Repeated fracture and healing of silicic magma generate flow banding and earthquakes?

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ABSTRACT

Textures in an exceptionally preserved effusive rhyolite conduit at Torfajökull, Iceland, indicate that rising magma repeatedly fractured and healed at shallow levels in the conduit (RFH process). Anastomosing tuffisite veins filled by fine-grained juvenile clasts were generated by shear fracture of highly viscous magma in the glass transition interval. Welding of the particulate material during subsequent deformation led to thorough healing of veins, allowing repeated fracture of the same body of magma. We propose that the RFH process is a rechargeable trigger mechanism for hybrid seismicity and show that the time scale of the process and the fractures formed by it are consistent with the repeat time and magnitude of hybrid earthquakes during silicic eruptions. The RFH process may also form the flow banding that is nearly ubiquitous in obsidian.

Keywords: volcanic earthquakes, obsidian, tuffisite, viscoelasticity, glass transition, conduit.

INTRODUCTION

The eruption of silicic lava domes is typically accompanied by repetitive long-period and hybrid earthquakes that originate from a small region of the upper conduit, typically <1.5 km from the dome surface (Chouet, 1996; Neuberg, 2000). Both hybrid and long-period earthquakes are small magnitude (M_o ~0–1) and contain similar frequencies, but hybrid events have mixed-polarity first motions, whereas long-period first motions are single polarity (Lahr et al., 1994). Repeat times between successive long-period and hybrid events are typically minutes to hours ($10^{2.5}$ to $10^{4.5}$ s) (Gil Cruz and Chouet, 1997; White et al., 1998; Voight et al., 1999; Uchida and Sakai, 2002). Although increased numbers of hybrid and long-period earthquakes may occur prior to, and thus give advance warning of, dome collapse and Vulcanian explosions (Chouet, 1996; Voight et al., 1999; Neuberg, 2000), their origins are controversial. Long-period earthquakes may be triggered when gas released by foam collapse excites preexisting cracks in the dome and conduit (Gil Cruz and Chouet, 1997), or by magma-water interaction (Neuberg, 2000), whereas hybrid earthquakes may be triggered by shear fracture, stick-slip motion, or hydraulic fracturing (Goto, 1998; White et al., 1998; Neuberg, 2000; Uchida and Sakai, 2002). To date, no trigger model has drawn on the geologic evidence preserved at ancient, dissected conduits for processes that occur at shallow levels during magma ascent. We describe textures at a rhyolitic conduit in Iceland that point toward repeated shear fracture and welding of magma as a rechargeable trigger mechanism for hybrid earthquakes. Simple fracture-welding models and the nature of the fractures formed are used to argue that the process is consistent with the characteristics of hybrid earthquakes worldwide.

RHYOLITIC CONDUIT AT TORFAJÖKULL

Partial flank collapse of southeast Rauðufossafjöll, a ca. 60 ka subglacial rhyolite tuya at Torfajökull, Iceland, has exposed a 10-m-wide dike-like conduit (Fig. 1) 20–30 m beneath the subaerial peralkaline rhyolite lava flow that it fed (Tuffen, 2001; Tuffen et al., 2003). The 10^6 m^3 lava flow represented the final effusive phase of an initially explosive eruption. Multiple generations of angular, anastomosing tuffisite veins 1–60 mm wide and ranging from tens of centimeters to >1 m in length cut the vesicle-free, microlite-free, dark gray obsidian of the conduit margins (Fig. 1D). Veins are filled by densely welded pale gray clastic material (fragments of magma and broken phenocrysts); the clasts are mostly 10–200 μm across (Fig. 2A), and they are disposed in complex sedimentary structures, including planar bedding and cross-bedding (Fig. 2B). Clasts are of varying grain size and sorting and make up commonly folded and deformed beds ranging from <0.1 mm to 10 mm in thickness. Beds containing the finest-grained material are locally adjacent to vein walls (Fig. 2B). Viscous deformation of juvenile clasts, with shear strain between 1 and 10, has removed all pore space in the vein-filling material (Fig. 2A). It has led to a pervasive foliation (eutaxitic texture), which overprints bedding orientations and is commonly crenulated. Locally, vein walls are cut by microfractures and are adjacent to trains of smaller particles that they appear to have shed (Fig. 2C).

Earlier veins have undergone viscous deformation parallel to the magma flow direction and appear as elongate, often crenulated mid-gray bands that are progressively rotated toward vertical with increasing strain (Fig. 2D). They are locally cut by less-deformed veins. Axial strain is typically 2–10 in deformed veins and generally increases toward the center of the conduit. Relict bedding is distinguishable in less-deformed veins, whereas the most-deformed veins appear as bands of subtly paler color than the surrounding obsidian.

INTERPRETATION OF TEXTURES

The tuffisite veins are interpreted as shear fractures formed by the non-Newtonian response of highly viscous magma to flow-related strain in the conduit (Goto, 1998). The fine-grained material produced during shear on fracture planes (Fig. 2C; Sparks et al., 2000; Schwarzkopf et al., 2002) was redeposited by flow of a gas-particle mixture through the fracture system (Heiken et al., 1988; Stasiuk et al., 1996). The gas phase was probably derived from vesicular magma rising in the conduit center (Heiken et al., 1988; Stasiuk et al., 1996). Gas accumulation in the center may have increased strain rates and shear stress in the conduit margins, leading to fracture (Uchida and Sakai, 2002).

Ductile deformation of veins indicates that magma underwent solid-like and fluid-like deformation on different time scales (Dingwell, 1996; Sparks, 1997; Marti et al., 1999). Welding of vein-filling material allowed such thorough healing that magma regained mechanical isotropy, and later fractures cut earlier ones. This process contrasts with cataclasite shear zones on surfaces of spines at the Montserrat lava dome, which never completely heal (Sparks et al., 2000). The magma at Torfajökull could heal more efficiently because of its lower crystallinity (<15% as opposed to >90% at Montserrat). Progressive deformation and rotation of earlier veins during magma flow have created flow bands of distinctive glass color and crystal sizes. Such bands are nearly ubiquitous in obsidian (e.g., Smith, 2002; Rust et al., 2003).

Together, the textures are thought to record repeated fracture and healing of rising magma (RFH process).

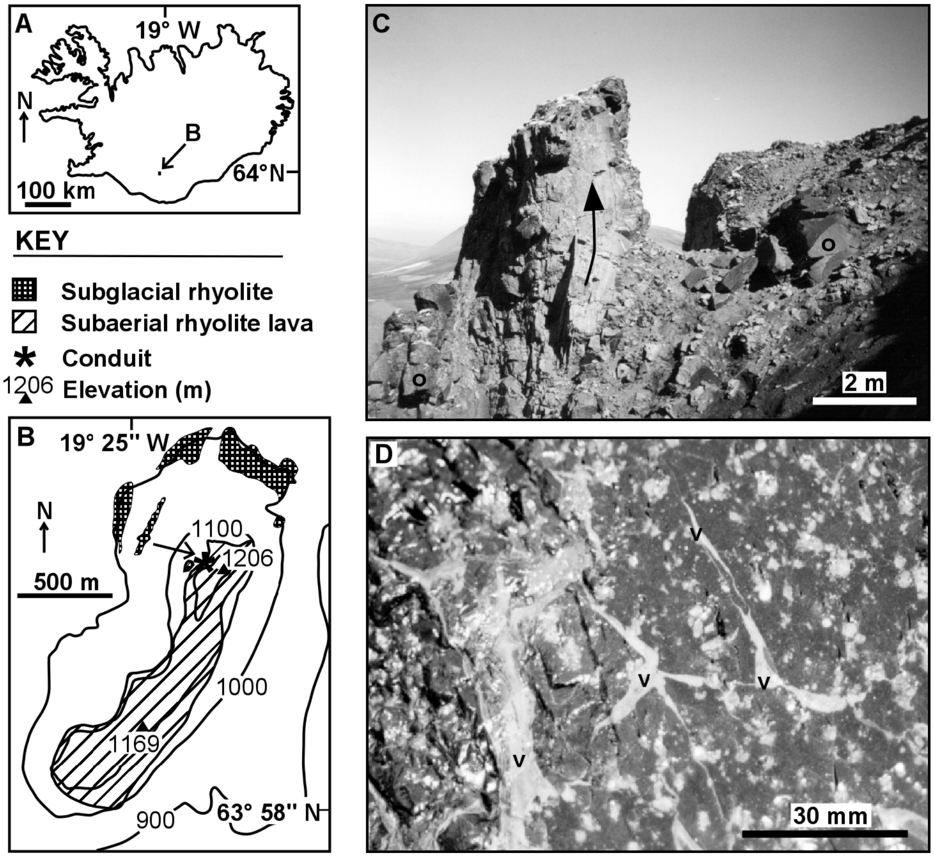

Figure 1. Location and photographs of conduit. A: Location of southeast Rauðufossafjöll in south-central Iceland. B: Geologic map of southeast Rauðufossafjöll, simplified from Tuffen et al. (2003), showing location of conduit. C: Overview of conduit, showing dark gray obsidian walls (o) and near-vertical flow banding in devitrified interior (arrow). D: Network of angular, branching, pale gray tuffisite veins (v) in conduit-wall obsidian. Pale blobs are feldspar phenocrysts.

VEIN FORMATION AS A TRIGGER FOR HYBRID EARTHQUAKES?

We propose that the RFH process is a trigger mechanism for hybrid earthquakes and support the proposal with the following lines of evidence: (1) Veins record repeated fracture of a small body of magma (RFH process) and thus point to a rechargeable trigger mechanism (Neuberg, 2000). (2) Sedimentary structures in veins record flow of a gas-ash mixture through a crack, a process that may generate seismic signals (Chouet, 1988, 1996). (3) The dimensions of tuffisite veins described here are similar to the ''precursor crack'' inferred to have been excited during long-period seismicity at Galeras (Gil Cruz and Chouet, 1997). Since there is little difference in the frequency content of hybrid and long-period events (Lahr et al., 1994), fractures associated with hybrid events are likely to have similar dimensions. (4) The grain size of vein-filling material (10–200 μm) is compatible with estimates of particle size from fluid-driven crack models (Kumagai and Chouet, 1997). (5) Fracture events are likely to generate earthquakes of a magnitude similar to that of recorded hybrid and long-period events. The seismic moment M_o associated with tuffisite vein formation is calculated to be $10^{8.5}$ N·m on the basis of the equation $M_o = DGA$ (Shearer, 1999) and reasonable estimates of mean displacement D (~10 mm), shear modulus G (~10^{10} Pa), and fault area A (~3 m^2). This seismic moment equates to a moment magnitude of roughly −1, similar to hybrid and long-period events at Satsuma-Iojima, Galeras, and Unzen (Umakoshi et al., 1993; Gil Cruz and Chouet, 1997; Uchida and Sakai, 2002).

However, it is necessary to determine whether the time scale of the RFH process is also consistent with observed repeat times of hybrid and long-period earthquakes during eruptions.

TIME SCALE OF RFH PROCESS

Strain Rate–Induced Fracture of Viscoelastic Magma

Our model of the RFH process involves (1) shear-stress accumulation during viscoelastic deformation, (2) stress release by brittle fracture, and (3) subsequent healing and relaxation of magma, allowing stress reaccumulation and a repeat of the process. In order to estimate the cycle time between successive fracture events (Gomberg, 2001), we first estimate the time taken for accumulating stress to cause fracture.

Unrelaxed magma deformation, which allows accumulation of shear stresses during flow, occurs when the product of strain rate and shear viscosity exceeds 10^7 Pa (Webb and Dingwell, 1990). Linear viscoelastic deformation, which occurs when strain rate times viscosity is 10^7 to 10^{10} Pa (Webb and Dingwell, 1990), obeys Maxwell's equation (Maxwell, 1867):

$$\sigma_s + \frac{\eta_s}{G}\frac{\partial \sigma_s}{\partial t} = \dot{\varepsilon}\eta_s, \qquad (1)$$

where σ_s is shear stress, η_s is shear viscosity, G is shear modulus (~10^{10} Pa; Webb and Dingwell, 1990), t is time, and $\dot{\varepsilon}$ is shear-strain rate. If we apply the initial condition that $\sigma_s = 0$ at $t = 0$ and we assume a constant strain rate, solving equation 1 to give shear stress as a function of time yields

$$\sigma_{st} = \dot{\varepsilon}\eta_s(1 - e^{-tG/\eta_s}). \qquad (2)$$

Fracture will occur if shear stress exceeds shear strength τ_s, at time t_f given by

$$t_f = -\frac{\eta_s}{G}\ln(1 - \tau_s/\dot{\varepsilon}\eta_s), \qquad (3)$$

obtained by rearranging equation 2. Analysis of equations 2 and 3 shows that fracture will only occur if $\dot{\varepsilon}\eta_s > \tau_s$, which demonstrates that fracture is not an inevitable consequence of non-Newtonian deformation—an assumption implicit in existing models of strain-induced fracture (Goto, 1998; Papale, 1999). However, because $\dot{\varepsilon}\eta_s$ must exceed 10^7 Pa for viscoelastic deformation to occur and because the shear strength of natural magma is typically 10^6 to 10^7 Pa (Romano et al., 1996; Voight et al., 1999), fracture is likely to accompany viscoelasticity. Magma strengths of 10^6 and 10^7 Pa are considered in this paper.

Next we estimate the strain rate in conduits during effusive silicic eruptions. The highest strain rate during Newtonian flow of uniformly viscous magma in a cylindrical conduit occurs at the walls and is given by $4Q/\pi r^3$, where Q is magma flux (in $m^3 \cdot s^{-1}$) and r is conduit radius (in m) (Goto, 1998). This is only a rough approximation of true strain-rate maxima, because cooling and degassing will create a viscosity gradient (Wylie et al., 1999) and flow will become non-Newtonian. Vesicle morphologies in conduit wall–derived obsidian from the Rock Mesa pyroclastic deposit, Oregon, indicate a strain rate of 10^{-2} s^{-1} (Rust et al., 2003). By comparison, values of magma-discharge rate and conduit diameter from recent dome-building eruptions at Montserrat (Voight et al., 1999), Unzen (Goto, 1998), and Merapi (Hammer et al., 2000) provide Newtonian strain-rate maxima between $10^{-2.5}$ and 10^{-6} s^{-1}. Thus, a plausible range of strain rates is 10^{-2} to 10^{-6} s^{-1}.

Healing of Fractures by Welding

Welding in tuffisite veins is likely to be far more rapid than welding in pyroclastic flow deposits (e.g., Sparks et al., 1999), because the welded material undergoes negligible cooling and is isolated from insoluble atmospheric gases. Welding involves a diffusion-related process (sintering), in which cohesion between surfaces of adjacent particles is established (Sparks et al., 1999; Gottsmann and Dingwell, 2002), and viscous deformation, in which pore space between imperfectly packed particles is removed (Sparks et al., 1999). The rate of the diffusion-related process t_d may be roughly approximated by the relaxation time (Gottsmann and Dingwell, 2001), hence $t_d = \eta_s/G$. Tuffisite textures indicate that viscous strain of ~1 in the glass particles was sufficient to remove porosity (Fig. 1D). The time scale for viscous deformation, t_v, is therefore given by $1/\dot{\varepsilon}$, the time for a shear strain of 1.

The total time T_t for each RFH cycle is the sum of the fracture time and the welding time, $T_t = t_f + t_d + t_v$, and is shown in Figure 3 as a function of magma viscosity.

Total Cycle Time and Magma Viscosity

Assuming that each fracture event during the RFH process triggers a seismic signal, and only one fracture forms at a time, the repeat time of seismic signals is equal to T_t. At the reasonable values of strain rate and magma strength already given, T_t is similar to the repeat times of recorded hybrid and long-period events when magma viscosity is in the range 10^9–10^{14} Pa·s (Fig. 3). This corresponds well to the range of viscosities extant in supercooled liquid magma within the glass transition interval (Gottsmann et al., 2002). Experiments indicate that this viscosity range translates to a temperature range of 136 K in basalt and 211 K in pantellerite (Gottsmann et al., 2002). RFH behavior may only occur if magma reaches this temperature range without completely crystallizing, because welding requires a melt phase. The minimum cooling rate necessary to avoid crystallization depends upon magma composition and is indicated by the slowest cooling rates measured by relaxation geospeedometry on natural glassy samples. Basalt crystallizes rapidly and must be cooled at least 0.1 K/s (Wilding et al., 2000), whereas pantellerite crystallizes more slowly and may be cooled as slowly as 10^{-5} K/s (Gottsmann and Dingwell, 2002). At these cooling rates, basalt could dwell only 10^3 s in the viscosity range 10^9–10^{14} Pa·s, insufficient for multiple cycles, whereas the corresponding time for pantellerite, 10^7 s, permits many cycles of fracture and welding. RFH behavior may thus be a characteristic feature of silicic magma compositions only.

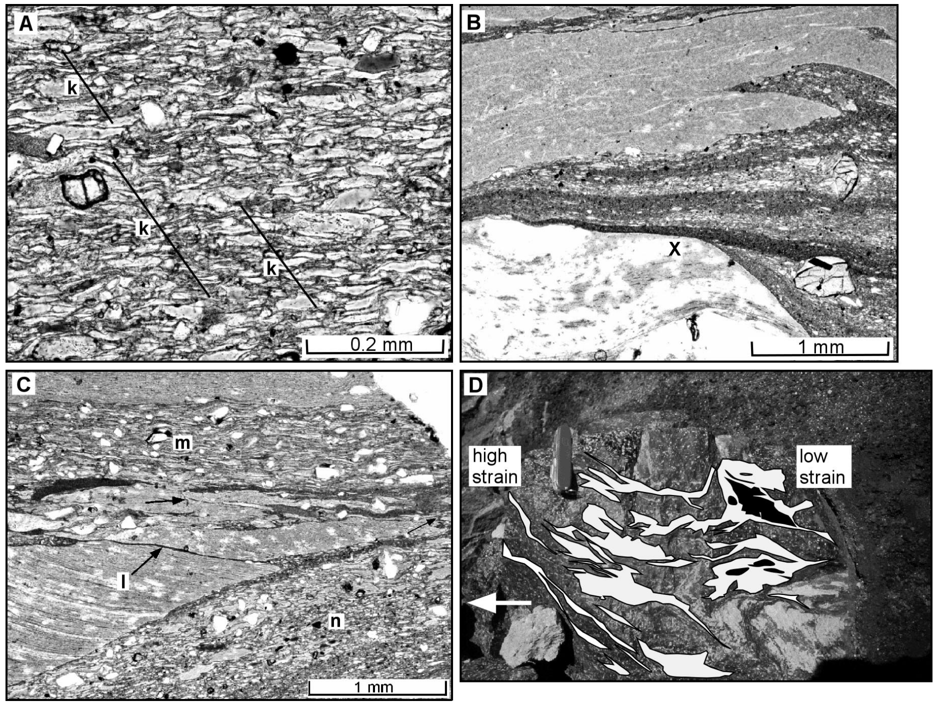

Figure 2. Textures in tuffisite veins. A: Photomicrograph of eutaxitic texture in densely welded tuffisite. Shear strain of ~1 in pale gray glassy fragments has removed all pore space. Subtle kink bands (k) in foliation cross boundaries between adjacent fragments, indicating that cohesive deformation of welded material occurred (Marti et al., 1999), rather than cataclastic flow (Sparks et al., 2000). B: Photomicrograph of bedded tuffisite vein (center). Fine-grained bed (dark) is adjacent to vein wall (pale gray, bottom) at X. Presence of finest-grained material on fracture surfaces demonstrates that local clastic redeposition occurred. In situ cataclasis may also generate "bedding," but coarsest-grained material is likely to occur on fracture surfaces (Schwarzkopf et al., 2002). C: Photomicrograph of obsidian wall (l) between two vein branches (m, n), which is cut by small shear fractures (arrows). This process appears to have generated much of fragmental material during opening and deformation of veins. Note high strain in vein branch m and low strain in branch n in plane of thin section. D: Tuffisite veins are increasingly deformed and rotated toward center of conduit (arrow). Veins overdrawn for clarity; penknife is 7 cm long. Modified from Tuffen (2001).

In contrast with the conduit described here, significant microlite crystallization occurs at andesitic-dacitic lava domes such as Montserrat and Unzen and leads to increased viscosity and pressurization of magma (Sparks, 1997; Voight et al., 1999). It may also lead to RFH behavior, because (1) tuffisite veins occur at Montserrat and other domes (Sparks, 1997), (2) measured magma viscosities also fall within the 10^9–10^{14} Pa·s range (Goto, 1998; Voight et al., 1999; Sparks et al., 2000), and

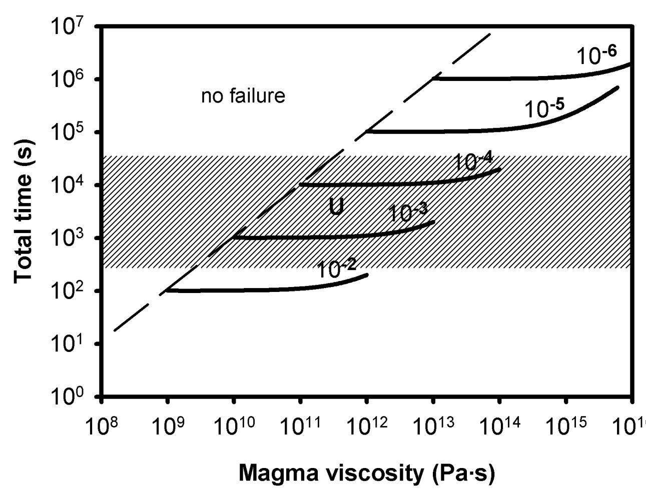

Figure 3. Calculated total time T_t for each RFH (repeated fracture and healing) cycle during conduit flow. Curves are for different strain rates, indicated in units of s^{-1}. No fracture occurs to left of dashed line. Shaded area indicates repeat time of hybrid and long-period earthquakes during recent silicic dome eruptions (Gil Cruz and Chouet, 1997; Voight et al., 1999). Magma viscosities of 10^9–10^{14} Pa·s give total times consistent with these observations. U indicates inferred viscosity and strain rate of magma undergoing shear fracture at Unzen (Goto, 1998).

(3) there is textural evidence for mixed ductile-brittle deformation within highly crystalline domes (Smith et al., 2001). Pressurization may provoke fracture by increasing strain rates, and magma far from the dome surface may retain sufficient melt to heal (cf. Sparks et al., 2000).

The RFH process may occur anywhere in the conduit where the magma viscosity and strain rate are sufficiently high. Regions of the conduit where heat flux through the walls is high (e.g., because of hydrothermal circulation) would be especially prone to fracture, as cooling would increase magma viscosity and form a constriction (Wylie et al., 1999), leading to increased strain rates.

CONCLUSIONS AND IMPLICATIONS

Tuffisite veins in a dissected rhyolitic conduit at Torfajökull, Iceland, are thought to record shallow, repeated fracture and healing of highly viscous magma. This process is attributed to non-Newtonian deformation of crystal-poor magma and is likely to be restricted to silicic compositions. Fracture events may generate seismic signals with similar magnitudes and repeat times to observed hybrid and long-period seismicity.

We emphasize the similarity between the deformed tuffisite veins described here and bands of discrete glass color and microlite content in obsidian. Trails of broken lithic fragments have been observed elsewhere parallel to similar flow banding in conduit-wall obsidian (Rust et al., 2003) and suggest that that particulate material may be incorporated into short-lived fractures in melt prior to such thorough welding that the melt phase is seemingly intact. A possible conclusion is that flow bands are textural records of earthquakes within silicic magma.

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