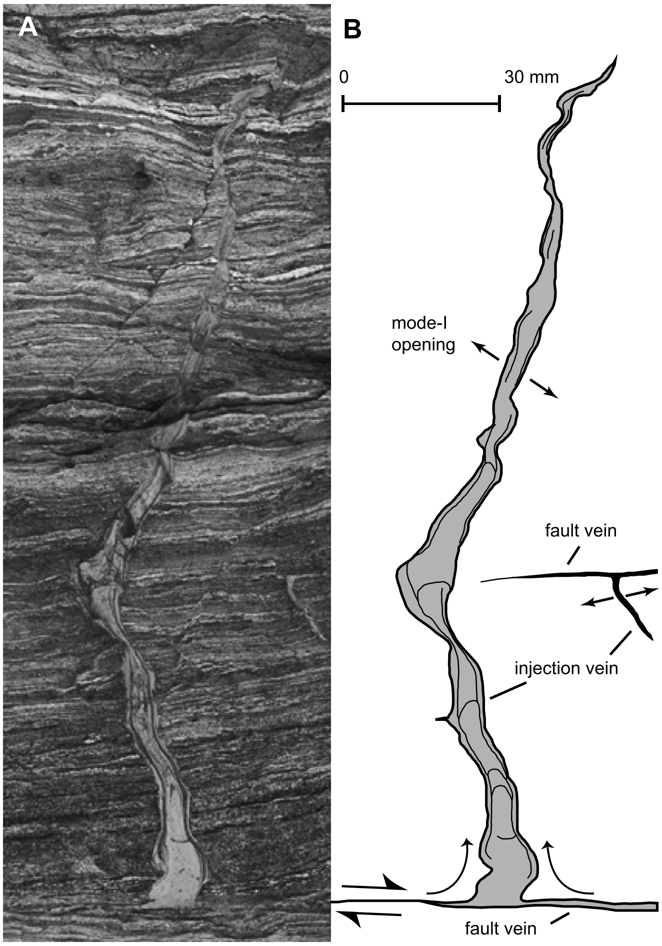

Fig. 1. A large injection vein from the Fort Foster Brittle Zone showing dominantly mode-I opening. Especially in the anisotropic wall rock of Fort Foster, many injection veins show non-idealities, including small shear displacements, grain removal (erosion), and arcuate centerlines Banded coloration is interpreted as evidence for concurrent cooling and flow.

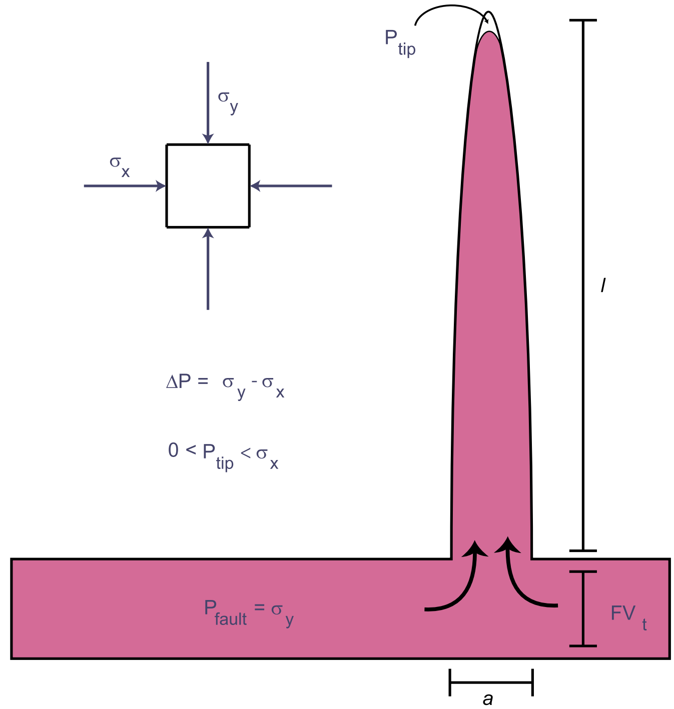

Fig. 2. The injection vein is idealized as a semi-elliptical fluid filled crack of length l and maximum aperture a. Pressures in the fluid are determined by the remote stresses: fault vein pressure is equal to the fault normal stress, opening is a function of the deviatoric stress and wall rock stiffness.

tion veins thus form under the physical conditions present during and immediately after earthquake slip, and their crack-like shape provides a well-developed theoretical framework for interpreting these conditions.

An evolving conceptual model for the formation of pseudotachylyte injection veins (Di Toro et al., 2005a; Griffith et al., 2012; Griffith and Prakash, 2015; Sibson, 1975) suggests a general process whereby 1) a propagating rupture front creates a dynamic stress field that generates tensile cracks. 2) Slip along the fault produces frictional melt. 3) Melt flows from the fault surface into the recently formed cracks due to pressure gradients generated by an anisotropic stress tensor (Fig. 2). 4) The melt solidifies preserving the coseismic structural geometries.

This conceptual model has been coupled with theoretical and experimental work to estimate a variety of source parameters and conditions from measurement of pseudotachylyte injection veins along exhumed faults. Rupture directivity and velocity (Di Toro et al., 2005a), as well as velocity weakening behavior (Ngo et al., 2012), have been inferred from the inclination of injection veins relative to the fault surface. Rupture size, stress drop, and fracture energy have been found using injection vein length (Griffith and Prakash, 2015). The near-fault stress field (Rowe et al., 2012) and coseismic wall rock softening (Griffith et al., 2012) have been investigated using length to aperture ratios.

These studies generally assume that injection veins preserve coseismic fracture orientations and lengths and that melt flows freely to the end of cracks before quenching. Rowe et al. (2012) evaluated this assumption using an approximate analytical solution derived by Rubin (1995b) for modeling the intrusion of igneous dikes and found that quench times far exceed flow propagation times for a set of likely physical conditions. Here we revisit this analytical model and show that flow limiting (i.e. quenching before reaching equilibrium) may occur under some conditions. We then develop a more complete finite element model that couples elastic wall rock deformation, viscous flow of the melt, and cooling. Using this model we find that key assumptions of the analytical solution are likely unrealistic and that flow limiting may therefore occur under a wider range of conditions than previously thought.

2. Field surveys of pseudotachylyte injection veins

Two previous studies have cataloged length and base aperture of pseudotachylyte injection veins. Rowe et al. (2012) report 215 tonalite-hosted injection veins from the Asbestos Mountain Fault, USA. Griffith et al. (2012) report two sets of injection veins from the Gole Larghe Fault Zone, Italy: 22 cataclasite-hosted and 28 tonalite-hosted. We combine these with a new set of 49 gneiss-hosted injection veins from the Fort Foster Brittle Zone, USA to form a composite data set of 314 injection veins used in this analysis (Fig. 3). Aperture and length data from all three sites overlap, with aspect ratios (ratio of aperture to length) ranging from 0.014 to 1.94, generally larger than aspect ratios typical of magmatic dikes (10^{-2} to 10^{-4}, Rubin, 1995a). The composite data set also reveals a weak trend toward decreasing aspect ratio with length. Here we briefly describe each locality, while noting that factors relevant to injection vein formation (Table 1) are similar among all three sites.

2.1. Fort Foster brittle zone

The Fort Foster brittle zone has been the focus of studies by Swanson (2006; and references therein) who used the pseudo-