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The viscosity of pāhoehoe lava: *in situ* syn-eruptive measurements from Kilauea, Hawaii

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Abstract

Viscosity is one of the most important physical properties controlling lava flow dynamics. Usually, viscosity is measured in the laboratory where key parameters can be controlled but can never reproduce the natural environment and original state of the lava in terms of crystal and bubble contents, dissolved volatiles, and oxygen fugacity. The most promising approach for quantifying the rheology of molten lava in its natural state is therefore to carry out direct field measurements by inserting a viscometer into the lava while it is flowing. Such *in-situ* syn-eruptive viscosity measurements are notoriously difficult to perform due to the lack of appropriate instrumentation and the difficulty of working on or near an active lava flow. In the field, rotational viscometer measurements are of particular value as they have the potential to measure the properties of the flow interior rather than an integration of the viscosity of the viscoelastic crust + flow interior. To our knowledge only one field rotational viscometer is available, but logistical constraints have meant that it has not been used for 20 years. Here, we describe new viscosity measurements made using the refurbished version of this custom-built rotational viscometer, as performed on active pāhoehoe lobes from the 61G lava flow of Kilauea's Pu'u 'Ō'ō eruption in 2016. We successfully measured a viscosity of ~ 380 Pa s at strain-rates between 1.6 and 5 s⁻¹ and at 1144 °C. Additionally, synchronous lava sampling allowed us to provide detailed textural and chemical characterization of quenched samples. Application of current physico-chemical models based on this characterization (16±4 vol.% crystals; 50±6 vol.% vesicles), gave viscosity estimates that were approximately compatible with the measured values, highlighting the sensitivity of model-based viscosity estimates on the effect of deformable bubbles. Our measurements also agree on the range of viscosities in comparison to previous field experiments on Hawaiian lavas. Conversely, direct comparison with sub-liquidus rheological laboratory measurements on natural lavas was unsuccessful because recreating field conditions (in particular volatile and bubble content) is so far inaccessible in the laboratory. Our work shows the value of field rotational viscometry fully-integrated with sample characterization to quantify three-phase lava viscosity. Finally, this work suggests the need for the development of a more versatile instrument capable of recording precise measurements at low torque and low strain rate, and with synchronous temperature measurements.

42 **1 Introduction**

43 Understanding and describing the complexity of lava flow behavior is a major challenge
44 and a long-term objective in modern volcanology. Modeling of lava flows leads to significant
45 improvements in hazard assessment, as well as contributions to our understanding of volcanic
46 activity and history on other planets. Rheology, which is directly linked to the intrinsic
47 chemical and physical properties of the magma (chemical composition, oxygen fugacity,
48 volatile content, temperature, and shape and size of bubbles and crystals) is a key influence on
49 the transport of magma from its source to the surface (e.g., Dingwell 1996). As lava flows,
50 cooling and degassing trigger crystal and bubble growth and interstitial melt differentiation,
51 driving constant evolution of the chemical and physical properties (e.g., Crisp et al. 1994;
52 Applegarth et al. 2013). This continuous transformation leads to variations in rheological
53 properties (viscosity, yield strength, strain-rate dependency) which directly impact the
54 dynamics of lava flow emplacement (e.g., Pinkerton and Norton 1995; Harris and Rowland
55 2001).

56 Several lava flow emplacement models exist in the literature (see Cordonnier et al. 2015
57 for comparison between the different models). Most of these models require parameterization
58 of the lava physical properties (such as viscosity) and of the eruption conditions (such as
59 eruption temperature or effusion rate), all of which are challenging to measure. Lava rheology
60 can be determined using various methods. Following the pioneering study of Nichols (1939),
61 lava rheological parameters can be estimated from flow velocity, underlying slope and
62 channel dimensions assuming Newtonian or Bingham rheology. The advantage of this
63 method is that channel velocity is a parameter that can be measured at any type of flow and
64 provides the flow-scale ‘bulk rheology’ (e.g., Moore 1987; James et al. 2007). However, this
65 method cannot quantify the heterogeneity of rheological properties within and across a flow.

66 Another approach is to perform laboratory measurements using re-melted natural samples
67 at super- and sub-liquidus conditions. Recent examples include Ishibashi (2009), Vona et al.
68 (2011), Vetere et al. (2013), Chevrel et al. (2015), Sehlke et al. (2014), and Kolzenburg et al.
69 (2016). These measurements are usually performed using a concentric cylinder apparatus, and
70 the full rheological curve may be constructed for a given crystallinity and temperature. Recent
71 experiments have explored the effect of cooling rate on crystallinity and the rheological
72 response of the lava (Kolzenburg et al. 2016, 2017). Laboratory measurements have the
73 advantage that they are made in an environment that allows key parameters to be controlled
74 and precise rheological measurements to be made. However, they are unable to replicate the
75 range of crystal and bubble contents, dissolved volatiles, and oxygen fugacity of natural lavas.

76 When laboratory experiments cannot be carried out, or when an active flow has not been
77 observed, a common practice is to estimate viscosity from a “petrologic” approach. This
78 involves applying empirical physico-chemical models based on previous laboratory
79 experiments to estimate viscosity from groundmass chemical composition and crystal content
80 (e.g., Pinkerton and Stevenson 1992). This approach is clearly the best long-term method of
81 providing rheological data for modeling volcanic processes because, being based on sample
82 texture characterization, it can be applicable to present, past or extraterrestrial deposits. The
83 petrologic approach may be applied to quenched samples from an active flow, where the
84 groundmass crystallization will evolve as a function of cooling through time and distance

85 from the vent (e.g., Crisp et al. 1994; Riker et al. 2009). The effect of bubbles (term used
86 when describing the molten lava) may also be taken into account from estimation of the
87 vesicle (term used when describing the rock) content, which may also vary down flow
88 (Robert et al. 2014). Another use of this method is to determine the viscosity from the
89 crystallization sequence as calculated at thermodynamic equilibrium (e.g., Harris and
90 Rowland 2001; Riker et al. 2009; Chevrel et al. 2013). However, care must be taken when
91 assuming thermodynamic equilibrium because lava flows are undercooled systems whose
92 properties (crystallization and hence rheology) are cooling-rate dependent (Kolzenburg et al.
93 2016). During flow, lava does not reach the crystal/melt equilibrium and this disequilibrium
94 leads to a delay in crystallization that must be accounted for when calculating lava viscosity
95 down flow.

96 Currently, the only way to determine the complex rheological behavior of lava in its
97 natural state is to measure it directly in the field by inserting a viscometer into the molten lava
98 while it is flowing. Such *in-situ* viscosity measurements are notoriously challenging to
99 perform due to the difficulty of approaching an active lava flow, and the lack of appropriate
100 instrumentation. A small number of viscosity measurements have been made using either
101 penetrometers (Einarsson 1949; Gauthier 1973; Panov et al. 1988; Pinkerton and Sparks
102 1978; Belousov and Belousova 2018) or rotational viscometers (Pinkerton et al. 1995;
103 Pinkerton 1994). Among these studies, measurements performed using simple lava
104 penetrometers (a metal rod pushed into the lava) produce results that are influenced by the
105 outer viscoelastic layer. Measurements start as soon as the sensor is inserted into the lava so
106 that the viscosity of the viscoelastic crust + flow interior is integrated. However, all rotational
107 viscometers, and the custom-build penetrometer used by Pinkerton and Sparks (1978), have
108 the potential to measure the properties of the flow interior because measurements start once
109 the isothermal interior is reached. The viscous core of large 'a'ā flows remains inaccessible for
110 field viscometry, due to the problems of penetrating the overlying breccia layer. Low
111 viscosity lava flows, such as pāhoehoe type and small channelized flows are the only targets
112 so far accessible by field viscometry.

113 To our knowledge, viscometers developed by the University of Lancaster in the 1980's
114 and 1990's (Pinkerton 1994; Pinkerton et al. 1995a,b) are the only portable rotational
115 viscometers to have been used *in situ* on active lava flows, with the last measurements
116 performed more than 20 years ago (Pinkerton 1994; Pinkerton et al. 1995b). Since then no
117 further work has been presented due to lack of suitable conditions and personnel (and funds)
118 dedicated to the project. Conversely, over the past decades, extensive laboratory
119 measurements on natural or analogue mixtures have greatly improved our understanding of
120 the chemical control of the melt phase on viscosity (Giordano et al. 2008), as well as the
121 rheology of two-phase mixture (Mader et al. 2013). As a result, although many physico-
122 chemical based models now exist to estimate the rheology of magmas and lavas, no field
123 measurements have been performed to test whether, and how, they can be applied to natural
124 lava flows. Additional field validation is therefore required to provide confidence in the
125 petrologic approach.

126 In this work, we restored the unique field rotational viscometer of Pinkerton et al.
127 (1995b) and performed viscosity measurements on pāhoehoe lobes at Kilauea, Hawaii. The
128 aims of this paper are to present this refurbished instrument and our new field measurements.

129 Our viscometry results are described in detail, and complemented by textural and chemical
 130 analyses performed on quenched samples, which we use to implement, and compare with, a
 131 petrologic approach.

132 **2 Methods**

133 **2.1 Viscometry**

134 *2.1.1 Description of the field viscometer*

135 We restored the rotational viscometer used by Pinkerton et al. (1995b) for field measurements
 136 (Fig. 1). This instrument consists of a 24-V DC variable speed Bosch drill that drives a vane,
 137 which is inserted into the lava. The vane geometry is unlike many laboratory instruments,
 138 where the immersed spindle is often a cylinder. Instead it was designed for field use to
 139 minimize disturbance of the fluid during immersion whilst minimizing slippage between the
 140 spindle and lava. The vane is attached to the rotating inner shaft which is protected with a
 141 fixed outer tube equipped by bearing assemblies (containing graphite rings to minimize
 142 friction). This helps to maintain alignment and low-friction rotation of the inner shaft (Fig.
 143 1a), which is driven by the drill via a 15:1 reduction gearbox, a torque limiter (2 Nm), and a
 144 torque and rotation rate sensor (TORQSENSE E300 Rayleigh Wave Transducer from Sensor
 145 Technology Ltd). The sensor is linked to a stand-alone E302 interface/readout connected to a
 146 laptop via USB, and is a different version to the one in Pinkerton et al. (1995b). In 2016, the
 147 torque sensor and transducer were calibrated by Sensor Technology and small adjustments in
 148 communication were made so that the computer simultaneously recorded the rotation rate and
 149 torque every 0.05 s through the software provided (TORQVIEW2). At rest, we recorded a
 150 sensor sensitivity of ± 0.02 Nm. When a rotation was applied with the instrument mounted
 151 with the vane in air, an oscillation of ± 0.05 Nm was recorded, although efforts were made to
 152 reduce this by improving the alignment of the rotating rod between the motor and the vane.
 153 New shear vanes were made using the same type of high temperature-resistant stainless steel
 154 (BS 321 S20 or Z6CNT18.10) as used for the inner shaft and outer tube. Two vane sizes were
 155 employed, both composed of four paddles (2 mm thick) welded at 90° onto a 1 cm diameter
 156 rod, so that the vane diameter across the fins is 40 mm for the 60 mm-long vane (hereafter
 157 S60/20), and 50 mm for the 80 mm-long vane (hereafter S80/25). The total length of the
 158 assembled apparatus is 2.7 m, has a weight of about 15 kg, and can be dismantled into four
 159 pieces for transport.

160 *2.1.2 Data processing to extract viscosity*

161 The theory employed is that of wide-gap concentric cylinder viscometry. Here, the torque is
 162 converted into shear stress and rotational speed into strain-rate using the spindle geometry via
 163 the Couette theory for Newtonian or non-Newtonian fluids (Spera et al. 1988; Pinkerton and
 164 Norton 1995; Stein and Spera 1998; Vona et al. 2011). Material trapped between the paddles
 165 will move as the spindle rotates and therefore a virtual cylinder of sample material is used for
 166 the calculation. The shear stress is calculated via:

$$\tau = \frac{M}{2\pi h R_i^2} \quad (1)$$

167 where M is the torque recorded by the torque sensor, h is vane length and R_i is the equivalent
 168 radius of the rotating vane. Strain rate is obtained from the applied angular velocity via (Stein
 169 and Spera 1998):

$$\dot{\gamma} = \frac{2\Omega}{n \left(1 - \left(\frac{R_i}{R_o}\right)^{2/n}\right)} \quad (2)$$

170 where Ω is angular velocity (in rad/s), n is the flow index, and R_o is the radius of the outer
 171 cylinder. In the case of field measurements, the vane is effectively immersed into an
 172 unconstrained medium (i.e., R_o approaches infinity). Now, following Barnes (1989; see
 173 supplement), the calculation of strain rate (for a range of 0.1 to 10 s⁻¹) can be reduced to:

$$\dot{\gamma} = \frac{2\Omega}{n} \quad (3)$$

174 When several angular speeds are applied, n is usually obtained by calculating the slope of the
 175 measured $\ln(\tau)$ vs. $\ln(\Omega)$ relation. The flow curves (i.e., the graph of strain rate versus shear
 176 stress) can then be established to determine the fluid's rheological model. This is Newtonian
 177 when viscosity is proportional to strain rate ($n = 1$):

$$\eta = \frac{\tau}{\dot{\gamma}} \quad (4)$$

178 or non-Newtonian when viscosity varies with strain rate ($n \neq 1$) as, for example, in a power
 179 law model:

$$\tau = K\dot{\gamma}^n \quad (5)$$

180 Here K is the flow consistency, which corresponds to viscosity at unit strain rate.

181 In practice, when measuring rheology, if one or only a few angular velocities are applied, the
 182 full flow curve cannot be reliably established so that n cannot be accurately determined. A
 183 common practice is therefore to calculate the apparent viscosity that is equivalent to the
 184 Newtonian viscosity. This can be determined at each applied strain rate by assuming $n = 1$.

185 **2.1.3 Testing the field viscometer in the laboratory**

186 The instrument was tested in the laboratory using the viscosity reference standard N190000
 187 from Cannon Instrument Company®. This has been certified to be 33.06, 143.8, 523.3 and
 188 843 Pa s at 60, 40, 25 and 20 °C, respectively. These certified values were used to define the
 189 exponential relationship: $\eta = 3990.7e^{-0.081T}$ ($R^2=0.99$), allowing us to estimate the viscosity of
 190 the N190000 standard at experimental temperatures. To perform the measurements, 1.5 liters
 191 of N190000 viscosity standard were poured into a plastic container, which was 12 cm in
 192 diameter and 15 cm deep. Before each experiment, the fluid was placed overnight in an oven
 193 at the desired temperature to allow equilibration and removal of all air bubbles. Prior to each
 194 calibration, the container was removed from the oven and the temperature of the fluid
 195 measured using a K-type thermocouple located in the liquid beside the vane. Temperatures
 196 across the container varied by less than 2 °C and were constant near the vane during the
 197 experiment, with a maximum variation of ± 0.6 °C. The instrument was oriented at an angle of
 198 45° and the container was inclined so that the vane was fully immersed into the liquid. Both
 199 vanes were tested at several temperatures between 20 and 40 °C and over rotation speeds of 2

200 to 20 rpm, resulting in strain rates adjacent to the vane of 0.6 to 5 s^{-1} (calculated using Eq. 2).
201 Higher strain rates were not applied because of shear thinning effects that will bias the
202 measurements (Cannon Instrument Company, personal communication, October 2016). The
203 average torque was obtained over 8 to 60 s of stable reading at different strain rates at each
204 temperature (Fig. 2 and supplement). The $\ln(\tau)$ vs. $\ln(\Omega)$ trends (Fig. 2b) had slopes of $n =$
205 1 ± 0.09 as expected for Newtonian behavior of the N190000 viscosity standard. Apparent
206 deviation from Newtonian behavior was observed when torque was less than 0.1 Nm
207 (equivalent to stresses of 318 and 663 Pa for vanes S80/25 and S60/20, respectively). This is
208 attributed to limits in the torque transducer capability at low torque values, and therefore only
209 higher torque measurements were considered. Viscosity was then calculated following wide
210 gap theory (Eqs. 1, 2 and 4) for Newtonian behavior. Less than 5 % of error and less than 50
211 Pa s of deviation from the standard values was found (Fig. 2c).

212 **2.1.4 Operating the field viscometer in the field**

213 To perform a measurement in the field, two people held the instrument. The operator closest
214 to the lava inserted the vane into the active lobe and held it in position in the middle of the
215 fluid core taking care not to ground the vane. The second person controlled the drill speed and
216 monitored the data being collected on the computer. When the targeted lava lobe was
217 surrounded by other hot surfaces, the computer would be monitored by a third person located
218 a couple of meters away in cold air and who would direct operations. At the same time,
219 temperature measurements were made with a K-type thermocouple (Fig. 1b). This was done
220 only for the first measurement because, after this, the third person was needed to perform
221 other measurements. Before insertion, the vane was pre-heated by being placed close to the
222 lobe surface and exposed to the radiant heat. However, this pre-heating procedure did not last
223 more than few seconds and could not always be performed because the active lobe cooled too
224 rapidly so that an impenetrable outer crust formed, or because operators could not handle the
225 radiant heat themselves. The instrument was then rapidly inserted into the hottest and most
226 fluid part of the active lobe and the measurement started. As the lava advanced and its surface
227 began to solidify, the instrument was slowly pulled backwards by the operator. Each
228 measurement lasted less than one minute, mainly due to lava cooling around the rod to
229 prevent rotation. Radiant heat was also a limiting factor for the operators, despite the use of
230 heat protective suits and hoods (Fig. 1). Although we aimed to reach a stable reading over 20
231 s (as in the laboratory), it was not always possible because the surface cooled too quickly and
232 imprisoned the spindle. To record a range of strain rates, the angular velocity was manually
233 increased (“up path”) and then decreased (“down path”) by changing the drill speed.
234 However, practicalities meant that it was not always possible to cover the full up and down
235 path ranges. To estimate the apparent viscosity, the torque recorded during constant drill
236 speed over at least 3 to 23 s was then averaged and the standard deviation from the mean used
237 for error bars (see example in Fig. 3a and raw data in supplement).

238 **2.2 Lava sampling and textural analyses**

239 Samples were collected after each viscosity measurement by quenching the lava attached to
240 the vane in a water bucket. Another set of samples was collected using a stainless steel tube
241 inserted into an active pāhoehoe lobe. The tube was inserted into the lobe front and withdrawn

242 from the lava before quenching with water, effectively coring the tube. Additionally, one
243 control sample was collected from a pāhoehoe lobe emplaced a few weeks earlier. Bulk rock
244 major element analysis of one sample was carried out with Inductively Coupled Plasma –
245 Atomic Emission Spectroscopy at the Laboratoire Magmas et Volcans (LMV, Université
246 Clermont-Auvergne, France). Thin sections were made from all samples, and textural and
247 chemical analyses were carried out at LMV. Olivine and glass chemical compositions were
248 obtained from around 10-20 analyses for each thin section via the electron microprobe
249 (CAMECA SX 100), operating at 15 kV and with a focused beam of 15 nA for olivine and a
250 20 µm defocused beam of 8 nA for glass. Total water content was determined from double
251 polished samples by Fourier Transform Infrared Spectroscopy, using a Bruker Vertex 70
252 spectrometer coupled with a Hyperion microscope system, following the methods given in
253 Mercier et al. (2010, see supplement). Crystallinity, vesicularity and vesicle size distribution
254 were estimated from analyses of the thin sections through FOAMS following the methods
255 described in Shea et al. (2010). For each thin section, high magnification images were
256 acquired with scanning electron microscopy (SEM) in BSE (backscattered electron imaging
257 mode) at ×25 magnification (six images in total), and ×100 (fifteen images in total). The
258 smallest object measured was 10 pixels across (equivalent to 0.012 mm).

259 A mean value (averaged from two to four measurements) for the vesicle-free rock
260 density (DRE density) was determined by powdering the rock and measuring the volumes of
261 known masses using an Accupyc 1340 Helium Pycnometer. The bulk density of the samples
262 was measured using a pycnometer (Micromeritics Geopyc 1360 envelope density analyzer).
263 This instrument calculates the envelope density of the sample, which is the mass divided by
264 its encompassing volume, where the encompassing volume includes pores and small cavities.
265 The measurement technique consists of measuring the difference in the volume of a quasi-
266 fluid medium (DryFlo™, composed of tiny, rigid spheres) with and without the sample
267 embedded in the medium. Prior to immersion samples were wrapped with parafilm® to
268 preserve external irregularities but to avoid the medium entering the porous sample. The
269 density-derived vesicularity was then calculated using the relationship given by Houghton and
270 Wilson (1989).

271 **3 Results**

272 The targeted lava flow was the 61 G flow of Kilauea's Pu'u 'Ō'ō eruption (Hawaii) which
273 had been active since May 2016. At the time of the field campaign, the lava was mainly
274 flowing in tubes from the vent down to the ocean entry, but on November 23, 2016, we were
275 able to deploy the instrument on several pāhoehoe lobes at N19.349537, W155.048793.
276 These had broken out from the tube 7.2 km from the vent overnight. The lava flow field
277 consisted exclusively of S-type pāhoehoe lava with a bubble-rich silvery surface. Each
278 observed lobe was 10 to 30 cm thick upon emplacement and was active for about three to five
279 minutes before stalling, inflating and erupting another lobe from its base. Core temperature
280 was measured at 1144 °C with a K-Type thermocouple inserted to 5 to 8 cm into the lobe
281 (Fig. 1b).

282 **3.1 Viscometry**

283 Viscosity measurements were successfully performed on seven distinct lobes. For each
284 run, between one and four strain rates associated with stable torque readings could be
285 collected before the spindle stopped rotating due to lobe cooling (the example of run 12 is
286 given in Fig. 3a) or due to operator discomfort because of having to stand on an active surface
287 or strong radiative heat. For four runs (R2, R9, R10, R11), data could also be collected during
288 the down path but showed a marked hysteresis when compared with the up path, resulting in a
289 higher apparent viscosity (see supplement). A similar viscosity increase was also recorded for
290 some measurements within the up path phase (for example R2, R8, R9), which could be
291 interpreted as representing shear thickening. However, shear thickening has not been
292 observed in previous lava rheology measurements, so the effect is more likely to be due to
293 rapid cooling of the lobe, or to the accumulation of cooled lava around the vane. Both would
294 have significantly increased the effective diameter of the spindle. Considering data that were
295 not affected by this phenomenon, rotation velocities ranged from 7.6 to 23.8 rpm,
296 corresponding to strain rates between 1.6 and 5 s⁻¹ at the vane. Torque was recorded between
297 0.11 and 0.55 N m, reflecting shear stresses of between 755 and 2132 Pa (Table 1). The
298 apparent viscosity at each strain rate was determined to be between 261 and 483 Pa s.
299 Unfortunately, the limited number of measurements possible at each lobe did not allow us to
300 construct the full rheological flow curve with confidence. We also note that no yield strength
301 was measured. Gathering all runs into a single plot (Fig. 3b) shows that the lava had a
302 Newtonian viscosity (Eq. 4) of 379 Pa s (R²=0.83). Treating the data as a power-law rheology
303 (Eq. 5) gave a flow index of 0.88 and a consistency of 424 Pa s (R² = 0.79).

304 **3.2 Sample chemical analyses and textural characterization**

305 Bulk rock analysis revealed 50.8 wt. % SiO₂ and a Mg# of 0.38 (Table 2), with a DRE density
306 of 2847 kg m⁻³. The interstitial glass chemical composition was identical and homogenous in
307 all samples and slightly more evolved than the bulk rock, with a water content of 0.077±0.015
308 wt.% (Table 2). All samples had a porphyritic texture containing phenocrysts mainly of
309 olivine and rarely of plagioclase, along with microlites (<0.1 mm) of olivine and plagioclase,
310 as well as minor pyroxenes and minor oxides (usually as inclusions in olivine phenocrysts).
311 These were embedded within a glassy matrix (Fig. 4). Olivine crystals had euhedral and sub-
312 euhedral shapes and in some samples (CN, C1a and R9), they were organized in
313 glomerocrysts with plagioclase (Fig. 4c). Plagioclase occurs mostly as microlites (in some
314 samples all plagioclase were as microlites) and pyroxene was the least abundant phase and
315 occurred only as microlites. The aspect ratio (length vs. width) of the mafic minerals was 1.8
316 and 3.1 for plagioclase. The vesicle-free crystal fraction (phenocrysts + microlites) varied
317 from 0.12 to 0.21 (Table 3). Overall, the similarity in crystal shape and content between the
318 control sample and the quenched samples indicated that our sampling technique did not affect
319 the texture of the lava. Therefore, the quenched samples could be used to estimate the effect
320 of crystals on viscosity.

321 In terms of vesicularity, the quenched samples showed some differences with the control
322 sample. The control sample had a bulk density of 1441 kg m⁻³, which lead to a density-derived
323 vesicularity of 0.49. Image analysis of the control sample revealed a 2D vesicularity of 0.52
324 (Table 3). In contrast, quenched samples had lower densities (averaged at 1161±171 kg m⁻³)

325 and therefore higher density-derived vesicularities (averaged at 0.60 ± 0.06 ; Table 3). The
326 difference in vesicularity between the control sample and the quenched samples was due to
327 the presence of isolated vesicles larger than 8 mm in the latter (see R12 in Fig. 4). Although
328 not always observed in thin section, these large vesicles were always present in the quenched
329 samples (as observed in hand specimen and as inferred from the higher density-derived
330 vesicularity). The formation of these large vesicles was likely due to the ingestion of air in the
331 molten lava during sampling, either when the tube was inserted or when the vane was
332 withdrawn. To evaluate the bubble fraction in the flowing lava and during viscosity
333 measurements, the vesicularity of the quenched samples therefore needed to be corrected for
334 these large vesicles that represent artifacts introduced by the sampling process. Vesicle size
335 distributions revealed that, for all the samples, there was a common population of spherical
336 (when single) to convoluted (when two or more bubbles had coalesced) vesicles that range
337 between 0.1 and 5 mm in size (Fig. 5). The average vesicle fraction obtained from the images
338 (Table 3), which is that used here to estimate the effect of bubbles on viscosity, was
339 0.50 ± 0.06 . All samples also contained a population of irregular micro-vesicles smaller than
340 0.03 mm. These were probably diktytaxitic voids related to the crystallization of microlites.
341 We note that samples quenched after the viscosity measurement (R9, R10 and R12) also had a
342 vesicle population between 0.03 to 0.1 mm that was not observed in either the control sample
343 or the quenched sample from the sampling tube (Fig. 5). This population may have formed
344 because of shearing during viscometry that led to disruption of larger bubbles to form smaller
345 bubbles (Stein and Spera 1992).

346 4 Comparison with viscosity estimated from other techniques

347 4.1 Petrologic approach using textural and chemical analyses

348 The parameters used for viscosity estimations via the petrologic approach are given in
349 Table 4. Using the glass composition, and including the H₂O content (Table 2) and the
350 measured temperature (1144 °C), the viscosity of the melt phase was calculated using the
351 model of Giordano et al. (2008) to be 330 Pa s. Note that a variation of ± 1 °C affected the
352 melt viscosity by 2 %. Considering the average vesicle-free crystal fraction, the mixture (melt
353 + crystals) viscosity was estimated via the method described by Mader et al. (2013) for rough
354 particles with an aspect ratio of 2.4, this being the average value calculated for all the crystals.
355 The resulting bubble-free mixture viscosity is 699 Pa s. Note that a variation of ± 1 vol. % in
356 crystallinity changed the viscosity by 6 %. The effect of bubbles on the mixture viscosity
357 depends on their ability to deform. We calculated the bubble capillary number (Ca) from the
358 applied shear rates during the viscosity measurements (3.5 s^{-1} on average), with a modal
359 bubble radius of 0.34 mm. Using the melt viscosity as calculated above and a bubble-liquid
360 interfacial tension of 0.3 Nm^{-1} (Murase and McBirney 1973), we obtained a Ca of 1.3.
361 Following Llewellyn and Manga (2005), 50 vol. % of deformable bubbles would lower the
362 viscosity by a factor of 0.31, to give a bulk viscosity of the three-phase mixture
363 (melt+crystals+bubbles) of 220 Pa s. Accounting for the variability in crystal (± 4 vol. %),
364 bubble (± 6 vol. %) and water (± 0.015 wt. %) content this value varied by ± 130 Pa s. Thus,
365 when accounting for deformable bubbles, the petrologic model provided a reasonable

366 approximation to the field-measured viscosity. In contrast, neglecting the effect of bubbles, or
367 considering bubbles as non-deformable solid particles, would lead to a significant
368 overestimation in viscosity (this being $>10^3$ Pa s). We note that the differences in viscometer-
369 measured viscosity between each lobe did not exactly correlate with the model-based
370 viscosity estimation made from the crystal and bubble content of the quenched samples (Fig.
371 3). This can either be explained by our field viscosity measurements needing better accuracy,
372 or because the rheological models used in the petrologic approach were inappropriate.

373 4.2 Laboratory results from previous studies

374 Laboratory viscometry of crystallizing Hawaiian lavas at subliquidus temperatures
375 were performed by Shaw (1969), Ryerson et al. (1988), and Sehlke et al. (2014). The main
376 difference between these experiments and field measurements is the absence of bubbles in the
377 laboratory experiments. Another important difference is that crystallization in the laboratory
378 always takes place at a higher temperature than in nature and, consequently, viscosity will
379 always be greater at any given temperature in the laboratory experiments. This is mainly due
380 to three reasons. First, laboratory experiments are usually performed under atmospheric
381 conditions at 1 atm with an oxidized oxygen fugacity and a completely degassed melt.
382 Second, constant stirring of the melt during viscosity measurement enhances crystallization
383 (Kouchi et al. 1986; Vona and Romano 2013; Chevrel et al. 2015). Third, most laboratory
384 experiments apply isothermal conditions and are at thermodynamic equilibrium. This results
385 in higher crystal contents than under steady cooling (disequilibrium) as in nature (Kolzenburg
386 et al. 2016). For example, at 1144 °C (the lava temperature measured in the field),
387 experiments by Sehlke et al. (2014) would predict a crystal content of almost 100% and a
388 viscosity of more than 10^5 Pa s. Comparing the experiments of Shaw (1969) and Ryerson et
389 al. (1988) at this same temperature, viscosity would be predicted to be almost the same as we
390 measured but with a much higher crystal content [25 and > 45 vol. % for Shaw (1969) and
391 Ryerson et al. (1988), respectively].

392 Following Ryerson et al. (1988) the lava should have a yield strength of 28 Pa and 125
393 Pa for 15 and 25 vol. % crystals, respectively, while following Sehlke et al. (2014), the yield
394 strength should be lower. However, whether a crystal content as low as 15 to 25 vol.% would
395 build a crystal framework and develop a yield strength is a matter of ongoing debate (Saar et
396 al. 2001). Any yield strength present during our experiments was smaller than the level of
397 detectability of the instrument which means that - if present - the yield strength is less than
398 300 Pa. Lower strain rates and a more sensitive torque sensor are required to improve
399 measurement sensitivity. Additionally, better constraints on estimating the yield strength from
400 the petrologic approach and that considers crystals and bubbles are needed (see discussion in
401 Chevrel et al. 2013; Castruccio et al. 2014).

402 4.3 Previous field-based viscometry measurements

403 Two previous *in situ* field viscosity measurements were undertaken on Hawaiian
404 lavas. The first measurements were made at Makaopuhi lava lake by Shaw et al. (1968) using
405 a vertical rotational viscometer. They recorded a viscosity of 650-720 Pa s for a unit strain
406 rate and yield strengths of 70 and 120 Pa. The collected samples and *in situ* temperature
407 measurements revealed <5 % vesicles and a crystallinity of 25% at 1130 ± 5 °C. Although our

408 samples had a higher silica content, our viscosity measurements were slightly lower. This is
409 explained by a combination of lower crystal fraction, higher content of deformable bubbles
410 and higher temperature. The other set of measurements was performed by Pinkerton et al.
411 (1995) on three 0.2 to 0.5 m thick pāhoehoe lobes erupted in September 1994 at Kilauea using
412 the same rotational viscometer as used in this study but equipped with a more sensitive torque
413 sensor. Maximum measured temperatures were 1146 °C and apparent viscosities at unit strain
414 rate were in the range 234-548 Pa s. The lowest viscosity lobe was also the closest to
415 Newtonian behavior and was best characterized by a power law model of the form $\tau =$
416 $234\dot{\gamma}^{0.77}$. The highest viscosity lobe departed significantly from Newtonian behavior and
417 fitted a power law model with the form $\tau = 548\dot{\gamma}^{0.53}$. The non-Newtonian behavior measured
418 in 1994 might reflect different vesicularities or crystallinities compared with those of the 2016
419 lavas, however samples collected in 1994 were not analyzed. Alternatively, it could be the
420 result of operating the instrument at lower rotational speeds and hence strain rates ($< 1 \text{ s}^{-1}$) in
421 1994. This permitted construction of a complete rheological curve (Fig. 3). Although some
422 differences were observed between the 1994 and 2016 measurements, the results of both
423 studies agreed on the range in apparent viscosities at unit strain rate (Fig. 3).

424 5 Discussion

425 We have compared our field viscosity measurements with estimations of lava viscosity
426 from the petrologic approach and from previous laboratory and field measurements. However,
427 the measured values represent only a “snap shot” of the lava interior behavior over a short
428 time scale and at a single temperature. Indeed, pāhoehoe lobes cool very quickly (e.g., Hon et
429 al. 1994; Ball et al. 2008; Gottsmann et al. 2004). Ball et al. (2008) showed that small
430 stationary lobes (without advection of hot lava) and non-stationary lobes cool to 800 °C in 25
431 s and 50 s, respectively. Thus, lobe cooling will lead to a rapid increase in viscosity that will
432 quite quickly impede viscosity measurement. This was observed during our measurements
433 when the vane became stuck or when viscosity measurements dramatically increased,
434 sometimes after only 10 s. In general, we observed that viscosity always increased with time;
435 which likely reflected the cooling effect of the whole lobe. The increase of viscosity with
436 time, could also be due to accumulation of lava around the vane due to the chilling effect of
437 the vane being inserted, which increased the apparent vane diameter. To discriminate between
438 lobe cooling or accumulation effects, further field viscosity measurements need to be
439 performed while continuously recording the temperature at the vane. For this, the rotating
440 vane should be equipped with a thermocouple, as has been recently achieved in the laboratory
441 (Kolzenburg et al. 2016). This type of measurement will allow tracking of the temperature,
442 and therefore the cooling rate – viscosity relationship, which is a key to understanding the
443 thermo-rheological control of lava flow emplacement (Giordano et al. 2007; Kolzenburg et al.
444 2017, 2016). Another problem that was faced during our measurements was the cooling of the
445 lobe crust around the rotating shaft. Indeed, the lobe surface cooled more rapidly than its
446 interior (Hon et al. 1994), which may lead to friction around the rotating shaft and disturbed
447 the measurements. Future instrument refinement is required to protect the shaft from the outer
448 cooling crust.

449 The results presented here, including the integration of viscosity field measurement and
450 detailed textural analyses, are a first step toward quantifying the behavior of lava whilst
451 accounting for all its components (melt, crystals and bubbles). Indeed, a major advantage of
452 field measurements compared with those made in the laboratory is their ability to measure the
453 behavior of a three-phase mixture of lava in its natural and original state. One of the
454 difficulties in laboratory experiments is that sample preparation (i.e., melting the lava in the
455 laboratory) leads to degassing and loss of volatiles, making accurate measurement of lava
456 containing bubbles challenging, if not impossible. Direct comparisons between the laboratory
457 experiments and measurements made in the field are therefore difficult for now. Recreating
458 field conditions in the laboratory (in particular volatile content, oxygen fugacity, cooling rate
459 and shear rate) is an ongoing challenge and a goal for future experiments (Kolzenburg et al.
460 2017). Therefore, field measurement using a rotating viscometer offers a promising solution
461 to quantifying three-phase lava viscosity relations at high temperature. Future field
462 viscometry holds the potential to evaluate the effects of three-phase mixtures on rheology, in
463 particular the role of bubbles, and bubble-bubble or bubble-crystal interactions, over a large
464 range of strain rate.

465 For this, future field viscometers need to be more versatile so as to measure small
466 torques at low applied strain rates. This will allow the complete flow curve to be recorded
467 (Pinkerton et al. 1995b). Future instruments also need to be lighter so that one operator can
468 carry out rapid measurements from a vent to a flow front, and in very remote places. Such
469 measurements can be envisaged on well-channelized narrow flows with stable levées or at
470 breakouts at various distances from the vent (e.g., Belousov and Belousova 2018). With
471 associated sample analyses and synchronous temperature measurement, field viscometry will
472 be sufficiently precise to record the temperature- and time-dependent rheological
473 transformations of lava and provide a benchmark for calibrating lava flow emplacement
474 models. Measurements on various lava compositions, temperatures, and/or crystal and bubble
475 content will also lead to improved quantification of lava rheology.

476 **6 Conclusions**

477 Viscosity measurements performed in the field by introducing a rotational viscometer directly
478 into flowing lava, along with simultaneous sampling to allow the associated textural and
479 chemical characteristics to be defined, are non-existent. We successfully measured the
480 viscosity of several lobes that had an average of 380 Pa s for strain-rates between 1.6 and 5 s⁻¹
481 and a temperature of 1144 °C. Although the full rheological curves could not be measured
482 due to instrumental limitations and challenging field conditions, this result is in agreement
483 with previous studies and confirms the range of apparent viscosities at unit strain rate for
484 Hawaiian lavas. In contrast to previous studies, our measurements were made alongside
485 simultaneous collection of quenched lava samples, which we thoroughly characterized by
486 quantifying the chemical and textural characteristics. This provides a unique benchmark
487 allowing field-based, laboratory-based and theoretical models to be compared and their
488 accuracy, error and uncertainty to, for the first time, be assessed. Comparison of our
489 measurements with viscosity estimated from a petrologic approach or from previous field and
490 laboratory studies shows that the petrologic approach, when carried out with rigorous textural

491 analyses of the collected samples, provides viscosity estimates that are in approximate
 492 agreement with field measurements. Quantification of the effect of crystals and bubbles is,
 493 however, extremely important if we are to correctly apply a model. Isothermal laboratory
 494 measurements prove to be the most precise method in describing the full flow curve, but
 495 cannot be applied directly to natural flows as crystallization takes place at higher temperatures
 496 and they cannot account for the effect of bubbles. We thus find that dynamic cooling
 497 experiments in conjunction with field measurements are needed to fully understand the lava
 498 emplacement rheology. Field viscometry accompanied by thorough analyses of quenched
 499 samples is the most promising approach to quantify evolving lava rheology in time and space.
 500 Collecting several measurements down a single flow system or at several flow units with
 501 different characteristics (temperature of effusion, cooling rate, composition, crystal and
 502 bubble content) will lead to proper benchmarking for lava flow modeling.

503

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521

522 **References**

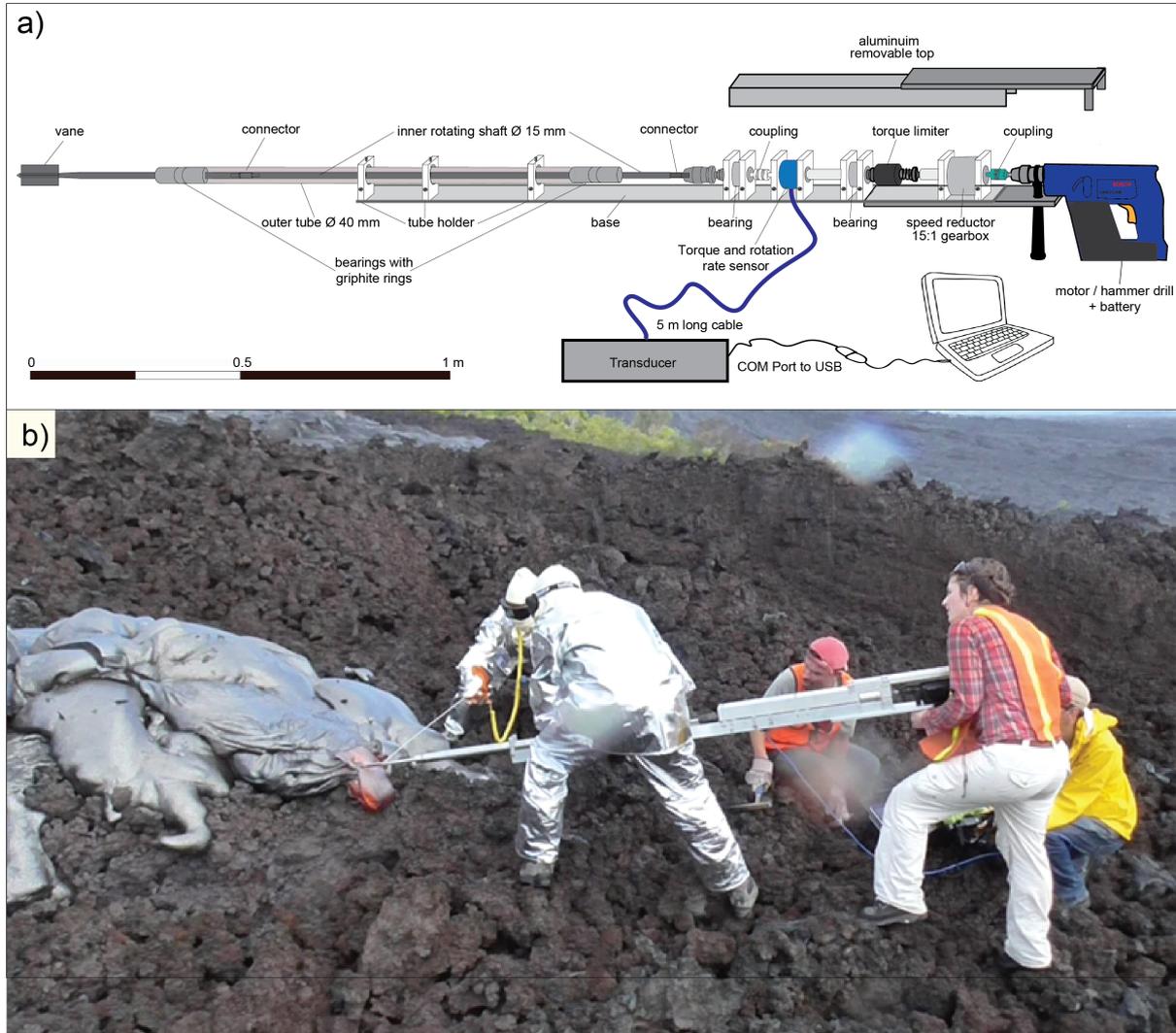
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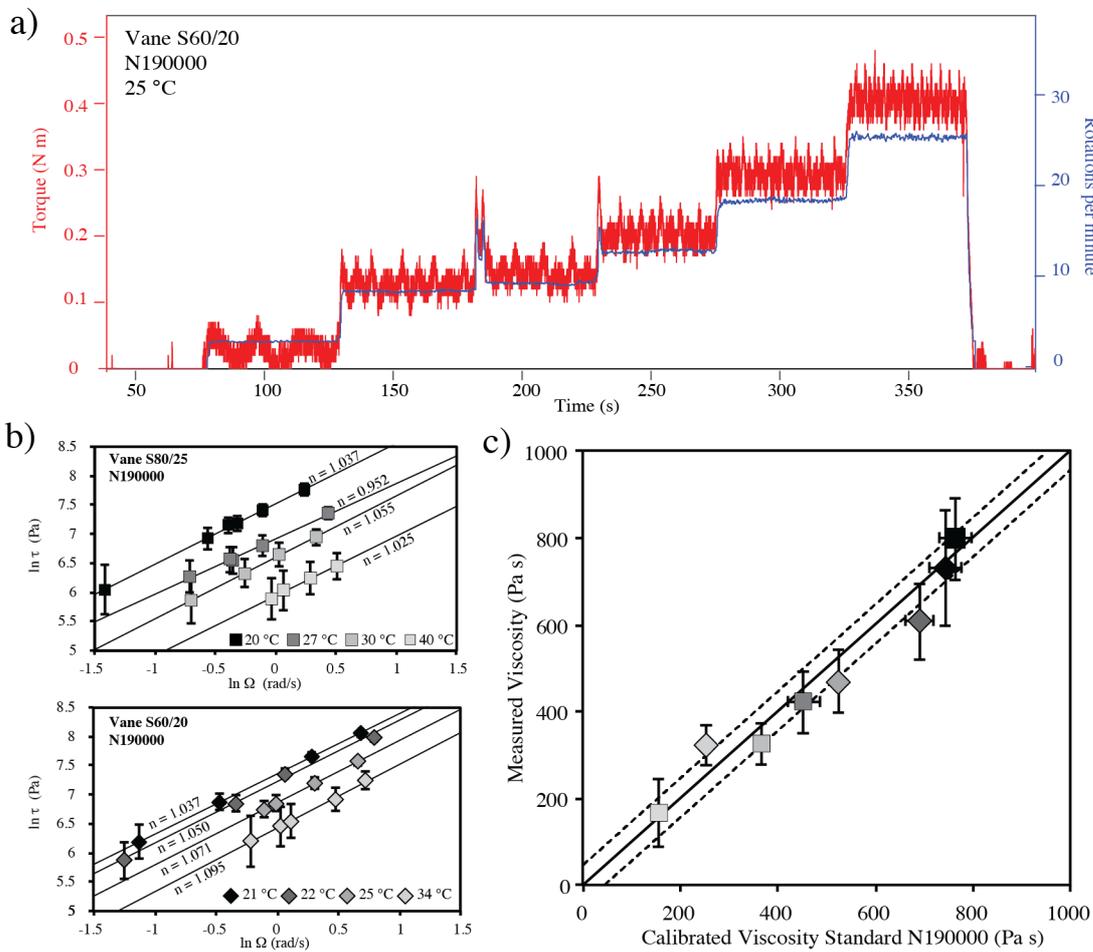
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- 665
666

667 **Figure 1:** a) Schematic of the viscometer. b) Field viscosity measurements (Run 1) of the 61
 668 G lava break out on November 23, 2016 (N19.349537, W155.048793). The two people most
 669 exposed to the hot lava are equipped with heat suits and goggles. One is holding the
 670 viscometer in position and the other is taking temperature measurements with an 80 cm long,
 671 K-type thermocouple with a 15 mm thick sheath.



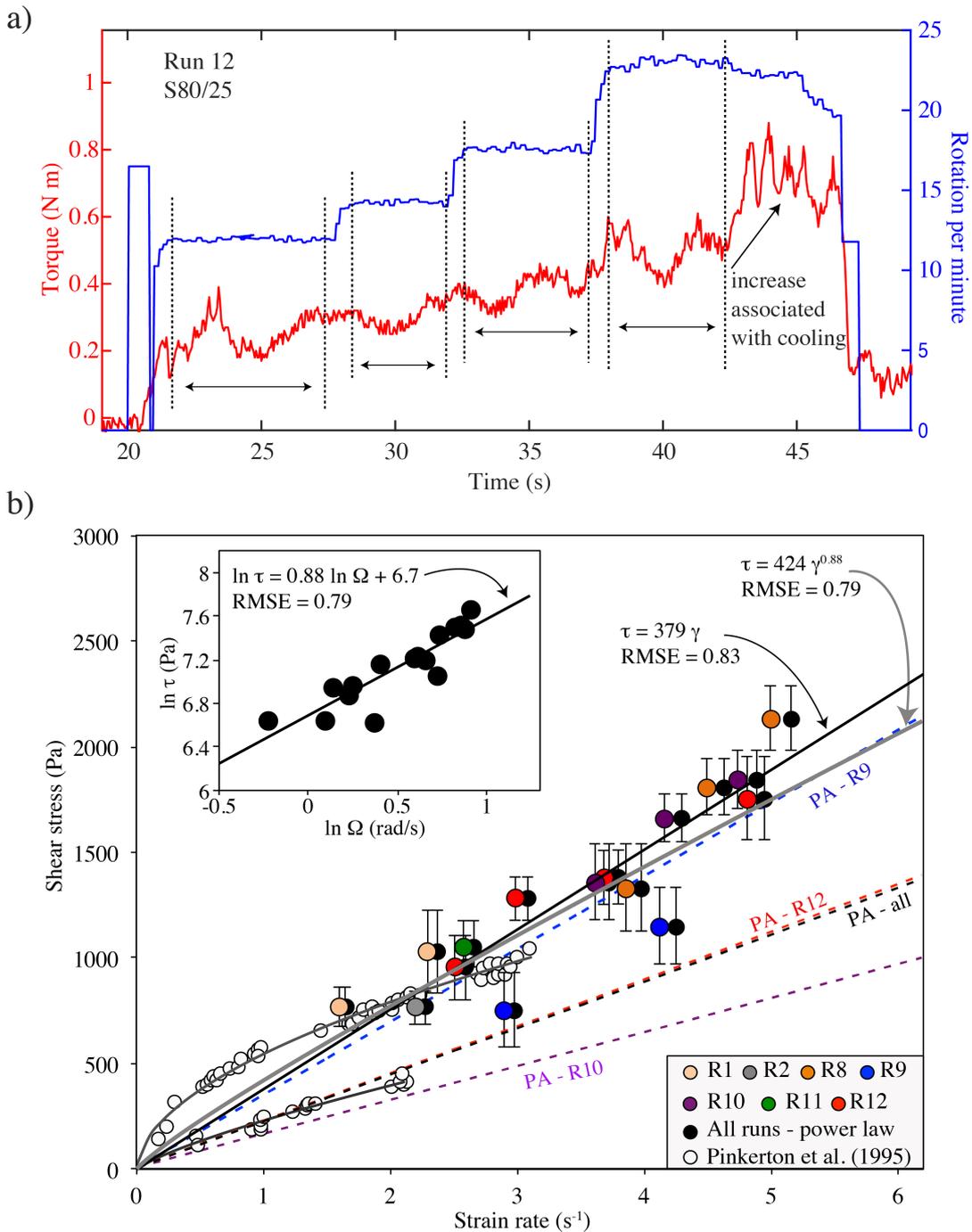
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674 **Figure 2:** Results of testing the rotational field viscometer in the laboratory, using the
 675 viscosity standard N190000 from Cannon Instrument Company® at various temperatures; a)
 676 Example of raw data acquired in the laboratory; b) Flow curves obtained using both vanes; c)
 677 measured viscosity versus theoretical values of the standard viscosity liquid calculated using
 678 the relationship obtained from certified values at the experimental temperature. Horizontal
 679 error bars represent the viscosity variation across the plastic container due to the temperature
 680 gradient (if not visible they are smaller than the symbol). Vertical error bars represent the
 681 range of estimated viscosity over the different strain rates and instrument accuracy. The *solid*
 682 *line* gives the 1:1 relationship and *dashed lines* delimit an interval of ± 50 Pa s. *Squares* are for
 683 measurements using the 80 mm long and 50 mm diameter shear vane (S80/25) and *triangles*
 684 are for measurements using the 60 mm long and 40 mm diameter shear vane (S60/20).



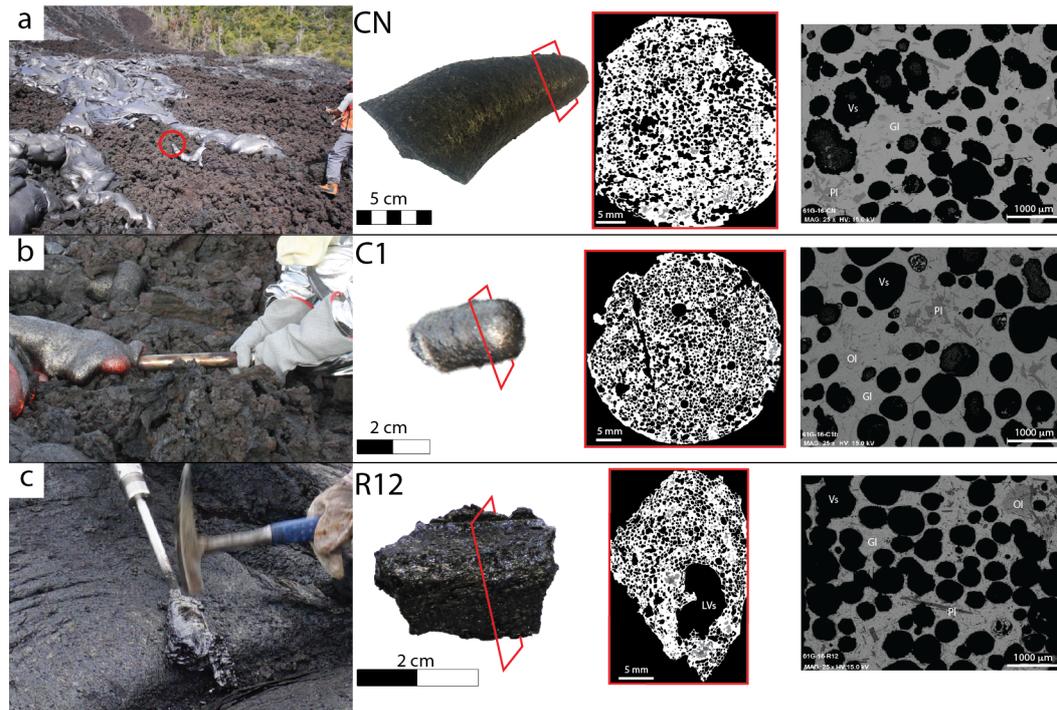
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688 **Figure 3:** In-situ measurements obtained at the 61G lava flow, on November 23, 2016
 689 (N19.349537, W155.048793): a) Example of raw data acquired where *horizontal double*
 690 *arrows* show the range of constant speed over which torque was averaged; b) each data point
 691 is an average value over stable readings and error bars represent the fluctuation of the torque
 692 measurements (see supplement). *Colored symbols* are for individual runs treated as
 693 Newtonian, *black symbols* represent runs treated as having a power law rheology, and *white*
 694 *symbols* are the measurements from Pinkerton et al. (1995) which are treated as a power law
 695 rheology. The *grey curve* represents the best power law fit and the *black line* is the linear
 696 Newtonian fit; the *dashed lines* represent the viscosity values as calculated from the
 697 petrologic approach (PA) using the chemical and textural characteristics averaged for all
 698 samples, and for samples quenched after viscosity measurements (R9, R10 ad R12).



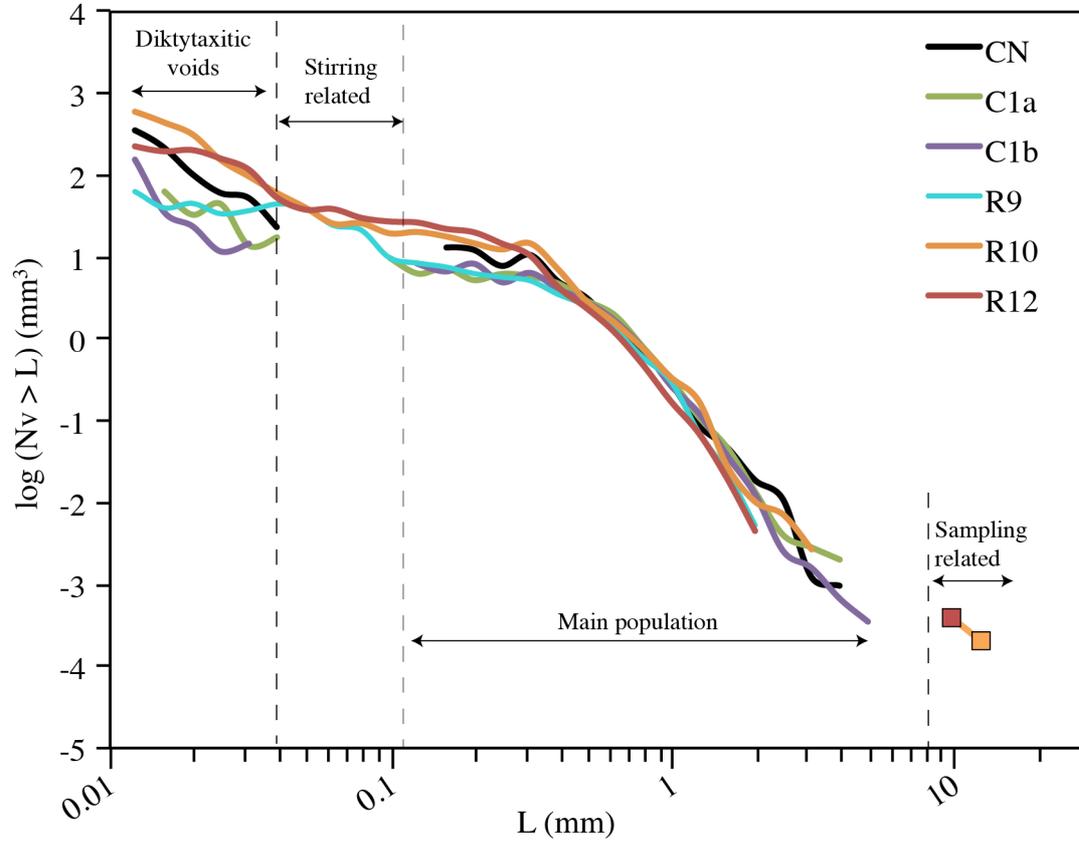
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700 **Figure 4:** Collected samples, from left to right field setting, hand sample, binary image of
 701 thin section scans (white is the glass, black are the vesicles and grey are the phenocrysts),
 702 SEM image at $\times 25$ magnification: a) control sample (CN), collected on a breakout pāhoehoe
 703 lobe a few weeks old; b) example of a sample (C1) collected using a stainless steel tube
 704 inserted into the front of a pāhoehoe lobe and quenched rapidly in water, c) example of a
 705 sample (R12) collected from the lava attached to the vane after viscosity measurement and
 706 quenched in water. Red boxes indicate the thin section locations. Abbreviations are: Gl:
 707 Glass; Ol: Olivine, Pl: Plagioclase; Vs: Vesicles; LVs: Large vesicles formed during sampling
 708 (observed in quenched samples but absente from the control sample).



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711 **Figure 5:** The cumulative vesicle number density plot considers the vesicle number density
 712 per volume in mm^{-3} (N_v) with diameter greater than L (the equivalent diameter in mm) for all
 713 samples. C1a and C1b are both from sample C1 but from thin sections made perpendicular to
 714 each other. The *orange* and *red squares* represent the large vesicles related to the injection of
 715 air during sampling for R10 and R12, respectively.



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718 **Table 1:** Field viscometry results.

Exp. number	Vane	Time (s)	Rotations per minute	Angular velocity (rad/s)	Torque (N m)	+/-	Shear stress* (Pa)	+/-	Strain rate** (s ⁻¹)	Viscosity † (Pa s)
Run 1	80/25	7	7.6	0.80	0.24	0.03	769	90	1.6	483
		7	11.0	1.15	0.32	0.05	1030	194	2.3	449
Run 2	80/25	23	10.5	1.10	0.24	0.02	767	79	2.2	349
Run 8	60/20	3	18.6	1.93	0.20	0.04	1332	204	3.9	345
		3	21.5	2.25	0.27	0.02	1810	135	4.5	403
		4	23.8	2.50	0.32	0.02	2132	154	5.0	427
Run 9	60/20	3	13.8	1.44	0.11	0.03	755	173	2.9	261
		7	19.7	2.06	0.17	0.03	1152	179	4.1	280
Run 10	60/20	6	17.2	1.80	0.21	0.03	1359	177	3.6	377
		4	19.9	2.08	0.25	0.02	1664	116	4.2	400
		4	22.6	2.37	0.28	0.02	1842	135	4.7	389
Run 11	60/20	6	12.3	1.29	0.16	0.04	1062	119	2.6	413
Run 12	80/25	6	11.9	1.25	0.30	0.05	955	153	2.5	382
		11	16.3	1.49	0.40	0.03	1284	104	3.0	430
		5	17.6	1.84	0.43	0.04	1380	128	3.7	375
		5	23.0	2.40	0.55	0.06	1756	200	4.8	366

*calculated with Eq. 1

**calculated with Eq. 3 and $n = 1$

† calculated with Eq. 4

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722 **Table 2:** Chemical composition of the 61G lava flow (bulk rock from sample R12) and
 723 average of the interstitial glass composition (average of 10 to 15 analyses per sample;
 724 numbers in parentheses are the standard deviations).

	Bulk rock (wt.%)	Glass (wt.%)
SiO ₂	50.82	51.95 (0.09)
TiO ₂	2.45	2.77 (0.03)
Al ₂ O ₃	13.71	13.33 (0.05)
FeO *	11.18	11.84 (0.18)
MnO	0.18	0.18 (0.01)
MgO	6.91	6.27 (0.1)
CaO	11.41	10.73 (0.08)
Na ₂ O	2.43	2.42 (0.03)
K ₂ O	0.62	0.50 (0.01)
P ₂ O ₅	0.24	0.03 (0.01)
Cr ₂ O ₃	-	0.02 (0.01)
H ₂ O ^{tot}	-	0.077(0.015)
LOI	-0.68	-
Total	99.36	100
Mg #	0.38	0.35

* total iron is presented as FeO

Bulk rock oxide composition is normalized to a total of 100% but measured total is also reported

LOI: Loss of Ignition

H₂O_{tot} measure by FTIR see supplementary material

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727 **Table 3:** Textural analyses of the samples. Bulk density is the density of clasts measured with
 728 the Geopyc; density-derived vesicularity is obtained from bulk density and DRE density of
 729 2847 kg m⁻³. Standard deviations are based on two-to-four measurements per samples and are
 730 given in parentheses. ϕ_v = fraction of vesicles (2D vesicularity); Ol+Px vol. % = percentage
 731 of olivine + pyroxene; R_{ol+px} = aspect ratio of olivine + pyroxene; Plg vol. % = percentage of
 732 plagioclase; R_{plg} = aspect ratio of plagioclase; ϕ_{xtl} = vesicle-free crystal (phenocrysts +
 733 microlites) fraction.

Sample	Bulk density (kg.m ⁻³)	Density- derived vesicularity ϱ	ϕ_v	Ol+Px vol. %	R_{ol+px}	Plg vol. %	R_{plg}	ϕ_{xtl}
CN	1441 (0.03)	49.37 (0.96)	0.52	3.6	1.7	6.7	2.8	0.21
C1a	1030 (0.17)	63.87 (6.15)	0.53	3	1.9	2.8	3	0.12
C1b	960 (0.02)	66.18 (0.53)	0.49	2.7	1.7	3.2	3.3	0.12
R9	1294 (0.18)	54.52 (6.22)	0.42	6.3	1.8	5.4	3.3	0.20
R10	1096 (0.12)	61.49 (4.21)	0.57	2.3	2	3.4	3.2	0.13
R12	1145 (0.04)	59.75 (1.27)	0.44	3.6	1.7	4.7	2.9	0.15

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736 **Table 4:** Rheological parameters estimated via the petrologic approach using the chemical
 737 and textural characteristics averaged for all samples, and for samples quenched after viscosity
 738 measurements (R9, R10 ad R12).

		All samples	R9	R10	R12
Melt Viscosity					
VFT parameters ^a	A	-4.55			
	B	5901.7			
	C	582.2			
Melt viscosity (Pa s) at 1144 °C ^a		330			
Effect of crystal on viscosity					
Mean crystal fraction ^b	ϕ_{xtl}	0.16	0.19	0.14	0.13
Average crystal aspect ratio	R	2.4	2.6	2.6	2.3
Maximum packing ^c	ϕ_m	0.51	0.50	0.50	0.52
Relative viscosity (effect of crystals) ^d		2.0	2.6	1.9	1.8
Melt + crystal viscosity (Pa s)		699	849	632	590
Effect of bubbles on viscosity					
Mean vesicle fraction	ϕ_v	0.5	0.42	0.57	0.44
Mean vesicle radius		0.34	0.39	0.39	0.31
Relative viscosity (effect of bubbles) ^e		0.31	0.41	0.24	0.38
Melt + crystal + bubble viscosity (Pa s)		220	345	155	225

a: calculated using glass composition (Table 2) via Giordano et al. (2008)

b: bubble-free mixture considering phenocrysts and microphenocrysts

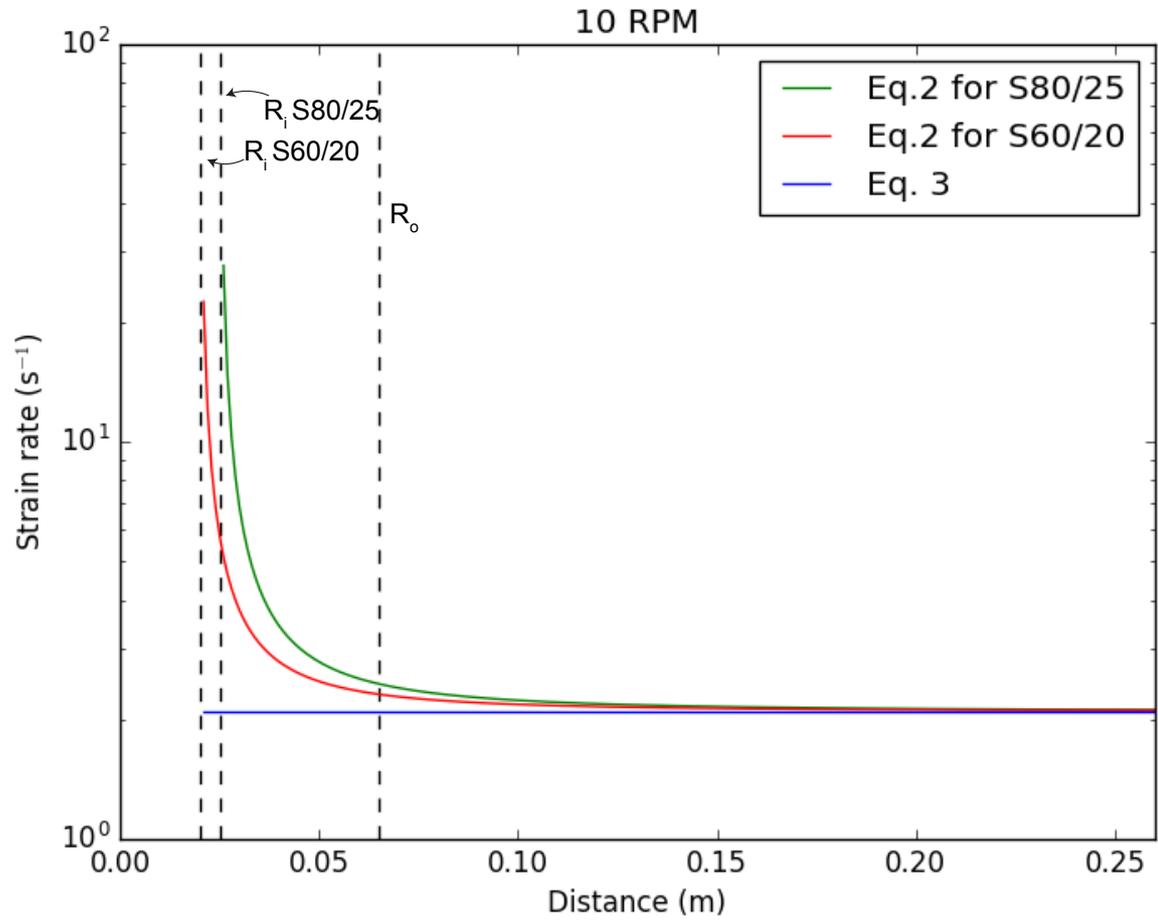
c: calculated for rough particles according to Eq. 49 in Mader et al. (2013)

d: calculated via Maron-Pierce (1956)

e: calculated via Llewellyn and Manga (2005) for $Ca > 1$

Supplementary material 1

1) Plot showing the convergence of Eq. 2 to Eq. 3 at $Ro = \infty$



2) Results of test of the rotational field viscometer in the laboratory, using the standard viscosity N190000 from Cannon Instrument Company® at various temperatures

Temperature (°C)	T dev (°C)	Vane	Time (s)	Rotation per minute	Angular velocity (rad/s)	Torque (N m)	+/-	Shear stress* (Pa)	+/-	Strain rate** (s ⁻¹)	Viscosity (Pa s)	+/-
21	0.6	60/20	33.5	3.1	0.33	0.07	0.02	488	138	0.7	677	191
			32.3	6.0	0.63	0.15	0.02	971	143	1.4	700	103
			12.25	12.7	1.33	0.32	0.02	2137	147	2.9	728	50
22	0.6	60/20	8.15	18.9	1.98	0.47	0.03	3146	175	4.4	719	40
			47.8	2.7	0.29	0.05	0.02	353	106	0.6	557	168
			26.1	6.9	0.72	0.14	0.02	944	132	1.6	594	83
25	0.6	60/20	24.8	10.2	1.07	0.24	0.02	1602	128	2.4	680	54
			11.6	21.1	2.21	0.44	0.03	2914	178	4.9	598	36
			44	8.6	0.90	0.13	0.02	852	121	2.0	427	61
34	0.6	60/20	38	9.5	0.99	0.14	0.02	947	123	2.2	432	56
			38	13.0	1.37	0.20	0.02	1349	138	3.0	447	46
			35	18.6	1.95	0.29	0.02	1942	136	4.3	451	31
34	0.6	60/20	21	9.9	1.03	0.10	0.03	637	209	2.3	279	92
			38	7.7	0.80	0.07	0.03	495	206	1.8	278	116
			9	10.8	1.13	0.10	0.03	694	196	2.5	279	79
			27.5	15.4	1.62	0.15	0.03	1020	205	3.6	286	57
			35.6	19.7	2.07	0.21	0.03	1399	217	4.6	306	47
			<hr/>									
20	0.6	80/25	11.5	6.9	0.73	0.41	0.03	1310	170	1.7	768	100
			60	12.2	1.28	0.74	0.04	2351	236	3.0	785	79
			19.5	8.6	0.90	0.52	0.03	1663	175	2.1	790	83
27	0.6	80/25	25.5	6.4	0.67	0.40	0.02	1269	162	1.6	802	103
			22	5.5	0.57	0.32	0.03	1014	185	1.3	756	138
			44	2.3	0.24	0.13	0.03	423	169	0.6	744	297
27	0.6	80/25	8.1	6.7	0.70	0.22	0.02	699	163	1.6	424	99
			16.6	6.6	0.69	0.22	0.02	708	154	1.6	439	96
			31.7	4.7	0.49	0.17	0.02	529	140	1.1	461	122
30	0.6	80/25	46.4	8.5	0.89	0.28	0.02	902	161	2.1	430	77
			30.2	14.8	1.55	0.49	0.03	1568	171	3.6	430	47
			35	4.7	0.50	0.11	0.02	350	129	1.2	300	111
40	0.6	80/25	21	7.4	0.77	0.18	0.02	563	137	1.8	310	76
			28	9.8	1.03	0.24	0.02	768	154	2.4	317	64
			21	13.4	1.40	0.33	0.02	1042	144	3.3	317	44
40	0.6	80/25	36	10.2	1.07	0.13	0.02	417	136	2.5	167	54
			45	15.8	1.66	0.20	0.02	634	141	3.9	163	36
			39	12.7	1.33	0.16	0.02	512	141	3.1	164	45
			12.5	9.3	0.97	0.11	0.02	360	122	2.3	158	53

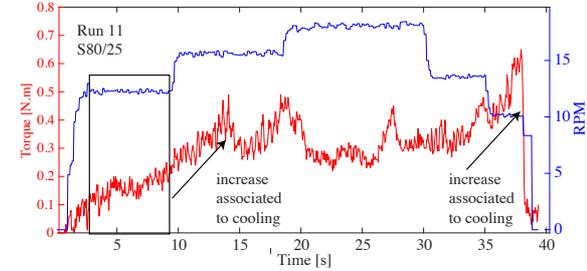
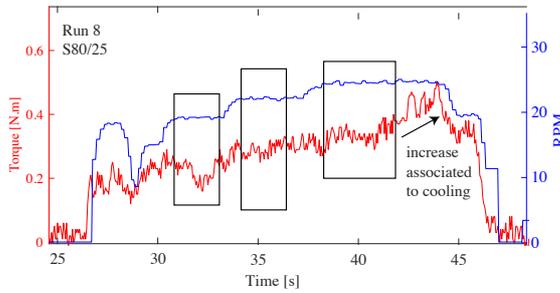
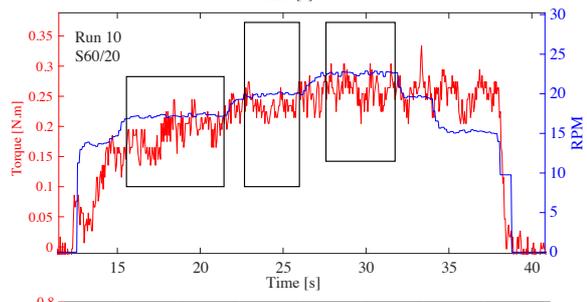
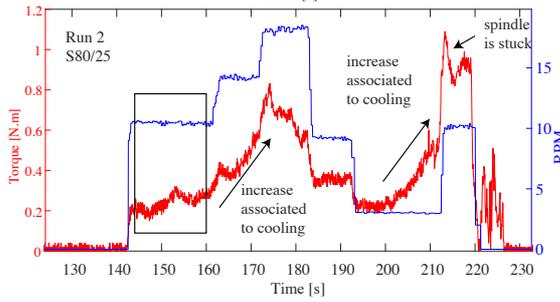
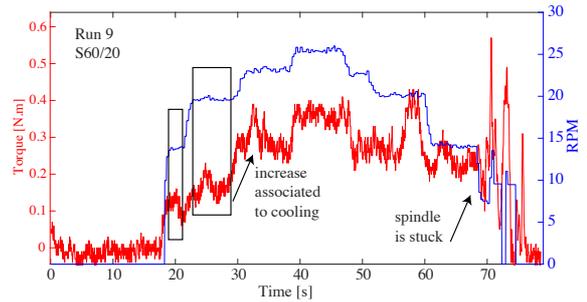
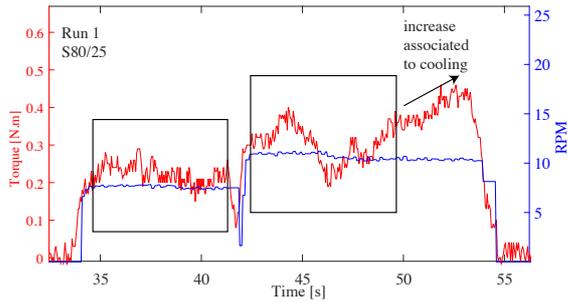
*calculated with Eq. 1

**calculated with Eq. 2 n=1

3) FTIR method to determine the water content in the glass:

Total water content was determined by Fourier Transform Infrared Spectroscopy, using a Bruker Vertex 70 spectrometer coupled with a Hyperion microscope system, housed at LMV. Spectra were recorded using a Globar light source, a KBr beamsplitter and a MCT (Mercury-Cadmium-221 Tellurium alloy) detector. Double polished samples were placed on a CaF₂ window. Absorbance and background spectra of the glasses were obtained by acquisition of 300 and 100 scans, respectively. Beam size was about 50 × 50 μm and spectral resolution was 4 cm⁻¹. Water concentration (OH groups + molecular H₂O) was determined from the height of the absorbance band at ~3550 cm⁻¹, using the Beer-Lambert law. We used the molar absorption coefficient provided by Mercier et al. (2010), 62.8 ± 0.8 L mol⁻¹ cm⁻¹. Peak integration was performed using OPUS software.

4) Raw data from field viscometry



Black boxes indicate where data were selected at constant speed to extract the average torque.
 Black arrows show when the torque strongly increased due to cooling preventing good measurement.

