Rheological controls on the emplacement of extremely high-grade ignimbrites

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Rheological controls on the emplacement of extremely high-grade ignimbrites

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ABSTRACT

Extremely high-grade, lava-like welded ignimbrites are produced by many large explosive eruptions with volumes typically 10³–10⁶ km³. However, understanding of the physical properties of these unusual deposits, and their transport and depositional mechanisms, is incomplete. The lava-like and rheomorphic Grey’s Landing ignimbrite, Idaho (western United States), provides abundant field evidence supporting the upward migration of a transient, <2-m-thick, sub-horizontal ductile shear zone at the interface between the pyroclastic density current and the deposit, through which all of the aggrading pyroclastic material passed. Here we use a combination of rheological experiments and thermo-mechanical modeling to test the syndepositional shear zone model. We show that syndepositional welding and ductile flow are achievable within a very restricted field of likely temperature–strain rate space, where rapid deformation is favored by higher emplacement temperatures (≥850 °C). The field of ductile deformation is broadened significantly by accounting for strain heating, which permits a sustained temperature increase of up to 250 °C within the shear zone and helps to explain the tremendous extents of lava-like lithofacies and the intense rheomorphism recorded in extremely high-grade ignimbrites. Recognition of strain heating within rheomorphic ignimbrites suggests that large pyroclastic density currents may travel over a hot substrate, potentially hotter than the density current itself.

INTRODUCTION

Extremely high-grade ignimbrites exhibit lava-like lithofacies characterized by intense welding resulting in pervasive flow banding, flow folding (rheomorphism), lower and upper vitrophyres, columnar jointing, minor autobreccias, and a paucity of the vitroclastic textures (e.g., lamme) that are common in lower-grade examples (Branney and Kokelaar, 1992). Although characteristic of several large igneous provinces, including the Snake River Plain, Idaho (western United States; Branney et al., 2008), and disproportionally associated with the largest silicic eruptions documented (>1800 km³; volcanic explosivity index ≥8.5; Bryan et al., 2010), high-grade ignimbrites are atypical of most metaluminous volcanic sequences. Extremely high-grade tuffs exist toward the high-temperature and low-viscosity end of a welding continuum between non-welded tuffs and agglutinated fountain-fed lavas (Branney and Kokelaar, 1992). The evolving rheological and mechanical behaviors of low- and moderate-grade tuffs (Quane and Russell, 2005a) and fountain-fed lavas (Summer et al., 2005) are well documented; in contrast, despite several field descriptions of lava-like tuffs (e.g., Summer and Branney, 2002; Andrews and Branney, 2011), the evolution of physical properties during transport, deposition, welding, and rheomorphic flow is not well understood.

Lava-like lithofacies are the result of intense welding and rheomorphism whereby hot, pyroclastic material is rapidly ductilely deformed such that non-coaxial flow of the deposit is pervasive (Branney et al., 2004). In the field, they are often indistinguishable from lavas (Henry and Wolff, 1992); their pyroclastic origin is often only recognizable at the microscopic level in low-strain domains. While rheomorphism is far from uncommon in ignimbrites, it is typically coaxial, controlled by local topographic gradients (Chapin and Lowell, 1979), and localized to discrete zones within otherwise lower-strain domains (Wolff and Wright, 1981; Kobberger and Schmincke, 1999). Lava-like tuffs are end-member examples of extreme welding and pervasive, intense, non-coaxial strain rheomorphism affecting an entire deposit. Based on field observations of the Grey’s Landing (Idaho) ignimbrite, it has been proposed that lava-like tuffs form by deformation of the pyroclasts in a transient, vertically migrating shear zone synchronous with deposition and welding (Fig. 1).

The Grey’s Landing Ignimbrite

The ignimbrites of the Miocene Rogerson Formation (Andrews et al., 2008), Snake River Plain volcanic province, include two that are pervasively rheomorphic and lava-like. They are examples of metaluminous, Snake River–type ignimbrites (Branney et al., 2008) and are inferred to have low magmatic water contents (<1.5 wt%), based on anhydrous crystal assemblages and crystallization experiments (Almeev et al., 2012). Mineral thermometry suggests magmatic temperatures of ≥850 °C (Cathey and Nash, 2004; Andrews and Branney, 2011).

The pervasively rheomorphic Grey’s Landing ignimbrite records strains of 10–1000 based on estimates from stretched vesicles, and several lines of evidence suggest that rheomorphism was syndepositional (Andrews et al., 2008; Andrews and Branney, 2011); the most important of these are that (1) intense rheomorphism is recorded throughout the entire deposit, including in the rapidly quenched lower and upper vitrophyres, and (2) inferred syndepositional rheomorphic fabrics were pervasively refolded by later, demonstrably postdepositional, gravity-driven flow.

METHODS

Viscosity Measurements

We used parallel-plate viscometry to measure the apparent viscosity of the basal Plinian ash-fall tuff (GLB; Andrews et al., 2008), which
Strain Heating Modeling

Rheomorphism may also be promoted by viscous heating caused by ductile deformation within the migrating shear zone. Viscous heating in melts has been investigated in the context of lavas and volcanic conduits (Costa and Macedonio, 2005; Cordonnier et al., 2012), but not in welded tuffs. We modeled strain heating in the shear zone in one dimension by solving the heat-flow equation numerically (Equation 9 in Table 1; Fig. 1B), using the finite difference method implemented in MATLAB (see the Data Repository). The widths of the enveloping surfaces of curvilinear folds and shear folds observed in the field constrain the vertically migrating shear zone to 1–2 m in width (Andrews and Branney, 2011). The maximum total time for deformation is the duration of the eruption (up to tens of hours; Self, 2006). Strain rate can be estimated independently based on finite strain from field measurements, and assuming deposition from a quasi-steady pyroclastic current, with a constant strain-rate distribution across the shear zone. This is equivalent to the strain rate experienced by a pyroclast deforming in a vertically migrating shear zone with a linear translation velocity profile, where strain rate is defined as the ratio of translation velocity to shear zone thickness. We leave shear stress to be defined by the apparent viscosity of the material being deformed in our experiments because it is not possible to obtain independent constraints on shear stress experienced by the deposit during deformation. The intensity of strain ($\dot{\varepsilon}$) recorded at any particular height in a lava-like rheomorphic ignimbrite is a function of both the strain rate, $\dot{\varepsilon}_{\text{app}}$, and the duration of the transient period in which that particular level resided within the migrating shear zone, $t_{\text{res}}$. The deformation time scale is defined as the inverse of the strain rate. The apparent viscosity ($\eta_{\text{app}}$) data derived from our viscosity experiments allow us to calculate the Deborah number, $De$, defining the lowest-temperature or highest-strain-rate conditions at which ductile deformation is possible. The relaxation time scale of the melt is obtained through the Maxwell relation $\tau_{\text{rel}} = \eta_{\text{app}}/G_{\infty}$, where $G_{\infty}$ is the unrelaxed elastic shear modulus (~1010 Pa; Dingwell and Webb, 1989; Whittington et al., 2012). The evidence for ductile deformation obtained from field relationships implies that the deformation time scale in the shear zone had to be longer than the relaxation time scale ($De < 1$). In practice, the deformation in the shear zone will be brittle before $De = 1$ is reached, and the onsets of non-Newtonian and brittle behavior occur three and two orders of magnitude before the theoretical Maxwell criterion, respectively (Webb and Dingwell, 1990; Cordonnier et al., 2012).

### TABLE 1. PARAMETERS AND EQUATIONS USED IN THIS STUDY

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Equation</th>
<th>Value*</th>
<th>Unit</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_d$</td>
<td>Eruption duration</td>
<td>$\text{Tens (5–50)}$</td>
<td>h</td>
<td>Self (2006)</td>
<td></td>
</tr>
<tr>
<td>$h_{\text{dep}}$</td>
<td>Deposit thickness</td>
<td>$\text{Up to 100 (50)}$</td>
<td>m</td>
<td>Andrews and Branney (2011)</td>
<td></td>
</tr>
<tr>
<td>$h_{\text{sz}}$</td>
<td>Shear zone thickness</td>
<td>$\text{1–2 (2)}$</td>
<td>m</td>
<td>Andrews and Branney (2011)</td>
<td></td>
</tr>
<tr>
<td>$v_{\text{sz}}$</td>
<td>Shear zone vertical migration velocity</td>
<td>$v_{\text{sz}} = \frac{h_{\text{dep}}}{t_d}$ (EQ. 1)</td>
<td>1–10</td>
<td>m h$^{-1}$</td>
<td>This study</td>
</tr>
<tr>
<td>$t_{\text{res}}$</td>
<td>Residence time in the shear zone</td>
<td>$t_{\text{res}} = \frac{h_{\text{sz}}}{v_{\text{sz}}}$ (EQ. 2)</td>
<td>&lt;&lt;50</td>
<td>(0.2–20)</td>
<td>h This study</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Observed strain</td>
<td>$100–1000 (100)$</td>
<td>m</td>
<td>Andrews and Branney (2011),</td>
<td>Andrews et al. (2008)</td>
</tr>
<tr>
<td>$\dot{\varepsilon}_{\text{def}}$</td>
<td>Deformation strain rate</td>
<td>$\dot{\varepsilon}<em>{\text{def}} = \frac{\varepsilon}{t</em>{\text{res}}}$ (EQ. 3)</td>
<td>$1.4 \times 10^{-2}$–$1.4 \times 10^{-1}$</td>
<td>s$^{-1}$</td>
<td>This study</td>
</tr>
<tr>
<td>$\tau_{\text{def}}$</td>
<td>Deformation time scale</td>
<td>$\tau_{\text{def}} = \frac{1}{\dot{\varepsilon}_{\text{def}}}$ (EQ. 4)</td>
<td>7.2–72</td>
<td>s</td>
<td>This study</td>
</tr>
<tr>
<td>$\eta_{\text{app}}$</td>
<td>Apparent viscosity of deposit</td>
<td>$\log \eta_{\text{app}} = -4.5 + \frac{13.441}{T (K)} - 304.5$ (EQ. 5)</td>
<td>Pa·s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_{\text{rel}}$</td>
<td>Relaxation time scale</td>
<td>$\tau_{\text{rel}} = \frac{\eta_{\text{app}}}{G_{\infty}}$ (EQ. 6)</td>
<td>s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$De$</td>
<td>Deborah number</td>
<td>$De = \frac{\tau_{\text{def}}}{\tau_{\text{rel}}}$ (EQ. 7)</td>
<td>$10^{10}$</td>
<td>Pa</td>
<td>Dingwell and Webb (1989),</td>
</tr>
<tr>
<td>$G_{\infty}$</td>
<td>Unrelaxed elastic shear modulus</td>
<td>$10^{10}$</td>
<td>Pa</td>
<td></td>
<td>Whittington et al. (2012)</td>
</tr>
<tr>
<td>$T_{\text{dep}}$</td>
<td>Deposition temperature</td>
<td>$&lt;1050$</td>
<td>°C</td>
<td></td>
<td>See text</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Heat capacity</td>
<td>$1323$</td>
<td>J kg$^{-1}$K$^{-1}$</td>
<td>Bouhidj et al. (2006)</td>
<td></td>
</tr>
<tr>
<td>$D$</td>
<td>Thermal diffusivity</td>
<td>$0.5 \times 10^{-6}$</td>
<td>m$^2$s$^{-1}$</td>
<td>Romine et al. (2012)</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
<td>$2300$</td>
<td>kg m$^{-3}$</td>
<td>This study</td>
<td></td>
</tr>
<tr>
<td>$Q_{\text{strain}}$</td>
<td>Strain heating</td>
<td>$Q_{\text{strain}} = \eta_{\text{app}} \times \dot{\varepsilon}_{\text{def}}$ (EQ. 8)</td>
<td>W m$^{-3}$</td>
<td>This study</td>
<td></td>
</tr>
<tr>
<td>$\frac{\partial T}{\partial t}$</td>
<td>Temperature change over time</td>
<td>$\frac{\partial T}{\partial t} = -\frac{1}{C_p \rho} \left( \frac{\partial T}{\partial z} \right) \frac{G_{\infty}}{C_p D}$ (EQ. 9)</td>
<td>K s$^{-1}$</td>
<td>This study</td>
<td></td>
</tr>
</tbody>
</table>

*Values used in calculations are as listed or specified in parentheses.
RESULTS

Rheology of the Grey’s Landing Ignimbrite

Our viscosity measurements show that high deposition temperatures (>900 °C), or lower temperatures if the melt contained some dissolved water (~850 °C for ~0.1 wt% H₂O), would allow for syndepositional rheomorphism to impose total strain up to ~100 in ~2 h. A deposition temperature higher by ~50 °C in both dry and slightly hydrous scenarios allows for syndepositional rheomorphism to impose total strain up to 100 in ~12 min. Alternatively, total strain up to 1000 may be applied during syndepositional rheomorphism in ~2 h at those higher temperatures.

Rheomorphism can occur on the short time scales required by the field observations (i.e., synchronous with aggradation) only if deposition temperatures matched the high magmatic temperatures of the Grey’s Landing ignimbrite. For example, dry GLB at ~900 °C plots just inside the field of possible rheomorphism for a 2 h shear zone residence time (dark gray arrow in Fig. 2). Shorter residence times (e.g., light gray arrow in Fig. 2) require higher deposition temperatures or dissolved volatiles for deformation to be ductile. If strain heating is not considered, only high deposition temperature–low strain rate combinations allow for ductile deformation. The dry melts making up the Grey’s Landing deposit would require excessively long deformation times of days to weeks to produce the strain measured in the deposit.

The Contribution of Strain Heating

In Figure 3, we show a compilation of models with deposition temperature–strain rate (or residence time) combinations that allow for ductile deformation within the shear zone. Field evidence in favor of ductile deformation is overwhelming, and we therefore reject all conditions resulting in brittle deformation (De > 10⁻²), for which strain heating as defined in Equation 8 (in Table 1) is no longer applicable. Thermal modeling demonstrates that strain heating of at least a few tens of degrees will occur under likely deposition conditions, with higher strain rates resulting in higher peak temperatures (Fig. 3). The rate of temperature increase is initially large just after deposition when viscosity of the material is high. As deformation progresses, the temperature increase due to strain heating results in a decrease of viscosity, which in turn slows the rate of further heating. If dynamic thermal equilibrium is achieved, heat will concentrate in the center of the shear zone (e.g., Figs. 3H–3K). For shorter residence times, where steady-state has not been achieved, the temperature profiles are truncated and plug like (e.g., Figs. 3A–3C). For longer shear zone residence times at lower strain rates than shown in Figure 3, conductive heat loss exceeds heat production by strain heating.

DISCUSSION

The results demonstrate that initial deposition temperatures of 850–900 °C are consistent with syndepositional rheomorphism for shear zone residence times on the order of ~2–20 h, with strain heating resulting in peak temperatures of ~1030–1100 °C. Therefore, pervasive rheomorphism leading to lava-like lithofacies does not require high pre-eruptive temperatures (≥1000 °C, depending on the amount of cooling during transport) or high volatile contents to reduce the viscosity. Strain heating is only efficient above a critical strain rate, which is higher for hotter deposition temperatures. Below this critical strain rate, strain heating simply
buffers cooling of the deposit. When strain rates are too high, deformation is brittle, and thus the influence of strain heating in syndepositional rheomorphism is restricted; initial deposition temperature–strain rate conditions must be at $De < 1$ for strain heating to start.

Pervasive syndepositional rheomorphism resulting in lava-like lithofacies therefore requires an unusual concatenation of circumstances, with strain rates restricted to a narrow window. If strain heating begins quickly during the deposition of a large ignimbrite, then the pyroclastic density current will travel over a hot substrate, potentially hotter than the current itself, which would have important implications for the thermal budget of the current and runout distance of the deposit. These large ignimbrites will be very hot, thoroughly welded, and lava-like by the time they emerge from the depositional shear zone, and can be easily remobilized; for example, the middle and upper parts of thick sections of the Grey’s Landing deposit are pervasively refolded (Andrews and Branney, 2011).

Once a volume of the deposit has passed out of the high-strain-rate regime of the depositional shear zone, it may still be above the glass transition and still be able to weld or vesiculate, even if it was not hot enough to deform ductily within the shear zone. In many ignimbrites that are only locally rheomorphic (e.g., the Huckleberry Ridge Tuff, Idaho; Geissman et al., 2010), rheomorphism probably occurred entirely postdeposition. Just as gravity-driven strain heating has been suggested as a contributing factor to extensive, sustained flow of viscous lavas (Nelson, 1981; Avard and Whittington, 2012), it could equally facilitate localized postdepositional rheomorphism. Our modeling shows that cooling can be buffered for as long as strain rates $>10^6$ s$^{-1}$ can be sustained in a 50-m-thick deposit (or lava) at 700 °C. This overlaps with the upper end of strain rates for welding by compaction (Quane and Russell, 2005b). Strain heating is an inevitable result of magma transport both pre- and post-eruption, and should be taken into account in thermal-rheological modeling of volcanic processes at both high and low strain rates.

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