



Experimental generation of volcanic pseudotachylytes: Constraining rheology

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ABSTRACT

Volcanic systems are highly dynamic environments that comprise rocks and magmas, which, in the process of strain localisation (e.g., in catastrophic flank collapse or dome-building events), are candidate materials for the occurrence of frictional melting and the formation of pseudotachylytes. We evaluate the frictional behaviour of a plagioclase-, two-pyroxene- and glass-bearing andesite and introduce an approach to constrain the rheology of frictional melts. Frictional slip at a rate of 1.3 m/s under an axial stress of 1.5 MPa induces heating at a rate approximating 130 °C per metre of slip and frictional melting of the andesite occurs at >1000 °C, which corresponds to a peak in shear stress. With continuing displacement, the shear stress decreases by ~25% from the peak strength and stabilises while the temperature equilibrates to 1230–1290 °C. The shear stress for the system is congruent with a non-Arrhenian temperature-dependent frictional melt rheology exhibiting a non-Newtonian viscosity evolving from approximately 10^{4.2} to 10^{3.4} Pa s. Post-experiment analysis shows a gradation from 1) the host rock, to 2) an extraordinary zone of unmelted, yet viscously deformed material, to 3) a thin, outer region of chemically heterogeneous protomelts, and to 4) an inner region of chemically homogeneous frictionally generated/modified melt in the core of the slip zone. We discuss the role and identification of frictional melting in volcanic systems and the implication of viscous remobilisation of magmatic plugs during frictional slip of glass-bearing volcanic materials.

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1. Introduction

In recent years, frictional melts generated in localised slip zones in faults have been shown to exert control on coseismic faulting and earthquake slip (Spray, 1987; Hirose and Shimamoto, 2005; Di Toro et al., 2006b, 2011). During earthquakes where fault slip is localized to narrow slipping zones (at ca. >0.1 m/s), most frictional work is converted to heat; for instance, more than 1400 °C can be generated during seismic slip events along slip zones thinner than 10 mm if the shear strength remains constant (e.g., Rice, 2006). Such temperature increases are sufficient to melt the wallrocks along the slip zone, producing frictional melts which cool to form a pseudotachylyte (Sibson, 1975), which is often used to infer seismic fault motion on exhumed faults (Cowan, 1999).

Melting of rocks under such rapid-heating events is perceived to be a non-equilibrium thermodynamic process (Spray, 1992) in which selective melting of individual crystal phases depends on their fusion temperatures (Lin and Shimamoto, 1998). Sustainability of slip and friction (along a discrete slip plane) regulates melting and the retreat of the rock–melt interface along seismogenic faults – a thermodynamic phenomenon described as a Stefan problem (Hirose and Shimamoto, 2005). As melting ensues, the chemical composition of the melt evolves, which is an additional factor controlling the shear resistance of faults coated by frictional melts (Hirose and Shimamoto, 2005). The shear resistance of the viscous layer is determined by the viscosity and shear strain rate of the molten layer, previously approximated as a Newtonian liquid with Arrhenian temperature dependence of viscosity (e.g., Spray, 1993; Ujiie et al., 2007; Piccardo et al., 2010). Frictional melts may act as lubricants to seismic motion as strong velocity-weakening of faults occurs during melt generation, which has a significant effect on the frictional properties in slip zones (Di Toro et al., 2006a). When a molten layer separates a fault during seismic

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slip, it is no longer rock-to-rock friction but viscous energy dissipation that becomes the heat source. During deceleration and cessation of slip, the heat generated by friction dissipates into the surrounding country rocks and the melt succumbs to one of two fates: 1) crystallization or 2) quenching to a glass, both preserved henceforth, in the geologic record, as pseudotachylytes. But dynamically, how do frictional melts evolve? And equally important, what are the rheological consequences of chemically evolving frictional melts on the frictional properties of slip zones?

The most common rock-forming minerals are silicates and as such, frictional melting results primarily in the generation of silicate melts. Initial melting events, although a non-equilibrium process, mix and reach equilibrium with slip (Hirose and Shimamoto, 2005). Chemical mixing of silicate melts is controlled by diffusion and convection (Mezic et al., 1996; Perugini and Poli, 2004; Perugini et al., 2010). During non-equilibrium frictional melting, slip forces convection. This action stretches the interface between melt batches (from selective melting) and increases the surface area available for chemical diffusion, thereby enhancing the efficiency of chemical homogenization. The chemical composition of a melt strongly influences the rheology of silicate melt (Dingwell and Webb, 1989). The viscosity of silicate liquids has been extensively studied in the Newtonian region for a range of compositions (Murase and McBirney, 1970; Bottinga and Weill, 1972; Shaw, 1972; Dingwell et al., 1985, 1996, 1997; Persikov et al., 1990; Dingwell, 1991; Yue and Brückner, 1994; Hess and Dingwell, 1996; Richet et al., 1996; Scaillet et al., 1996; Dingwell and Hess, 1998; Schulze et al., 1999; Liebske et al., 2003; Sato, 2005; Malfait et al., 2011), including mineral compositions (Cukierman and Uhlmann, 1973; Cranmer and Uhlmann, 1981; Richet, 1984; Tauber and Arndt, 1987; Neuville and Richet, 1991; Taniguchi, 1992; Askarpour et al., 1993; Toplis et al., 1997; Schilling et al., 2001); it is known to exhibit a strong non-Arrhenian temperature dependence and recent models for its estimation are reasonably accurate over a wide range of geochemical compositions (Hui and Zhang, 2007; Giordano et al., 2008). The onset of non-Newtonian rheology in melts is also well-documented empirically (Li and Uhlmann, 1968, 1970; Simmons et al., 1982, 1988; Dingwell and Webb, 1989, 1990; Brückner and Yue, 1994; Simmons, 1998) and found to correlate with strain rates approaching the relaxation rate of the liquid structure (to within 3 orders of magnitude; e.g., Webb and Dingwell, 1990). In the case of partially molten rocks, such as those produced by frictional slip, the presence of crystals and bubbles may also affect the rheological properties both by influencing the Newtonian (static) suspension viscosity and by the addition of strain-rate dependence (Bagdassarov and Dingwell, 1992; Stein and Spera, 1992, 2002; Bagdassarov et al., 1994; Lejeune and Richet, 1995; Stevenson et al., 1996; Lejeune et al., 1999; Caricchi et al., 2007; Lavallée et al., 2007; Cordonnier et al., 2009). Frictional melting thus results in the generation of a complex, disequilibrium multiphase magma with the result that its rheological properties are almost unknown. The frictional properties of faults which produce complex frictional melts are thus intimately linked to the chemical and physical evolution of the melt.

To date, frictional melting experiments have been conducted primarily on intrusive, metamorphic and sedimentary rocks (Spray, 1987, 1988, 1995; Kennedy and Spray, 1992; Shimamoto and Lin, 1994; Tsutsumi and Shimamoto, 1997; Hirose and Shimamoto, 2005; Di Toro et al., 2006a,b; Tsutsumi and Mizoguchi, 2007; Del Gaudio et al., 2009; Sato et al., 2009; Ujiie et al., 2009; Kim et al., 2010; Niemeijer et al., 2011). The majority of these studies focus on the control of frictional melts on coseismic earthquake dynamics of seismogenic crustal-scale faults, which commonly initiate near the brittle–ductile transition at some ca. 10-km depth.

Volcanic regions, however, with their ambient temperatures above that of the typical crustal geotherm (for a given depth) as well as their perpetually deforming nature stand as ideal candidates for frictional melting and formation of pseudotachylytes. Yet, the potential for frictional melting in this geological setting as well as the frictional properties of volcanic rocks has been, to date, unexplored.

Volcanic systems are dynamic environments, which are highly seismogenic. Magma ascent and eruptions are accompanied by complex seismic signal trigger mechanisms ranging from failure of conduit wallrocks and magma, to frictional slip and degassing (e.g., Sparks, 2003). In recent years, magma has been increasingly recognised as a seismic source triggered by strain localisation, leading to fracturing and subsequent slip (e.g., Iverson et al., 2006; Neuberg et al., 2006; Johnson et al., 2008; Lavallée et al., 2008; Tuffen et al., 2008). The role and extent of friction-controlled ascent in conduits has been quantified with regard to viscous flow (e.g., Melnik and Sparks, 1999; Costa et al., 2007; Melnik et al., 2009), stick-slip behaviour (e.g., Tuffen et al., 2003; Neuberg et al., 2006; Melnik et al., 2009), cataclastic flows of gouge material (e.g., Cashman et al., 2008; Kennedy et al., 2009; Kennedy and Russell, 2011), ejections of pyroclasts during explosive eruptions (e.g., Wilson et al., 1980; Ramos, 1995; Bower and Woods, 1996), and recently with regard to frictional melting (e.g., Kendrick et al., 2012). In fact, to our knowledge, only five studies exist evaluating pseudotachylytes in volcanic systems: including the aforementioned study of frictional melting in volcanic conduit, complementary studies have also alluded to the occurrence of frictional melting in a sector collapse (Legros et al., 2000), in pyroclastic/block-and-ash flows (Grunewald et al., 2000; Schwarzkopf et al., 2001) and in caldera subsidence-controlling faults (Kokelaar, 2007).

Volcanic rocks (in contrast to intrusive, sedimentary and metamorphic rocks) present an additional complexity in that their groundmass commonly comprises an initial fraction of interstitial glass. Glass does not form via a phase transition in the Gibbsian thermodynamic sense, rather, liquid and glassy melts are two physical states of the same phase, discriminated by strain rate and temperature (Dingwell and Webb, 1989). The ability of silicate melts in magmas, to switch from a liquid to a glassy state (and back) is well described by a Maxwell body viscoelasticity with a transition known as T_g , the glass transition (Webb and Dingwell, 1990). T_g is a kinetic barrier, dependent predominantly on chemical composition and temperature; it typically occurs at a temperature hundreds of degrees below the melting point in simple congruently melting systems and often well below the range of crystallisation in magmas. Volcanic rocks preserving the glassy groundmass phase may thus be remobilised to viscous liquids at temperatures well below their melting temperatures or those of their constituent phases. Thus the remobilisation of pseudotachylyte in volcanic systems forms a special material case with potentially surprising characteristics. Understanding the frictional properties of volcanic rocks subject to selective melting and formation of volcanic pseudotachylyte may greatly improve our ability to predict the flow and strain localisation observed in volcanic domes and inferred for volcanic conduits. As such flow models are an essential ingredient of reliable interpretation of volcano monitoring signals, the mitigation of volcanic eruptions stands to gain from a better understanding of the role of frictional melting and pseudotachylyte development in volcanic environments. Here, we introduce a method which combines frictional, geochemical and rheological data to constrain the rheology of frictional melts and present results from a high-velocity rotary experiment on a glass-bearing andesitic rock to evaluate the role and generation of pseudotachylyte in volcanic environments.

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