DYNAMICS OF STROMBOLIAN EXPLOSIONS: THE FEBRUARY 2020 ETNA SEQUENCE

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ABSTRACT:

Mt. Etna, in Italy, is one of the most active basaltic volcanoes on the Earth and is characterized by a wide range of explosive styles. Strombolian activity is very frequent and a powerful spectacle attracting thousands of tourists every year, approaching the volcano summit with sparse safety measures. At this moment, despite the extensive monitoring of this volcano, little is known on their exact dynamics, precluding precise quantification of the hazard associated with it. For this reason, we have analysed video recordings of an explosion sequence occurred in February 2020 recorded from the Voragine and Bocca Nuova craters rims in parallel with UAV surveys. We analysed videos to obtain the frequency of explosions, particle exit speeds and study eruption dynamics. Survival analysis of the repose time between explosions revealed that they are distributed according to log logistic distributions, in analogy with known sequences at other open vent volcanoes. We found differences among low intensity and high intensity explosions. Low intensity events are characterized by instantaneous pulses of magma associated with the burst of a gas slug. High intensity events are composed by multiple pulses, where volcanic particles can reach speeds of up to 150 m/s, separated by gas streaming and followed by a stationary phase, where particles are emitted at constant velocity, and a declining phase emitting a few small particles with speeds lower than 10 m/s. Finally, we emphasize how remote sensing monitoring of small-scale explosions is a very effective tool providing data for their quantification and modelling.

1. INTRODUCTION

Basaltic volcanic manifestations are characterized by a large style range, including lava flows, outgassing explosive events of variable intensity, from lava fountaining to ash plumes. (Edwards et al., 2018). Their eruptive style depends to various parameters like magma viscosity and volatile content, rise and feeding rates (Taddeucci et al., 2015).

In particular, the explosion frequency in Strombolian dynamics is related to the rising dynamics of gas slugs, whose rapid expansion leads to the fragmentation and release of magma, and, in some cases, small quantities of lithic stones present inside the conduct (Balckburn et al., 1976). Exit speeds can exceed 150 m/s and ejecta can reach distances up hundreds of m up to a few km from the vent. Strombolian activity is also a nature spectacle attracting tourists and local people who climb volcanoes up to a short distances from the active vents (Scollo et al., 2013). For this reason, the study of Etna's Strombolian eruptions is relevant not only for understanding the dynamics of these events but also for the hazard quantification. Unfortunately, despite Etna is one of the most studied and monitored volcano in the world, Strombolian activity is often overlooked, because of its limited impact with respect to lava fountain events, reaching up to Subplinian scale (Branca and Del Carlo, 2005). Monitoring Strombolian eruptions, whose product are hard to sample because they typically occur at open vent volcanoes is ideally made by collecting ground remote sensing data.

This study aims to provide useful data to quantify and model the Strombolian activity of this volcano through the measurement and analysis of spatial and temporal parameters, also by comparing it with other volcanic systems with similar characteristics. In this paper, we discuss on the Strombolian dynamics events that occurred at Etna on February 2020. This study is based on quantitative analysis of high resolution videos, that were recorded on the 25th February 2020 on the edges of Voragine and Bocca Nuova Craters.

2. MATERIALS AND METHODS

The data collection was possible by the acquisition of four videos, documenting the activity of 25th February 2020. These videos were acquired with a frequency of 25 fps (frames per second) and a resolution of 1080x1920 pixels. Images were acquired with a Nikon Coolpix P1000 camera equipped with a 4.3-539 mm optical zoom. Sensor size is 6.16x4.62 mm.

The films were then splitted into individual frames, studied with image analysis techniques using the software Fiji (Schindelin et al, 2012).

Video	Date (local hour)	Duration	Recording distance from cone	number of explosions
		[min:s]	[m]	
8039	25/02/2020, 12:39	1:57	136	34
8081	25/02/2020, 13:58	3:41	136	41
8073	25/02/2020, 13:22	4:53	403	76
8079	25/02/2020, 13:29	3:58	403	71

Table 1. Videos analysed and their characteristics

2.2 Image calibration

The images were calibrated for the distance conversion from pixels to meters.

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Definition of the FOV (Field of View) area was in fact obtained using known distances (i.e. the crater rim diameter), measured by UAV surveys. Sometimes, image sequences from single videos have required multiple calibrations if the optical zoom of the camera was activated. Moreover, to reduce the measure uncertainty, pixel calibration was repeated and averaged over a sequence of fixed optics images. Image resolution was calculated as the inverse of the average scale factor calculated based on Fiji analysis of the calibration images:

$$m = \frac{D}{d} \tag{1}$$

where m = resolution, px/m
D = known distance, m
d = known distance, px

2.1. Time series analysis

Time series data were obtained by calculating the time between consecutive images obtained by converting the videos based on recording speed (fps). Time between images (in seconds) was calculated as:

$$t = \frac{nf}{fps} \tag{2}$$

where nf= number of frames between two images in the series

Duration of explosions was calculated based on the number of frames comprised between the one showing the first particle exiting the vent and the one showing the last particle exiting the vent).
The repose time between two contiguous explosions was calculated as the difference between the starting times of two consecutive explosions:

$$trt = ti_2 - ti_1 \tag{3}$$

where trt = repose time
ti_1= starting time of the first explosion
ti_2 = starting time of the next explosion

Finally, the interval between two contiguous explosions, defined as the difference between the second explosion starting time and the first explosion ending time, was calculated:

$$i = ti_2 - tf_1 \tag{4}$$

where i = repose time
ti_2 = second explosion starting time
tf_1= first explosion ending time

2.3. Distances and particle exit speeds

For each explosion, we calculated the vertical exit speed of the emitted particles, based on two algorithms.
When the particles remained within the FOV along their entire trajectory, conservation of energy was applied:

$$U_0 + U_1 = K_0 + K_1 \tag{5}$$

where U_0 = initial potential energy
U_1 = final potential energy
K_0 = initial kinetic energy
K_1 = final kinetic energy

Neglecting friction (which is not relevant considering the uncertainty of the measures) we obtain:

$$v = \sqrt{2gh} \tag{6}$$

where v = particle speed
g = gravitational acceleration
h = maximum particle height above the crater rim

When the particle trajectory exceeded the FOV, speed where calculated measuring the distance covered in a time of 3 consecutive frames:

$$v = (h_2 - h_1)\frac{25}{2} \tag{7}$$

where v = particle speed
h_2 = particle height in the third consecutive frame
h_1 = particle height in the initial frame

2.2. Particle tracking

The four largest explosions, characterized by the longest duration, and the largest number of particles emitted, were studied in detail. Time evolution of the eruption parameters (i.e. particle speed and size) was quantified with temporal resolution of tenths of seconds.

3. RESULTS

The videos recorded a sequence of 34 to 76 explosions, occurring from up to two vents within the Voragine crater (table 1). Explosions lasted from 0.04 to 8 s, with average values around 1 s in all recorded videos. Repose times between explosions ranged between 0.76 to 13.24 s with average values around 4 s. Time intervals ranged between 0.04 to 11.28 s (table 2).
Survival analysis of the repose times revealed that they are best reproduced by log logistic distributions, even if a Gaussian distribution could reproduce data satisfactorily; other known distribution such as the exponential one, instead do not fit satisfactorily the empirical probability curves (Table 3).

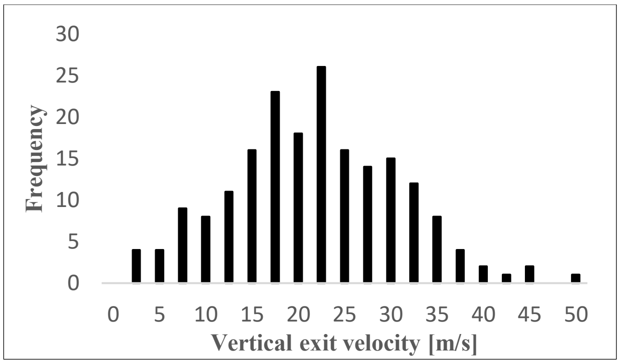

Figure 1. Analysis of speed frequencies.

Particle vertical exit speed were measured for the fastest particles in each of the 222 explosions studied. Speeds range from varies from 1.3 to 47.7 m/s, with average value of about 20 m/s. Speeds distribute accordingly to an almost symmetrical trend, with two modes close to the median values. Maximum exit speed was measured in the 4 major explosions (fig. 1, table 4).

Repose times (s)				
Video	Average	Median	Minimum	Maximum
8039	3.49	3.08	0.76	10.96
8081	5.403	4.96	1.4	13.24
8073	3.85	3.40	1.16	10.32
8079	3.34	3.02	1.08	7.28
Explosion durations (s)				
Video	Average	Median	Minimum	Maximum
8039	1.21	1.16	0.04	6.12
8081	1.58	1.2	0.04	6.96
8073	2.26	1.8	0.2	8
8079	1.77	1.64	0.04	5.2
Time interval between contiguous events (s)				
Video	Average	Median	Minimum	Maximum
8039	2.27	2.12	0.12	5.64
8081	3.82	3.52	1.2	11.28
8073	1.59	1.44	0.08	7.52
8079	1.57	1.16	0.04	5.6

Table 2. Basic statistical parameters

Repose times								
Video	Log logistic			Gaussian			Exponential	
	μ	σ	LL	μ	σ	LL	μ	LL
8039	4.3	0.3	171	87.1	51.3	176	230.2	180
8081	4.8	0.3	208	133.1	62.4	210	466.6	223
8073	4.4	0.3	383	96.2	46.6	393	123.2	417
8079	4.3	0.3	354	83.4	41.1	359	99.3	379

Table 3. Fitting results of repose times between explosions
LL= negative log likelihood

Vertical maximum speed				
Video	Medium value	Median	Minimum	Maximum
8039	21.12	21.14	8.46	37.76
8081	24.23	23.59	13.43	36.09
8073	18.14	15.24	1.30	47.75
8079	20.88	20.66	2.48	33.66

Table 4 Statistical speed analysis

2.4. Dynamics of the four major explosions

Major explosions lasted from 2.04 to 2.56 seconds. They were divided into three to four phases, with distinct dynamics. Firstly, an intense outgassing that the explosion onset (fig. a, e). First particles, ash and lapilli-sized, exited from the vent during the onset.

In a few tenths of seconds, the number of particles emitted suddenly increase, forming a thicker eruptive column (second pulse). In three explosions, a third pulse follow the second one; it is the most intense (in terms of number of emitted particles) and it is characterised emission of larger particles (bombs to lapilli sized) accompanied by limited gas emission (fig. b, c, d, f).

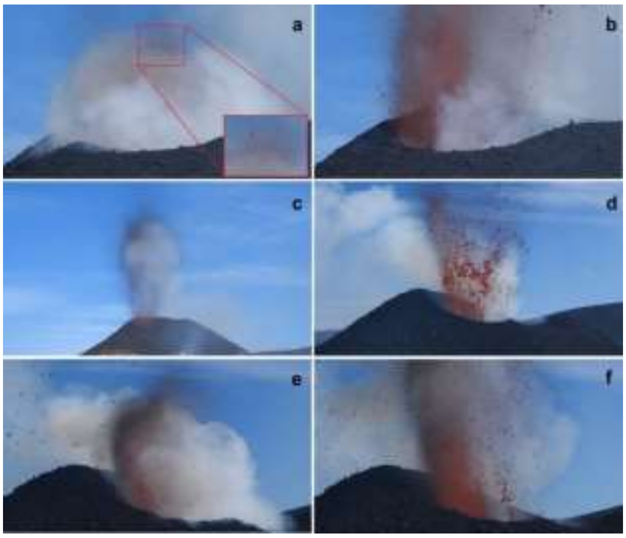

Figure 2. Dynamics of major explosions as pictured in the recorded frames: outgassing during first and second (in the frame) pulses, characterized respectively by a large and a smaller eruptive column thickness (a); Bombs and lapilli erupted during sustained phase (b, c d and f); first pulse with ash emission and outgassing (e).

Particle tracking within consecutive frames of major explosions showed a typical decrease in energy from onset to subsequent pulses (Alatorre-Ibargüengoitia et al., 2011) followed by a stationary phase (second to third pulse) lasting less than 1 s.

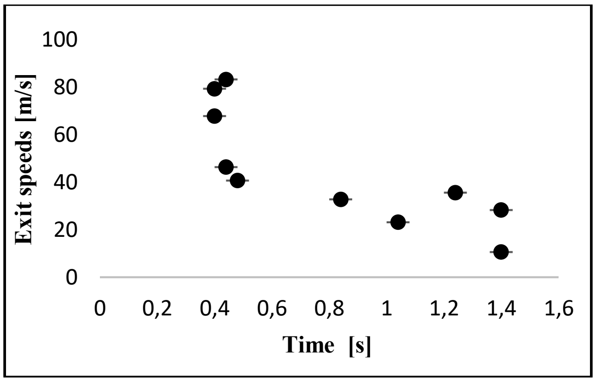

Figure 3. Evolution of speeds during a major explosion. Error on speed estimation is smaller than the symbol used.

3. CONCLUSIONS

This study estimated fundamental parameters of the Strombolian dynamics at Etna volcano. Strombolian activity consists of regular (i.e. time between explosion follow log logistic distributions) series of explosions with very similar dynamics. Short median repose times suggest low viscosity of the emitted (Dominguez et al., 2016), associated with limited gas emission, (corresponding to low particles exist speeds, (Alatorre - Ibargüengoitia et al., 2011). Therefore, explosions are marked by heights and speeds much lower than typical Strombolian regime (Taddeucci et al., 2012). Data presented here, although representing the first assessment of Strombolian dynamics at Etna, are only preliminary. We underline the importance of ground remote sensing systems of explosive eruptions as the main method for collecting low intensity eruption parameters which could not be estimated by the study of tephra collection or using satellite techniques.
This data could be compared with other volcanic systems to have a deeper and more general understanding of Strombolian activity.
Strombolian dynamics is very similar to other type volcanoes such as Stromboli and Yasur (Taddeucci et al., 2012; Gaudin et al., 2014). Explosions are fed by the rise of pressurized gas slugs rupturing the free magma surface into fragments of variable size (ash to bombs), with dynamics similar to the sudden release of a mass of pressurized gas within a shock tube (Alatorre - Ibargüengoitia et al., 2011). In major explosions, multiple pulses suggest the rise of a series of slugs.
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5. REFERENCES

Alatorre-Ibargüengoitia, M. A., Scheu, B., Dingwell, D. B., 2011. Influence of the Fragmentation Process on the Dynamics of Vulcanian Eruptions: An Experimental Approach. *Earth and Planetary Science Letters*, 302(1–2), pp. 51-59, https://doi.org/10.1016/j.epsl.2010.11.045

Blackburn, E. A., Wilson, L., Sparks J., 1976. Mechanisms and Dynamics of Strombolian Activity. *Journal of the Geological Society*, 132(4), pp. 429-440, https://doi.org/10.1144/gsjgs.132.4.0429

Branca, S., Del Carlo, P., 2005. Types of Eruptions of Etna Volcano AD 1670–2003: Implications for Short-Term Eruptive Behaviour. *Bulletin of Volcanology*, 67(8), pp. 732-42, https://doi.org/10.1007/s00445-005-0412-z

Dominguez, L., Pioli L., Bonadonna C., Connon, C. B., Andronico, D., Harris, A. J. L., Ripepe, M., 2016. Quantifying Unsteadiness and Dynamics of Pulsatory Volcanic Activity. *Earth and Planetary Science Letters*, 444, pp. 160-68, https://doi.org/10.1016/j.epsl.2016.03.048

Edwards, M. J., Pioli, L., Andronico D., Scollo, S., Ferrari, F., Cristaldi, A., 2018. Shallow Factors Controlling the Explosivity of Basaltic Magmas: The 17–25 May 2016 Eruption of Etna Volcano (Italy). *Journal of Volcanology and Geothermal Research*, 357, pp. 425-36, https://doi.org/10.1016/j.jvolgeores.2018.05.015

Gaudin, D., Taddeucci, J., Scarlato P., Morini, M., Freda, C., Gaeta M., Palladino, D.M., 2014. Pyroclast Tracking Velocimetry Illuminates Bomb Ejection and Explosion Dynamics at Stromboli (Italy) and Yasur (Vanuatu) Volcanoes. *Journal of Geophysical Research: Solid Earth*, 119(7), pp. 5384-97, https://doi.org/10.1002/2014JB011096

Schindelin, J., Arganda-Carreras, I., Frise, E., Kaynig, V., Longair, M., Pietzsch, T., Preibisch, S., Rueden, C., Saalfeld, S., Schmid, B., Tinevez, J., White, D. J., Hartenstein, V., Eliceiri, K., Tomancak, P., Cardona, A., 2012. Fiji: An Open-Source Platform for Biological-Image Analysis. *Nature Methods*, 9(7), pp. 676-82, https://doi.org/10.1038/nmeth.2019

Scollo, S., Coltelli, M., Bonadonna, C., Del Carlo, P., 2013. Tephra Hazard Assessment at Mt. Etna (Italy). *Natural Hazards and Earth System Sciences*, 13(12), pp. 3221-33, https://doi.org/10.5194/nhess-13-3221-2013

Taddeucci, J., Scarlato P., Capponi, A., Del Bello, E., Cimarelli, C., Palladino, D.M., Kueppers, U., 2012. High-Speed Imaging of Strombolian Explosions: The Ejection Velocity of Pyroclasts. *Geophysical Research Letters*, 39(2), pp. 1-6, https://doi.org/10.1029/2011GL050404

Taddeucci, J., Edmonds, M., Houghton, B., James, M. R., Vergniolle, S., 2015. “Hawaiian and Strombolian eruptions.” In: *Encyclopedia of volcanoes,* ed. H. Sigurdsson. Academic Press, pp. 485-503, https://doi.org/10.1016/B978-0-12-385938-9.00027-4