Journal of Volcanology and Geothermal Research xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Transport properties of glassy and molten lavas as a function of temperature and composition

Anne M. Hofmeister [a,*], Alexander Sehlke [b,e], Geoffroy Avard [b,c], Anthony J. Bollasina [b], Geneviève Robert [b,d], Alan G. Whittington [b]

[a] Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130, USA
[b] Department of Geological Sciences, University of Missouri, Columbia, MO 65211, USA
[c] OVSICORI-UNA, Heredia, Costa Rica
[d] Department of Geology, Bates College, Lewiston, ME 04240, USA
[e] Nasa Ames Research Center, Moffett Field, CA 94035, USA

ARTICLE INFO

Article history:
Received 14 March 2016
Received in revised form 5 July 2016
Accepted 19 August 2016
Available online xxxx

Keywords:
High-temperature
Thermal diffusivity
Viscosity
Heat capacity
Thermal conductivity
Lavas
Glass
Melt

ABSTRACT

We provide measurements of thermal diffusivity (D), heat capacity (C_P), and viscosity (η) for 12 remelted natural lavas and 4 synthetic glasses and melts, ranging in composition from leucogranite to low-silica basalt, and calculate their thermal conductivity. Both viscosity and the glass transition temperature decrease with decreasing melt polymerization. For basaltic glasses, D is low, ~0.5 $mm^2\ s^{-1}$ at room temperature, decreases slightly with increasing temperature, and then drops upon melting to ~0.25 to 0.35 $mm^2\ s^{-1}$. Other samples behave similarly. Despite scatter, clear correlations exist between D of glass or melt with Si content, density, NBO/T, and, most strongly, with fragility (m). Glass thermal diffusivity is represented by $D = FT^{-G} + HT$, where F, G and H are fitting parameters. For melts, $\partial D/\partial T$ was resolved only for dacite-andesite and MORB: a positive slope is consistent with other iron-bearing samples. Glass and liquid C_P depend on density and other physical properties, but not exactly in the same manner as D. We calculate thermal conductivity (k) from these data and demonstrate that k for glasses is described by a Maier-Kelly formula. Large scatter exists for k at 298 K, but silicic to intermediate melts have k between 1.8 and 1.3 $Wm^{-1}\ K^{-1}$, whereas basaltic melts are constrained to ~1.4 ± 0.1 $Wm^{-1}\ k^{-1}$. Low values for thermal diffusivity and viscosity for basaltic melts suggests that basalts transfer heat much more efficiently by advection than by conduction alone, and that partially molten zones in the mantle quickly become more thermally insulating than non-molten zones, potentially contributing to melt localization during decompression melting.

1. Introduction

Heat transport plays a crucial role in the thermal evolution of high-temperature, magmatic regimes (e.g., Nabelek et al., 2012). Conduction of heat is quantified by Fourier's law based on thermal conductivity (k). However, large uncertainties exist in k because conventional experimental techniques involving physical contacts are inaccurate for materials that bond poorly with metal contacts or are partially transparent, such as glasses and melts, especially at high temperatures (T) relevant to magmatic processes (e.g., Hofmeister et al., 2007). In contrast, thermal diffusivity (D) can be measured with a high degree of accuracy (~±2%) using laser-flash analysis (LFA: Parker et al., 1961). This method is contact-free and lacks systematic errors associated with conventional methods, such as thermal losses at interfaces of ~10% per contact (Hofmeister, 2007). Most importantly, removal of boundary-to-boundary radiative transfer gains (Degiovanni et al., 1994; Mehling et al., 1998), which can overwhelm intrinsic behavior at temperatures as low as 1000 K, makes the LFA technique optimal for measuring glasses and melts which are partially transparent in the near-IR. Measurements up to several hundred K above the glass transition (i.e., prior to flow or crystallization) are also possible using LFA, thereby providing information on the liquid state. Combining measurements of heat capacity at constant pressure (C_P), density (ρ), and D allows determination of k associated with vibrational modes from its definition:

$$k_{lat} = \rho C_P D. \quad (1)$$

For melts, heat can also be transported by advection. Mass transport depends on melt viscosity, which can be measured by various means (e.g. Dingwell, 1995), and provides information on the liquid state to high temperatures.

Our previous efforts using LFA focused on the dependence of thermal and mass transport properties on melt chemistry by studying magma analogs. We began with simple glass compositions corresponding to crustal minerals: quartz (SiO_2), alkali feldspar ($XAlSi_3O_8$ where

* Corresponding author.
E-mail address: Hofmeist@wustl.edu (A.M. Hofmeister).

http://dx.doi.org/10.1016/j.jvolgeores.2016.08.015
0377-0273/

X = Li, K, Na), anorthite ($CaAl_2Si_2O_8$), and clinopyroxene ($XYSi_2O_6$ where XY = CaMg or LiAl) (Pertermann et al., 2008; Hofmeister et al., 2009; Hofmeister and Whittington, 2012), and found that mass and heat transport properties are linked: felsic liquids have both high viscosity and high thermal diffusivity compared to mafic liquids. This correlation also holds for more complex melt compositions with high silica contents (71–80 wt% SiO_2), despite variable quantities of Al_2O_3, FeO, MgO, CaO, Na_2O, and K_2O (Hofmeister et al., 2014a). The latter measurements further indicate that Ca and Fe strongly affect transport properties. The effect of Fe on *D*, in the absence of Al, was probed by examining the enstatite-ferrosilite binary, which showed strong and positive $\partial D/\partial T$ at high temperature (Hofmeister et al., 2014b).

The present paper reports coordinated LFA, heat capacity, and viscosity measurements on synthetic and remelted natural lavas. Effects of oxidation state and minor crystallites are also probed. Our focus is on basaltic compositions, which are important due to their ubiquitous occurrence on Earth and other planetary bodies. We find that *D* depends roughly on density, NBO/T, and fragility, which in turn largely depend on Si content, although a predictive model for *k* remains elusive. Viscosity and *D* for basaltic melts are particularly low, implying that heat transfer by advection is relatively more efficient than conduction. Our new measurements pave the way for an improved understanding of magmatic processes.

2. Experimental methods

2.1. Synthesis procedures

Synthetic rhyodacite glass was prepared by weighing and mixing reagent grade oxides in the desired proportions with acetone in an iron-free platinum crucible. The mixture was decarbonated slowly during heating over many hours from 900 to 1100 °C prior to fusion in the same platinum crucible in a muffle furnace in air at 1600 °C for 60 min. The crucible was removed from the furnace and allowed to cool to room temperature, producing a clear crystal-free glass. If not, samples were reground and remelted until a homogeneous glass was obtained. Chemical homogeneity and absence of crystallites were ascertained by visual inspection with an optical microscope, and by electron microprobe analysis and scanning electron microscopy, see below. Synthetic andesite, basaltic andesite, and basalt were made in a similar way.

Likewise, twelve glasses were made by remelting the lavas described in Table 1. Crushed rock was placed in iron-saturated platinum or platinum-rhodium crucibles and remelted in a muffle furnace in air at 1600 °C for between 1 and 2 h, stirred, then quenched to form glasses either by dipping the bottom of the crucible in water, or by pouring on to a copper plate.

The as received sample of MORB had glassy rims sufficient in size to make measurements of thermal diffusivity. The small size of the rims, and rapid crystallization at high *T*, prohibited remelting and viscosity measurements.

2.2. Sample preparation

For parallel plate viscometry, cylindrical samples were cored from glass lumps using a diamond core drill, avoiding visible bubbles. The cylinders were cut to lengths of 5 to 10 mm using a diamond wafer saw, polished on successively finer grit papers, and parallel faces were verified using a micrometer. For LFA, sections were sawed and ground into disks of ~12 mm diameter with 0.2 to 1.1 mm thicknesses and nearly parallel surfaces, and sand-blasted with 50–150 μm alumina grit. For calorimetry, samples were cut into flat disks (4–5 mm in diameter) with uniform thickness, of ~600–1100 μm, and weights between 40 and 60 mg. For spectroscopic measurements, double-polished sections were prepared. Polished chips were used in electron microprobe analysis.

2.3. Chemical analyses

Samples were characterized by wavelength dispersive analysis (WDS) using standard procedures on the JXA-8200 electron microprobe at Washington University. We used "Probe for Windows" for data reduction (see http://www.probesoftware.com/). The measured data were corrected using CITZAF after Armstrong (1995). Oxide and silicate standards were used for calibration (e.g., Amelia albite for Na, Si; microcline for K; Gates wollastonite for Ca; Alaska Anorthite for Al; synthetic fayalite for Fe; synthetic forsterite for Mg; synthetic TiO_2 for Ti; synthetic Mn-olivine for Mn; synthetic Cr_2O_3 for Cr). Large beam size and measurement of Na at first during each analysis was used to avoid

Table 1
Sample descriptions.

Lava type	Abbrev.	Density[a] kg m^{-3}	Color[b]	Type and origin	Previous Sample No.	Reference
Leucogranite	Leuco	2338	Pale brown	Remelted Harney Peak, SD	Leuco	*D* Hofmeister et al. (2014a); η Whittington et al. (2009a)
Rhyolite	Rhyo	2333	Lt. brown	Remelted Mono Craters, CA	NCAR	*D* Romine et al. (2012); η Romine and Whittington (2015)
Rhyodacite	Rhyo-dac	2415	Colorless	Synthetic	SRD	–
Dacite	Dac	2632	Brown	Remelted Mt. St. Helens	SH305	–
Dacite-andesite	Dac-and	2630	Green	Remelted Santiaguito, Guatemala	SA05–14	–
Andesite	And	2459	Colorless	Synthetic	BD	–
Andesite-basalt	And-bas	2611	Colorless	Synthetic	SBA	η Robert et al. (2013)
Basalt-andesite	Bas-and	2655	Brown	Remelted Fuego, Guatemala	Fu18	–
Dolerite	Dolerite	2740	Brown	Remelted Chengwatana, WI[c]	Lab. Expt.	η Sehlke and Whittington (2016)
Basalt	Bas	2679	Colorless	Synthetic	SB	η at $T < 1000$ K Robert et al. (2015); $T > 1000$ K Robert (2014)
Arc basalt	Arc bas	2770	Black	Remelted Fuego, Guatemala	Fu06	η at $T < 1000$ K Robert et al. (2015); $T > 1000$ K Robert (2014)
Ocean island	OIB1	2822	Black	Remelted Mauna Kea quarry, HI	WU31–108	–
Ocean island	OIB2	2816	Black	Remelted Mauna Ulu, HI	MU-SQ-4	η Sehlke et al. (2014)
MORB	MORB	2783	Black	Glassy rim, East Pacific Rise[d]	14Nov04	–
Icelandic	P-MORB	2753	Black	Remelted lava tube roof, Iceland	LAKI	–
Continental basalt	Contl	2873	Black	Remelted Mt. Nyiragongo, DR. Congo[e]	NYI001	η Sehlke and Whittington (2016)

[a] At ~298 K. The last digit is uncertain, except for MORB for which three different pieces with varying water contents gave a range from 2765 to 2798 kg m^{-3}. Details on MORB will be presented elsewhere.
[b] From ~mm thick sections.
[c] Sample described by Lev et al. (2012). Successive remelts of a continental basalt incorporated silica sand: the composition provided here is for the material studied here.
[d] Collected in an Alvin dive by Mitch Schulte.
[e] Sample provided by Benoît Smets and Matthieu Kervyn.

Please cite this article as: Hofmeister, A.M., et al., Transport properties of glassy and molten lavas as a function of temperature and composition, J. Volcanol. Geotherm. Res. (2016), http://dx.doi.org/10.1016/j.jvolgeores.2016.08.015