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Stronger or longer: Discriminating between Hawaiian and Strombolian eruption styles

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ABSTRACT

The weakest explosive volcanic eruptions globally, Strombolian explosions and Hawaiian fountaining, are also the most common. Yet, despite over a hundred years of observations, no classifications have offered a convincing, quantitative way of demarcating these two styles. New observations show that the two styles are distinct in their eruptive timescale, with the duration of Hawaiian fountaining exceeding Strombolian explosions by ~300–10,000 seconds. This reflects the underlying process of

whether shallow-exsolved gas remains trapped in the erupting magma or is decoupled from it. We propose here a classification scheme based on the duration of events (brief explosions versus prolonged fountains) with a cutoff at 300 seconds that separates transient Strombolian explosions from sustained Hawaiian fountains.

INTRODUCTION

Kīlauea, Hawaii, USA, and Stromboli, Aeolian Islands, Italy, are among the most intensely monitored, continually active volcanoes in the world, and their activity has given rise to two of the most frequently used names for eruption styles, Hawaiian and Strombolian. Both styles are also well represented in the recent eruptions at Etna, Italy. Continuity of eruptive activity and of real-time geophysical and geochemical observations makes these three volcanoes natural sites to delineate these eruption styles rigorously.

Recent debate within the volcanological community clearly emphasizes that the confusion in characterizing and classifying eruptions has greatly hindered our capability to identify potential eruptive scenarios and assess the associated hazards at these and other volcanoes (Bonadonna et al., 2014). This is particularly crucial in the cases of small-scale eruptions, which are the most frequent, but the most difficult to characterize, mostly due to limited dispersal of the products and/or brief durations. Thus, the characterization and classification of volcanic eruptions are not only crucial to our scientific understanding, but also for hazard and risk assessment, as well as communication to the public. Kīlauea, Etna, and Stromboli are locations of large and growing volcano-tourism operations. Their eruptions pose particular issues for management agencies because the volcanoes are highly accessible. Hawaii Volcanoes

National Park records ~5000 visitors per day to the summit of Kīlauea, while the population of Stromboli increases ten-fold to ~4000 people in the summer tourist season. Etna, a UNESCO world heritage site since 2013, is one of the most visited volcanoes in the world.

CLASSIFICATIONS

Both eruption names were introduced qualitatively, based on direct observations of eruptions at these volcanoes (Mercalli, 1881; Macdonald, 1972). They were subsequently first classified quantitatively on the basis of deposit characteristics (Walker, 1973), using principally the rate at which the products thin with distance from vent as some measure of dispersal of the ejecta, which in turn is a proxy for mass discharge rate (intensity). By these criteria, collectively all Hawaiian and Strombolian eruptions are ‘weak’ with low mass eruption rate, as they have limited ranges of tephra dispersal and form steep-walled pyroclastic cones or ramparts rather than aerially extensive sheet-like deposits. A major issue with the use of the Walker classification for weak eruptions arises because no Hawaiian deposits and no products of eruptions at Stromboli and Etna were used in arriving at this classification. In fact, contrary to the Walker classification, the data presented here show that normal Strombolian activity is weaker (in terms of mass eruption rate, i.e., kg/s), not stronger, than Hawaiian fountains (Fig. 1). Consequently, subsequent classifications avoided delineating Hawaiian and Strombolian, by either excluding Hawaiian (Pyle, 1989) or grouping Strombolian and Hawaiian together (Bonadonna and Costa, 2013).

A quantitative demarcation between the two styles, however, would be particularly useful, because eruptive activity at basaltic volcanoes shifts frequently between both eruptive styles (Spampinato et al., 2012). Three volcanoes, Stromboli, Kīlauea, and Etna, are of exceptional value to address quantitative classification of basaltic explosive eruptions as both duration and erupted mass are known for numerous events. Elsewhere, durations of Strombolian and Hawaiian events are generally well constrained, but there is a paucity of data for erupted mass and hence mass discharge rate, due both to their local dispersal and the high risk in the near-field. For this reason we explore possible classification criteria using initially well-constrained eruptions at Kīlauea, Stromboli and Etna. We then use a larger data set of events of known duration as validation for our new approach.

EXPLOSIONS AT STROMBOLI

Stromboli, the 'type locality' for Strombolian explosions, has shown an extraordinary level and diversity of activity for at least 1300 years (Rosi et al., 2013; Taddeucci et al., 2015). Eruptions have been described qualitatively (Table 1) as normal, major, or paroxysmal explosions (Rosi et al., 2013). Normal activity (Fig. 2) typically involves <20-second-long explosions which eject centimeter- to meter-sized pyroclasts to heights of 50–400 m (Rosi et al., 2013), on time scales of fewer than 5 to more than 25 events per hour. Data in Rosi et al. (2013) suggest that the durations of normal explosions range between 1.3 and 30 seconds (mean 7 seconds). In the most detailed analysis of individual events, Patrick et al. (2007) list 136 explosions recorded in June-July 2004 with durations between 6 and 41 seconds (average 15 +/− 6 seconds). The erupted mass of normal explosions has been estimated at between 1 and 10^4 kg (Ripepe et al., 1993; Harris et al., 2013; Gaudin et al., 2014; Bombrun et al., 2015). The high variability of mass ejected during each event also led to classification issues among the normal

Strombolian events (Leduc et al., 2015). Recent use of high speed imagery (Gaudin et al., 2014; Taddeucci et al., 2015) shows that each normal explosion consists of multiple sub-second pulses, each releasing a meter-diameter pocket of gas. A similar range of erupted mass and duration was also recorded during normal Strombolian explosions at Yasur volcano, Vanuatu (Fig. 1), during 10–12 July 2011 (Gaudin et al., 2014).

Larger events known as “major explosions” are recorded several times each year, while paroxysms occur “every few decades” (Rosi et al., 2013; Gurioli et al., 2013). Both are related to the rapid rise of gas-rich magma and are characterized by durations of tens of seconds to a few minutes and eruptive masses of 10^5 and 10^7-10^8 kg respectively. Although mass discharge rates for paroxysms overlap with those of Hawaiian fountains (Fig. 1), all three types of activity at Stromboli are of short duration, relative to Hawaiian activity. Background activity to all types of explosive eruptions at Stromboli consists of two forms of shallow-derived outgassing: passive gas-streaming and small gas bursts (‘puffing’) (Burton et al., 2007; Harris and Ripepe, 2007).

FOUNTAINS AT KĪLAUEA

Kīlauea, the reference volcano for Hawaiian fountaining, has been in near-continuous eruption since 1983. Forty-seven Hawaiian fountaining episodes were recorded at Pu‘u ‘Ō‘ō between January 1983 and July 1986, each sustained at fountain heights of 30–470 m for at least 5 h and up to 12 days, erupting 4×10^9 to 7×10^{10} kg of magma (Wolfe et al., 1988). Single fountaining episodes during two other prolonged eruptions, in 1959 and 1969, had fountain heights of 30–579 m, were sustained between 2 h and 7 days, and erupted masses of 3×10^9 to 1×10^{11} kg (Richter et al., 1970; Swanson et al., 1979). These fountains are clearly distinguished from any Strombolian explosions by their longer durations (Fig. 1) despite almost total overlap in erupted mass and mass eruption rates with Strombolian paroxysms. Hawaiian fountains are sustained in the sense that continuous mass discharge is maintained for hours to days, but are also unsteady in nature, i.e., fluctuate in height and mass eruption rate at frequencies of up to 1 Hz (Fig. 3).

EXPLOSIVE ERUPTIONS AT ETNA

Etna has an extraordinary frequency, and diversity, of Strombolian to subplinian activity since 1990. Etna is an invaluable third ‘type’ volcano because, while Kīlauea is dominantly Hawaiian in style and Stromboli is overwhelmingly Strombolian, Etna’s explosivity offers a third perspective as activity is episodic; while some explosive episodes are purely Strombolian, others are purely fountaining and some show alternations of both styles, often on time scales of hours or less. Transitions between normal Strombolian explosions and fountaining have occurred repeatedly in the 21st century (Andronico et al. 2005; 2014). Transitions are rapid and marked by a short period of increased frequency of Strombolian explosions (‘rapid Strombolian’ in the sense of our Table 1 below) before the sharp onset of sustained fountaining. The tempo of eruption at Etna has increased steeply since 1998, with numerous fountaining episodes now recorded every year (Andronico et al. 2014).

A NEW APPROACH TO CLASSIFICATION

A large gap exists, from 10^2-10^4 seconds, between the typical duration of transient explosions and fountains at Kīlauea, Etna and Stromboli. In comparison, overlaps in terms of both erupted mass and mass discharge rate rule out either of these parameters as a principal basis to distinguish these two eruptive styles (Fig. 1). Based on the typical durations of events in Figure 1, we propose a classification for low-intensity explosive eruptions in which the first-order criterion is duration of the event. We suggest that a natural division between Strombolian explosions of all sizes, and Hawaiian fountaining episodes is a duration of 300 seconds, close to the middle of this wide gap.

We can test the validity of using duration as a parameter to separate Hawaiian and Strombolian eruptions by looking at an extended data set that includes activity where event durations are well constrained but no estimates exist for eruptive mass. This includes a much larger number of fountaining episodes at Etna in 2000 and 2011, plus transient Strombolian explosions at Yasur, Erebus and Villarrica volcanoes (Fig. 4). Across all of these data, for 860 events, there is a gap between 40 and 1.2×10^3 seconds with no recorded events.

For Strombolian eruptions, there is insufficient data for larger eruptions to extend the three-fold classification used at Stromboli for use elsewhere, at this time. However we propose the addition of a category called *rapid* explosions to represent sequences of very closely spaced and, generally, very weak explosions, with a periodicity at least two orders of magnitude higher than normal explosions at Stromboli. Such activity has been seen and recorded on surveillance cameras at Stromboli, Etna, and Yasur (Andronico et al., 2005; Gaudin et al., 2014).

For Hawaiian fountains, any informal sub-classification based on erupted mass is less meaningful, as some eruptions occur from long fissures and others from point sources, and some eruptions are of low mass eruption rate but long duration and vice versa. Both low and very high fountains can thus have comparable erupted mass, depending on the surface area of the vent and the duration of the eruption. For example, the 1959 Kīlauea Iki episode 16 from a point vent erupted 10^{10} kg of magma in 3 h, with a peak height of 457 m (Richter et al., 1970). Episode 1 of the Mauna Ulu 1969 eruption ejected a comparable mass over 34 h from a 4-km-long fissure (Swanson et al., 1979) with a peak height of less than 50 m. Instead, we propose an informal split into low, moderate, and high fountaining at sustained fountain heights of <100, 100–400, and >400 m (Table 2).

‘MISFITS’: OTHER ERUPTION STYLES AT KĪLAUEA AND STROMBOLI

Other styles of magmatic activity occur at both volcanoes. These include passive outgassing and puffing, weak spattering, gas pistoning, and non-explosive effusion of lava. A comprehensive classification will need to include these but is beyond the scope of this paper, which merely addresses the more tractable part of the classification problem.

CONCLUSIONS

Distinction between Strombolian and Hawaiian eruptions is part of a more generic issue in that existing deposit-focused quantitative classifications cannot distinguish between sustained and transient eruption styles, i.e., between Hawaiian, subplinian, and Plinian eruptions versus Strombolian and Vulcanian explosions. This is arguably a first order distinction in physical volcanology, linked to the extent to which shallow exsolved gas remains mechanically coupled to, or decoupled from, the melt phase in the very shallow conduit. The problem not only exists for Hawaiian and Strombolian eruptions, but also at higher mass eruption rates where subplinian and Vulcanian eruptions also cannot be distinguished on deposit characteristics alone. To be functional, any unambiguous classification of these eruptive styles also requires inclusion of some measure of event duration. More data are perhaps needed to address the subplinian versus

Vulcanian issue, and the separation between Vulcanian and Strombolian activity, and we hope this paper will provoke that classification debate.

An unresolved issue is what criteria can be applied to classify unobserved prehistorical eruptions and products as Strombolian or Hawaiian. The outlined classification neither improves nor worsens the situation as NO other system has ever worked for these events either. A textural criterion, based on the fact that Strombolian eruptions typically involve slightly more viscous magmas and produce more ragged pyroclasts whereas Hawaiian deposits are rich in fluidal achneliths reflecting lower viscosity, is a possibility if such a contrast can be borne out by the componentry of eruptions at Kīlauea, Etna and Stromboli (Taddeucci et al., 2015).

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FIGURE CAPTIONS

Figure 1. Plot of duration (derived either by direct observation or analysis of web cam records) versus erupted mass for selected 20th and 21st century explosive activity at Stromboli, Etna, and Kīlauea. Also included are eight explosions at Yasur, New Hebrides which appear to define the short duration, small mass endmember amongst normal Strombolian activity. Red dashed lines connect points of equal mass discharge rate. All references for these eruptions are provided in the data repository.

Figure 2. Examples of normal Strombolian events. (A) plot of unpublished data showing discrete explosions recorded over a one-day interval on 20 June 2009, (B) Plot of pyroclast exit velocity used to delineate multiple pulses during a single 28-second long explosion on 20 June 2009, (C) extension of 2-second time interval within (B) showing velocity measurements for individual pyroclasts during 3 pulses, and images showing (D)

the initial, and (E) the strongest, pulses during the event captured in (B). All references for these eruptions are provided in the data repository.

Figure 3. Examples of Hawaiian fountaining behavior. (A) Fountain height with time for seven fountaining episodes over five days at the close of the 1959 Kīlauea Iki eruption. (B) Enlargement of the plot for episode 15, the highest fountain ever recorded at Kīlauea. Like many Hawaiian episodes the fountain builds rapidly from a weak onset (C), to low sustained fountaining (D), reaches a short-lived maximum height (E), then stabilizes at a lower level (F), before entering an unsteady phase prior to the close of the episode (G). Data after Richter et al. (1970).

Figure 4. Plot of event durations for well constrained sequences of transient Strombolian explosions (red) and sustained Hawaiian fountaining (blue). The number of sampled events is indicated in brackets. Triangles are average durations in seconds, filled circles represent the longest and shortest events. Erebus is a special case in which every explosion lasted less than 1 second, and represented bursting of a single short-lived bubble. Villarrica explosions were divide by Gurioli et al., (2008) into 3 groups. Type 1 events comprised gas-only emissions. Type 2, involving the emission of gas and ejecta, were divided into 2a and 2b which involved less heavily and more heavily loaded ejecta clouds respectively. Type 3 events involved the ejection of coherent sheets of magma, and detached blebs. All references for these eruptions are provided in the data repository.

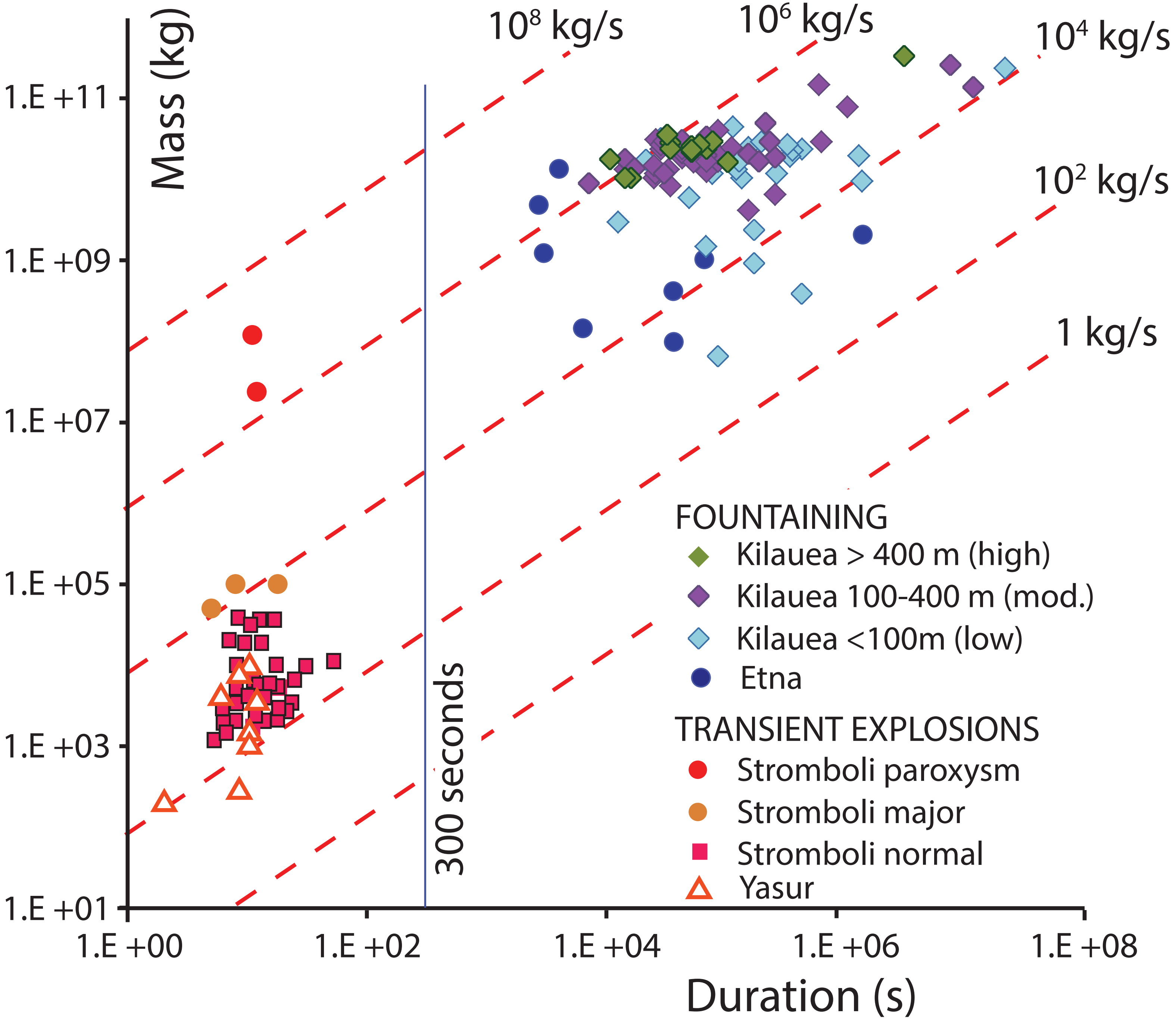
1GSA Data Repository item 2016xxx, xxxxxxxx, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

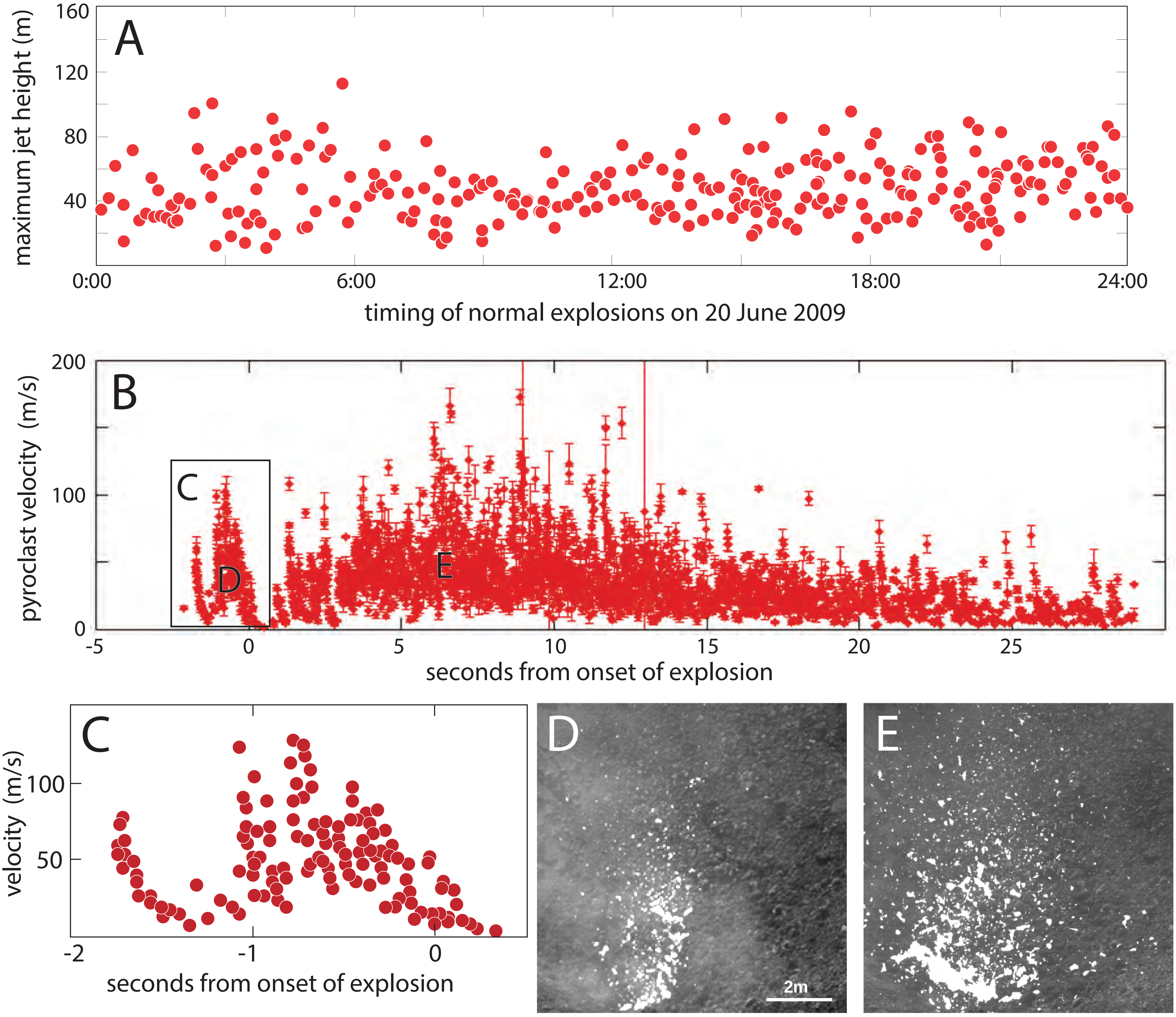
TABLE 1. SUBCLASSES OF ACTIVITY AT STROMBOLI

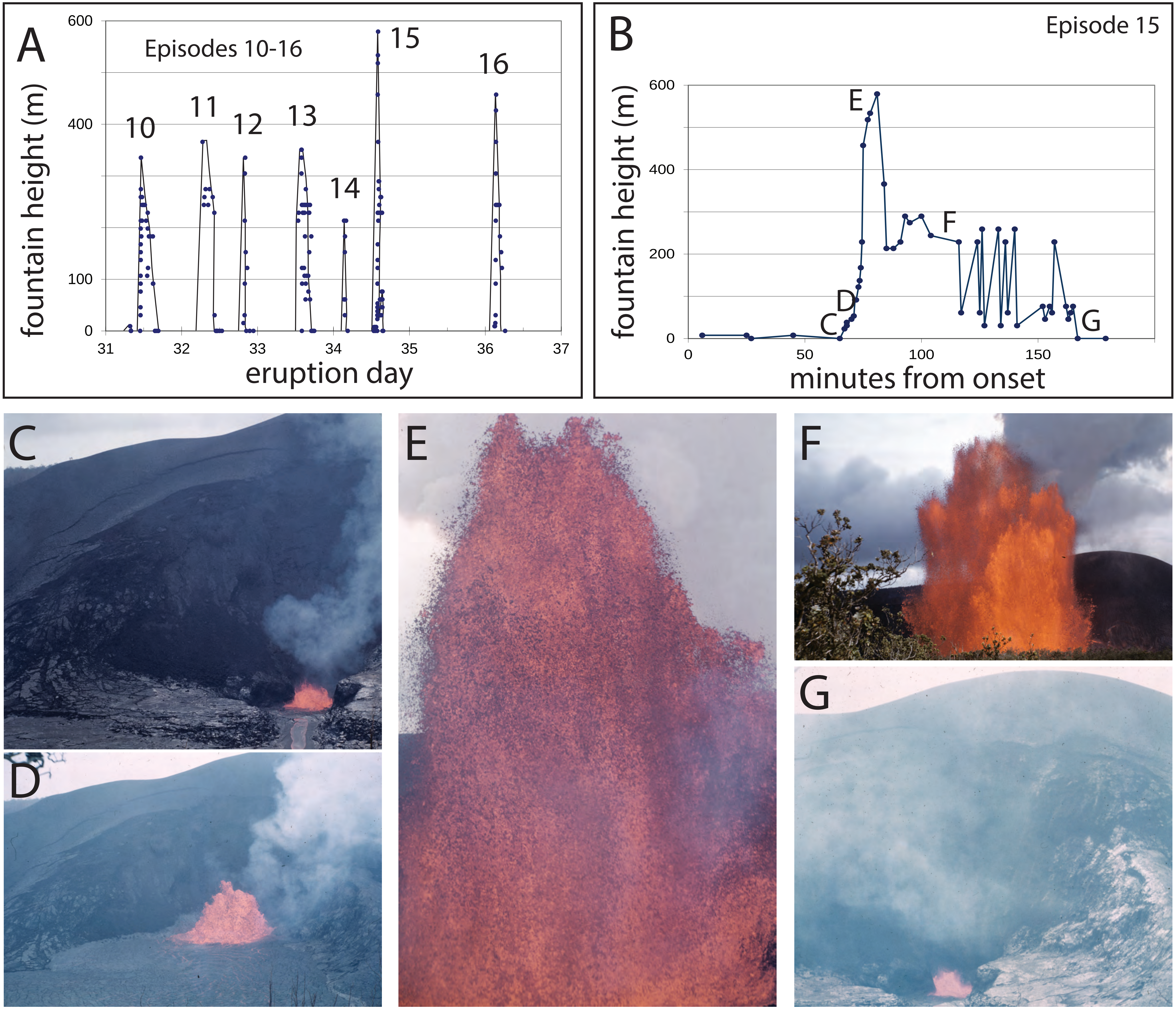
Eruption subclass	Mass (kg)	Frequency	VEI	Duration (s)	Repose (s)
Normal	1 - 10^4	several per hour	–3 to –6	1–10	10^2 to 10^4
Major	10^4- 10^5	1–8 per year	–3–0	~10	10^5 to 10^6
Paroxysm	10^7 - 10^9	0–4 per decade	0–1	10–10^2	10^8 to 10^9

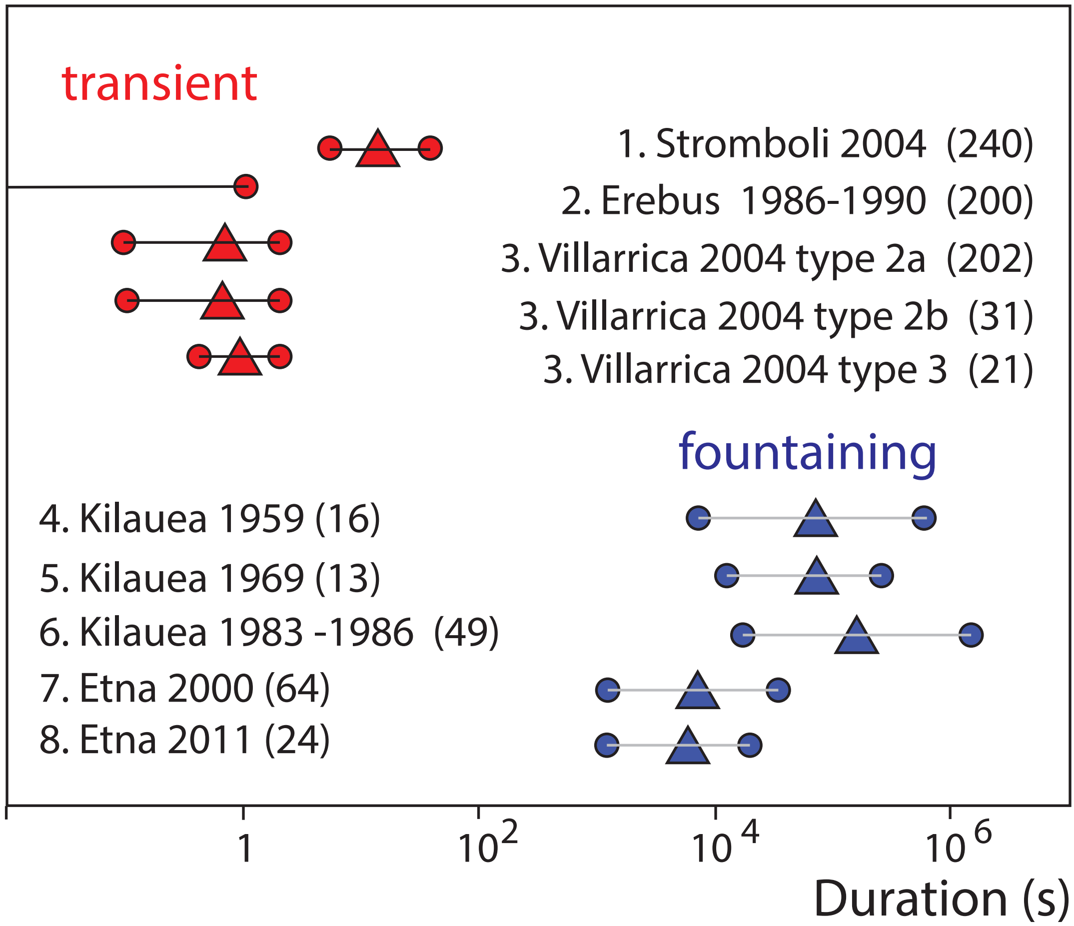
TABLE 2. PROPOSED SUBCLASSES OF HAWAIIAN FOUNTAINING

Hawaiian class	*Peak height (m)*
High	>400
Moderate	100 – 400
Low	<100


Mass (kg)
Duration (s)
1.E +11
1.E +09
1.E +07
1.E +05
1.E +03
1.E +01
1.E +00
1.E +02
1.E +04
1.E +06
1.E +08
10^8 kg/s
10^6 kg/s
10^4 kg/s
10^2 kg/s
1 kg/s
300 seconds
FOUNTAINING
Kilauea > 400 m (high)
Kilauea 100-400 m (mod.)
Kilauea <100m (low)
Etna
TRANSIENT EXPLOSIONS
Stromboli paroxysm
Stromboli major
Stromboli normal
Yasur


A
maximum jet height (m)
160
120
80
40
0:00
6:00
12:00
18:00
24:00
timing of normal explosions on 20 June 2009
B
pyroclast velocity (m/s)
200
100
0
-5
0
5
10
15
20
25
seconds from onset of explosion
C
D
E
C
velocity (m/s)
100
50
-2
-1
0
seconds from onset of explosion
D
2m
E

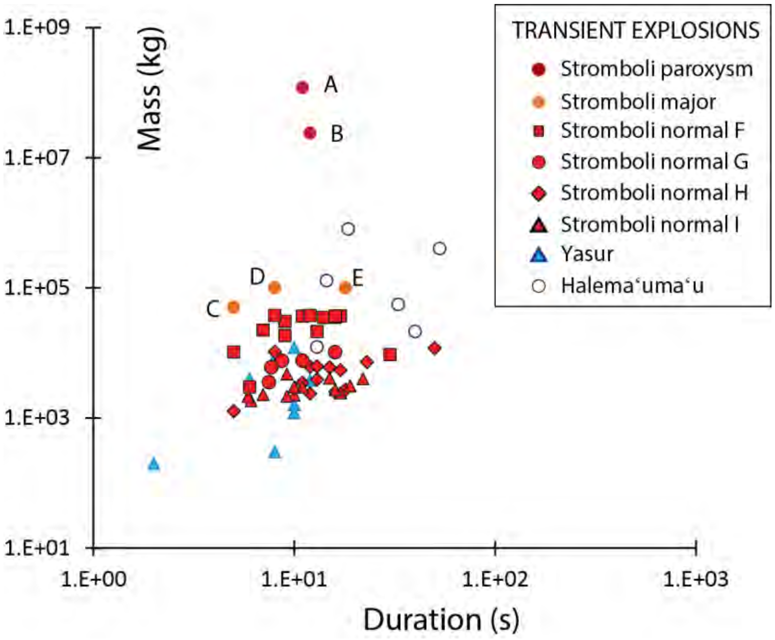

A
Episodes 10-16
fountain height (m)
600
400
100
0
10
11
12
13
14
15
16
31
32
33
34
35
36
37
eruption day
B
Episode 15
fountain height (m)
600
400
200
0
E
F
D
C
G
0
50
100
150
minutes from onset
C
D
E
F
G


transient
1. Stromboli 2004 (240)
2. Erebus 1986-1990 (200)
3. Villarrica 2004 type 2a (202)
3. Villarrica 2004 type 2b (31)
3. Villarrica 2004 type 3 (21)
fountaining
4. Kilauea 1959 (16)
5. Kilauea 1969 (13)
6. Kilauea 1983 -1986 (49)
7. Etna 2000 (64)
8. Etna 2011 (24)
1
10^2
10^4
10^6
Duration (s)

Supplementary Material

DATA USED IN FIGURE 1

Figure 1 and Supplementary Figure 1 combine estimates of erupted mass derived from measurement of the explosion products on the grounds for most categories of eruption, with estimates based on forward looking infrared imagery to detect and measure particles down to 5.3 cm (Bombrun et al., 2015) and visible/near-infrared down to 10 cm (Gaudin et al., 2015) for normal Strombolian explosions. As such these estimates will be slightly lower than the total erupted mass but, as documented by Gurioli et al., (2013), these size fractions dominate pyroclast populations during Strombolian explosions. These approaches have given us our first good erupted mass data for such explosions, as the products of normal Strombolian activity are typically (1) confined to less than 200 from vent, (2) buried by and mingled with the products of subsequent explosions on time scales of minutes to house and (3) deposited in a highly dangerous environment where it is not possible to make direct measurements of the ejecta safely. Eruption durations were either observed directly or inferred from web cam records.



Supplementary Figure 1: Enlargement of the short-duration, small mass portion of Figure 1 to ascribe data points to source references: see below.

A 5 April 2003 paroxysm at Stromboli: Rosi et al., (2006), Pistolesi et al., (2008)

B 15 March 2007 paroxysm at Stromboli: Andronico et al., (2007), Pistolesi et al., (2011)

C 3 May 2009 major explosion at Stromboli: Andronico et al., (2010)

D 8 November 2009 major explosion: Andronico et al., (2010) E 24 November 2009 major explosion at Stromboli: Andronico et al., (2010)

F 14 normal Strombolian explosions from the SW and NE craters in 2014: Gaugin et al., (2015)

G 13 normal Strombolian explosions from the SW crater in 2012: Bombrun et al., (2015)

H 13 normal Strombolian explosions from the SW crater in 2014: Bombrun et al., (2015)

I 5 normal Strombolian explosions from the NE crater in 2014: Bombrun et al., (2015)

Yasur 8 normal Strombolian explosions at Yasur in 2011: Gaudin et al., (2015)

Halemaʻumaʻu 7 externally-triggered explosions in 2008: Houghton et al., (2011). Data added at a referee's request to show the occurrence of transient explosive activity at Kīlauea.

SOURCES OF DATA USED IN FIGURES 1, 2, 4

Figure 1: Andronico et al. (2008); Andronico and Pistolesi (2010); Bombrun et al. (2015); Gurioli et al. (2013); Macdonald et al. (1986), Patrick et al. (2007); Pistolesi et al. (2008; 2011); Richter et al. (1970); Rosi et al. (2006); Swanson et al. (1979) and Wolfe et al. (1988).

Figure 2: Taddeucci et al. (2012) Taddeucci et al. (2013) and Gaudin et al. (2014)

Figure 4: 1. Patrick et al. (2007), 2. Dibble et al. (2008) and P. Kyle (pers. com. 2015). 3. Gurioli et al. (2008), 4. Richter et al. (1970), 5. Swanson et al. (1979), 6. Wolfe et al. (1988), 7. Alparone et al. (2003), 8. D'Agostino et al. (2013), (see supplementary material).

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