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Large historical eruptions at subaerial mud volcanoes, Italy

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Abstract. Active mud volcanoes in the northern Apennines, Italy, currently have gentle eruptions. There are, however, historical accounts of violent eruptions and outbursts. Evidence for large past eruptions is also recorded by large decimeter rock clasts preserved in erupted mud. We measured the rheological properties of mud currently being erupted in order to evaluate the conditions needed to transport such large clasts to the surface. The mud is well-characterized by the Herschel-Bulkley model, with yield stresses between 4 and 8 Pa. Yield stresses of this magnitude can support the weight of particles with diameters up to several mm. At present, particles larger than this size are not being carried to the surface. The transport of larger clasts to the surface requires ascent speeds greater than their settling speed in the mud. We use a model for the settling of particles and rheological parameters from laboratory measurements to show that the eruption of large clasts requires ascent velocities $> 1\,\mathrm{m\,s^{-1}}$, at least three orders of magnitude greater than during the present, comparatively quiescent, activity. After regional earthquakes on 20 May and 29 May 2012, discharge also increased at locations where the stress changes produced by the earthquakes would have unclamped feeder dikes below the mud volcanoes. The magnitude of increased discharge, however, is less than that inferred from the large clasts. Both historical accounts and erupted deposits are consistent in recording episodic large eruptions.

1 Introduction

Mud volcanoes are features that erupt from depth mixtures of water, fine sediment, and gas. Their eruption rates and temperatures are considerably lower than those of magmatic volcanoes. Hence the hazard mud volcanoes pose is primarily local. There are notable exceptions, however. The Lusi mud flow in Indonesia has been erupting from May 2006 until present, with peak discharge of $180\,000\,\mathrm{m^3\,day^{-1}}$ (Mazzini et al., 2007), $> 40\,000$ people displaced, and economic losses that may exceed $4B US (Richards, 2011). It is expected to continue erupting for years (Rudolph et al., 2012) to decades (Davies et al., 2011; Rudolph et al., 2011).

Discharge is not steady over long time scales. Occasional outbursts at subaerial mud volcanoes can discharge $10^6\,\mathrm{m^3}$ of mud and rock fragments in a day (Tingay, 2010), and up to 500 million $\mathrm{m^3}$ of flammable, self-igniting methane in a few hours (Kopf, 2002). The reasons for outbursts and unsteady eruption are not known. Cyclicity may arise from feedbacks between the mud sources and its ascent (Zoporowski and Miller, 2009). Local and regional earthquakes with large enough magnitude have also been shown to increase eruption rate or initiate new eruptions (Mellors et al., 2007; Manga et al., 2009; Bonini, 2009). However, violent eruptions can also occur in the absence of seismicity (Bonini, 2009).

Here we estimate the prehistoric eruption rates at mud volcanoes in the northern Apennines, Italy. The deposits at these features sometimes contain rock fragments with dimensions greater than tens of centimeters, much greater than the particle sizes currently being carried to the surface. We use the observation of large clasts preserved in erupted mud along with measurements of mud rheology, to calculate the ascent speed of mud that is needed to bring these clasts to the surface. We infer eruption rates at least a few orders of magnitude greater than at present. At present the mud volcanoes are tourist attractions, drawing tens of thousands of visitors each year (Castaldini et al., 2005). Past eruptions of the inferred magnitude, however, damaged local property, covered roads, and greatly increased turbidity in streams. They have the ability to be local natural hazards.

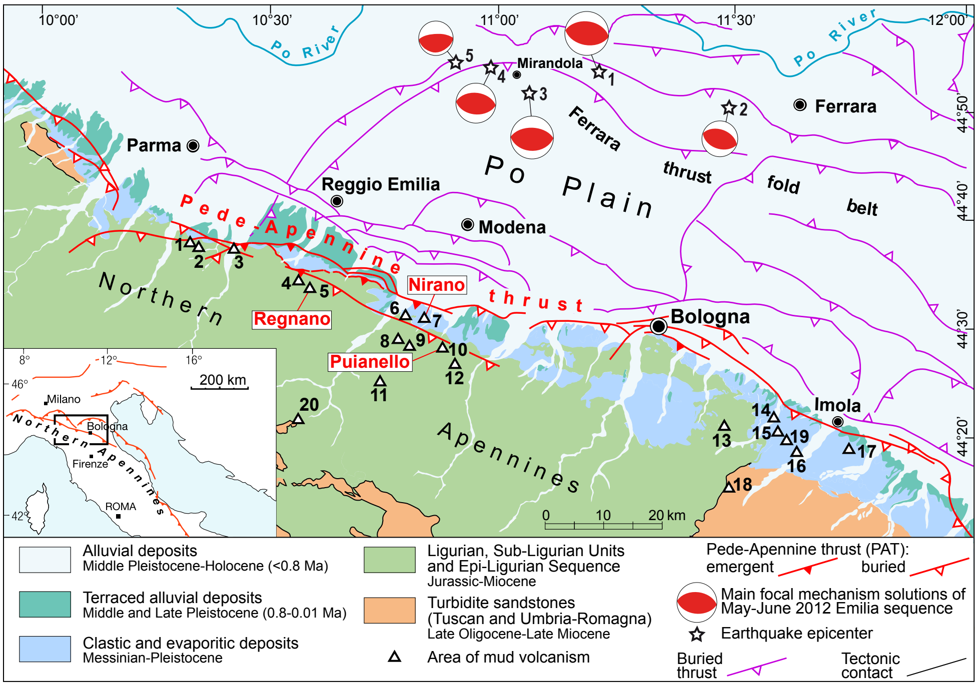

Fig. 1. Location and geological setting of the mud volcanoes of the northern Apennines. 1, Rivalta; 2, Torre; 3, San Polo d'Enza; 4, Casola-Querzola; 5, Regnano; 6, Montegibbio; 7, Nirano; 8, Montebaranzone; 9, Centora; 10, Puianello; 11, Canalina; 12, Ospitaletto; 13, Dragone di Sassuno; 14, S. Martino in Pedriolo; 15, Sellustra valley; 16, Casalfiumanese; 17, Bergullo; 18, Cà Rubano; 19, Pedriaga; 20, Macognano. Focal mechanism solutions of earthquakes with $M > 5$ of the May–June 2012 Emilia seismic sequence are reported (from INGV, 2012a); numbers indicate earthquake chronology: 1, $M = 5.9$ depth 6.3 km (20 May 2012); 2, $M = 5.1$ depth 4.7 km (20 May 2012); 3, $M = 5.8$ depth 10.2 km (29 May 2012); 4, $M = 5.3$ depth 6.8 km (29 May 2012); 5, $M = 5.1$ depth 9.2 km (03 June 2012). Epicentral distance of mud volcanoes: $M_w = 5.9 - 6$ 20 May 2012: Nirano, 52 km; Puianello, 55 km; Regnano, 63 km. $M_w = 5.8$ 29 May 2012: Nirano, 42 km; Puianello, 46 km; Regnano, 52 km.

2 Field setting

Mud volcanoes occur along the Pede-Apennine margin of the northern Apennines, a feature separating the exposed thrust wedge from the topographically flat Po Plain (Fig. 1). The Pede-Apennine margin corresponds to a system of SSW-dipping thrust faults referred to as the Pede-Apennine thrust (e.g., Bonini, 2012). The mud volcanoes occur above the hanging wall of the active Pede-Apennine thrust, and thus have their origin in the deformation associated with this regional structure. Active thrusts are also buried in the Po Plain beneath a Late Miocene–Quaternary clastic sedimentary sequence that may exceed 7–8 km in thickness (Pieri and Groppi, 1981). The mud volcano emissions cluster in subsided areas extending up to 0.6–0.7 km^2. The typical conical extrusive edifices have relatively small dimensions, their height rarely exceeding 3 m; in the past, some edifices reached 6–7 m (or more) in height.

Historical chronicles report that the Pede-Apennine mud volcanoes experienced several large eruptions. Famous is the 91 BC eruption mentioned by Plinius that presumably occurred at the Montegibbio mud volcano (currently almost extinct) nearly contemporaneous with the strong earthquake that struck the nearby Po Plain (Spallanzani, 1795). Dé Brignoli di Brunnhoff (1836) described in detail the eruption of 4 June 1835, which may exemplify the many other violent eruptions that occurred at the same locality. More specifically, following the local earthquake and subsequent outburst, mud and rock fragments of variable dimensions were thrown ~ 40 m up into the air and a smoke column with flames and sparks accompanied the eruption.

2.1 Material erupted at mud volcanoes

Mud was collected from three of the mud volcanoes shown in Fig. 1: Nirano (cones "A" and "B"), Regnano and Puianello (Fig. 2). Paroxysmal events have been reported for these mud volcanoes as well. Regnano has been the most active, with at least 22 eruptions or episodes of anomalous activity since 1754 (Bonini, 2009).

Ferrari and Vianello (1985) used X-ray diffraction to study the composition of mud (size fraction $< 2\,\mu$m) erupted at the Pede-Apennine mud volcanoes, including those considered here. They identified illite, chlorite, kaolinite, and smectite (and other unidentifiable minerals). Illite was the dominant mineral in all mud volcanoes (53 % at Nirano, 60 % at

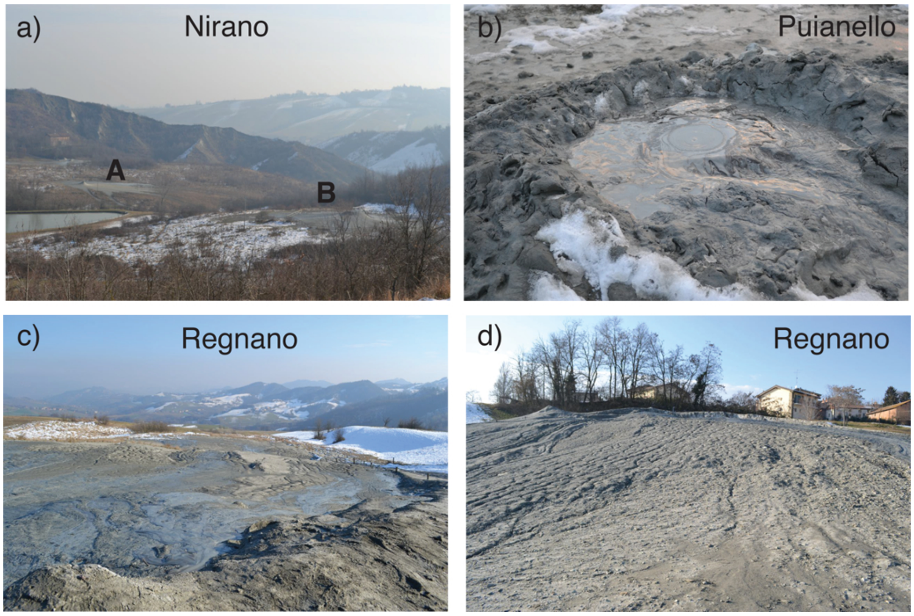

Fig. 2. Photos of the Pede-Apennine mud volcanoes (26 January 2011): **(a)** Nirano, showing vents A and B; **(b)** Puianello; **(c)** Regnano looking downhill; **(d)** Regnano looking uphill.

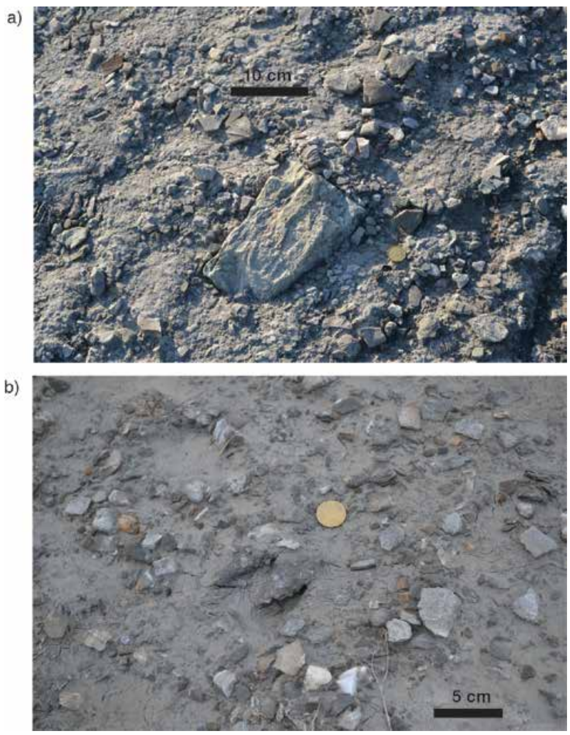

Fig. 3. Erupted clasts in paleodeposits from **(a)** Regnano and **(b)** Puianello. The largest clasts in these images are 22.9 cm and 4.5 cm, respectively.

Regnano, and 63 % at Puianello). The abundances of chlorite and kaolinite were both around 10 %. Smectite was absent at Puianello, but comprised 14 % and 10 % of the mud at Nirano and Regnano, respectively.

The paleodeposits around the mud volcanoes often contain large clasts, such as at Regnano and Puianello (Fig. 3). Old chronicles corroborate the idea that such clasts were expelled during past eruptions. For instance, Taramelli (1881) described the expulsion of boulder-size, marly-limestone clasts during an eruption at Regnano on 24 June 1881. Also, Spallanzani (1795) reported that a limestone stone 800 pounds (about 260 kg) in weight was erupted and thrown a distance of ~ 9 m during the Montegibbio eruption of 13 June 1790. Assuming a rock density of 2500 kg m^{-3}, the approximate dimensions of the ejected stone would be that of a sphere with radius of 29.5 cm, or a cube with sides of 47 cm.

Most of the erupted clasts originate from the Ligurian units, an assemblage of rock units made mostly of pelagic shales and limestones (Fig. 1). These units form a layer that functions as an efficient fluid barrier that is as thick as 1.5 to 4.5 km in the area with mud volcanoes. The mud volcanoes dominantly occur above the Ligurian units, with exception of Nirano that is situated above the Pliocene–Pleistocene claystones that overlie the Ligurian units. Methane and saline waters are supplied from the turbidite sandstones (Marnoso Arenacea) underlying the Ligurian units, as well as from deeper Triassic source rocks (Lindquist, 1999).

Fig. 4. Fresh mud flow erupted at Puianello shortly after the 20 May 2012 earthquake (photo taken 24 May 2012). The mud flow contains several ~ 2 cm clasts. During sampling in January 2011, no large clasts were being transported to the surface.

2.2 Mud volcano response to the May–June 2012 Emilia seismic sequence

The May–June 2012 Emilia seismic sequence was localized at the compressive front of the buried Ferrara fold and thrust belt (Fig. 1). The main seismic shocks were characterized by shallow depth (<10 km) and nearly pure compressive focal mechanism solutions. The sequence began with the 20 May 2012 $M_\mathrm{w} = 5.9$ (INGV, 2012a)–$M_\mathrm{w} = 6.0$ (USGS, 2012) earthquake that occurred on a blind thrust west of Ferrara (Fig. 1). Rupture on a S-SSW-dipping plane induced coseismic horizontal displacement of 17 to 22 mm in a N10°E direction (INGV, 2012b). The event was accompanied by ground uplift up to 15 cm, and liquefaction was widespread in the epicentral area (INGV, 2012b). A few days later, a $M_\mathrm{w} = 5.8$ earthquake struck the Mirandola region on 29 May 2012 (INGV, 2012a; USGS, 2012; Fig. 1). The event was likely related to rupture of a thrust fault southwest of the earthquake that generated the 20 May 2012 seismicity (Fig. 1). Both main seismic shocks of 20 and 29 May produced enhanced shaking along the Pede-Apennine margin up to 4–5 MCS (INGV, 2012b).

Inspection of the mud volcanoes a few days after the 20 May 2012 shock revealed, qualitatively, increased activity at all the mud volcanoes studied here. Regnano created a 25–30 m long mud flow, and normally inactive or poorly active mud cones at Nirano and Puianello became active or showed increased activity. In particular, the tallest mud cone at Puianello extruded a mud flow containing several angular clasts with maximum size of 2.5 cm (Fig. 4). Following the same earthquake, new small vents formed at Casola-Querzola near Regnano (Fig. 5a). In particular, a 50-cm-tall cone formed at a location previously unaffected by seepage. Changes were also documented after the $M_\mathrm{w} = 5.8$ 29 May 2012 earthquake. Regnano created a 20-m-long mud flow from a ~ 10 cm diameter lateral vent of the main cone, and extruded at about 1 cm s^{-1} on 31 May 2012. Activity continued at the ~ 50-cm-tall new cone of Casola-Querzola, where intermittent bursts ejected mud and gases (Fig. 5b). Some Nirano vents still showed increased activity, whereas activity at Puianello appeared somewhat reduced. A significant reduction of activity was also observed at Regnano several days after the 29 May 2012 earthquake. In particular, on 10 August 2012 the main cone had extruded an approximately 60-m-long mud flow that was completely dry (Fig. 5c); mud extrusion from the lateral vent slowed down to 0.33 cm s^{-1} creating a ca. 8-m-long fresh mud flow overlying the dry one.

The mud volcanoes we consider (Nirano, Puianello, Regnano) lie within a distance of 52–63 km and 42–52 km from the epicenters of the 20 May and 29 May 2012 earthquakes, respectively (Fig. 1). Mud volcano response is thus consistent with established epicentral distance vs. earthquake magnitude relations (Manga and Brodsky, 2006; Manga et al., 2009). We evaluated the potential effect of static stress changes induced by the Emilia earthquakes on mud volcano activity using Coulomb version 3.3 (Lin and Stein, 2004; Toda et al., 2005). We calculated normal stress changes induced by the earthquakes using the focal mechanism solutions from INGV (2012a), and fault geometry from the empirical scaling of Wells and Coppersmith (1994). Earthquake ruptures are assumed to occur along N110°E-striking and 40°-dipping blind thrust faults based on the focal mechanism solutions and aftershock distribution (INGV 2012a, b). The stress change is computed as a change in clamping or unclamping of N10°E-oriented mud dikes (e.g., Nostro et al., 1998), which are envisaged as the main feeder systems of Pede-Apennine mud volcanoes (e.g., Bonini, 2012). All three considered mud volcanoes lie in the unclamping region created by the 20 May event (Fig. 6a). Though the magnitudes of the normal stress changes are small, the applied stress would act to open N10°E-trending mud dikes. Normal stress changes are greatest at Regnano, which had enhanced activity. The unambiguous response of the Casola-Querzola mud volcano (a few km away; Fig. 1) is also consistent with the relatively large unclamping stresses characterizing this area (Fig. 6a). Normal stress changes following the 29 May event leave only Regnano in the region with unclamping stresses, whereas Nirano and Puianello occur in an area of clamping stresses that would act to close the N10° E-trending feeder mud dikes, and thus inhibit fluid discharge (Fig. 6b). Indeed, there was reduced activity at Puianello and partly at Nirano, whereas enhanced activity was noted at both Regnano and Casola-Querzola after this seismic event.

3 Methods

Rheology of the mud was measured using a cone-and-plate HAAKE RheoScope.

Fig. 5. Field observations of mud volcano response to the May 2012 Emilia earthquakes. **(a)** New mud cone at Casola-Querzola, looking northwest (24 May 2012). This ∼ 50-cm-tall cone and other smaller vents developed after the 20 May 2012 earthquake on top of a decametre-sized mud mound that had remained inactive during at least the last 7 yr; hammer for scale. **(b)** Same cone (looking southeast) as that in **(a)**, where significant activity continued after the 29 May 2012 earthquake; on 31 May 2012 (the date of this photo), activity was characterized by intermittent bursts that ejected mud and gases. **(c)** Large mud flow at Regnano. The main cone started to extrude mud after the $M_w = 5.9-6.0$ 20 May 2012 earthquake, and continued extruding for several days after the $M_w = 5.8$ 29 May 2012 earthquake. The final outcome is an approximately 60-m-long mud flow, which was completely dry on 10 August 2012 (the date of this photo); persons (circled) for scale.

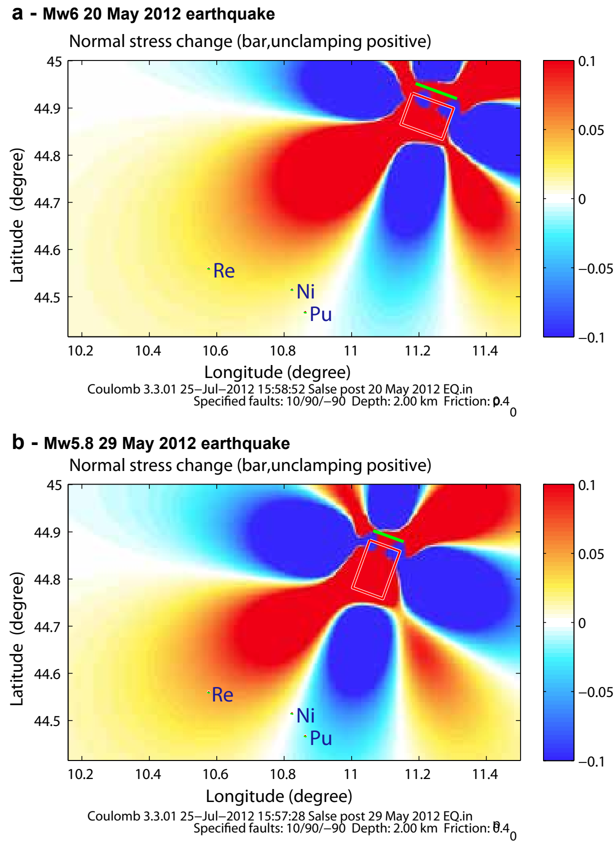

Fig. 6. Computed changes in normal stresses (unclamping positive, clamping negative) produced by the 20 May and 29 May 2012 earthquakes (panels **a** and **b**, respectively). Stresses are computed on N10° E-oriented mud dikes. After the 20 May event, discharge increased at all three mud volcanoes considered here (Re, Regnano; Ni, Nirano; Pu, Puianello). The computed stresses favor unclamping of dikes at all three locations. After the 29 May event, discharge increased at Regnano, and activity was reduced at the other two mud volcanoes, consistent with the stress changes induced by the earthquake.

Sample volume was 8 ml. The cone and plate were covered by sandpaper to prevent slip between the mud and the rheometer. A cone-and-plate geometry was used so that the strain rate was uniform in the sample. Mud was sieved to remove particles with diameters > 100 microns, as the gap at the center of the cone was 0.144 mm and we needed to ensure that particles did not get jammed in the rheometer.

Temperature was held fixed at 10.2 °C for all measurements, close to the mud temperature on the day the mud was collected in the field.

We applied a steady rotation rate, and hence shear strain rate $\dot{\gamma}$, and measured the shear stress τ. We attempted strain rates between 0.01 s^{-1} and 5 s^{-1} but could only obtain quality measurements (nearly steady stresses and strain rates, and high signal-to-noise ratio) for a narrower range of strain rates.

Bulk density ρ_b was determined by weighing a known volume. Water content was calculated from measurements of weight before and after drying in an oven.

Size distribution of particles that comprise the mud was measured by laser diffraction using a CILAS 1190 Particle Size Analyzer that measures the size range between 0.04 microns to 2.5 mm. Sodium monophosphate was added to the mud to deflocculate any clay. For each mud volcano three samples were analyzed and measurements were averaged. The diameters of the largest particles in the ∼ 50 ml of

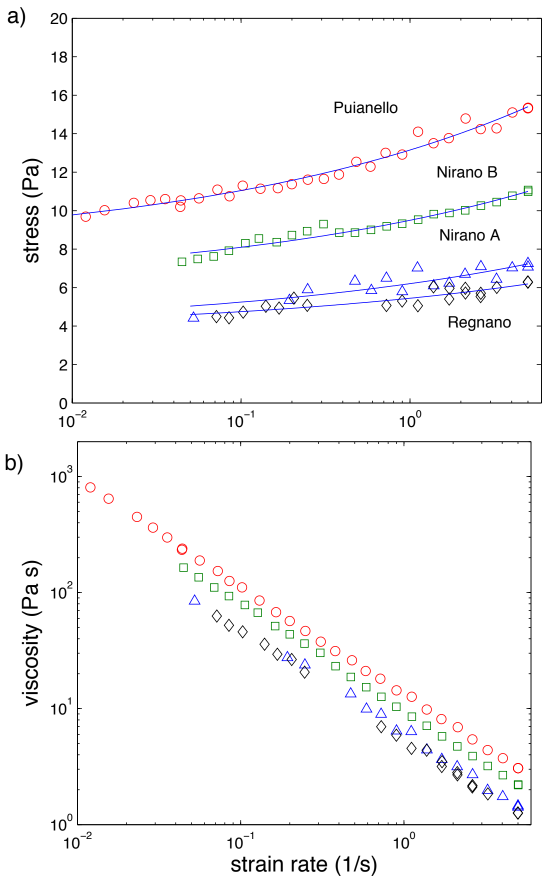

Fig. 7. Rheological measurements showing **(a)** shear stress as a function of strain rate and **(b)** apparent viscosity (shear stress/strain rate) as a function of strain rate. The curves in **(a)** are best fits of the Herschel-Bulkley model with $n = 0.22$ (parameters listed in Table 1). Symbols and colors in **(a)** and **(b)** are the same.

mud collected at each mud volcano were determined by wet sieving the mud and measuring the size from images taken with a microscope.

Where we subsequently fit models and equations to the data, we determined model parameters and their uncertainties using the nonlinear least-squares Marquardt-Levenberg algorithm (chapter 15.5, Press et al., 1992). Reported uncertainties on model fits are standard errors from the regression.

4 Results

Figure 7a shows the relationship between shear stress τ and shear strain rate $\dot{\gamma}$ for all 4 mud samples. The relationship between stress and strain rate we observe is characteristic of "yield-pseudo-plastic" fluids (Nguyen and Boger, 1992).

Figure 7b shows the same data, but plotted as apparent viscosity $(\tau/\dot{\gamma})$ as a function of strain rate. The apparent viscosity decreases with increasing strain rate.

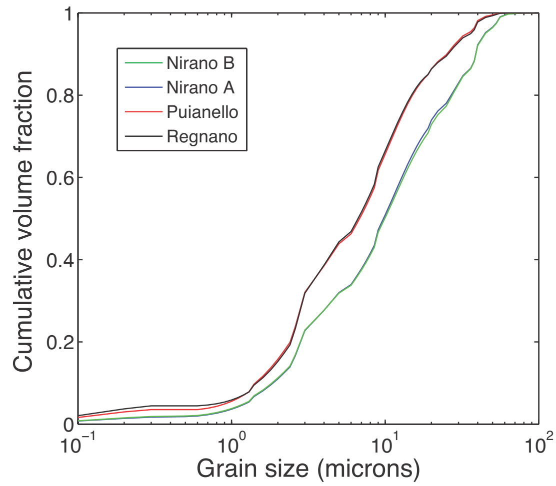

Fig. 8. Cumulative grain size distribution measured by laser diffraction for all 4 mud volcanoes. Each curve is the mean of three samples. Data for Nirano A and B overlap; data for Puianello and Regnano overlap as well.

The rheology of mud is often characterized with the Herschel-Bulkley model:

$$\tau = \tau_y + k\dot{\gamma}^n \quad (1)$$

where τ_y is the yield stress, the minimum stress needed for flow, k is called the consistency, and n is a dimensionless power. The Bingham rheological model corresponds to $n = 1$. While Eq. (1) is an oversimplification of rheology (aging and microstructural evolution during deformation are neglected), the motion of particles within a Herschel-Bulkley fluid is well-studied, and hence we can use this model to relate the clasts that are erupted to properties of the mud and its ascent.

The best fit to measurements on mud from Puianello, for which we could obtain the best measurements, gives $n = 0.22 \pm 0.04$. We adopt $n = 0.22$ for all the mud samples. Yield stresses and consistency are summarized in Table 1, and best-fit models are shown along with the data in Fig. 7a. Table 1 shows that as yield stress increases so does consistency.

The cumulative size distribution of particles is shown in Fig. 8, and the diameters, for which 10 %, 50 % and 90 % of particles are smaller (d_{10}, d_{50}, d_{90}), are listed in Table 1. Mean particle diameter is $\sim$ 10 microns. The size distribution has two peaks: one around 10 microns, and a smaller peak between 40 and 50 microns. Both mud volcanoes at Nirano have nearly identical size distributions. Puianello and Regnano have very similar size distributions that differ from Nirano. Sand-size particles (largest particle size is reported in Table 1) comprise a very small volume fraction of the mud.

Table 1. Rheological parameters and mud properties.

Name	τ_y (Pa)	k (Pa s$^{0.22}$)	ρ_b (g cm^{-3})	ϕ	d_{10}, d_{50}, d_{90} (μm)	d_{max} (mm)
Nirano A	3.8±0.4	2.4±0.4	1.376	0.18	2.0, 10.9, 42.2	2.1
Nirano B	6.0±0.2	3.5±0.2	1.392	0.21	2.1, 10.8, 42.0	2.5
Puianello	7.9±0.1	5.3±0.2	1.352	0.19	1.6, 7.3, 28.2	3.0
Regnano	3.7±0.2	1.8±0.2	1.384	0.20	1.7, 7.2, 28.9	4.9

4.1 Comparison with other rheological measurements

Our value of n is near the low end of the range of values found for debris flow and lahar mudflows, $0.22 < n < 0.48$ (Coussot and Piau, 1994; Bisantino et al., 2010) and up to ~ 0.7 (Scotto di Santolo et al., 2010) for natural, sandy debris flow materials. We note that our model fit is based on extending the measurements to much lower strain rates than in these cited studies. Low strain rates are important for identifying τ_y (e.g., Barnes and Walters, 1985). Our measurements are consistent with those made on mud from mud volcanoes in the Salton Sea (Rudolph and Manga, 2010): we find a similar functional relationship between viscosity and strain rate, but we measure a lower yield stress reflecting a higher water content in the mud. The yield stress we find is similar to that of natural mud flows with similar particle concentrations (O'Brien and Julien, 1988).

The volume fraction of solids φ is between 0.18 and 0.21. Both consistency and yield stress increase with increasing particle concentration in muds (e.g., Kaitna et al., 2007). In our measurements there is no clear relationship between φ and τ_y, though there is little variability in φ, and τ_y varies by only a factor of 2.

5 Transport of clasts to the surface

With a model for mud rheology, we can calculate (1) the size of particles whose weight can be supported by the yield strength of the mud and (2) the speed at which larger clasts will settle through the mud.

The motion of particles in a Herschel-Bulkley fluid is characterized by 3 dimensionless parameters. The Reynolds number characterizes the relative importance of inertial and viscous forces:

$$\mathrm{Re} = \frac{\rho_b U^2}{k(U/d)^n}, \tag{2}$$

where U is the particle velocity and d the particle diameter. The Bingham number characterizes the relative magnitude of the yield stress and viscous stresses:

$$\mathrm{Bi} = \frac{\tau_y}{k(U/d)^n}. \tag{3}$$

The yield number is the ratio of the yield stress to buoyancy stresses:

$$\mathrm{Y} = \frac{3\tau_y}{gd(\rho_s - \rho_b)}, \tag{4}$$

where g is the gravitational acceleration, ρ_b is bulk density and ρ_s is clast density.

Given experimental measurements of mud rheology, and a model for how particles are transported in mud, we can now interpret the size of particles being carried to the surface at present and in the past. In particular, we use Y (Eq. 4) to determine when clasts are able to move relative to the mud owing to their buoyancy. Once they can move, the settling speed U can be related to Re and Bi (Eqs. 2 and 3).

5.1 Size of particles supported by the yield stress

The critical value of the yield parameter $\mathrm{Y_c}$, above which there is no motion of a spherical particle in a Herschel-Bulkley fluid, has been determined by numerical simulations (e.g., Beris et al., 1985) and experiments (e.g., Tabuteau et al., 2007) to be 0.145. Using $\rho_s - \rho_b = 1.37\,\mathrm{g\,cm^{-3}}$, yield stresses between 3.7 and 7.9 Pa (Table 1) allow particles with diameters smaller than 5.7 to 12 mm to be held in place by the yield stress. Except for Regnano where the measured largest particle is similar to that calculated from the yield stress, the largest particle we find is smaller than the maximum size that can be supported by the yield stress. There are 4 possible implications of not finding particle sizes up to the critical size: (1) in some cases there may be no source of larger particles (unlikely given the past and recent eruption of much larger clasts); (2) the volume we sampled is not representative (however, at Regnano we do find particles of the maximum size that can be supported by the yield strength); (3) on time scales longer than the longest $\dot{\gamma}^{-1}$ in our experiments, particles do settle and the yield stress we measure is not meaningful over very long time scales (Barnes and Walters, 1985); (4) the rheology we measure in erupted mud is not representative of that at depth; in particular, the yield strength at depth may be lower, perhaps owing to a higher water content.

Note that the equivalent critical value of the yield parameter for bubbles is 0.53 (Sikorski et al., 2009). The same range of yield stresses implies that bubbles must have minimum diameters of 2.1 cm to 4.4 cm in order to rise through the mud. All the mud volcanoes considered here have bubbles that burst on their surfaces. These minimum sizes are comparable to the smallest bubbles we observed.

Particles that are small enough such that $Y < Y_c$ can be carried to the surface for all ascent speeds of the mud. The large decimeter- to meter-size clasts we see in paleodeposits (Fig. 3) have $Y > Y_c$ and hence will require a minimum ascent speed of the mud to overcome their settling speed relative to the mud. Y_c will not be affected by the presence of large clasts unless their concentration is high (Ancey and Jorrot, 2001).

5.2 Settling speed

The settling speed of (small) clasts relative to the mud can be estimated from empirical relationships for spheres in a Herschel-Bulkley fluid. Atapattu et al. (1985) found that numerical and experimental data can be fit with a drag coefficient,

$$C_D = \frac{24}{\mathrm{Re}}[X + 0.823\mathrm{Bi}], \quad (5)$$

over a wide range of Re and Bi. The numerical constant in front of Bi is uncertain: Ansley and Smith (1967) proposed a value of 1; Atapattu et al. (1985) found a best fit of 0.614. More recent studies of Beaulne and Mitsoulis (1997) and Tabuteau et al. (2007), using a more extensive data set, found 0.823, the value we adopt. The value of X for $n = 0.22$ is 1.43 (Dazhi and Tanner, 1985).

The settling speed can then be obtained from the definition of drag coefficient:

$$U = \sqrt{4gd(\rho_\mathrm{s} - \rho_\mathrm{b})/3\rho_\mathrm{b} C_\mathrm{D}}. \quad (6)$$

Note that because C_D depends on parameters that are functions of velocity, Eq. (6) is implicit for U.

Once particles are large enough to start moving with respect to the mud (Sect. 5.1), their velocity increases rapidly with increasing size owing to the small value of n: small n results in viscosity decreasing rapidly as strain rate increases (Fig. 7b). For clasts with diameters greater than a few centimeters, Re becomes so large that empirical scalings such as (5) have not been established in Herschel-Bulkley fluids. For $\mathrm{Re} > 20$, we use high Re scaling of Turton and Levenspiel (1986),

$$C_\mathrm{D} = \frac{24}{\mathrm{Re}}\left[1 + 0.173\mathrm{Re}^{0.657}\right] + \frac{0.413}{1 + 16300\mathrm{Re}^{-1.09}}, \quad (7)$$

valid for Re up to 2×10^5. Re is based on the measured viscosity (Fig. 7), and because it is a function of U, Eq. (6) with C_D given by Eq. (7) is an implicit function for U. For Re greater than about 10^3, C_D becomes approximately constant as drag is dominated by the pressure drag rather than viscous drag, and hence C_D is no longer influenced by viscosity. We also note, that for non-spherical particles, such as the clasts that are erupted, C_D could be in error by as much as a factor of 2, though the error is likely less than 15 % (Chhabra et al., 1999).

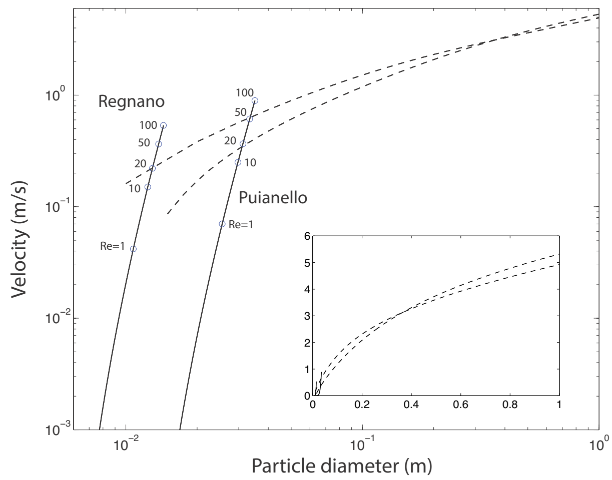

Fig. 9. Velocity of clasts (assumed spherical with density of $2500\,\mathrm{kg\,m^{-3}}$) as a function of their diameter for Puianello and Regnano muds. The solid curves are based on the the empirical Herschel-Bulkley scaling, Eq. (5). Numbers next to circles on these curves indicate the Reynolds number. The dashed curves are Eq. (7) with viscosity in Re based on our measurements. Inset shows the same curves on linear scales.

Figure 9 shows the predicted settling speeds for the muds with the highest and lowest yield stresses, Puianello and Regnano, respectively. We assume a clast density of $2500\,\mathrm{kg\,m^{-3}}$. The break in slope corresponds to a change in the empirical scaling law for C_D, from the Herschel-Bulkley model (5) to Eq. (7). If we assume that the vertical ascent velocity must exceed these speeds to bring clasts of a given size to the surface, then 10 cm and 1 m clasts require ascent speeds greater than $1\,\mathrm{m\,s^{-1}}$ and $5\,\mathrm{m\,s^{-1}}$, respectively.

6 Implications for past eruptions

Current ascent speeds in the conduits feeding the vents are unknown. However, given the absence of large clasts in mud currently being erupted, Fig. 9 implies ascent speeds less than $10^{-3}\,\mathrm{m\,s^{-1}}$. The inferred ascent speeds of $> 1\,\mathrm{m\,s^{-1}}$ based on large clasts in paleodeposits (examples in Fig. 3 are 4.5 cm at Puianello and 22.9 cm at Regnano) imply eruption rates at least 10^3 times greater than current background activity, assuming the mud properties did not change appreciably and that conduit width did not decrease. In fact, greater ascent rates likely reflect increased pressures or permeabilities at depth, which would lead to wider conduits. The increase in eruption rate is thus probably greater, and perhaps much greater, than the increase in ascent speed.

The trigger for larger eruptions is unknown. It is, however, established that local and large regional earthquakes can increase discharge at already-erupting mud volcanoes (e.g., Chigara and Tanaka, 1997; Mellors et al., 2007; Rukavickova and Hanzl, 2008; Bonini, 2009; Manga et al., 2009; Rudolph and Manga, 2010, 2012). All the mud volcanoes studied here responded to the 20 and 29 May 2012 Emilia earthquakes with epicenter 52–63 km and 42–52 km away from the mud volcanoes, respectively (section 2.2). The extrusion velocity of $1\,\mathrm{cm\,s^{-1}}$ estimated at Regnano after the 29 May earthquake, if representative of that at depth, would not carry large clasts such as those shown in Fig. 3 to the surface (see Fig. 9). However, this velocity, if representative of that at Puianello which has more viscous mud, would be able to carry the $\sim$ 2 cm size clasts (Fig. 4) that erupted at Puianello after the 20 May earthquake. However, this velocity is still far less than that needed for emplacing the large clasts preserved in older deposits and mentioned in chronicles. For instance, the stone ejected at Montegibbio on 13 June 1790 (Sect. 2.1) would require a speed of the order of $4\,\mathrm{m\,s^{-1}}$. Thus it may be that the large clasts preserved in older deposits are recording paleoseismic events, though at none of these sites did such large clasts erupt after the 20 and 29 May 2012 earthquakes.

On the other hand, most outbursts at Apennine mud volcanoes in historical times cannot be attributed to earthquakes (Bonini, 2009). In particular, none of the 15 documented paroxysmal eruptions at Regnano between 1754 and 1907 are linked to earthquakes (Govi, 1908) although 3 large eruptions since then appear to be triggered by earthquakes (Bonini, 2009). At Nirano, 3 of 8 historical paroxysms occurred after earthquakes (Bonini, 2009).

In summary, we infer that decimeter-sized clasts in erupted mud preserve a record of large outbursts at mud volcanoes in the northern Apennines. The inferred ascent speed of mud and hence eruption rate was at least three orders of magnitude greater than at present in order to transport these large clasts to the surface.

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