

# Measuring the viscosity of lava in the field: A review

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## Abstract

Many scientists who have worked on active lava flows or attempted to model lava flows have recognized the importance of rheology in understanding flow dynamics. Numerous attempts have been made to estimate viscosity using flow velocities in active lava channels. However, this only gives a bulk or mean value, applies to channelized flow, and the need to estimate flow depth leads to a large degree of uncertainty. It is for this reason that some scientists resorted to more direct methods for measuring the lava viscosity in the field. Initial attempts used crude instruments (such as forcing a rod into a flow using the operators body-weight), and even the latest instruments (motor-driven rotational viscometer) are significantly less refined than those one would encounter in a well-equipped laboratory. However, if suitable precautions are taken during instrument design, deployment in the field and post-processing of data, the results form an extremely valuable set of measurements that can be used to model and understand the complex rheological behavior of active lava flows. As far as we are aware, eleven field measurements of lava rheology have been published; the first took place in 1948, and the latest (at the time of writing) in 2016. Two types of instrument have been used: penetrometers and rotational viscometers. Penetrometers are suitable for relatively high viscosity ( $10^4$ - $10^6$  Pa s) lava flows, but care has to be taken to ensure that the sensor is at lava temperature and measurements are not affected by the resistance of outer cooled crust. Rotational viscometers are the most promising instruments at lower viscosities ( $1$ - $10^4$  Pa s) because they can operate over a wider range of strain rates permitting detailed flow curves to be calculated. Field conditions are challenging and measurements are not always possible as direct approach to and contact with active lava is necessary. However it is currently the only way to capture the rheology of lava in its natural state. Such data are fundamental if we are to adequately model and understand the complex behavior of active lava flows.

34

## 35 **Keywords**

36 Lava flow, Rheology, Field Viscometry, Shear Stress, Strain Rate, Viscosity, Yield Strength,  
37 Penetrometer, Rotational viscometer

## 38 **1 Introduction**

39 Lava flow dynamics and flow length are influenced by a number of factors including effusion  
40 rate at the vent, ground slope, channel dimensions, flow velocity, eruption duration, insulation  
41 and, critically, the rheology of the lava (e.g., Walker 1973; Pinkerton and Wilson 1994;  
42 Keszthelyi and Self 1998; Griffiths 2000; Harris et al. 2005; Kerr and Lyman 2007; Harris  
43 and Rowland 2009; Castruccio et al. 2013). During an eruption, estimates of the effusion rate  
44 and mean ground slope can be made, and these can be used as source terms in lava flow  
45 emplacement models to assess potential hazards (e.g., Vicari et al., 2011; Ganci et al., 2012;  
46 Mossoux et al., 2016; Coppola et al., 2017). However, the rheological properties of the  
47 flowing and modeled lava are subject to major uncertainties. Current lava flow models (e.g.,  
48 Crisci et al. 1986; Harris and Rowland 2001; Hidaka et al. 2005; A Vicari et al. 2007; Herault  
49 et al. 2009; 2011; Bilotta et al. 2014; Kelfoun and Vargas 2016; Chevrel et al. 2018a) use  
50 rheological data that are either unchanging during flow development or vary down flow as a  
51 function of evolving temperature and crystal content. However, these do not accurately reflect  
52 the behavior of lava during emplacement because they neglect the effects of volatile content,  
53 oxygen fugacity, cooling rate, degassing, strain rate and bubble growth.

54 Lava is composed of crystals and bubbles in suspension in a silicate liquid and its  
55 rheology depends on the viscosity of the liquid phase and on the effect of the particles  
56 (bubbles and crystals) it contains (cf. Pinerton and Stevenson 1992; Crisp et al., 1994;  
57 Cashman et al., 1999; Mader et al., 2013). The viscosity therefore changes down flow because  
58 lava temperature, bubble content and crystallinity evolve as functions of both time (i.e., as  
59 eruption progresses) and space (i.e., with distance from the source) (Lipman et al., 1985;  
60 Lipman and Banks, 1987; Moore, 1987; Crisp et al., 1994; Cashman et al., 1999; Soule et al.,  
61 2004; Riker et al., 2009; Chevrel et al., 2013; Robert et al., 2014; Rhéty et al., 2017). Upon  
62 eruption, the liquid phase is Newtonian and its viscosity depends on chemical composition  
63 (including major elements and volatiles) and temperature. The viscosity of silicate melts is  
64 relatively easily measured as a function of temperature in the laboratory and composition-  
65 based empirical models have been established (e.g., Bottinga and Weill, 1972; Shaw, 1972;

66 Hess and Dingwell, 1996; Giordano and Dingwell, 2003; Hui and Zhang, 2007; Giordano et  
67 al., 2008; Sehlke and Whittington, 2016). In contrast, the effect of particles is more difficult  
68 to quantify because the mixture becomes non-Newtonian and yield-strength, shear thinning  
69 and thixotropic behavior may appear. The mixture (melt + particles) rheology depends on  
70 particle concentration, aspect ratio (for crystals), ability to deform (for bubbles), size  
71 distribution, shear stress and applied strain rate (Barnes, 1989; Larson, 1999). The effect of  
72 particles has been estimated via several theoretical and empirical models based on  
73 experiments of analogue material (e.g., Einstein, 1906; Krieger and Dougherty, 1959; Maron  
74 and Pierce, 1956; Costa et al., 2009; Mueller et al., 2010; Castruccio et al., 2010; Cimarelli et  
75 al., 2011; Moitra and Gonnermann, 2015; Klein et al., 2018). These have been applied to  
76 constrain lava flow rheology in several studies (Pinkerton and Stevenson, 1992; Crisp et al.,  
77 1994; Cashman et al. 1999; Guilbaud et al., 2007; Harris and Allen, 2008; Riker et al., 2009;  
78 Chevrel et al., 2013; Le Losq et al., 2015; Castruccio and Contreras, 2016; Chevrel et al.  
79 2016; Rhéty et al., 2017). The effect of crystals has also been explored through crystallization  
80 experiments of molten lavas (e.g., Ryerson et al. 1988; Pinkerton and Norton, 1995; Sato,  
81 2005; Ishibashi and Sato, 2007; Vona et al., 2011; Vetere et al., 2013; Sehlke et al., 2014;  
82 Soldati et al., 2014; Chevrel et al., 2015; Kolzenburg et al., 2016, 2017) and by deformation  
83 of natural crystal-rich samples near the glass transition temperature (e.g., Caricchi et al., 2008;  
84 Champallier et al., 2008; Cordonnier et al., 2009; Avard and Whittington, 2012; Lavallée et  
85 al., 2012, 2007; Vona et al., 2013). The effect of bubbles on crystal-free lava rheology has  
86 been investigated using analogue material or theoretically (e.g., Stein and Spera, 1992; Manga  
87 et al., 1998; Lejeune et al., 1999; Saar and Manga, 1999; Bagdassarov and Pinkerton, 2004;  
88 Rust and Manga, 2002a; Llewelin and Manga, 2005) as well as using bubble-bearing high  
89 viscosity silicate melts near the glass transition (Bagdassarov et al., 1994; Bagdassarov and  
90 Dingwell, 1993, 1992; Vona et al., 2016). The combined effect of bubbles and crystals has  
91 been studied via laboratory experiments on magmas (Bagdassarov et al., 1994; Pistone et al.,  
92 2016, 2013, 2012; Vona et al., 2017, 2016) and the three-phase theory (Phan-Thien and  
93 Pham, 1997; Harris and Allen, 2008). Although laboratory measurements are well controlled,  
94 they are not representative of field conditions because of differences in volatile content  
95 (dissolved and in the form of gas bubbles), oxygen fugacity and crystallinity changes during  
96 heating episodes in the laboratory. To generate realistic models of lava flow advance and to  
97 place laboratory measurements in reference to nature, we thus need a basic knowledge of the  
98 rheology of the molten mixture itself in its natural setting (i.e., in the field).

99           One method that is commonly used to obtain information on the rheological properties  
100 of lavas in the field involves measuring the post-emplacment dimensions of the flows (e.g.,  
101 Hulme, 1974; Moore and Schaber, 1975; Fink and Zimbelman, 1986; Moore, 1987; Kilburn  
102 and Lopes, 1991; Wadge and Lopes, 1991). Most of these studies are based on the assumption  
103 that lavas can be approximated as Bingham fluids, and that their flow dimensions are  
104 controlled by the yield strength and plastic viscosity. However, post emplacement subsidence,  
105 complex lava flow fields and lava flow inflation may induce under- or over-estimation of  
106 flow viscosity using this method (e.g. Kolzenburg et al., 2018c). Another method involves  
107 measuring the mean velocity of lava in active channels to derive the rheological parameters. It  
108 is often assumed that the lava behaves as a Newtonian fluid and the flow has a parabolic  
109 velocity profile. In that case, the Jeffreys (1925) equation is applied to calculate the viscosity  
110 (e.g., Nichols, 1939; Krauskopf, 1948; Walker, 1973; Rose, 1973; Harris et al., 2004; James  
111 et al., 2007). Other studies showed that non-Newtonian flow behavior is preferable and  
112 consider a plug-flow model to extract yield strength and viscosity (e.g., Cigolini et al., 1984;  
113 Moore, 1987; Harris et al., 2002; Balmforth et al., 2007;). An additional field method can be  
114 used when flows undergo super-elevation when they encounter sharp bends in channels  
115 (Heslop et al., 1989; Woodcock and Harris, 2006). Unfortunately, there are few situations  
116 where this method can be applied. All these methods are based on the whole flow behavior,  
117 and therefore, suffer from potentially large uncertainties due to difficulties to measure channel  
118 shape, depth, lava density and underlying slope (cf. Hon et al., 2003; Lefler, 2011; Chevrel et  
119 al., 2013; Lev and James, 2014; Kolzenburg et al., 2018b). In addition, the calculated  
120 properties are not necessarily representative of the viscosity of the material itself but represent  
121 the behavior of the flow as a whole (fluid interior plus brittle and viscoelastic crust).  
122 Consequently, to constrain the rheological parameters of lava in its natural state, we must use  
123 field-based instrumentation.

124           The only way to directly establish lava rheology in the field is to measure it by  
125 inserting a viscometer into the flowing molten rock. If this technique is applied down an  
126 active channel and is combined with simultaneous temperature measurement and sampling, it  
127 is possible to capture the evolution of lava rheology as a function of cooling, degassing and  
128 crystallization. However, *in-situ* viscosity measurements are challenging due to the difficulty  
129 of approaching an active lava flow, and the problems of designing equipment that will make  
130 reliable measurements under such difficult conditions. Besides, during eruption, lava flows  
131 are continuously changing (advancing, cooling, degassing, advecting) therefore the

132 measurement timescales needs to be adapted with the timescale for which the lava is at  
133 constant conditions (mainly temperature). This is often a limitation for the measurements  
134 because low torques and low deformation rates are difficult to reach due to the fast thermal  
135 dynamics. As a result, only a small number of investigators have accepted the challenge of  
136 measuring the rheological properties in the field. Their studies are reported here. In this  
137 article, we thus review how rheological properties can be measured using field  
138 instrumentation. We then collate all field viscometry experiments made to date in  
139 chronological order. For each of these eleven cases found, we include a discussion of the field  
140 conditions, and instrument description, and review the main results and conclusions.

## 141 **2 Measuring lava rheology in the field**

### 142 **2.1 Methods and theory**

143 Quantification of rheology is described by the relationship between the applied stress, and the  
144 rate of deformation i.e. strain rate. These quantities are measured using a viscometer. There  
145 are essentially two types of viscometer that have been used to measure the rheological  
146 properties of lava in the field. One measures the resistance to penetration of an object, which  
147 moves into the lava, and the other measures the torque required to rotate a shear vane that is  
148 immersed in the lava. These viscometers are based on the principle of applying either a stress  
149 or a strain rate while measuring the response either of the strain rate or the stress. When using  
150 a rotational viscometer, the shear strain rate is a function of the rotation rate and the geometry  
151 of the vane. For a penetrometer it is a function of the penetrometer head shape and the axial  
152 penetration rate. Shear stress is a function of the torque acting on the rotating spindle or the  
153 force acting on the penetrating head. If the rotational viscometer or penetrometer has the  
154 ability to vary the speed of rotation or penetration, or the applied force, a graph of strain rate  
155 versus stress can be constructed to produce, following the term given by Lenk (1967), “flow  
156 curves”. Depending on the lava properties being measured, one of the following rheological  
157 models can be fitted to the data (see Chapter 5 in Chester et al., 1986). All parameters used  
158 for the following equations are given in Table 1.

159 For Newtonian behavior, the strain rate ( $\dot{\gamma}$ ) is directly proportional to shear stress ( $\tau$ ). The  
160 proportionality coefficient is the viscosity ( $\eta$ ) and is defined by:

$$\tau = \eta \dot{\gamma} \quad (1)$$

161 Bingham behavior is identified when a minimum stress (i.e., the yield strength,  $\tau_0$ ) needs to  
162 be overcome before deformation occurs. In that case, once the yield strength is overcome, the  
163 strain rate is proportional to shear stress. The proportional coefficient is the consistency (K),  
164 otherwise termed the Bingham or plastic viscosity. This is defined via:

$$\tau = \tau_0 + K\dot{\gamma} \quad (2)$$

165 When strain rate is not proportional to shear stress, and the lava has no discernible yield  
166 strength, the material is best characterized as a power law flow, defined as:

$$\tau = K\dot{\gamma}^n \quad (3)$$

167 where, if  $n$ , the flow index, equals unity this reduces to the Newtonian case (Eq. 1).

168 The last rheological model used to describe lava behavior, is when a minimum stress is  
169 present and once it is overcome the shear stress follows a power law with strain rate. This is  
170 termed the Herschel-Bulkley model and described by:

$$\tau = \tau_0 + K\dot{\gamma}^n \quad (4)$$

171 For all fluids, the value of  $n$  in Eqs. 3 and 4, is evaluated graphically or numerically from the  
172 experimentally determined values of strain rate and shear stress. When  $n > 1$ , the fluid is  
173 dilatant (also termed shear thickening), i.e. viscosity increases with strain rate. Evidence for  
174 this behavior has been found in dykes (Smith, 1997, 2000), but has yet to be encountered in  
175 flowing lava. When  $0 < n < 1$ , the material is thinning with deformation, so that viscosity  
176 decreases with strain rate. In that case, the fluid follows a pseudo-plastic behavior. After a  
177 few percent of crystallization, it has been recognized that lavas preferentially follow this  
178 behavior (Pinkerton and Stevenson, 1992).

## 179 **2.2 Instrumentation**

### 180 **2.2.1 Penetrometers**

181 There are three types of penetrometer. A “simple” penetrometer is based on a penetrometer  
182 used for measurement of soil physical properties (Lunne et al., 1997) and is basically a metal  
183 rod, with a semi-spherical head, pushed into the lava. Penetrometers can be used to measure  
184 yield strength by establishing the minimum force required to initiate movement (Pinkerton  
185 and Sparks, 1978) or can be used to estimate viscosity by inserting the rod into the lava at a  
186 given constant force and recording the speed of penetration (Einarsson, 1949, 1966; Gauthier,  
187 1973; Pinkerton and Sparks, 1978; Panov et al. 1988; Belousov and Belousova, 2018). Using

188 a semi spherical penetration head and assuming that the potential effect of lava sticking to the  
189 rod is negligible, the viscous drag is equal to half of Stokes' force acting on a sphere  
190 penetrating through a viscous medium (Panov et al., 1988; Belousov and Belousova, 2018).  
191 The lava viscosity is then calculated via:

$$\eta = \frac{F}{3\pi u R_{eff}} \quad (5)$$

192 where  $F$  is the force of penetration (viscous drag),  $u$  is the speed of penetration, and  $R_{eff}$  is the  
193 effective radius of the rod. The force is recorded by a hand gauge and the velocity is measured  
194 from the penetration depth and time to reach that depth. This results in a single viscosity  
195 measurement point, which is averaged over the duration of penetration. For a given  
196 penetration depth the viscosity may then be obtained from prior calibration (Einarsson, 1966,  
197 1949; Gauthier, 1973; Pinkerton and Sparks, 1978).

198 The second type of penetrometer is termed "ballistic" penetrometer as used by  
199 Gauthier (1971, 1973). This technique involves shooting a spear at high-speed  
200 perpendicularly into the lava and measuring its penetration depth. The viscosity is then  
201 calculated based on previous laboratory calibrations using the same spear on various liquids  
202 of different viscosities. The high initial penetration velocity prevents lava advance rates from  
203 influencing the measurement and limits cooling of the lava around the spear during  
204 penetration. The major disadvantage of such penetrometers is that they are inserted through  
205 the outer, cooled part of a flow, thus the force required to penetrate the lava is the result of a  
206 summation of shear stresses induced within the thickness penetrated, the major resistance to  
207 shearing being due to the more viscous outer (crusted) regions. This penetrometer thus tends  
208 to give a semi-quantitative measurement of the shear strength of the cooler exterior of a flow,  
209 and little indication of the rheological characteristics of the hot interior.

210 This problem can be overcome using a third type of penetrometer that is first  
211 preheated and inserted through the cooled outer regions before being activated, so only the  
212 nose of the penetrometer that had been placed into the flow interior is moved forward  
213 (Pinkerton and Sparks, 1978). This instrument used a compressed spring as the energy source  
214 for penetration. The controlled reduction in axial force during penetration was recorded,  
215 together with the simultaneous piston advance rates. This type of dynamic penetrometer  
216 permitted the shear stress - strain rate characteristics of the lava to be determined using the  
217 method outlined in Pinkerton (1978).

218

Symbol	Description	Unit
$\eta$	Viscosity	Pa s
$\tau$	Shear stress	Pa
$\dot{\gamma}$	Strain rate	s <sup>-1</sup>
$\tau_0$	Yield strength	Pa
K	Consistency	Pa s
$n$	Flow index	
<i>Penetrometer</i>		
$F$	Force of penetration	N
$u$	Speed of penetration	m s <sup>-1</sup>
$R_{eff}$	Effective radius of the rod	m
<i>Rotational viscometer</i>		
$M$	Torque	N m
$\Omega$	Angular velocity	rad s <sup>-1</sup>
$h$	Vane length	m
$R_i$	Vane radius	m
$R_o$	Container radius	m

220 **Table 1:** Notation of parameters and units

221

### 222 2.2.2 Rotational viscometer

223 Rotational viscometers involve a rotating spindle immersed into the molten lava. Two types  
 224 of rotational viscometer have been employed in the field: a fixed rig sited on the top of a lava  
 225 lake (Shaw et al., 1968) and a portable instrument inserted by hand through the flow surface  
 226 and into the lava interior (Pinkerton, 1994; Pinkerton et al., 1995a, 1995b; Pinkerton and  
 227 Norton, 1995; Chevrel et al., 2018a). In use, the spindle can be operated in either controlled  
 228 strain rate or controlled shear stress mode. The theory employed with this instrument is that of  
 229 wide-gap concentric cylinder viscometry where the torque is converted into shear stress and  
 230 the rotational speed into strain-rate using the spindle geometry via the Couette theory, which  
 231 is similar to the theory used for the laboratory viscometers described in Dingwell (1986) and  
 232 Spera et al. (1988). Unlike most laboratory experiments where the immersed spindle is  
 233 cylindrical, vane geometry is commonly used in the field to lower the weight, ease  
 234 penetration, reduce disturbance of lava during insertion, minimize the effects of cooling and  
 235 reduce slippage between the edge of the vane and the lava. The material between the vanes is  
 236 trapped and therefore a virtual cylinder of sample material is used for the calculation. The  
 237 shear stress is then calculated via:



$$\tau = \frac{M}{2\pi h R_i^2} \quad (6)$$

238 where  $M$  is torque,  $h$  is vane length and  $R_i$  is the radius of the rotating cylinder (or equivalent  
239 radius of the vane). The strain rate is obtained from the angular velocity of the rotating vane  
240 via (Stein and Spera, 1998):

$$\dot{\gamma} = \frac{2\Omega}{n \left(1 - \left(\frac{R_i}{R_o}\right)^{2/n}\right)} \quad (7)$$

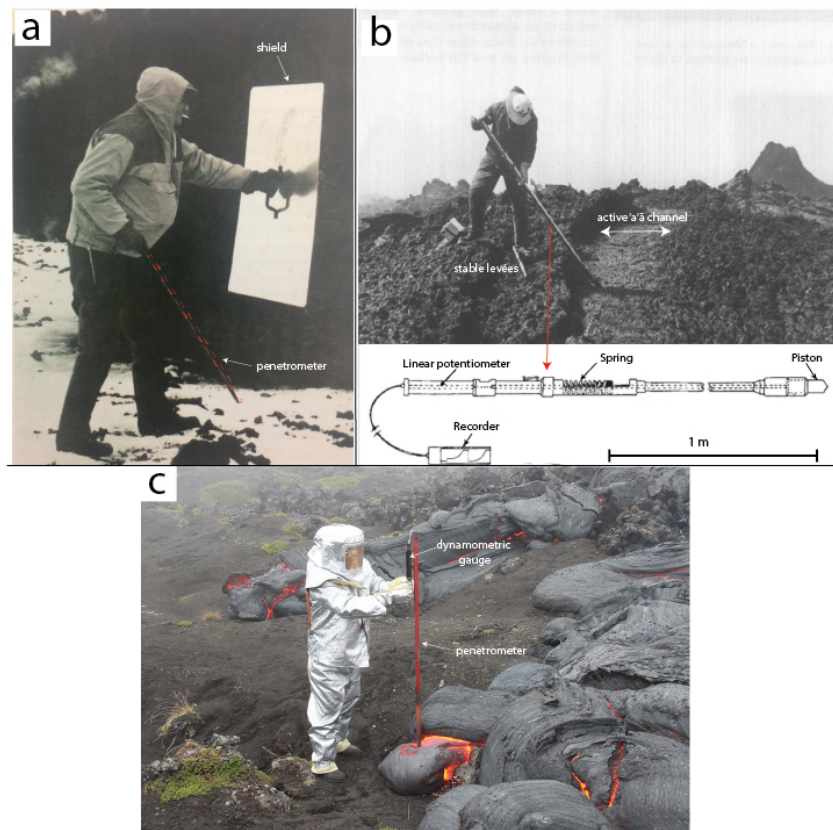
241 where  $\Omega$  is angular velocity,  $n$  is flow index (obtained by calculating the slope of the  
242 measured  $\ln(\tau)$  against  $\ln(\Omega)$ ), and  $R_o$  is the radius of the outer cylinder.

### 243 **3 Review of lava viscometry experiments in the field**

#### 244 **3.1 An iron rod thrust into the lava by Einarsson (1949) at Hekla, Iceland**

245 While observing lava emplacement on Hekla in 1948, Einarsson quickly realized that the lava  
246 presented interesting changes in vesicularity, temperature, crystallinity and apparent viscosity  
247 (Einarsson 1949). To measure viscosity, he used a simple iron rod and thrust it by hand into  
248 the lava. Einarsson applied a force on the rod manually and measured the time needed to  
249 penetrate the lava. From a qualitative approach, he could “feel” different behaviors. The most  
250 fluid lava allowed him to push the iron rod in with one hand, which reached depth of 20 to 30  
251 cm in one or two seconds. In the most viscous lava, he could thrust the rod only 2-3 cm into  
252 the flow (also in 1 to 2 s) and this was achieved by putting his whole body weight onto the  
253 rod. To quantify viscosity, back into the laboratory, Einarsson established a relationship  
254 between viscosity and velocity of penetration from repeated measurements using the iron rod  
255 plunged into a hot mixture of Trinidad asphalt and asphalt oil. He estimated the viscosity of  
256 the lava at Hekla to be between  $5 \times 10^4$  Pa s and  $1.5 \times 10^6$  Pa s, and he estimated an error of  
257 about half order of magnitude. The erupted lavas were basaltic-andesite (55 wt.% SiO<sub>2</sub>) and  
258 were described as ‘a’ā to block type. The maximum temperature was estimated using an  
259 optical pyrometer as 1150°C (Einarsson 1949). Analyses of the lava texture revealed that the  
260 low viscosity values corresponded to “spongy, uncrystallized fluid”, while the high viscosity  
261 value corresponded to denser lava. Einarsson (1949) concluded that accurate measurements of  
262 viscosity using this technique on this type of lava are difficult because of the lack of time  
263 available to make instrumental measurements and because of hazards arising from blocks

264 falling from the steep rubbly flow margin and high radiant heat. In 1961, Einarsson intended  
265 to measure the lava viscosity at Askja (Iceland; Fig. 1a) but no data were recorded.



266  
267 **Figure 1:** a) Einarsson holding the penetrometer in one hand and a shield in another hand, advancing toward  
268 the lava flow during Askja (Iceland) eruption in 1961 (photo modified from Solbnes et al. 2013). b) Pinkerton  
269 using the penetrometer Mark 2 on a small channelized 'a'ā flow of Mont Etna (Italy) in 1978 (sketch modified  
270 from Pinkerton and Sparks, 1978). c) Belousov using a lava-penetrometer equipped with a dynamometric gauge  
271 on a pāhoehoe lobe during the Tolbachik (Russia) eruption in 2013 (modified from Belousov and Belousova  
272 2018).

### 273 3.2 Viscosity measurement at Surtsey, Iceland, by Einarsson (1966)

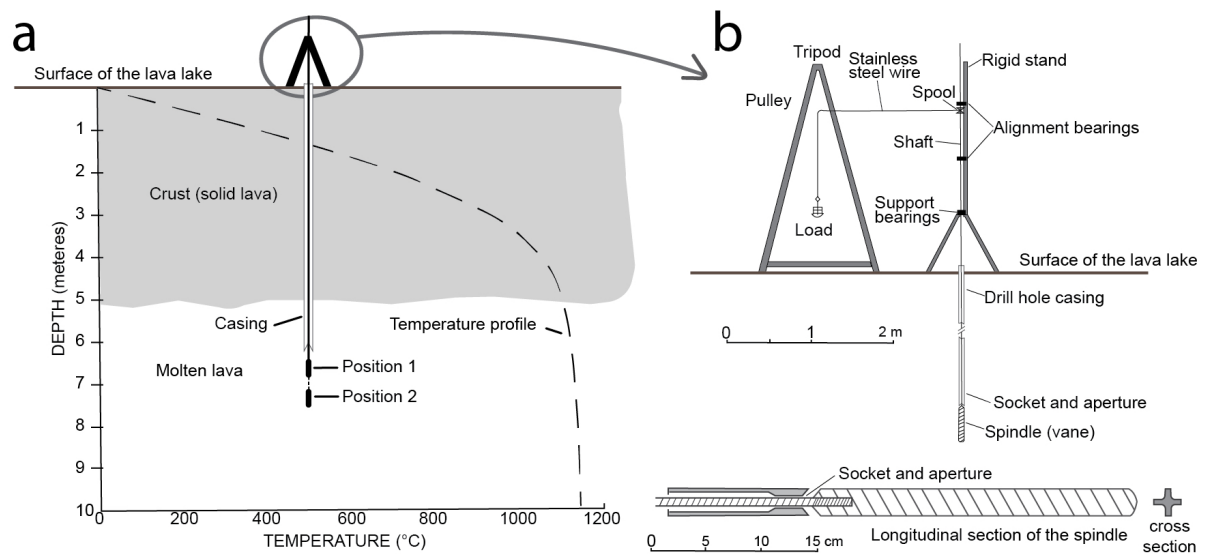
274 During the Surtsey eruption in 1964, Einarsson measured the viscosity of the flowing lava  
275 using the same approach as he applied at Hekla in 1948 (Einarsson 1966). Einarsson  
276 mentioned that this time the measurements were difficult to perform because the lava was too  
277 fluid. Because the penetrometer was pushed by hand, it was difficult to regulate the force of  
278 penetration to a minimum in order to measure the resistance of the fluid lava. After several  
279 attempts, Einarsson estimated that the penetrometer moved 10 cm vertically into the lava at  
280 the front of a lava lobe under its own weight in 0.5 s from which he obtained a viscosity  
281 estimation of  $5 \times 10^2$  Pa s. Einarsson noticed that this value was lower than expected because  
282 he estimated viscosity at  $10^3$  Pa s from lava wave amplitudes in the lava lake located over the

283 vent. This underestimation was attributed to the “foamlike” texture of the lava. At that time,  
284 Einarsson therefore sensed the potential effect of bubbles on lowering lava viscosity. The  
285 samples of spatter that he collected showed about 45 vol. % of vesicles and 40 vol. % of  
286 crystals (feldspar and olivine). The maximum temperature measured in the field with an  
287 optical pyrometer was 1140 °C. Given these thermal and textural characteristics, a viscosity  
288 value of  $5 \times 10^2$  Pa s seems, therefore, appropriate.

### 289 **3.3 Viscosity measurements performed by Shaw et al. (1968) at Makaopuhi lava lake,** 290 **Hawaii**

291 Shaw et al. (1968) used the rotational viscometry method to determine the rheological  
292 properties of lava at Makaopuhi lava lake in March 1965. Makaopuhi lava lake formed in 10  
293 days by eruption of lava into a pit crater forming an 85 m deep and 800 m wide “pond”, and  
294 after which the surface became stable and the upper part began to solidify. When the crust  
295 reached a thickness of 2 m, cores were drilled periodically for temperature measurements and  
296 lava sampling, as described in Wright and Okamura (1977). The viscosity measurements were  
297 performed using one of the drill holes once the crust reached a thickness of about 4 m. The  
298 experimental setup consisted of a support stand fixed on the top of the solidified lava lake  
299 surface. A shaft, with a vane attached to its lower end, was suspended from the stand and  
300 lowered vertically into the lava (Fig. 2). A casing was employed allowing the shaft to reach  
301 the molten lava at the bottom of the cooled crust, where the temperature reached its maximum  
302 (Fig. 2). A wire was spooled to the shaft, passed through a pulley and attached to a load,  
303 permitting the shaft to rotate. In this way, by changing the load weight, different torques were  
304 applied to the rotating vane. Flow curves were obtained by measuring the resulting rotational  
305 speed (using stopwatches). The setup had been previously calibrated using petroleum asphalt  
306 and uncertainties of 20 % on the viscosity were obtained. In the field, four different loads  
307 were applied at two different depths (position 1 at 6.8 m and position 2 at 7.5 m) using the  
308 same vane (Fig. 2). The temperature was measured at  $1130 \pm 5^\circ\text{C}$  and sample analyses  
309 revealed  $< 5\%$  vesicles and 25 % of crystals. Viscometry results indicated that the lava was  
310 non-Newtonian and thixotropic, which means that they observed a hysteresis between values  
311 acquired during increasing and decreasing load (“up” and “down” curves, i.e. the “down”  
312 stress-strain-rate path does not match the “up” path). Considering the up-curves, Shaw et al.  
313 (1968) established that the Bingham model was the most appropriate to fit their data. They  
314 estimated the yield strength to be 120 and 70 Pa, and obtained a plastic viscosity of  $6.5 \times 10^2$   
315 and  $7.5 \times 10^2$  Pa s, for positions 1 and 2, respectively over strain rates  $0.1 - 1 \text{ s}^{-1}$ . These

316 compare with values of 80 to 115 Pa s obtained for the lake interior by Wright and Okamura  
317 (1977) by applying Stokes' Law to olivine crystal setting; the difference is likely due to the  
318 latter estimate being for melt only and the former for a melt-crystal mixture. A re-analysis of  
319 the Shaw et al. (1968) data suggested that no yield strength was present and that power law  
320 models in the form of  $\tau = 974 \dot{\gamma}^{0.75}$  and  $\tau = 716 \dot{\gamma}^{0.54}$  provided a better fit with positions 1  
321 and 2, respectively (Heslop et al., 1989).  
322



323  
324 **Figure 2:** Set-up of the viscosity measurements performed by Shaw et al. in 1968 at Makaopuhi lava lake,  
325 Hawaii. Modified from Shaw et al. 1968. a) Schematic view of the stand fixed onto the top of the solidified lava  
326 surface (thickness of the crust was of about 4-5 m at that time) showing the two positions where measurements  
327 were performed and the temperature profile; b) zoom of the rotating viscometer device and spindle.

328  
329 Shaw et al. (1968) also performed a falling sphere experiment. This experiment  
330 consisted of a steel sphere attached to a fine stainless steel wire that passed through the same  
331 casing used for the rotational viscometer. The sphere was released into the lava at its hottest  
332 part and the movement of the wire behind the descending sphere provided information to  
333 calculate the viscosity. However, they obtained only one measurement because in all other  
334 attempts the wire broke before a measurement was taken. The apparent viscosity they  
335 obtained via Stokes Law was  $6 \times 10^4$  Pa s for a strain rate of  $0.004 \text{ s}^{-1}$ . Although this is larger  
336 than values calculated using the power law models, it is consistent with pseudo-plastic  
337 behavior.

338 These pioneering viscosity measurements are of uncontestedly good quality. However  
339 the technique employed is appropriate only for stable lava lake with a thick crust.  
340 Employment beyond such a setting is therefore limited.

341 **3.4 A shooting spear to measure lava viscosity on Mount Etna, Italy, by Gauthier**  
342 **(1973)**

343 During the eruption of Mount Etna between 1969 and 1971, Gauthier (1971, 1973) performed  
344 viscosity measurements using a crossbow to fire a ballistic penetrometer (a stainless steel  
345 spear), into the lava flow. The penetrometer had an initial speed of 22 m/s. Based on  
346 calibration, viscosity is determined from the final depth of penetration. The relation between  
347 viscosity and penetration depth was established from laboratory experiments on materials  
348 with different viscosities. The penetration depth was directly read from graduations on the  
349 spear. In May 1971, Gauthier performed three sets of measurements. The first set was  
350 completed during the first phase of the eruption at the lava flow front, 500 m from the vent.  
351 Here, the viscosity was measured to be  $\sim 1 \times 10^3$  Pa s and the temperature was 1050 °C.  
352 Measurements on several incandescent blocks yielded  $\sim 2.2 - 5.7 \times 10^3$  Pa s at a temperature  
353 of 1080 °C. For other blocks, where the surface viscosity was clearly higher, estimates of  
354 more than  $10^7$  Pa s were obtained for the outer few centimeters,  $\sim 4.3 \times 10^3$  Pa s at 13 cm and  
355  $\sim 8.5 \times 10^2$  Pa s at 33 cm. The second set of measurements, completed at the end of the first  
356 eruptive phase at the vent resulted in a viscosity of  $\sim 1.1 - 6.3 \times 10^5$  Pa s at a temperature of  
357  $1090 \pm 14$  °C. The third set of measurement was made at the beginning of the second eruptive  
358 phase near the vent. Here, a temperature of 1128 °C and viscosity of  $\sim 1.7 - 2.4 \times 10^3$  Pa s  
359 was measured. A sample collected near the vent from a depth of 50 cm was analyzed. The  
360 lava was a trachy-basalt with 44.6 vol.% of crystals, 22.8 vol.% of glass and 32.6 vol.% of  
361 bubbles.

362 Although viscosity values were obtained from these measurements, Gauthier (1973)  
363 concluded that “the objections to this method do not arise from difficulties of its application  
364 in the field conditions, but from rheological interpretation of the length of penetration”.  
365 Indeed, although the calibration fluids used in the laboratory had a vertical viscosity gradient  
366 between the upper layer and the material core, they did not represent the same gradient as  
367 natural lava. In other words, it was extremely difficult to calibrate the method by using a  
368 similar viscous gradient to that found in a lava flow.

369 Gauthier (1971) also designed a simple penetrometer, which included a dynamometric  
370 gauge and a thermocouple at the rod end. This instrument, when associated with video  
371 footage, would allow measurement of the temperature of the lava and its viscosity as deduced  
372 from the rate and depth of penetration. He believed that this rather simple and light-weight  
373 method was well adapted for fieldwork. Unfortunately, it was never built.

374 **3.5 Field measurements of rheology of lava by Pinkerton and Sparks (1978) at Mount**  
375 **Etna, Italy**

376 Pinkerton and Sparks (1978) deployed three instruments to characterize the rheological  
377 properties of the lava flows erupted at Mount Etna during the 1975 eruption. The most  
378 sophisticated was the “Mark 2” field viscometer. The Mark 1 was considerably heavier than  
379 the Mark 2 and was used only once during the 1973 eruption on Heimay—with limited  
380 success. It had two large (~100 mm diameter) pistons moving out of an even larger cylinder  
381 that was inserted into the flow. It was extremely cumbersome and difficult to use, and  
382 preheating it was a major issue. However, parts of the Mark 1 instrument were used in the  
383 construction of the Mark 2.

384 The Mark 2 instrument was designed to overcome the problems with previous  
385 penetrometer methods. The penetrometer’s head was protected from the cooler crust through  
386 which it passed by an outer stainless steel tube. Once it had passed through the thermal  
387 boundary layer and reached thermal equilibrium with the surrounding lava, it was propelled  
388 into the flow by a compressed spring. This resulted in a gradually decreasing axial force being  
389 applied and hence a decreasing shear stress being applied to the isothermal region adjacent to  
390 the advancing piston (Fig. 1b). The position of the piston and hence velocity was recorded  
391 using a hot wire pen recorder. On each occasion that the viscometer was used, the piston did  
392 not extend fully, indicating that the lava had a measurable yield strength. Prior to field  
393 deployment, the instrument had been calibrated in a viscous sucrose solution. The method  
394 used to calculate the rheological properties is detailed in Pinkerton (1978). This first  
395 instrument was employed 3 m down flow from the active vent. Measurements were made at a  
396 depth of 20 cm where the temperature was  $1086 \pm 3$  °C and the crystallinity of the flow  
397 interior was 45 vol.%. More than 20 data points were obtained for shear rates  $< 0.15$  s<sup>-1</sup>. The  
398 results indicated that the lava behaved in a pseudo-plastic manner, though it could be  
399 approximated to a Bingham fluid at the applied shear rates. The best fit revealed a yield  
400 strength of  $370 \pm 30$  Pa and a plastic viscosity of  $9.4 \times 10^3 \pm 1.5 \times 10^3$  Pa s.

401 The second instrument employed was a conventional penetrometer, which comprised a  
402 2 m long, 3 cm diameter stainless steel rod. A pressure transducer allowed the axial force  
403 during insertion to be measured. This instrument was used in a dynamic mode by measuring  
404 the time taken by the pre-heated penetrometer to move 10 cm when inserted into the flow  
405 interior under a range of applied axial forces. Methods used to calibrate this instrument and to  
406 calculate rheological properties were similar to those used for the Mark 2 viscometer

407 (Pinkerton, 1978). One apparent yield strength measurement of 860 Pa was made at the same  
408 point as the Mark 2 viscometer. This value is higher than the previous measurement due to  
409 shear along the length of the shaft in contact with the outer thermal boundary layer and  
410 confirms the limitations of simple penetrometers. Another yield strength measurement made  
411 at a depth of 10 cm inside an advancing flow front was 6500 Pa at a temperature of 1045 °C.

412 The final instrument used was a stainless steel shear vane attached to a torque wrench  
413 that allowed yield strength to be measured by slowly applying torque until the shear vane  
414 began to rotate. The vane was preheated to lava temperature and inserted into the isothermal  
415 core to avoid the effects of the cooler flow margins. To minimize the effects of shearing by  
416 the cooler flow on the shaft, a ‘dummy end’ was used at each location. Additionally, the  
417 measured torque required to initiate movement of the shaft at the same immersion depth  
418 without the vane was subtracted from the torque with the vane attached. This instrument was  
419 used at eight locations on two lava flows at different distances from the vent. The results  
420 indicated that the yield strengths measured using the torque wrench were compatible with the  
421 values obtained with the Mark 2 viscometer. Values increased from  $6.05 \times 10^2$  Pa at 1083 °C,  
422 close to the vent, to  $1.4 \times 10^3$  Pa at 1080 °C, 7 m down flow and  $2 \times 10^3$  Pa at 1070 °C, 24 m  
423 down flow from the vent. These measurements demonstrate the potential to make systematic  
424 measurements down an active flow.

### 425 **3.6 Simple penetrometer employed at Klyuchevskoy, Russia, by Panov et al. (1988)**

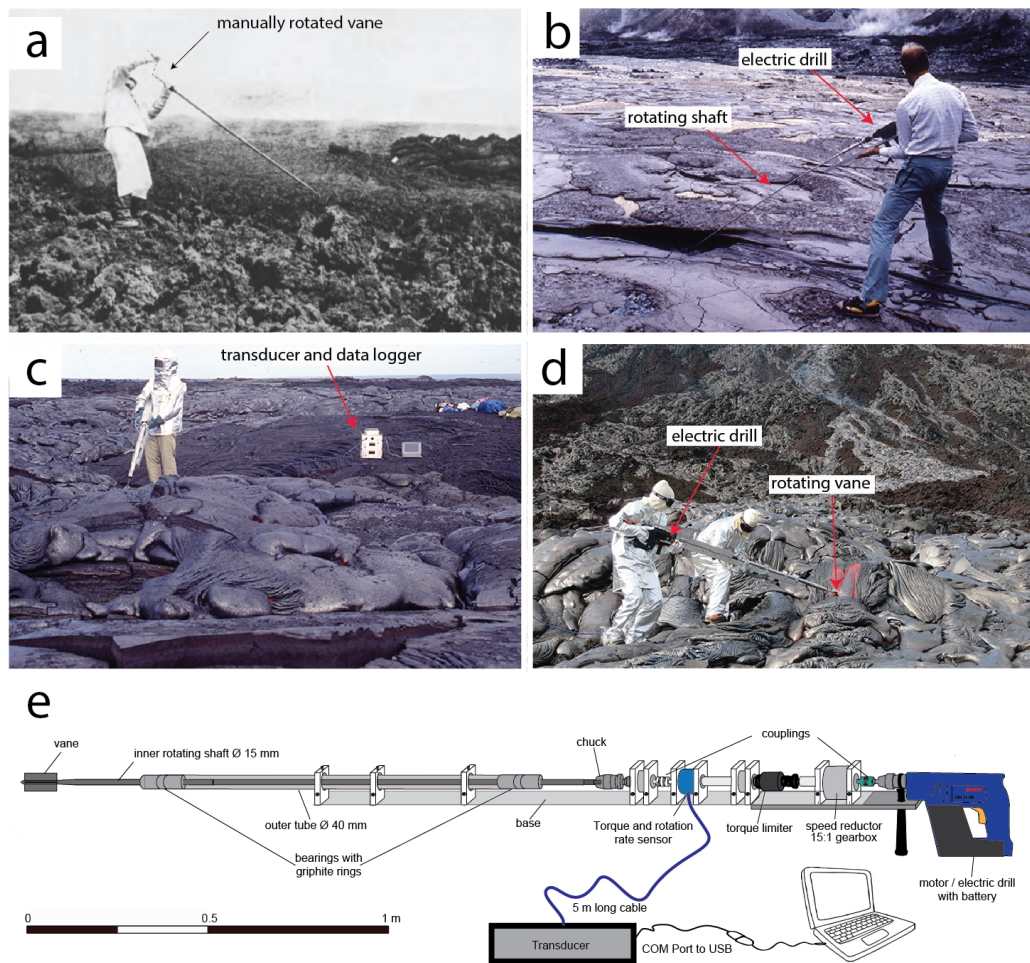
426 During the 1983 Predskazannyi eruption at Klyuchevskoy volcano, Panov et al. (1988)  
427 employed a simple penetrometer (Panov et al., 1985 in Russian, later translated into English  
428 by Panov et al., 1988). The instrument was a steel pole, 14 mm in diameter and 2 m long,  
429 with a rounded end. Viscosity was estimated from the measurement of the speed at which the  
430 rod penetrated the lava under a known force and by assuming that the viscous drag was equal  
431 to half of Stokes’ force (Eq. 5). In practice, the penetration speed was measured from the time  
432 interval between the submersion of marks noted on the rod. The force acting on the rod was  
433 the combined weight of the rod itself and the muscular effort applied. The rod was not pre-  
434 heated, therefore when it was plunged into the lava a chilled margin formed around it. To  
435 correct for this effect, Panov et al. (1988) added 1 to 2 mm to the rod diameter for the  
436 calculation of viscosity. During measurements, the penetration rate did not change under  
437 constant applied force, independently of the depth of penetration. The viscosity was measured  
438 to be between  $1.1 \times 10^4$  Pa s and  $3.6 \times 10^5$  Pa s. No systematic variation was observed with  
439 distance from the vent to the measurement location (15 to 35 m). Panov et al. (1988) noticed

440 the similarity (within an order of magnitude) of the penetrometer results with estimation of  
441 viscosity obtained using the Jeffreys (1925) equation. No data on the lava chemistry and  
442 crystal and bubble content was given.

### 443 **3.7 Vane rotated by hand to measure viscosity of Mount Etna 1983 lava flow by** 444 **Pinkerton and Norton (1995)**

445 Pinkerton and Norton (1995) presented results of viscosity measurements performed during  
446 the eruption of Mount Etna in 1983. These viscosity measurements were performed using a  
447 rotating vane system on a breakout from the main channel where the measured temperature  
448 was 1095 °C. The vane was pre-heated and then inserted into the lava and rotated at different  
449 rates by hand (Fig. 3a). The system was equipped with a torque meter to measure the torque  
450 required to rotate the vane and rotation speeds were monitored with an optical tachometer.  
451 Four data points were acquired before the lava began to develop an impenetrable crust. In  
452 view of the limited range of rotation rate (5 – 9 rad/s), no unique rheological model could be  
453 applied. Assuming Newtonian behavior, the viscosity was calculated to be  $1.385 \times 10^3$  Pa s.  
454 Applying a Bingham model, the yield strength was  $3.7 \times 10^2$  Pa with a plastic viscosity of  
455  $1.26 \times 10^3$  Pa s and at unit strain rate the apparent viscosity is  $1.63 \times 10^3$  Pa s. This range of  
456 values was consistent with those measured in the laboratory on melted samples from the same  
457 lava flow (Pinkerton and Norton, 1995, 1983). The lava was a trachy-basalt but unfortunately  
458 crystal and bubble content was not given. However, field viscosity values are in close  
459 agreement with those measured at the same temperature in the laboratory at for crystal content  
460 between 30 and 40 vol. %.





461

462 **Figure 3:** Rotational viscometers: a) Pinkerton taking rheological measurements in 1983 at Mount Etna using a  
463 manual shear vane (Chester et al., 1986) ; b) Pinkerton in 1988 at Oldoinyo Lengai using the first motor-driven  
464 shear vane (Pinkerton et al. 1995); c) Pinkerton et al. (1994) at Kilauea holding the new version of the motor-  
465 driven rotational viscometer: d) Chevrel et al. (2018b) using the refurbished viscometer in 2016 at Kilauea. e)  
466 Schematic representation of the refurbished viscometer, modified from Chevrel et al. (2018b)

467

### 468 3.8 Portable rotational viscometer to measure the viscosity of carbonatite at Oldoinyo 469 Lengai, Tanzania, by Pinkerton et al. (1995a)

470 Rheological field measurements performed in November 1988 on natrocarbonatite lavas at  
471 Oldoinyo Lengai by Pinkerton et al. (1995) (Fig. 3b) were made using a motor-driven version  
472 of the equipment used on Etna in 1983. A 24-V DC Bosch drill was used to drive a vane at  
473 different, constant, rotation rates, which were measured using an optical tachometer. Torques  
474 corresponding to different rotation rates were measured using a torque meter that was  
475 mounted coaxially between the drive mechanism and the vane. This set of measurements  
476 revealed that the vesicle-free natrocarbonatite lavas behaved as inelastic Newtonian fluids  
477 with viscosities ranging from 1 to 5 Pa s. In contrast, highly vesicular lavas had apparent

478 viscosities of  $0.7 - 1.2 \times 10^2$  Pa s at a strain rate of  $1 \text{ s}^{-1}$  and apparent viscosities of  $0.3 - 3$  Pa  
479 s at a strain rate of  $3 \text{ s}^{-1}$ . These measurements were slightly higher than those measured  
480 subsequently in the laboratory by Norton and Pinkerton (1997) who concluded that these  
481 differences arose from differences in vesicularity and volatile contents between laboratory  
482 and field measurements.

### 483 **3.9 Portable rotational viscometer to measure the viscosity of pāhoehoe lobes at** 484 **Kilauea, Hawaii, by Pinkerton et al. (1995b)**

485 Pinkerton (1994) and Pinkerton et al. (1995b) performed rheological measurements on small  
486 pāhoehoe lobes erupted at Kilauea in September 1994 using a new rotational portable  
487 viscometer based on the prototype employed at Oldoinyo Lengai. The viscometer was driven  
488 by a 24-V DC Bosch drill motor connected to a (15:1) reduction gearbox, a torque limiter and  
489 a torque-rotation rate sensor (Fig 3c). The sensor (DORT Optical rotary torque transducer  
490 from Sensor Technology Ltd) was linked via a transducer to a data logger. After each set of  
491 measurements, raw rotation rate and torque data were downloaded to a laptop and later  
492 processed with custom software. The main drive shaft was protected from the cooler outer  
493 layer of the flow by an outer tube with bearing assemblies (containing graphite rings to  
494 minimize friction) at regular intervals. This helped to maintain alignment of the inner shaft.  
495 Three pāhoehoe lobes (20 to 50 cm thick) were measured, each of which had maximum  
496 internal temperatures of  $1146 \text{ }^\circ\text{C}$ . All lavas measured had properties that could be  
497 approximated by a pseudoplastic power law model with plastic viscosity ranging from 2.3 to  
498  $5.5 \times 10^2$  Pa s and with corresponding power law exponents of 0.77 and 0.53, respectively.  
499 Pinkerton et al. (1995b) concluded that the higher viscosities resulted from lava with higher  
500 crystallinity and bubble content, but quenched samples collected following each measurement  
501 were not analyzed until the present study when one sample was analyzed (see appendix). The  
502 lava can be classified as porphyritic basalt with 4 vol.% of olivine phenocrysts and 12 vol.%  
503 of microlites (olivine + plagioclase + clinopyroxene) within a glassy matrix (55.1 wt. %  $\text{SiO}_2$   
504 and Mg # = 48). The vesicle content was measured at 34 vol. % from image analyses and  
505 from density-derived measurements. The viscosity of the interstitial liquid was calculated  
506 from the glass composition (including 0.07 wt. %  $\text{H}_2\text{O}$ ) using the model of Giordano et al.  
507 (2008) at  $1146 \text{ }^\circ\text{C}$ . The effect of crystals and of bubbles on viscosity was estimated following  
508 the methods of Mader et al. (2013) and Llewellyn and Manga (2005), respectively.  
509 Considering deformable bubbles (capillary number  $>1$  for the strain rates applied during the  
510 measurements), the viscosity is estimated at  $3.5 \times 10^2$  Pa s, which is in agreement with the

511 field measurements at unit strain rate. Unfortunately no other sample could be analyzed to  
512 examine whether from one lobe to another the texture was different so as to explain the range  
513 of viscosities measured.

### 514 **3.10 Viscometry using a simple penetrometer on pāhoehoe lobes at Tolbachik, Russia,** 515 **by Belousov and Belousova (2018)**

516 In 2013, during the Tolbachik eruption, Belousov and Belousova (2018) performed viscosity  
517 measurements on several pāhoehoe lobes using a simple penetrometer (Fig. 1c) based on the  
518 method of Panov et al. (1985). In these experiments, Belousov and Belousova measured  
519 penetration rate of the rod as it passed through the pāhoehoe lobe producing a viscosity  
520 profile from the lobe top to the base (a distance of 10 to 25 cm). The speed of penetration was  
521 measured via video footage where marks on the penetrometer were tracked on each frame.  
522 The force of penetration was applied manually and recorded using a spring balance. Repeated  
523 measurements on each lobe and/or neighboring lobes (about 20 in total) gave interior  
524 viscosities between  $5 \times 10^3$  and  $5 \times 10^4$  Pa s. The viscosity of the upper and basal section of  
525 the lobes was measured as high as  $6 \times 10^4$  to  $4 \times 10^5$  Pa s. Measurements performed at  
526 various distances from the vent resulted in constant viscosity. The 'a'ā flow type could not be  
527 measured because of the impenetrable crust. Where the measurements were performed,  
528 maximum temperatures of 1082 °C were recorded with a K-type thermocouple at depths of  
529 several centimeters. The authors did not sample the lava at the moment of the measurements,  
530 but reported the chemical and textural analyses of previous studies. The lava was sub-aphyric  
531 basaltic trachyandesite (52 wt. % SiO<sub>2</sub>) with 25 to 43 vol.% of crystals (mainly plagioclase  
532 and olivine) and 6 vol.% of vesicles (Plechov et al., 2015). Plechov et al. (2015) estimated the  
533 lava viscosity at  $0.9 - 2.8 \times 10^3$  Pa s from chemical and textural characteristics. They used the  
534 model of Bottinga and Weill (1970) at 1100 °C for the melt viscosity and the Einstein-Roscoe  
535 model for the effect of crystals. As noted by Belousov and Belousova (2018), this estimate is  
536 in good agreement with their field viscosity measurements of the most fluid part of the  
537 pāhoehoe lobes. Recently, Ramsey et al. (2019) also estimated the viscosity from textural and  
538 chemical data given by Plechov et al. (2015) but using Giordano et al. (2008) for the  
539 interstitial melt viscosity at 1082°C. This revealed a slightly higher viscosity of  $1.9 \times 10^4$  Pa s,  
540 which is in better agreement with the Belousov and Belousova (2018) measurements.

541 **3.11 Portable rotational viscometer to measure the viscosity of pāhoehoe lobes of the**  
542 **61G lava flow at Kilauea, Hawaii by Chevrel et al. (2018b)**

543 In 2016, Chevrel et al. (2018a) used the same instrument as Pinkerton et al. (1995b) but it  
544 was refurbished and equipped with a different torque sensor (TORQSENSE E300 from  
545 Sensor Technology Ltd), communication system and new vanes. Tests in the laboratory using  
546 a calibrated viscosity standard, showed that the instrument could measure absolute viscosity  
547 with less than 5 % error, but was limited to strain-rates  $> 0.6 \text{ s}^{-1}$  and torque measurements  
548 above  $3 \times 10^2 \text{ Pa}$ . Chevrel et al. carried out measurements on pāhoehoe lobes from the 61G  
549 lava flow of Kilauea's Pu'u 'Ō'ō eruption (Fig. 3d). A Newtonian viscosity of  $3.8 \times 10^2 \text{ Pa s}$   
550 was measured for strain-rates  $> 1 \text{ s}^{-1}$  and at  $1144 \text{ °C}$ . No yield strength was measured  
551 indicating that yield strength, if present, must be below the 300 Pa measurement limit of the  
552 device. In contrast to Pinkerton et al. (1995b), low strain rates could not be measured (due to  
553 torque sensor sensitivity). The data could be fitted with a power law model of the form  
554  $\tau = 424 \dot{\gamma}^{0.88}$  but with a low fit coefficient of 0.79. Chevrel et al. also collected samples by  
555 quenching the lava attached to the share vane and completed textural and petrographic  
556 analyses, which allowed quantification of the effect of each phase on viscosity. The viscosity  
557 of the interstitial liquid was calculated from the glass composition (including 0.07 wt. %  $\text{H}_2\text{O}$ )  
558 using the model of Giordano et al. (2008). The effect of crystals (16 vol. %) and of bubbles  
559 (50 vol. %) on viscosity was estimated following the methods of Mader et al. (2013) and  
560 Llewellyn and Manga (2005), respectively. Considering deformable bubbles (capillary number  
561 was calculated  $> 1$ ), the results gave a viscosity of  $2.2 \times 10^2 \text{ Pa s}$ , in agreement with the field  
562 measurements. Considering the bubbles to be rigid spheres resulted in an overestimation of  
563 the viscosity by one-to-two orders of magnitude.

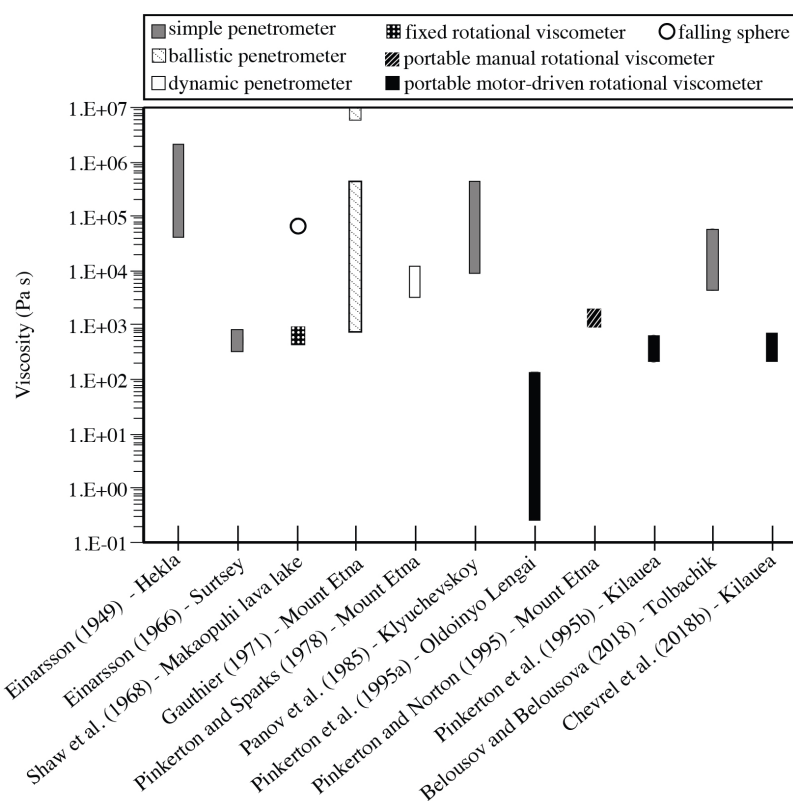
564 **4 Discussion**

565 **4.1 Field viscometers**

566 Penetrometers have been employed to measure lava's rheological properties from the  
567 first published measurement by Einarsson (1948) until recently (Belousov and Belousova,  
568 2018). This instrument has been favored because it is light, easy to build (it consists of a rod  
569 equipped with a dynamometric gauge) and permits quick estimates of the lava viscosity  
570 within a wide range ( $10^3 - 10^6 \text{ Pa s}$ ; Figure 4). However, as highlighted by Einarsson (1966),  
571 the penetrometer is not well adapted for low viscosity lava ( $< 10^3 \text{ Pa s}$ ) because it sinks too

572 rapidly into the lava. Additionally, simple penetrometers do not allow rheological flow curves  
 573 to be calculated because strain rate cannot be varied at the same position (viscosity is  
 574 estimated from penetration velocity). Furthermore, unless the rod has been pre-heated, or  
 575 meticulous calibration has been performed with similar condition as in the field (i.e., with a  
 576 gradient of viscosity due to cooler outer surface), the measurements are often biased by the  
 577 outer cooler surface of the lava. More sophisticated penetrometers such as the Mark 2  
 578 employed by Pinkerton and Sparks (1978) can prevent the effect of the cooler lava surface.

579 A falling sphere method was employed by Shaw et al. (1968), and although he obtained  
 580 a measurement at a low strain rate ( $0.004 \text{ s}^{-1}$ ), this method can only be employed on a stable  
 581 lava lake of sufficient depth, and with a suitable thick crust. Nonetheless this is currently the  
 582 only way to measure the viscosity of silicate liquids under pressure in the laboratory (Kono,  
 583 2018).



584  
 585 **Figure 4:** Viscosity range measured during field campaigns. The boxes are grey-shaded according to the type of  
 586 viscometers.

587  
 588 Rotational viscometry appears to be the most promising approach for field  
 589 measurement on low viscosity lava ( $< 10^4 \text{ Pa s}$ ; Figure 4). This instrument can apply various  
 590 strain rates ( $0.1 - > 5 \text{ s}^{-1}$ ; Figure 4) that permit the construction of full flow curves (Pinkerton

591 and Norton, 1995; Pinkerton et al.1995b). In 1968, the rotational viscometer set up by Shaw  
592 et al. (1968) provided accurate measurements. However it is unsuitable for active lava flows  
593 that are in constant motion and often have short-lived instable levées. In 1994, Pinkerton  
594 (1994) built the first generation of portable, motor-driven, rotational viscometer. The  
595 measurements presented in Chevrel et al. (2018a) showed that this instrument, equipped with  
596 a new torque sensor communication system, continues to work well, but has some important  
597 limitations. These are 1) it was not possible to achieve low strain rate ( $< 1 \text{ s}^{-1}$ ) because of  
598 limiting low rotation speeds and 2) this instrument is bulky and heavy ( $>15 \text{ kg}$ ) and requires  
599 two people to handle it and a third person to monitor the results, which hinders the easy, fast  
600 and flexible handling required in the field around an active lava.

601 We suggest that a combination of two instruments, a rotational viscometer for low  
602 viscosity range ( $< 10^4 \text{ Pa s}$ ) and a dynamic penetrometer for higher viscosities ( $10^3 - 10^6 \text{ Pa}$   
603  $\text{s}$ ), may therefore be the most appropriate procedure. For lavas with higher viscosity ( $> 10^6 \text{ Pa}$   
604  $\text{s}$ ) no field instruments are available for such measurement. Besides, field viscometry will be  
605 extremely challenging because such flows are usually ‘a’ā to blocky with an outer thick  
606 fragmented crust that is impossible to approach and penetrate. In addition, the time required to  
607 measure viscosity may expose the operator to unacceptable risk from falling blocks.

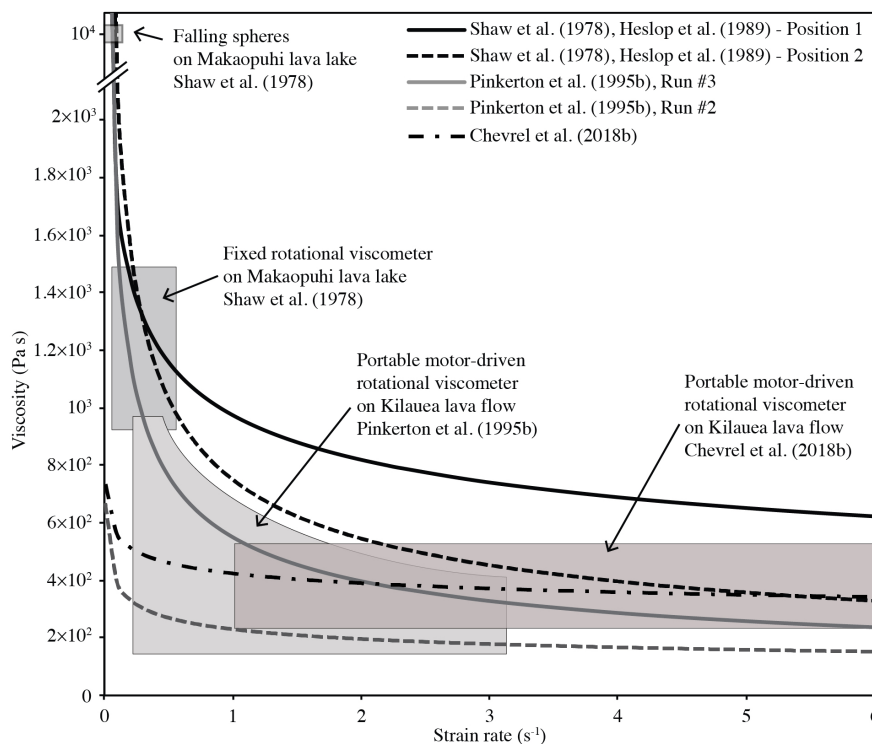
608

## 609 **4.2 Comparison of the rheological results in different geological settings**

### 610 **4.2.1 Hawaiian lavas**

611 Using rotational viscometers, the viscosity of Hawaiian lavas measured in the field at  
612 temperatures between  $1146 \text{ }^\circ\text{C}$  and  $1130 \text{ }^\circ\text{C}$ , falls within the range  $1.5 \times 10^3 \text{ Pa s}$  at strain  
613 rates less than  $1 \text{ s}^{-1}$  to  $2.6 \times 10^2 \text{ Pa}$  at strain rates higher than  $1 \text{ s}^{-1}$  (Figure 5). The  
614 measurements of Shaw et al. (1968) were performed at low strain rate ( $0.1 - 1 \text{ s}^{-1}$ ), and  
615 although the data were first fitted with a Bingham model, later Heslop et al. (1989) showed  
616 that a power law model would be more appropriate. Pinkerton et al. (1995) applied low-to-  
617 moderate strain rates ( $0.2 - 3.2 \text{ s}^{-1}$ ) that also showed the pseudo-plastic behavior of the lava.  
618 In contrast, Chevrel et al. (2018a) performed measurements at higher strain rates ( $>1 \text{ s}^{-1}$ ) and  
619 although they could be fitted with a power law, the Newtonian rheological model provided a  
620 better fit at  $3.8 \times 10^2 \text{ Pa s}$ . The similarity between the collected samples and the viscosities  
621 obtained at unit strain rate in 1994 and 2016, using almost the same instrument but 22 years  
622 apart, is consistent with the fact that temperature, composition and texture (amount of bubbles  
623 and crystals) was similar in the two field studies. These viscosities are lower than the values

624 obtained by Shaw et al. (1968), which is consistent with a higher temperature, lower crystal  
625 content and higher content of deformable bubble in the lava from Pinkerton et al. (1995) and  
626 Chevrel et al. (2018b). The value obtained by Shaw et al. (1968) using a falling sphere  
627 revealed even higher viscosities ( $> 10^4$  Pa s) at very low strain rates ( $0.004$  s $^{-1}$ ). All three data  
628 sets suggest a pseudo-plastic behavior of Hawaiian lavas under these conditions (Figure 5).



629  
630 **Figure 5:** Variation of viscosity with strain rate for Hawaiian lavas as obtained from field viscometry. Boxes  
631 represent the measured range of viscosity and strain rate and curves are best fits as given by the different  
632 studies.

633  
634 Among these field experiments at Hawaii, none have directly recorded a yield  
635 strength. The estimation of yield strength given by Shaw et al. (1968) was made by fitting the  
636 data to a Bingham model. According to laboratory experiments of Hawaiian lavas at  
637 subliquidus condition (Ryerson et al. 1988; Sehlke et al., 2014), yield strength may appear  
638 with crystallization but should be less than 200 Pa for the crystal content of the lavas  
639 measured in the field ( $< 25$  vol. %). Unfortunately, this relatively low yield strength is, to  
640 date, difficult, if not impossible, to measure using current field instruments. Further  
641 measurements at low shear stresses and low strain rates are needed to determine whether yield

642 strength can develop. Until then a power law model is considered to be the most appropriate  
643 model to characterize the behavior of Hawaiian lava at temperatures above 1130 °C (Figure  
644 5).

645 The agreement between field measurements and the model-based viscosity using  
646 textural and chemical characterization shows our capacity of estimating and measuring three-  
647 phase mixture viscosity. However, this is only true for a given temperature and only when an  
648 exhaustive sample analyses is generated. Further measurements on pāhoehoe lava need to be  
649 performed so as to test the sensitivity of viscosity to the effect small thermal, physical of  
650 chemical changes within a lava field.

#### 651 **4.2.2 Etnean lavas**

652 At Mount Etna, measurements were performed on ‘a‘ā type lava flows using different  
653 instruments including penetrometers and a manually-operated rotating viscometer (Figure 4).  
654 The measured viscosities (either on lava blocks or on channelized lava) range mostly between  
655  $10^3$  Pa s and  $10^4$  Pa s. Gauthier (1973) recorded very high viscosities ( $> 10^7$  Pa s) using a  
656 ballistic penetrometer but these high values are unduly influenced by the cooler outer crust  
657 (penetration depth was only 1 cm) and therefore do not represent the flowing lava interior.  
658 The viscosities measured by Pinkerton and Sparks (1978) using the Mark 2 penetrometer  
659 were higher ( $9.4 \times 10^3$  Pa s) than those measured by Pinkerton and Norton (1995) using a  
660 rotational viscometer (approx.  $1.3 \times 10^3$  Pa s). This difference is considered to be a result of a  
661 combination of factors, including different eruptive temperatures (1086 °C in 1975 compared  
662 with 1095 °C in 1983), different crystal content (45 vol. % in 1975 and  $< 40$  vol. % 1983),  
663 and lower strain rates used in 1975 ( $0 - 0.15$  s<sup>-1</sup>) compared with 1983 ( $0.7 - 1.4$  s<sup>-1</sup>).  
664 Pinkerton and Sparks (1978) measured lava yield strength using various instruments and they  
665 found a clear correlation with temperature and consequently crystallinity.

666 Although the rheological properties of Etnean lavas are now well constrained from  
667 laboratory experiments (e.g. Pinkerton and Norton, 1995; Vona et al., 2011; Vona and  
668 Romano, 2013), there are not enough field measurements to build flow curves under field  
669 conditions.

#### 670 **4.2.3 Kamchatka and Icelandic lavas**

671 The measurements on basaltic-andesite lavas from Klyuchevskoy and Tolbachik  
672 showed that the pāhoehoe lobes measured by Belousov and Belousova (2018) have slightly  
673 lower viscosities than the ‘a‘ā flow measured by Panov et al. (1988):  $0.5 - 5 \times 10^4$  Pa s and  
674  $0.11 - 3.6 \times 10^5$  Pa s, respectively. However, the investigation by Belousov and Belousova



675 (2018) at Tolbachik, revealed that the lava traveling within the ‘a‘ā channel was slightly less  
676 viscous than the early erupted pāhoehoe lava. This is consistent with some observations at  
677 Hawaii, where pāhoehoe flows formed from the rupture of ‘a‘ā front flow (Hon et al., 2003).  
678 In general the Kamchatka pāhoehoe lobes are more viscous than Hawaiian lavas, which is  
679 attributed to the lower temperature, higher silica content and higher crystallinity of the former  
680 in comparison to the later.

681 Finally, Einarsson (1949; 1966) measured viscosities at Surtsey as low as  $5 \times 10^2$  Pa s  
682 and up to  $1.5 \times 10^6$  Pa s at Hekla both using the same penetrometer. However the value at  
683 Surtsey was challenging to measure, as the rod sank too quickly under its own weight.  
684 Unfortunately, there are no other field measurements to compare with. This highlights the  
685 need for more data to build flow curves and determine the lava rheological behavior from  
686 these field locations in Russia and Iceland.

### 687 **4.3 Future requirements for field viscometry**

688 Reducing errors associated with field measurements requires accurate sensors as well  
689 as meticulous setup and calibration, which is difficult to achieve in the field where conditions  
690 are more complex than in the lab. Field measurements are always constrained by the lava’s  
691 thermal dynamics. To reduce the effects of crust formation during measurements the  
692 instrument needs to be pre-heated and inserted into fresh molten lava, emerging through  
693 breaches in the crust, or at the breaking point of pāhoehoe lobes, where little-to-no crust is  
694 present. The time of the measurements then needs to be always shorter than crust formation.  
695 Another procedure to minimize the effect of crust formation is to use viscometers like the  
696 “Mark 2” (Pinkerton and Sparks, 1978), which allow triggering the sensor once the lava  
697 isothermal core is reached. A detailed engineering drawing of the Mark 2 can be found in  
698 Pinkerton (1978; Figure 2). Note also that interpretation of the results is non-trivial, but pre-  
699 and post- calibration in fluids of different viscosity can be used to validate the results from an  
700 analysis of the raw data. Gauthier (1971) proposed a set up similar in sophistication to that  
701 used in the laboratory, where the viscometer head would float on the lava surface, protected  
702 from radiant heat by a cooling carapace. This would drive a sensitive spindle plunged in the  
703 lava. Although this instrument may produce useful data, it would be time-consuming and  
704 expensive to build, and there would be a high risk of losing it during utilization in the field.

705 Future viscometers need to be robust, light enough to be carried over rough ground to  
706 remote locations, easily mounted and easy to handle, ideally by one person. Additionally, in  
707 order to capture the full rheological behavior of lava, viscometers need to apply low strain

708 rates ( $< 1 \text{ s}^{-1}$ ) and record low shear stresses ( $< 200 \text{ Pa}$ ). This will constrain the dimensions of  
709 the shear vane or spindle, torque sensor capability and motor power. Using newer  
710 (electronically controlled) technology and a lighter and modern motorized system, a new  
711 generation of rotational viscometer seems to be the most suitable way forwards toward future  
712 measurements on basaltic lava.

713 The material used for field viscometer needs to be resistant to high temperatures. In  
714 the laboratory, crucibles containing the lava and rotating spindles are usually made of  
715 platinum-rhodium alloy or alumina ceramics. However, at the torques applied in the field, the  
716 former does not supply sufficient mechanical strength and may, therefore, deform too easily  
717 and the latter may break. Instead low carbon stainless steel alloy is often favored. This  
718 material is resistant both mechanically and to heat and seems to have the best value for  
719 money. Although its composition (of mainly iron) may contaminate the lava, the degree of  
720 contamination is considered to be insignificant considering the timescale of the  
721 measurements, although this should be investigated in detail during future experiments.

722 Finally, and most importantly, viscosity measurements must be made in combination  
723 with temperature measurements and lava sampling for textural analysis. The rheological  
724 evolution of lava during flow is controlled by the cooling rate (Giordano et al., 2007), which  
725 also controlled the crystal size distribution (Vetere et al., 2015). Recent laboratory-based  
726 work has shown that viscometry associated with synchronous temperature measurement is the  
727 key for understanding lava flow behavior at conditions pertinent to nature (Kolzenburg et al.,  
728 2017, 2016). This also includes changes in shear rate and oxygen fugacity (Kolzenburg et al.,  
729 2018a, 2018b). Future field viscometers should therefore incorporate a thermocouple.

730 Textural and petrographic analysis of the sample is the key to understanding how  
731 crystal and bubble content affect rheology during lava emplacement. The molten lava must  
732 always be sampled and quenched rapidly to conserve the texture at the location of the  
733 viscosity measurement. Future field campaigns should focus on measuring lava properties,  
734 temperature and lava texture as a function of distance from the vent to the front and across the  
735 flow, in order to map lava rheology in 4D through the flow.

## 736 **5 Conclusion**

737 Field viscometry at active lava flows is the only way to capture the rheology of lava in its  
738 natural state. It is also a very challenging method to employ in the field. Since the 1940's  
739 there are eleven studies. These field experiments and their results highlight that they have

740 considerable potential, but the definitive study has yet to be undertaken. The most important  
741 aspect is the choice and design of the viscometer. The rotational viscometer seems to be the  
742 most appropriate instrument for low viscosity lava ( $< 10^4 - 10^5$  Pa s) as it allows a large range  
743 of strain rate to be applied ( $0.1$  to  $> 5$  s<sup>-1</sup>). For higher viscosity lava ( $10^5 - 10^6$  Pa s), well-  
744 calibrated penetrometers designed to avoid the effects of the cooler outer lava surface are  
745 suitable. Above  $10^6$  Pa s measurement is not viable, as penetration becomes impossible.  
746 Using field measurements, flow curves could be established only for Hawaiian lavas and  
747 revealed a pseudo-plastic behavior. Further works still remain to be carried out on other  
748 basaltic volcanoes to ensure a full understanding of the lava rheological behavior under field  
749 conditions.

750 If suitable precautions are taken during measurements and post-processing of data,  
751 field viscometry in combination with simultaneous temperature measurements and laboratory  
752 studies of quenched samples collected at each measurement site will improve our  
753 understanding of evolving lava viscosity as a function of cooling rate, degassing and  
754 crystallisation. This will create the data required for the development of flow emplacement  
755 models. Future improvements include adding thermal sensors and building lighter and  
756 electronically controlled viscometers with simple operating systems that can achieve a wide  
757 range of strain- and stress-rates.

758

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