Nonlinear effects of hydration on high-pressure sound velocities of rhyolitic glasses

JESSE T. GU1†, SUYU FU1, JAMES E. GARDNER1, SHIGERU YAMASHITA2, TAKUO OKUCHI2‡, AND JUNG-FU LIN1,*

1Department of Geological Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas 78712, U.S.A.
2Institute for Planetary Materials, Okayama University, Misasa, Tottori 682-0193, Japan

ABSTRACT

Acoustic compressional and shear wave velocities ($V_p$, $V_s$) of anhydrous (AHRG) and hydrous rhyolitic glasses (HRG) containing 3.28 wt% (HRG-3) and 5.90 wt% (HRG-6) total water concentration ($H_2O$) have been measured using Brillouin light scattering (BLS) spectroscopy up to 3 GPa in a diamond-anvil cell at ambient temperature. In addition, Fourier-transform infrared (FTIR) spectroscopy was used to measure the speciation of $H_2O$ in the glasses up to 3 GPa. At ambient pressure, HRG-3 contains 1.58 (6) wt% hydroxyl groups (OH) and 1.70 (7) wt% molecular water ($H_2O_m$) while HRG-6 contains 1.67 (10) wt% OH and 4.23 (17) wt% $H_2O_m$ where the numbers in parentheses are ±1σ. With increasing pressure, very little $H_2O_m$, if any, converts to OH$^-$ within uncertainties in hydrous rhyolitic glasses such that HRG-6 contains much more $H_2O_m$ than HRG-3 at all experimental pressures. We observe a nonlinear relationship between high-pressure sound velocities and $H_2O_m$, which is attributed to the distinct effects of each water species on acoustic velocities and elastic moduli of hydrous glasses. Near ambient pressure, depolymerization due to OH$^-$ reduces $V_p$ and $G$ more than $V_s$ and $K_S$, $V_p$ and $K_S$ in both anhydrous and hydrous glasses decrease with increasing pressure up to ~1–2 GPa before increasing with pressure. Above ~1–2 GPa, $V_p$ and $K_S$ in both hydrous glasses converge with those in AHRG. In particular, $V_p$ in HRG-6 crosses over and becomes higher than $V_p$ in AHRG. HRG-6 displays lower $V_S$ and $G$ than HRG-3 near ambient pressure, but $V_S$ and $G$ in these glasses converge above ~2 GPa. Our results show that hydrous rhyolitic glasses with ~2–4 wt% $H_2O_m$ can be as incompressible as their anhydrous counterpart above ~1.5 GPa. The nonlinear effects of hydration on high-pressure acoustic velocities and elastic moduli of rhyolitic glasses observed here may provide some insight into the behavior of hydrous silicate melts in felsic magma chambers at depth.

Keywords: Hydrous glass, sound velocity, elasticity, water, rhyolite, Brillouin light scattering spectroscopy, FTIR spectroscopy, high pressure, diamond-anvil cell

INTRODUCTION

Igneous activity at Earth’s surface significantly affects society and also shapes the physical and chemical properties of the crust (Carn et al. 2009). The role of “water” in igneous processes is a topic of great interest due to the widespread occurrence of $H_2O$ in Earth’s crust and mantle (Mysen and Richet 2005). $H_2O$ is present in magmas and quenched silicate glasses as both molecular water ($H_2O_m$) and hydroxyl groups (OH$^-$), where OH$^-$ depolymerizes the silicate network (Stolper 1982a, 1982b). Even at low concentrations, incorporation of these $H_2O$ species has been shown to significantly alter the physical properties of glasses and melts, such as acoustic velocities and elastic moduli (Malfait et al. 2011; Whittington et al. 2012), melting temperature (Kushiro et al. 1968; Grove et al. 2012), density (Richet and Polian 1998; Ochs and Lange 1999; Richet et al. 2000), viscosity (Hess and Dingwell 1996; Richet et al. 1996; Whittington et al. 2000; Hui and Zhang 2007), chemical diffusivities (Behrens and Zhang 2001), and electrical conductivity (Ni et al. 2011; Guo et al. 2016). These effects are manifested in explosive volcanic eruptions, some of the largest of which involve felsic magmas. The intensity of volcanic eruptions is largely governed by the viscosity of constituent magmas and, correspondingly, the degree to which the magmas are polymerized or depolymerized due to the presence of water species. While $H_2O$ incorporated in silicate melts as OH$^-$ depolymerizes the silicate network and decreases the viscosity of respective melts, it still plays an important role in explosive eruptions (Shaw 1963). $H_2O$ solubility decreases during magma ascent and results in the exsolution of species into molecular $H_2O$ vapor, which expands rapidly at magmatic temperatures (Moore et al. 1995). This process, in combination with the inherently high viscosity of anhydrous felsic magmas, causes the explosiveness of felsic, $H_2O$-rich magmas (Shaw 1972).

Felsic eruptions can occur when differentiation of partially melted lower crustal materials produce melts with high silica contents (Borg and Clyne 1998). These melts have been reported to contain as much as ~6–8 wt% $H_2O$, at ~200–400 MPa and ~400–600 °C (Lowenstern 1994; Wallace et al. 1999; Wallace 2005). Some of the largest felsic eruptions are supervolcanic eruptions that formed the Long Valley and Yellowstone calde-