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Tying textures of breadcrust bombs to their transport regime and cooling history

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ABSTRACT

The thermal evolution of explosive eruptive events such as volcanic plumes and pyroclastic density currents (PDCs) is reflected in the textures of the material they deposit. Here we evaluate how the rinds of breadcrust bombs can be used as a unique thermometer to examine mafic to intermediate explosive eruptions. These eruptions can produce breadcrust bombs in either PDCs or as projectiles following nearly ballistic trajectories. We develop an integrated model to examine bubble growth, pyroclast cooling, and dynamics of PDCs and projectiles from buoyant plumes. We examine rind development as a function of transport regime (PDC and projectile), transport properties (initial current temperature and current density), and pyroclast properties (initial water content and radius). The model reveals that: 1) rinds of projectile pyroclasts are in general thicker and less vesicular than those of PDC pyroclasts; 2) as the initial current temperature decreases due to initial air entrainment, the rinds on PDC pyroclasts progressively increase in thickness; and 3) rind thickness increases with decreasing water concentration and decreasing clast radius. Therefore, the modeled pyroclast's morphology is dependent not only on initial water concentration but also on the cooling rate, which is determined by the transport regime.

1. Introduction

Pyroclastic density currents (PDCs) are some of the most destructive volcanic phenomena and understanding the many physical processes associated with these flows has proven difficult. Inherent opacity limitations and hazardous conditions have resulted in relatively poor constraints on flow dynamics, in particular on the thermal evolution. One mechanism that changes the thermal state of the current is entrainment of colder, ambient air (Sparks, 1986; Bursik and Woods, 1996). The extent to which a current will entrain ambient air depends on the particle concentration and concentration gradient, particle size distribution, current shear, and current temperature (Dufek and Bergantz, 2007a). These temporally and spatially variable conditions control the thermal evolution of a PDC, directly influence the total run out distance, and determine deposit characteristics (Hallworth et al., 1993; Bursik and Woods, 1996; Branney and Kokelaar, 2002; Clarke et al., 2002; Wilson and Houghton, 2002; Neri et al., 2003; Scott et al., 2008). To improve our knowledge of the thermal evolution of PDCs, a better understanding and application of thermal proxies in these flows must be developed.

Hot pyroclasts that are deposited from explosive volcanic eruptions, either from ballistic trajectories or PDCs, have the potential to be used as thermal proxies. Each pyroclast has a unique transport path that samples a portion of the volcanic environment (Kaminski and Jaupart, 1997; Vanderkluysen et al., 2012). A breadcrust bomb (see Fig. 1a) may be an especially useful thermal proxy due to its unique texture (Wright et al., 2007; Giachetti et al., 2010). A breadcrust bomb is a pyroclast that has many surface cracks, a dense rind, and a vesicular interior. The surface cracks likely develop as a product of the continual growth of gas bubbles in the hot interior, which causes expansion of the clast and subsequent cracking of the brittle rind (Walker, 1969; Wright et al., 2007). Some surface cracks may also be from thermal contraction or from the stress of impact (Wright et al., 2007). Breadcrust bombs are found in deposits from basaltic to rhyolitic explosive eruptions, typically of Vulcanian style (Walker, 1982; Morrissey and Mastin, 2002; Wright et al., 2007). Some volcanoes that have generated breadcrust bombs are Montserrat (Giachetti et al., 2010), Mayon (Moore and Melson, 1969), Cerro Galan (Wright et al., 2011), Lascar (Calder et al., 2000), Panum Dome (Anderson et al., 1994), Cotopaxi (Pistolesi et al., 2011), Guagua Pichincha (Wright et al., 2007), Tungurahua (Hall et al., 1999; Le Pennec et al., 2008; Douillet et al., 2013), Vulcano (Walker, 1969), and Ngauruhoe (Morrissey and Mastin, 2002). Breadcrust bombs are found as ballistically emplaced clasts in the crater or on the flank of volcanoes (Wright et al., 2007; Giachetti et al., 2010), but some are

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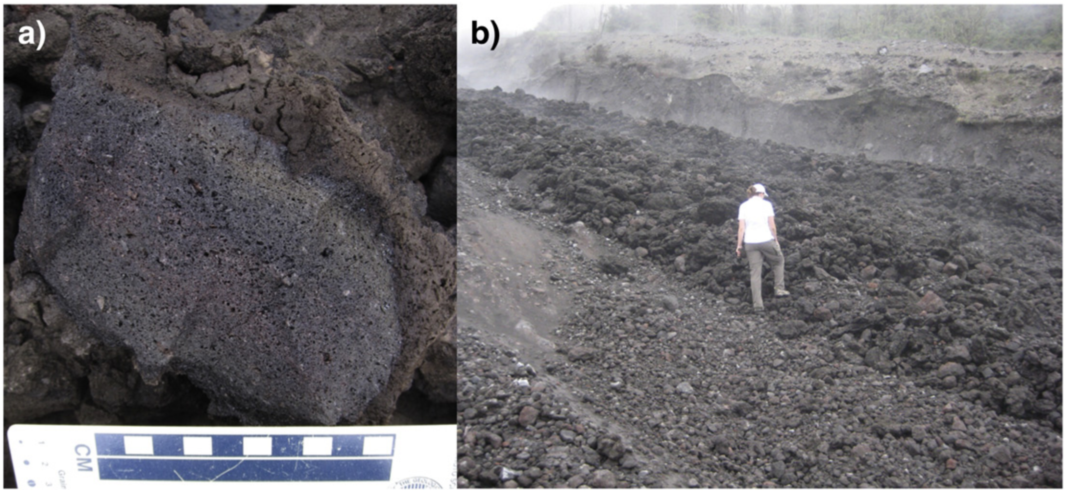

Fig. 1. Breadcrust bombs. a.) An example of a breadcrust bomb with a dense rind from Tungurahua volcano, Ecuador. b.) PDC deposit of breadcrust bombs at Tungurahua volcano, Ecuador.

also found in PDC deposits (Fig. 1b) kilometers away from the vent (Hall et al., 1999; Hall and Mothes, 2008; Giachetti et al., 2010; Samaniego et al., 2011; Douillet et al., 2013). The vesicularity gradient of a breadcrust bomb is hypothesized to be the result of syn-eruptive bubble nucleation and growth, and the quick cooling of the bomb's edge during transport (Walker, 1969, 1982; Giachetti et al., 2010).

The radial distribution of bubble sizes in the clasts can provide insight into each bomb's thermal history. Bubbles grow through diffusion of volatiles into the bubble, where growth and expansion is limited by magmatic viscosity, which changes by orders of magnitude during cooling and solidification (Sparks, 1978; Prousevitch et al., 1993; Proussevitch and Sahagian, 1996; Blower et al., 2001). Bubble nucleation in breadcrust bombs is thought to happen after fragmentation because of the small, isolated bubbles or the lack of bubbles in the rind (Giachetti et al., 2010). Immediately after eruption and fragmentation, breadcrust bombs are often above the glass transition temperature, the kinetic limit at which the material transitions from a viscous liquid to a glass (Gottsmann et al., 2002; Giordano et al., 2005). As the clast cools, viscosity increases and parts of the clast will cross the glass transition temperature. The increase in viscosity slows bubble growth, and bubble growth is terminated at high viscosities or when the temperature crosses the glass transition temperature. Therefore, the preserved radial bubble size distribution in the bomb provides a textural indicator of the relative timing between fragmentation and quenching (Giachetti et al., 2010). The radially dependent bubble size distribution within a given breadcrust bomb is proposed to be a function of bubble nucleation delay, bubble growth rate, cooling rate, and viscosity (Walker, 1969, 1982; Hoblitt and Harmon, 1993; Giachetti et al., 2010). Examining textural features of breadcrust bomb rinds after an eruption, when the depositional location of the pyroclast is known, provides an opportunity to retrace the thermal history of the pyroclast and of the eruption itself.

A combination of physical and mathematical models have been used to look at the cooling of pyroclasts that fell vertically (Thomas and Sparks, 1992), had ballistic trajectories (Capaccioni and Cuccoli, 2005; Wright et al., 2007), or were entrained within an eruption column (Kaminski and Jaupart, 1997; Hort and Gardner, 2000). Previous cooling models of falling pyroclasts have used convective and radiative heat transfer boundary conditions and conductive cooling in the clast interior (Thomas and Sparks, 1992). More recent models expanded on this by adding a ballistic transport model with flight path and velocity to calculate the cooling of pyroclasts on a parabolic trajectory (Capaccioni and Cuccoli, 2005; Wright et al., 2007). Wright et al. (2007) compared known rind thicknesses of breadcrust bombs from field data to their cooling model to determine the time required for the rind to cool below the glass transition temperature. The time for the rind to cool below the glass transition temperature was used as an approximation for rind formation time. The comparison suggests that rinds form relatively quickly (less than 45 s) after eruption and that some rinds on finely breadcrusted bombs form before impact.

A limited number of studies examine the interaction between cooling rates and syn-eruptive bubble growth. The model by Hort and Gardner (2000) on pumice cooling and bubble growth showed that water loss in pumice depends on the cooling rate. Pumice was almost completely degassed if the ratio of the cooling timescale to the degassing timescale was greater than approximately 50 (Hort and Gardner, 2000). A pumice clast was less vesicular at the edge compared to its interior because of rapid cooling and viscous quenching on clast margins (Kaminski and Jaupart, 1997). The impact of these timescales on textures stresses the need to couple numerical models of cooling and bubble growth to better interpret pyroclast textures. The pyroclast's transport path through the local environment will influence its final texture. All of these previous cooling models focus on either a parabolic path with no collisions or a collision-free fall through a uniform temperature environment. The examination of pyroclast cooling while entrained in a PDC has not been studied. No existing numerical model compares how different travel paths, such as ballistic versus PDC transport, affect a pyroclast's cooling history and, therefore, its texture.

In this study, a model of the thermal history and rind thickness of breadcrust bombs is developed to determine if path- and temperature-dependent textural information is imparted on multiple pyroclasts when transported either as projectiles in a buoyant eruption plume or within the body of a PDC. Throughout the text, pyroclasts entrained in PDCs will be referred to as PDC pyroclasts or PDC. The pyroclasts that are ballistically ejected out of a buoyant plume will be referred to as projectile pyroclasts or projectile. To evaluate how the cooling history influences rind thickness, we build on the pyroclast cooling models presented in Thomas and Sparks (1992), Capaccioni and Cuccoli (2005), and Wright et al. (2007) by adding a detailed transport system and a coupled model of cooling, viscosity, and bubble growth for individual pyroclasts. In each pyroclast, the radial change in bubble size allows for an explicit definition of rind thickness, where the rind contains the smallest bubbles. We also examine how varying the initial water concentration in the pyroclast affects the rind thickness. In this work, we focus on the end-member conditions of projectile pyroclasts ejected primarily through a cool, ambient atmosphere and pyroclasts transported in hot PDCs with variable entrainment histories. Here we do not focus on a specific eruption, but rather evaluate