

# Rheology of Natural Sediments and Its Influence on the Settling of Dropstones in Hemipelagic Marine Sediment

E. Knappe, M. Manga, A. Le Friant

### ▶ To cite this version:

E. Knappe, M. Manga, A. Le Friant. Rheology of Natural Sediments and Its Influence on the Settling of Dropstones in Hemipelagic Marine Sediment. Earth and Space Science, 2020, 7 (3), 10.1029/2019EA000876. hal-03004914

## HAL Id: hal-03004914 https://hal.science/hal-03004914

Submitted on 19 Nov 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1	Rheology of natural sediments and its influence on the settling of dropstones				
2	in marine hemipelagic sediment				
3	E. Knappe <sup>1,2</sup> , M.Manga <sup>1</sup> , A. Le Friant <sup>3</sup> and the IODP 340 scientists				
4	<sup>1</sup> University of California at Berkeley, Department of Earth and Planetary Science				
5	<sup>2</sup> University of Montana, Geoscience Department				
6	<sup>3</sup> Insitut de Physique du Globe de Paris, Sorbonne Paris Cite				
7					
8	Corresponding author: Michael Manga (manga@seismo.berkeley.edu)				
9	Key Points:				
10 11	• We obtain a new dataset of rheology measurements from naturally occurring hemipelagic sediment and a terrestrial mud volcano				
12 13	• Comparison with existing measurements indicates that particle composition influences yield stress and consistency.				
14 15 16	• Most pumice clasts recovered from IODP 340 are stratigraphically in place and thus date the occurrence of eruptions.				

#### 17 Abstract

We investigate the rheology of naturally occurring hemipelagic marine sediment and compare 18 measurements to another naturally occurring sediment from a terrestrial mud volcano and 19 literature values. The hemipelagic marine sediment, collected by IODP 340, has a median grain 20 size of 5.5 microns, is poorly sorted, and contains 31% clay, including smectite. The yield 21 stresses and consistency are calculated by applying a range of shear stresses and shear-rates 22 using a cone-and-plate rheometer. A Herschel-Bulkley model is fit to measured shear stresses 23 and shear rates to calculate the yield stress and consistency. These measurements are performed 24 at a range of particle concentrations and show that the hemipelagic sediment has a yield stress at 25 particle concentrations as low as 10%. Increasing particle concentration increases the yield stress 26 and consistency. We apply our results to show that natural pumice clasts need to have a radius 27 28 greater than about 1 cm in order to settle through hemipelagic sediment on the sea floor. Most recovered pumice clasts from IODP 340 are thus preserved in the same horizon in which they 29 were deposited. 30

31

#### 32 **1 Introduction**

The rheological properties of sediment are influenced by multiple factors including 33 particle concentration, size, size distribution, composition and pore-water salinity (Imran et al., 34 2001). Models for sediment rheology are often based on laboratory characterization of idealized 35 kaolinite and montmorillonite mixtures (e.g. Maar et al., 2001; Baas and Best, 2002; Talling, 36 2013). These idealized mixtures differ from naturally occurring submarine sediment in particle 37 size and distribution as well as composition. However, there are few studies of the rheology of 38 39 natural submarine deposits (e.g., Imran et al., 2001; Locat et al., 2004; Jeong, 2013; Menapace et al., 2019). 40

The composition of the sediment can affect its rheology and cohesive sediments exhibit 41 complex behaviors that are often difficult to characterize (Yang et al., 2014). When materials 42 contain high clay fractions, strong attractive colloidal forces can lead to thixotropic behavior, 43 that is, the viscosity of the material depends on the shear history (Santolo et al., 2005). 44 Thixotropy is caused by a time dependent microstructural evolution of a material. When a shear 45 stress or strain is applied to the material the viscosity decreases (Barnes, 1997). In sediment, this 46 decrease in viscosity could be caused by the particles developing a preferred orientation or by the 47 breakdown of flocs and aggregates which release entrapped fluid and increases the lubrication 48 between the particles (Barnes, 1997; Tregger et al., 2010). However, this evolution is reversible: 49 the longer a material is at rest, the more the microstructure rebuilds until it reaches its initial state 50 again. 51 In addition to the clay fraction, the type of clay can also influence rheology due to 52 differences in cohesion. Smectite and montmorillonite have high cohesion compared to kaolinite 53 and illite. The difference in cohesion affects how easily the microstructure can be broken down. 54 Naturally occurring sediments differ from idealized mixtures because they contain a range of 55

56 sediment sizes, fossils, minerals and clays.

57 Thixotropy is also influenced by salinity and particle concentration. At high salinity, 58 greater than 0.35 g/l to 0.55 g/l, the inter-particle forces are strong enough to favor fast 59 reconstruction of the microstructure, thus making the material strongly thixotropic (Perret et al., 60 1996). Particle concentration also affects the thixotropic behavior of a material. At low particle 61 concentrations, there are fewer interactions between the particles and thixotropic effects are less 62 significant (Santolo et al., 2012). The rheological behavior of sediment has implications for the initiation and flow of submarine sediment-laden density currents. Additionally, seafloor sediment preserves a record of volcanic eruptions in tephra and crypto-tephra layers including isolated cm-sized pumice clasts that record the occurrence of additional volcanic eruptions (le Friant et al., 2013, 2015; Palmer et al., 2016; Jutzeler et al., 2016). These eruptions can be dated using the surrounding sediments but this assumes that the clasts are at the same stratigraphic location and did not settle through underlying sediment upon deposition.

In this study we analyze naturally occurring hemipelagic sediment collected from the 70 71 seafloor adjacent to Lesser Antilles Volcanic Arc. To determine yield stress and consistency as a function of particle concentration a suite of rheometric tests are utilized. The yield stress and 72 consistency of a material depend strongly on the particle concentration. As particle concentration 73 increases, there is an increase in particle-particle interactions, which causes an increase in the 74 friction and thus increases the yield stress and consistency (Coussot and Piau, 1994). We thus 75 use a range of particle concentrations to develop a better understanding of how these natural 76 sediments flow. The same tests are performed on an additional naturally occurring sediment from 77 the Davis-Schrimpf mud volcanoes for further comparison. Additionally, our results are 78 79 compared to previously published measurements on other materials in order to better identify the factors that influence rheology. For illustrative purposes, we use our results to determine the size 80 of particles that would settle through the hemipelagic sediment on the seafloor and hence what 81 82 size particles would be preserved in situ within marine sediments. We use these results to assess whether volcanic dropstones collected by IODP 340 are preserved in situ. 83

84

85 **2 Methods** 

86	The hemipelagic sediment was collected offshore of the Lesser Antilles volcanic arc from
87	a water depth of 2745 meters. The Lesser Antilles volcanic arc is located at the eastern border of
88	the Caribbean plate. The proximity of our sampling location to volcanic islands, specifically the
89	active volcano Montagne Pelée, causes our sample to contain volcaniclastic sediment as well as
90	marine fossils (le Friant et al., 2008). The sample, 340 U1400C 3H 4, was collected during IODP
91	340 from 26 meters below the sea floor from a sedimentary unit that includes multiple landslide
92	deposits (le Friant et al., 2013; Lafuerza et al., 2015; Brunet et al., 2016); see supplementary
93	Figure S1a for a location map. For comparison, another natural mud from the Davis-Schrimpf
94	mud volcanoes located next to the Salton Sea in the Imperial Valley, California is analyzed (map
95	in supplementary Figure S1b). The Salton Sea mud volcanoes are driven by the ascent of $CO_2$
96	from underlying geothermal systems and the mud recirculates within the subsurface plumbing
97	system (Svenson et al., 2009).

#### 99 2.1 Sample Properties

Size distribution is measured using a Sequoia Portable XR Laser Diffraction Particle Size
 Analyzer. The cumulative size distribution for both samples is shown in Figure 1a. The median
 grain size for the hemipelagic sediment is 5.5 microns. Grain density was measured as 2700
 kg/m<sup>3</sup> on the IODP ship using helium pycnometry (le Friant et al., 2013).

104 Particle concentration, the amount of solids in the total mixture, is given by 105  $\phi = \frac{V_s}{V_t}$  (1)

106 where  $V_s$  the volume of solids, and  $V_t$  is the total volume. We measure  $\phi$  by weighing a known 107 volume of material. Uncertainty in  $\phi$  is dominated by uncertainty in measured volume. The 108 density of the hemipelagic sediment was confirmed to be 2700 kg/m<sup>3</sup>.

109	Figure 1b,c shows three dimensional x-ray microtomography reconstructions of the
110	samples imaged at the Advanced Light Source 8.3.2 beamline, Lawrence Berkeley National
111	Laboratory, with a resolution of 1.3 microns/pixel. The hemipelagic marine sediment is poorly
112	sorted and contains large voids (Figure 1b). Additionally, the sediment also contains foraminifera
113	fossils and crystal fragments, such as hornblende, quartz and muscovite, that are large compared
114	to particles in the surrounding matrix. The Salton Sea sediment has a more uniform size
115	distribution by comparison (Figure 1c).
116	Using x-ray diffraction, we determine that the hemipelagic sediment is composed of 20%
117	feldspar and plagioclase, 19% calcite, 16% quartz, 7% aragonite, and 31% clay. The Salton Sea
118	sediment is composed of 41% quartz, 3% dolomite, 16% plagioclase, 8% orthoclase and 26%
119	clay. The clay in both samples contains kaolinite, illite, and montmorillonite while the
120	hemipelagic sediment also contains smectite.
121	
122	<b>3</b> Rheology Measurement Methods
123	We measure the rheology using a HAAKE Rheoscope 1. To ensure uniform strain-rate
124	through the sample a cone and plate geometry, with a 4° cone angle and 60 mm diameter plate, is
125	used. We apply either a controlled angular velocity, and hence a shear rate, and then measure the
126	torque required to maintain this rate, or alternatively apply a torque and measure the resulting
127	deformation.
128	In order to prevent slippage, both the cone and the plate are covered in ANSI 150 grit
129	sand paper (average particle size of 100 microns). The gap size between the plate and the center
130	of the cone was 0.142 mm after adhesion of sand paper. Each test utilizes 8ml of sample. To
131	prevent jamming of particles within the gap, the mud is sieved to remove particles larger than

#### Confidential manuscript submitted to Earth and Space Science Technical Reports: Data

132	100 microns, which comprise less than a few percent of the volume of the sediment. The
133	volumetrically dominant fine particles have a larger controlling influence on the yield stress, so
134	we do not expect that the small number of fossils removed from the sample would alter the
135	rheology (Yu et al., 2013). In order to prevent temperature fluctuations from affecting the
136	measurements, the temperature of the mud is kept constant at 20°C using a Thermo Scientific
137	Haake DC30-K20 Digital Bath. At this temperature water viscosity is 1.05 mPa s compared to
138	1.57 mPa s at a seafloor temperature of 4 °C.
139	The hemipelagic sediment is from a marine setting so we control salinity of the water by
140	adding artificial seawater since the salinity of the water affects suspension rheology (Jeong,
141	2010). 35 grams of Instant Ocean salt mixture is added to 1 liter of water to create salinity
142	similar to that of the Caribbean Sea.
143	The thixotropic nature of the sediment led us to focus on the static yield stress, above
144	which the material will start to flow, and the dynamic yield stress, below which the material will
145	no longer flow. Two separate tests are performed: the first to quantify the static yield and the

second to determine the dynamic yield and consistency.

147

#### 148 **3.1 Flow Characteristics**

In order to characterize rheology we consider an idealized constitutive model. The most
frequently used model to describe naturally occurring sediments and muds is the HerschelBulkley model (Huang and Garcia, 1998):

152 
$$\tau = \tau_y + K \dot{\gamma}^n \tag{2}$$

where  $\tau$  is shear stress,  $\tau_y$  is the yield stress,  $\dot{\gamma}$  is strain rate, *K* is consistency, and *n* is the flow index. We adopt the Herschel-Bulkley model, but note that models without a yield stress have also been used to model mud rheology especially for low strain rates and high viscosities (e.g.,
Menapace et al., 2019).

During the measurements, it became apparent that both materials did not simply follow 157 the Herschel-Bulkley model (Supplementary Figure S2) as has been documented previously 158 (e.g., Yang et al., 2014). Different stresses are measured when applying increasing and 159 160 decreasing strain rates, indicating that the properties are history dependent, one signature of thixotropic rheology (Moller et al., 2009) (Supplementary Figure 2b). This leads to the static 161 yield stress, which is associated with the start of flow, being higher than the dynamic yield stress, 162 below which the material will stop flowing, due to the static yield stress having to breakdown the 163 microstructure that has formed while the material was at rest. The microstructure breakdown is 164 reversible; if the material is left at rest, the yield stress will increase again (Moller et al., 2009). 165 There are models that quantify the evolving microstructure (e.g., Dullaert and Mewis, 2006; de 166 Souza Mendes, 2009), however for this study we focus on the static yield stress and the dynamic 167 yield stress. Consistency is analogous to viscosity, and is also quantified prior to the cessation of 168 flow. 169

170

#### 171 3.2 Static Yield

Thixotropic fluids have a viscosity that decreases over time as they are sheared. To mitigate the variations in shear history, samples are allowed to rest for ten minutes between each test (Van Kessel and Blom, 1998). After running hysteresis tests at varying time intervals between tests, the material recovers most of its strength after 10 minutes. Ten minutes limits the amount of evaporation of water and settling of particles so as to not affect measurements. Static yield is measured using a controlled stress mode while the sample was maintained at a constant

178	temperature. For this controlled stress mode, an increasing shear stress, $\tau$ , or torque, is applied
179	and the resulting deformation is measured (Supplementary Figure S2a). Shear stress is increased
180	linearly in 70 steps from 0 Pa to 1500 Pa, for 10 seconds each step. Initially, strain increases
181	linearly with stress, however with further increases of stress the strain grows exponentially fast
182	and is immeasurable after a certain shear stress. The location of this exponential increase varied
183	with each test depending on the water content. To calculate static yield stress a Herschel-Bulkley
184	model is fit to the data from increasing portion of the test, providing $\tau_y$ , <i>K</i> , and <i>n</i> .
185	
186	3.3 Dynamic Yield
187	In order to determine the dynamic yield stress and the consistency, a shear strain rate, $\dot{\gamma}$ ,
188	is applied and the torque, or shear stress, $\tau$ , required to maintain this strain rate is measured.
189	Strain rate is increased in 40 steps uniformly spaced in the log of strain rate from 0.01 s <sup>-1</sup> to 1.5 s
190	<sup>1</sup> , and subsequently decreased in the same 40 steps, with each step lasting 15 seconds
191	(Supplementary Figure S3 shows results for two different particle concentrations). To determine
192	the dynamic yield stress and consistency, the decreasing portion of the test is fit with a Bingham
193	model.
194	
195	4 Results
101	

Figure 2a shows the relationship between particle concentration (%) and yield stress (Pa) for our samples compared to other studies. For the hemipelagic sediment and Salton Sea mud, the filled circles show static yield stress and the open circles show dynamic yield stress. Table 1 summarizes the results for our study and Supplementary Table 1 summarizes comparative studies. In our samples the dynamic yield stress is always lower than the static yield stress, with the exception of the Salton Sea mud at a concentration of 40.5%. This exception could be the result of sedimentation within the sample that allowed the material to start flowing at a lower static yield stress. In addition to measuring the static yield using a controlled stress mode, we can estimate the static yield from the inflection point of the increasing strain rate portion of the dynamic yield tests (Santolo et al., 2012), and the two separately determined yield stresses are similar.

A yield stress becomes apparent in the hemipelagic sediment at a particle concentration of ~10% and increases with increasing particle concentration. Figure 2a also shows the yield stress as a function of particle concentration measured in other studies (Coussot and Piau, 1994; Coussot et al., 1996; Huang and Garcia, 1998; Matel et al., 2005; Remaitre et al., 2005; Maciel et al., 2009; Santolo et al., 2010; Blasio et al., 2010; Manga and Bonini, 2012; Jeong et al., 2013; Yang et al., 2014; Tran et al., 2014). In Figure 2, non-natural sediments are represented with squares.

To determine the yield stress as a function of particle concentration, the hemipelagic data is fit with the model developed by Mueller et al. (2009):

216 
$$\tau_y = \tau^* \left( \left( 1 - \frac{\phi}{\phi_m} \right)^{-2} - 1 \right)$$
(3)

where  $\tau^*$  is a fitting parameter,  $\phi$  is the particle concentration,  $\phi_m$  is the maximum particle concentration. The fit of the Mueller et al. (2009) model to the hemipelagic static yield data is shown in Supplementary Figure 4. We find  $\tau^* = 34.9 \pm 6.9$  Pa and  $\phi_m = 0.23 \pm 0.004$ .

220 Consistency also increases with increasing particle concentration. Following Mader et al.
221 (2013), the hemipelagic data is fit to the model:

222 
$$K_r = \left(1 - \frac{\phi}{\phi_m}\right)^{-2} \tag{4}$$

where  $K_r = K/\mu_0$  where  $\mu_0$  is viscosity of the suspending fluid (Pa•s) (Supplementary Figure 5). We find  $\phi_m = 0.25 \pm 0.02$  Pa and  $\mu_0 = 0.14 \pm 0.05$  Pa s.

225

#### 226 **5 Discussion**

Both the static and dynamic yield tests indicate that the hemipelagic sediment is 227 thixotropic. In the dynamic tests, there is a significant difference between the increasing strain 228 rate section and the decreasing strain rate section (Supplement 2b). This indicates that the 229 material has a history dependence in its rheology and hence its microstructure. The higher the 230 particle concentration, the more dramatic this hysteresis. In the static yield tests, the material 231 initially behaves like a linear elastic material until a specific stress is overcome and then the 232 strain exponentially increases until the material reaches another critical point and flows too fast 233 for the rheometer to measure (Supplement 2a). Coussot et al. (1992) similarly found that the 234 response of their clay-rich material is essentially elastic until a critical point is reached and the 235 flow becomes unstable and fast. This behavior indicates that the material is initially structured, 236 but when the apparent yield stress is overcome the sediment becomes unstructured and starts to 237 flow at increasing velocities. Alignment of particles with the flow causes the material to flow 238 faster when a shear is applied (Barnes, 1997). Additionally, the static yield stress is significantly 239 larger than the dynamic yield stress, which is consistent with thixotropic behavior (Figure 2). 240

The scatter within our data could be caused by the history dependence of our samples due to slightly different handling of the material prior to testing. We tried to mitigate this effect by allowing the samples to rest between tests and by loading the samples into the rheometer in the same way. The scatter could additionally be caused by heterogeneities within the natural sample as each data point was obtained from a different aliquot of the mud.

The range of particle concentrations over which a yield stress can be measured for the 246 hemipelagic sediment is approximately between 10-20%. Below a concentration of 10% the 247 particles settle creating a muddy fluid top layer and particle rich layer underneath. Comparing 248 the results with other studies that used sediment suspensions, the hemipelagic marine sediment is 249 able to develop a static stress at comparatively low particle concentrations (Figure 2a). 250 251 Additionally, other studies that measured yield stresses at low particle concentrations were kaolinite and water mixtures produced in the lab (Figure 2a – laboratory produced mixtures are 252 represented with squares). 253

The clay content in the hemipelagic sediment is in the higher range compared to the other 254 studies shown in Figure 2a, although not all studies record clay content. The hemipelagic 255 sediment has approximately 31% clay, which could be one of the contributing factors to why 256 there is a yield stresses at such low particle concentrations. Huang and García (1998) measure a 257 yield stress at lower concentration, approximately 7%, but do not record the clay content of the 258 sample they used. The higher clay content increases electrostatic forces between the clay 259 particles. Yu et al. (2013) found that increasing the clay content from approximately 10% to 40%260 clay increased the yield stress by more than an order of magnitude, consistent with Jeong (2013) 261 who reported the highest clay content and similarly large yield stresses. While both the 262 hemipelagic sediment and Salton Sea mud have kaolinite, illite, montmorillonite, the 263 hemipelagic sediment also contains smectite, which is highly cohesive. The addition of this clay 264 265 type could also contribute to the higher yield stress and more thixotropic behavior compared to the Salton Sea mud. The yield stress of the hemipelagic sediment is also more than an order of 266 267 magnitude larger than kaolinite suspensions with similar particle concentrations suggesting that

the presence of sinectite is largery responsible for the higher yield stress (in Figure 2, compare
Huang and Garcia (1998) and Maciel et al. (2009) data with the present measurements).
The salinity of the hemipelagic marine sediment, at 35 g/l, is well above the salinity that
Perret et al. (1996) identify as influencing rheology. Above this salinity, there is fast
reconstruction of the microstructure, and below the material is likely to favor slower
reconstruction. Yang et al. (2014), however, found no effect on rheology of salinity in the range
of fresh water to 50 g/L salinity. Using the method outlined by Perret et al. (1996) to determine
the thixotropic nature of a material, the area between the hemipelagic sediment thixotropy test
curves is larger than that of the Salton Sea sediment, indicating that the hemipelagic material is
slower to recover back to its initial state. This indicates that the clay content has a larger effect
than salinity for the two samples we considered.
Materials with high clay contents have a slow rate of reconstruction, increasing their
recovery time (Barnes 1997). This is also the case for the two samples we considered. While the
Salton Sea mud has a significant portion of clay, the median particle size of the hemipelagic
sediment is much smaller at 5.5 microns, compared to the Salton Sea sediment 35.7 microns,

### 285 **5.1 Particle Settling through seafloor sediment**

which could account for the difference in recovery times.

Hemipelagic sediment often contains isolated "dropstones" delivered by melting icebergs or volcanic eruptions; in the case of sediments offshore the Lesser Antilles volcanic arc, these are predominately pumice clasts, deposited from rafts of pumice or fall out. Whether these clasts are preserved within their deposit or subsequently sink multiple clast diameters through underlying layers depends on their size and weight. In order to determine whether a larger particle with radius  $R_0$  can settle within mud, we approximate the clast as a completely submerged sphere. The force is

293 
$$F = \frac{4}{3}\pi(\rho_s - \rho)R_0^3 g$$
(5)

where  $\rho_s$  is the density of the sphere (kg/m<sup>3</sup>),  $\rho$  is the density of the mud,  $R_0$  is the radius of the sphere (m), and g is gravity (m/s<sup>2</sup>). The density of the sediment depends on the particle concentration (C<sub>v</sub>),  $\rho$ =1800·C<sub>v</sub>+1000 kg/m<sup>3</sup>. The sphere will cause yielding of the mud and sink when the yield stress parameter

298 
$$Y_g = \frac{2\tau_y \pi R_0^2}{F}$$
 (6)

exceeds a critical value of 0.143 (Beris et al., 1985). Pumice is porous, between 60-80% 299 porosity, and at the bottom of the seafloor these pores will be filled with water. The mean 300 density was calculated assuming 60% porosity and using a glass density of 2700 kg/m<sup>3</sup>. We use a 301 dynamic yield stress because we assume the clasts are initially moving when they reach the 302 303 seafloor. Using equation (6) and equation (3) to determine the yield stress as a function of particle concentration, we calculate the relationship between the particle concentration and the 304 radius of a clasts that would settle through the sediment (Figure 3). Below this radius, clasts 305 306 would not settle but instead be preserved in situ. Using an average mud concentration at the seafloor of 10% (Hamilton, 1976) a pumice clast would have to have a radius larger than about 307 1 centimeter to settle through uncompacted hemipelagic sediment. Most of the various volcanic 308 dropstones collected during IODP 340 (le Friant et al., 2013; Jutzeler et al., 2016) are thus in 309 310 place and their stratigraphic locations record the time of eruptions.

311

#### 312 6 Conclusion

By studying the rheology of a naturally occurring mud we can better discern some of the 313 influencing factors in rheology and thixotropic behavior. Particle concentration affects the yield 314 stress and consistency, with increasing particle concentrations leading to increasing yield stresses 315 and consistency. As particle concentration increases, the thixotropic behavior also increases and 316 the material becomes more history dependent. The particle concentration of the material also 317 318 dictates the sizes of clasts that can settle through seafloor sediment. Pumice clasts would need radii greater than ~1 cm to settle through the hemipelagic sediment, indicating that most pumice 319 clasts collected in IODP 340 are stratigraphically in place. Finally, the high smectite clay content 320 in the hemipelagic sediment leads to more attractive colloidal forces in the sample and appears to 321 influence the yield stress and enhance the thixotropic nature of the material. 322

323

#### 324 7 Acknowledgements

This research used samples provided by the Integrated Ocean Drilling Program (IODP). Funding 325 for this research was provided by a Post Expedition Activity award. We thank ANR-13-BS06-326 0009, Labex UnivEarth and Interreg Caraibes PREST for funding. The dedication and hard work 327 of entire staff and scientific party on the Joides Resolution contributed to the sampling and 328 analyses that made the present measurements possible, in particular O. Ishizuka, and staff 329 scientists N. Stroncik and A. Klaus. Additional support was provided from the National Science 330 Foundation. Aaron Tran and Max Rudolph helped with the sampling and analysis of the Salton 331 332 Sea muds. Laurel Larson provided the particle size analyzer. Dula Parkinson guided the XRay tomography and reconstruction, and beamtime was provided by the ALS at LBNL. Tim Teague 333 334 performed the XRD measurements and analysis. Rheologic measurements are available on

https://github.com/eknappe/rheology\_tech\_reports. We thank two reviewers for constructive 335

336 comments and suggestions.

337

338	8 References			
339	Baas, J. H., Best, J. L. 2002, Turbulence modulation in clay-rich sediment-laden flows and some			
340	implications for sediment deposition. Journal of Sedimentary Research, Vol 72, No. 3.			
341				
342	Barnes, H. A. 1997, Thixotropy — a review. Journal of Non-Newtonian Fluid Mechanics, Vol.			
343	70, pp. 1-33.			
344	Beris, A. N., Tsamopoulos, J. A., Armstrong, R. C., Brown, R. A. 1985, Creeping motion of a			
345 346	sphere through a Bingham plastic. Journal of Fluid Mechanics, Vol. 158, pp. 219-244.			
340	Blasio F. V. Breien H. Elverhai A. 2011 Modelling a cohesive frictional debris flow: an			
347	evnerimental theoretical and field-based study. Earth Surface Processes and Landforms			
3/0	Vol. 36 np. 753-766			
349	voi. 50, pp. 755-700.			
351	Brunet M. A. Le Friant G. Boudon, S. Lafuerza, P. Talling, M. Hornbach, O. Ishizuka, F.			
357	Lebas H. Guyard and IODP Expedition 340 Science Party (2016) Composition			
352	geometry and emplacement dynamics of a large volcanic island landslide offshore			
354	Martinique: From volcano flank- collanse to seafloor sediment failure? Geochem			
355	Geophys Geosyst 17-3 699–724 doi:10.1002/2015GC006034			
356	000phys. 000syst., 17 5, 077 724, 001.10.1002/201500000054.			
357	Coussot P. Leonov, A. L. Piau, I. M. 1992. Rheologic modeling and neculiar properties of			
358	some debris flows. Proceedings of International Symposium on Frosion. Debris Flows and			
359	Environment in Mountain Regions, I.A.H.S. Publication 209, pp. 207-216.			
360				
361	Coussot, P., Piau, J. M. 1994, On the behavior of fine mud suspensions. Rheologica Acta, Vol.			
362	33, pp. 175-184.			
363				
364	Coussot, P., Proust, S., Ancey, C. 1996, Rheological interpretation of deposits of yield stress			
365	Fluids. Journal of Non-Newtonian Fluid Mechanics, Vol. 66, pp. 55-70.			
366				
367	de Souza Mendes, P. R. 2009, Modeling the thixotropic behavior of structured fluids. Journal of			
368	Non-Newtonian Fluid Mechanics, Vol. 164, pp. 66-75.			
369				
370	Dullaert, K., Mewis, J. 2006, A structural kinetics model for thixotropy. Journal of Non-			
371	Newtonian Fluid Mechanics, Vol. 139, pp. 21-30.			
372				
373	Hamilton, E. L. 19/6, Variations of density and porosity with depth in deep-sea sediments.			
374	Journal of Sedimentary Petrology, Vol. 46, pp. 280-300.			
375				
376 377	Huang, X., Garcia, M. H. 1998, A Herschel-Bulkley model for mud flow down a slope. Journal of Fluid Mechanics, Vol. 374, pp. 305-333.			

378

379 380 381	Imran, J., Parker, G., Locat, J., Lee, H. 2001, 1D Numerical model of muddy subaqueous and subaerial debris flows. Journal of Hydraulic Engineering, Vol. 127, pp. 959-968.
382 383 384	Jeong, S. W. 2010, Grain size dependent rheology on the mobility of debris flows. Geoscience Journal, Vol. 14, pp. 359-369.
385 386 387	Jeong, S. W. 2013, Determining the viscosity and yield surface of marine sediments using modified Bingham models. Geosciences Journal, Vol. 17, pp. 241-247.
388 389 390 391 392	Jutzeler, M., M. Manga, J.D.L. White, P.J. Talling, A.A. Proussevitch, S.F.L. Watt, M. Cassidy, R.N. Taylor, A. Le Friant, and O. Ishizuka (2016) Submarine deposits from pumice-rich pyroclastic density currents dispersing over water: an outstanding example from offshore Montserrat (IODP 340), <i>Bulletin of the Geological Society of America</i> , doi: dx.doi.org/20.1130/B31448.1
<ul> <li>393</li> <li>394</li> <li>395</li> <li>396</li> <li>397</li> <li>398</li> <li>399</li> </ul>	<ul> <li>Lafuerza S., A. Le Friant, M. Manga, G. Boudon, B. Villemant, N. Stroncik, B. Voight, M. Hornbach, O. Ishizuka and the Expedition 340 Scientific Party. 2014, Geomechanical characterizations of submarine volcano flank sediments, Martinique, Lesse Antilles Arc. S. Krastel et al., (Eds.), Sumarine mass movements and consequences, <i>Advances in Natural and Technological Hazards Research</i>, Springer Inten. Publishing, Switzerland, 2014, 37, 73-81, doi 10.1007/978-3-319-00972-8_7.</li> </ul>
400 401 402 403 404	Le Friant, A., Lock, E.J., Hart, M.B., Boudon, G., Sparks, R.S.J., Leng, M.J., Smart, C.W., Komorowski, J.C., Deplus, C., Fisher, J.K. 2008, Late Pleistocene tephrochronology of marine sediments adjacent to Montserrat, Lesser Antilles volcanic arc. Journal of rthe Geological Society, London, (London, U. K.), Vol. 165, pp. 279–289.
404 405 406 407 408	Le Friant, A., Ishizuka, O., Stroncik, N. A., and the Expedition 340 Scientists 2013, Lesser Antilles Volcanism and Landslides, Integrated Ocean Drilling Program Expedition 340 Preliminary Report, doi:10.2204.iodp.pr.340.2012.
408 409 410 411 412 413 414 415 416 417 418 419	<ul> <li>Le Friant, A., Ishizuka, O., Boudon, G., Palmer, M.R., Talling, P., Villemant, B., Adachi, T., Aljahdali, M., Breitkreuz, C., Brunet, M., Caron, B., Coussens, M., Deplus, C., Endo, D., Feuillet, N., Fraas, A.J., Fujinawa, A., Hart, M. B., Hatfield, R.G., Hornbach, M., Jutzeler, M., Kataoka, K. S., Komorowski, J-C., Lebas, E., Lafuerza, S., Maeno, F., Manga, M., Martínez-Colón, M., McCanta, M., Morgan, S., Saito, T., Slagle, A., Sparks, S., Stinton, A., Stroncik, N., Subramanyam, K. S.V., Tamura, Y., Trofimovs, J., Voight, B., Wall-Palmer, D., Wang, F., Watt, S.F.L. 2015, Submarine record of volcanic island construction and collapse in the Lesser Antilles arc: First scientific drilling of submarine volcanic island landslides by IODP Expedition 340. <i>Geochem., Geophys., Geosyst, 16</i>, 2, 420-442.</li> </ul>
420 421 422	Locat, J, Lee, H.J., Locat, P., Imran, J. 2004, Numerical analysis of the mobility of the Palos Verdes debris avalanche, California, and its implication for the generation of tsunamis. Marine Geology, Vol. 203, pp. 269-280.

424 425 426 427	Maciel, G. F., Santos, H. K., Ferreira, F. O. 2009, Rheological Analysis of water clay compositions in order to investigate mudflows developing in canals. Journal of the Brazil Society of Mechanical Science and Engineer, 31, 64-74.
427 428 429 430	Mader, H.M., Llewellin, E. W., Mueller, S. P. 2013, The rheology of two-phase magmas: A review and analysis. Journal of Volcanology and Geothermal research, 257, 135-158.
431 432 433	Malet, J.P., Laigle, D., Remaitre, A., Maquaire, O. 2005, Triggering condition and mobility of debris flows associated to complex earthflow. Geomorphology, 66, 215-235.
433 434 435	Manga, M., Bonini, M. 2012, Large historical eruptions at subaerial mud volcanoes, Italy. Natural Hazards and Earth System Science, Vol. 12, pp. 3377-3386.
436 437 438 439	Menapace, W., Tangunan, D., Maas, M., Williams, T., Kopf, A. 2019, Rheology and biostratigraphy of the Maraian serpentine muds unravel mud volcano evolution. Journal of Geophysical Research, Vol. 124, doi.org/10.1029/2019JB018265.
440 441 442 443	Marr, J. G., Harff, P.A., Shanmugam, G., Parker, G. 2001. Experiments on subaqueous sandy gravity flows: The role of clay and water content in flow dynamics and depositional structures. GSA Bulletin, Vol. 113, No. 11, 1377-1386.
444 445 446 447	Moller, P., Fall, A., Chikkadi, V., Derks, D., Bonn, D. 2009, An attempt to categorize yield stress fluid behavior. Philosophical Transactions of the Royal Society, Vol. 367, pp. 5139-5155.
448 449 450 451	Mueller, S., Llewellin, E. W., Mader, H. M. 2009, The rheology of suspensions of solid particles. Proceedings of the Royal Society, Vol. 446, pp. 1201-1228.
452 453 454 455 456	Palmer, M., Hatter S.J., Gernon T.M., Taylor, R.N., Cassidy M., Johnson P., Le Friant A., Ishizuka, O., 2016, Discovery of a large 2.4 Ma Plinian eruption of Basse-Terre, Guadeloupe, from the marine sediment record. Geology, 44-2, 123-126, doi:10.1130/G37193.1
450 457 458 459	Perret, D., Locat, J., Martignoni, P. 1996, Thixotropic behavior during shear of a fine-grained mud from Eastern Canada. Engineering Geology, Vol. 43, pp. 31-44.
460 461 462 463	Remaitre, Al., Matel, J.P., Maquaire, O., Ancey, C., Locat, J. 2005, Flow behavior and runout modeling of a complex debris flow in a clay-shale basin. Earth Surface Processes and Landforms, 30, 479-488.
464 465 466	Santolo, A. S., Evangelista, A. 2005, Some observations on the prediction of the dynamic parameters of debris flows in pyroclastic deposits in the Campania region of Italy. Natural Hazards, Vol. 50, pp. 605-622.
467 468 469	Santolo, A. S., Pellegrino, A. M., Evangelista, A. 2010, Experimental study on the rheologic behavior of debris flow. Natural Hazards Earth System Science, Vol. 10, pp. 2507-2514.

470	
471	Santolo, A. S., Pellegrino, A. M., Evangelista, A., Coussot, P. 2012, Rheologic behavior of
472	reconstituted pyroclastic debris flow. Geotechnique, Vol. 62, pp. 19-27.
473	
474	Svensen, H., Hammer, O., Mazzini, A., Onderdonk, N., Polteau S., Planke, S., Podladchikov,
475	Y.Y. 2009, Dynamics of hydrothermal seeps from the Salton Sea geothermal system
476	(California, USA) constrained by temperature monitoring and time series analysis.
477	Journal of Geophysical Research, Vol. 114, B09201, doi:10.1029/2008JB006247.
478	
479	Talling, P. J. 2013, Hybrid submarine flows comprising turbidity current and cohesive debris
480	flow: Deposits, theoretical and experimental analyses and generalized models.
481	Geosphere, Vol. 9, No. 3, doi: 10.1130/GES00793.
482	
483	Tran. A., Rudolph, M.L., Manga, M. 2014, Bubble mobility in mud and yield stress fluids.
484	submitted to Journal of Volcanology and Geothermal Research
485	submitted to volume of volcanology and Geotherman Research.
486	Treager N.A. Pakula M.F. Shah S.P. 2010 Influence of clays on the rheology of cement
187	nastes Cement and Concrete Research Vol 40 nn 384-391
188	pastes. Cement and Concrete Research, vol. 40, pp. 504-571.
480	Van Kessel T and Blom C 1998 Rheology of cohesive sediments: comparison between anatural
400	and an artificial mud Journal of Hydraulic Research Vol. 36, pp. 501, 612
490	and an artificial mud. Journal of Hydraune Research, vol. 30, pp. 391–012
491	Yang, W.Y., Yu, GL. Tan, S., Wang, H.K. 2014, Rheological properties of dense natural
492	cohesive sediments subject to shear loadings. International Journal of Sediment Research.
493	Vol. 29. pp. 454-470.
494	
495	Yu. B., Ma. Y., Oi, X. 2013. Experimental study on the influence of clay mineral on the yield
496	stress of debris flows. Journal of Hydraulic Engineering. Vol. 139, pp. 364-373.
497	Saless of acons no we counter of thy araane Engineering, von 159, pp. 50 v 575
498	
499	<b>Figure 1</b> , a) The mean cumulative size distribution of the sediments. The hemipelagic sediment
500	shown in blue is the average of four tests and the Salton Sea sediment shown in red is the
501	average of two tests b) 3-D microtomography reconstructions of the materials Reconstruction of
502	the heminelagic sediment which is noorly sorted and contains large fossils () Reconstruction of
502	the Salton Sea sediment, which is much more uniform in size than the heminelagic sediment
503	the Sanon Sea sediment, which is much more dimorn in size than the hemperagic sediment.
504	Figure 2 a) Viald strong as a function of nortical concentration from multiple different studies
505	<b>Figure 2.</b> a) Field stress as a function of particle concentration from multiple different studies,
506	b) consistency as a function of particle concentration from multiple different studies. Clay
507	contents snown in numbers next to the respective data when reported. For our measurements,
508	open symbols snow static yield stress and filled symbols snow dynamic yield stress. All data in
509	Table I and Supplementary Table I.
510	
511	<b>Table 1.</b> The hemipelagic sediment and Salton Sea sediment measured in this study. Includes the
512	parameters used to fit the Herschel-Bulkley model. Data plotted in Figure 2.
513	
514	Figure 3. Particle concentration of hemipelagic sediment and the clast radius that would exceed
515	the yield stress parameter defined by Beris et al. (1985). For radii above the blue curve, clasts

- will settle through the hemipelagic marine sediment. Clasts are approximated as spheres of density 1.65 g/cm<sup>3</sup>. 516
- 517

Figure 1.



Figure 2.



Sample	Particle Concentration (%)	Dynamic Yield (Pa)	Consistency (Pa·s)	Static Yield (Pa)
Hemipelagic Marine	19.4 ± 1.1%	701.9 ± 2.6	126.4 ± 5.8	1440.9 ± 1.5
Sediment	17.8 ± 0.8%	111.4 ± 2.8	71.1 ± 4.1	634.2 ± 17.4
	16.9 ± 2.5%	218.1 ± 2.1	104.8 ± 3.5	445.3 ± 13.9
	12.4 ± 1.1%	39.8 ± 0.2	$15.5 \pm 0.6$	265.3 ± 3.2
	15.1 ± 1.1%	56.3 ± 0.7	35.5 ± 2.2	211.1 ± 9.4
	10.4 ± 0.9%	66.5 ± 0.3	20.0 ± 0.9	173.1 ± 5.6
	9.9 ± 0.9%	20.5 ± 0.6	8.9 ±1.4	108.1 ± 7.3
	10.1 ± 1.2%	18.3 ± 0.5	$13.1 \pm 1.0$	53.3 ± 3.9
Salton Sea Mud Volcano	44.2 ± 1.45%	769.1 ± 3.0	95.4 ± 22.3	1247.8 ± 2.6
	42.9 ± 1.6%	353.6 ± 0.7	125.1 ± 1.9	893.4 ± 0.2
	41.7 ± 1.6%	291.1 ± 0.8	$11.4 \pm 4.7$	458.3 ± 0.9
	40.5 ± 1.6%	189.4 ± 0.9	15.5 ± 8.2	229.7 ± 11.1
	40.5 ± 1.8%	145.3 ± 0.5	9.3 ± 4.9	55.8 ± 20.1

Density (g/cm^3)	% Clay	n
1.34	31	3.5
1.31	31	3.5
1.29	31	3.5
1.22	31	3.5
1.27	31	4.5
1.18	31	3.5
1.17	31	3.6
1.18	31	3.5
1.76	26	3.5
1.73	26	3.5
1.7	26	3.5
1.67	26	3.5
1.68	26	3.5

Figure 3.

