Pushing the Volcanic Explosivity Index to its limit and beyond: Constraints from exceptionally weak explosive eruptions at Kīlauea in 2008

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ABSTRACT

Estimating the mass, volume, and dispersal of the deposits of very small and/or extremely weak explosive eruptions is difficult, unless they can be sampled on eruption. During explosive eruptions of Halemaʻumaʻu Crater (Kīlauea, Hawaii) in 2008, we constrained for the first time deposits of bulk volumes as small as 9–300 m^3 (1×10^4 to 8×10^5 kg) and can demonstrate that they show simple exponential thinning with distance from the vent. There is no simple fit for such products within classifications such as the Volcanic Explosivity Index (VEI). The VEI is being increasingly used as the measure of magnitude of explosive eruptions, and as an input for both hazard modeling and forecasting of atmospheric dispersal of tephra. The 2008 deposits demonstrate a problem for the use of the VEI, as originally defined, which classifies small, yet ballistic-producing, explosive eruptions at Kīlauea and other basaltic volcanoes as nonexplosive. We suggest a simple change to extend the scale in a fashion inclusive of such very small deposits, and to make the VEI more consistent with other magnitude scales such as the Richter scale for earthquakes. Eruptions of this magnitude constitute a significant risk at Kīlauea and elsewhere because of their high frequency and the growing number of "volcano tourists" visiting basaltic volcanoes.

INTRODUCTION

Walker (1973, p. 433) stated "Explosive eruptions are evanescent phenomena. The presence of a trained observer on the scene is often fortuitous, and conditions are frequently such as to preclude close observation anyway." In this situation, pyroclastic fall deposits have proved an invaluable alternative for estimating mass eruption rates and defining styles of explosive volcanism (Walker, 1973; Pyle, 1989).

The Volcanic Explosivity Index (VEI) was introduced to offer a clear, simple classification of explosive eruptions by size (Newhall and Self, 1982). Eruptions were assigned to a VEI class based primarily on measures of magnitude (total ejecta volume) or intensity (mass flux as reflected by eruption plume height), more weight being given to the former. Pyle (1995) proposed a simpler logarithmic scale for VEI, based purely on erupted volume. VEI is extensively used by volcanologists in creating hazard maps and as a key parameter in the source term for tephra dispersal forecasting. The impact of the 2010 Eyjafjallajökull (Iceland) eruption, and other 20th century eruptions, has led to increasing use of the VEI scale by other agencies such as meteorological offices, federal aviation agencies, and the Volcanic Ash Advisory Centers. The scale is becoming a common language linking researchers and agency-level practitioners.

A VEI can be arrived at via eruptive magnitude (volume) or intensity (mass eruption rate). Studies use dispersal (the thinning rates for the products) both to calculate volume and as a proxy for eruption intensity (Walker, 1973; Pyle, 1989; Bonadonna et al., 1998). Many pyroclastic fall deposits show either power law or simple (single segment) to complex (multisegment) exponential thinning relationships with distance from source (Walker, 1973; Pyle, 1989; Fierstein and Nathenson, 1992; Rose, 1993; Bonadonna et al., 1998). Thinning is quantified by contouring mass per unit area (*m*/*a*) or thickness values. For simple exponential thinning behavior, there is a unique distance (b_t) over which the deposit thins by 50% (Pyle, 1989). This parameter scales with eruption plume height and therefore the intensity of the parent eruption. It is typically kilometers to tens of kilometers for powerful (Plinian) eruptions (Pyle, 1989) and 100–500 m for Hawaiian fountaining and Strombolian paroxysms (Cole et al., 2005; Rosi et al., 2006).

PROBLEM OF VERY SMALL DEPOSITS

Small and locally dispersed tephra deposits, including those of phreatic explosions, are troublesome in the context of both dispersal and eruptive volume. The preservation potential of products of extremely weak explosive eruptions is typically low, and it is generally impossible to measure the "footprint" of such eruptions from the often-meager permanent exposures. The smallest deposits used in 3 landmark papers describing tephra geometry have volumes of 2×10^5 m^3 (Bonadonna and Costa, 2012; VEI 1), 4×10^6 m^3 (Walker, 1973; VEI 2), and 4×10^7 m^3 (Pyle, 1989; VEI 3).

The VEI classification effectively includes all explosive eruptions of volume $<10^4$ m^3 in category 0 and labels them as "gentle, effusive" (Newhall and Self, 1982). Recent studies suggest that those deposits that currently compose category 0 cover at least six orders of magnitude of eruptive volume (Houghton et al., 2011; Taddeucci et al., 2012a), a significant part of the total range for pyroclastic products.

2008 EXPLOSIONS AT HALEMAʻUMAʻU, KĪLAUEA

Kīlauea, on the island of Hawaii (Fig. 1A), is a type example for basaltic explosive volcanism, along with Mounts Stromboli and Etna in Italy. The current East Rift Zone eruption, which began in 1983, is an excellent example of Hawaiian fountaining and lava production. A very

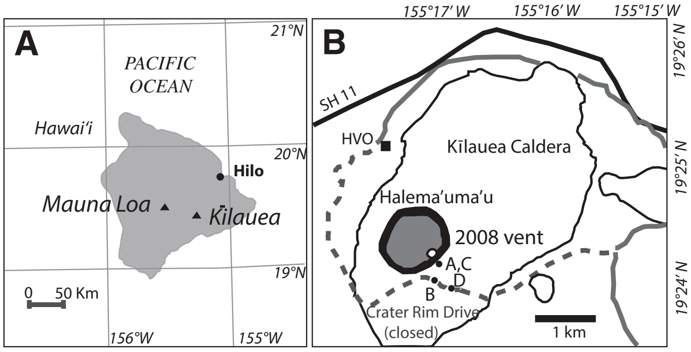


Figure 1. A: Location of island of Hawaii and Kīlauea volcano. B: Location of Kīlauea caldera and Halemaʻumaʻu crater. Proximity of 2008 vent to Hawaiian Volcano Observatory (HVO; 2.5 km) permitted unusually rapid sampling of deposits. Letters A–D mark locations shown in Figure 2.

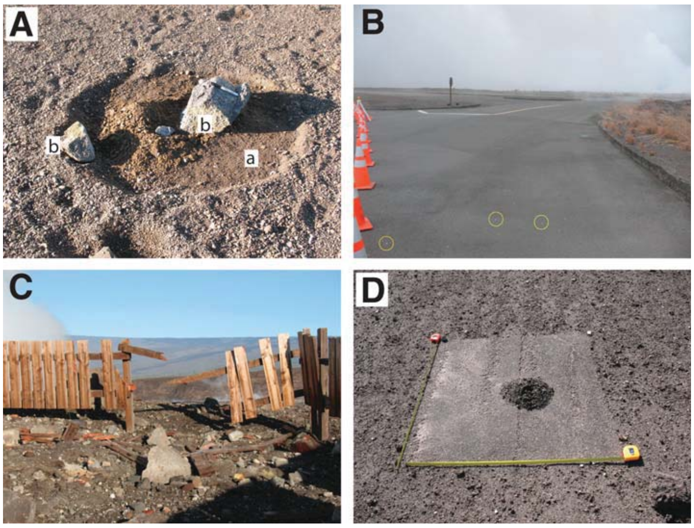


Figure 2. Representative views of 2008 fall deposits, Hawaii. A: Proximal 19 March 2008 fall deposit, 150 m southeast of vent, has mass/area of 4700 g m^{-2} (site A in Fig. 3A). Letter a is pre-eruptive ground surface; letters b indicate two broken portions of small ballistic clast. B: Scattering of widely separated lapilli (white particles) on far eastern margin of this deposit (site B in Fig. 3A), with mass/area of 10 g m^{-2}, equivalent of bed only 8 µm thick. Three lapilli are circled to aid in identification. C: 19 March 2008 ballistic block that hit guard rail at Halema'uma'u overlook, 60 m from new vent (site C in Fig. 3A). D: Isomass sample collected from 1 × 1 m square on Crater Rim Road for 2 September 2008 fall deposit (site D in Fig. 3D). Mass/area value of 147 g m^{-2} is equivalent of bed only 110 µm thick. All photographs by Bruce Houghton.

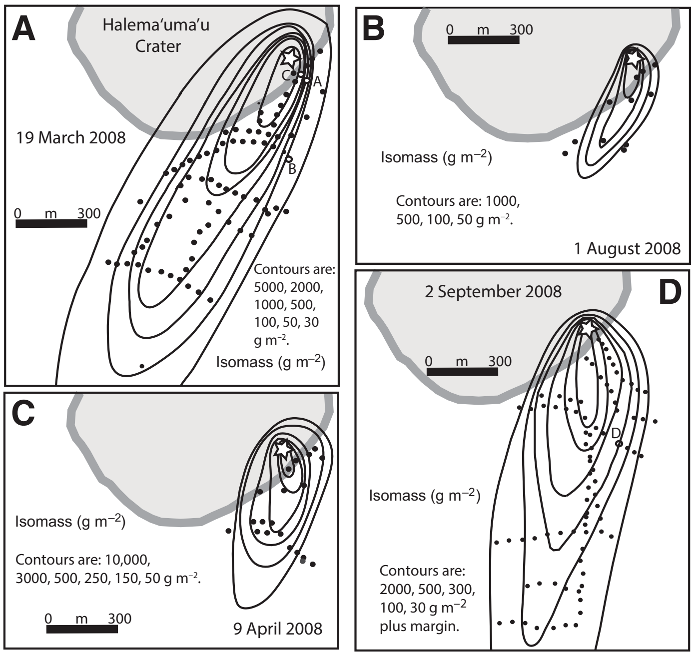


Figure 3. Isomass maps for representative examples of 2008 fall deposit (Hawaii), advected by strong northeasterly (trade) winds. A: 19 March 2008. B: 1 August 2008. C: 9 April 2008. D: 2 September 2008. Star marks vent location; letters A–D are locations in Figure 2.

different type of eruption at Kīlauea's summit began with the opening of a new 35-m-wide vent (Fig. 1B) on the southeastern floor of Halema'uma'u Crater on 19 March 2008 (Wilson et al., 2008; Houghton et al., 2011). The diameter of the vent has grown incrementally to 150 m during numerous wall-rock collapses on scales to 10^5 m^3 (Orr et al., 2012). The largest rockfalls triggered weak, impulsive explosive eruptions, which are the topic of this paper. The economic cost of this sequence of very small eruptions is significant and out of proportion to their magnitude. A significant part of Hawai'i Volcanoes National Park has remained closed since April 2008, and 2 formal evacuations of more than 2000 people have occurred.

The initial explosion, on 19 March 2008, ejected only wall rock (Houghton et al., 2011). The later explosions have ejected a mixture of vesicular basaltic bombs and lapilli, and wall-rock lithics, the latter representing a small proportion of the masses that collapsed from the vent and/or conduit walls to trigger the explosions (0.1%; Orr et al., 2012). The ejecta was partitioned between wind-advected plumes depositing downwind lobes of tephra (Figs. 2A and 2B) and minor ballistic blocks and bombs restricted to within several hundred meters from the vent (Figs. 2A and 2C). The wind-advected deposits (Fig. 3) were sampled from either measured areas (Fig. 2D) or buckets deployed at fixed sites in the vicinity of the crater, starting on the day of eruption. We traced the fall ejecta laterally to where it formed a discontinuous scattering of isolated clasts rather than a coherent bed (see Houghton et al., 2011, their figure 4). The samples were taken to the laboratory, dried, and weighed to calculate *m/a* as a proxy for thickness. We measured *m/a* values to <10 g m^{-2}, which is equivalent to a thickness of <10 µm, assuming a deposit density of 1300 kg m^{-3} (Fig. 3).

QUANTIFYING THE 2008 DEPOSITS

A plot of *m/a* against $A^{1/2}$, where *A* is the area enclosed by each isomass contour, indicates that the seven largest 2008 deposits show simple and rapid exponential thinning (Fig. 4). The thinning half-distances are short, ranging from 13 m for the 14 October 2008 deposit to 46 m for the 2 September deposit (Table 1). These are, to our knowledge, the most locally dispersed pyroclastic fall deposits yet quantified, although photoballistic analysis of airborne clasts in typical normal discrete explosions at Mount Stromboli (Chouet et al., 1974; Ripepe et al., 1993) suggests that their products probably have similar dispersal.

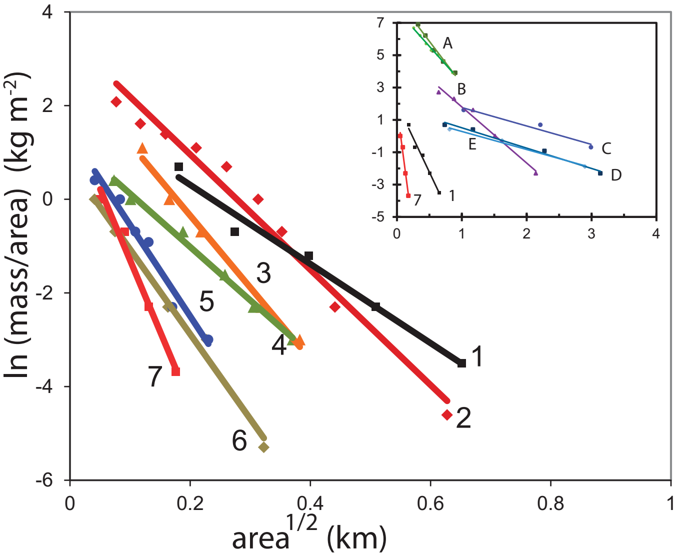


Figure 4. Plot of isomass values against area$^{1/2}$ for 2008 deposits (Hawaii) showing very restricted dispersal of these fall deposits. Deposits are numbered in order of decreasing mass eruption rate. 1—2 September 2008; 2—19 March; 3—9 April; 4—12 October; 5—27 August; 6—1 August; 7—14 October. Inset plot shows, for comparison, data from Hawaiian fountaining (A—Kīlauea Iki, 1959 episodes 1 and 15–16; our data) and Strombolian paroxysms (B—Stromboli, 5 April 2003, Rosi et al., 2006; C—Arenal, Costa Rica, 13 June 1990; D—Arenal, 15 January 1997; E—Arenal, 2 September 1997, Cole et al., 2005).

TABLE 1. CHARACTERISTICS OF THE EXPLOSIVE ERUPTIONS AT HALEMA‘UMA‘U CRATER (HAWAII) IN 2008 AND THEIR DEPOSITS

Event	m_0 (kg m^{-2})	b_t (m)	Duration (s)	Mass (kg)	Mass discharge rate (kg s^{-1})	Bulk volume (m^3)	Dense rock volume (m^3)	VEI
19 March 2008	30.5	32	53	4.0×10^5	7.6×10^3	3.1×10^2	149	–2
9 April 2008	15.2	26	14.5	1.3×10^5	8.9×10^3	1.0×10^2	48	–2
1 August 2008	2.1	22		1.3×10^4		1.0×10^1	4.8	–3
27 August 2008	4.1	20	40	2.1×10^4	5.4×10^2	1.6×10^1	7.9	–3
2 September 2008	7.4	46	18.6	2.1×10^5	1.1×10^4	2.1×10^2	76	–2
12 October 2008	3.5	35	33	5.5×10^4	1.7×10^3	4.3×10^1	21	–3
14 October 2008	5.7	13	28	1.2×10^4	4.4×10^2	0.9×10^1	4.6	–4

Note: Dense rock equivalent volumes are calculated with a density of 2700 kg m^{-3}; bulk volumes are calculated using a measured field density of 1300 kg m^{-3}. Durations are after Fee et al. (2010). m_0—value of mass per unit area (*m*/*a*) at the vent; b_t—distance over which the deposit thins by 50%. VEI—Volcanic Explosivity Index.

The masses and volumes of the 2008 ejecta are commensurately small. Total eruptive masses for fall deposits showing simple exponential thinning (M_t) may be calculated from the formula $M_t = 13.08\, m_0 b_t^{1/2}$, where m_0 is the value of *m*/*a* at the vent (after Pyle, 1989). The 2008 deposits have eruptive masses of 10^4 to 10^5 kg, corresponding to dense rock equivalent volumes of 4.6–150 m^3 (VEI 0). Deposits of typical Strombolian explosions have not been quantified in this fashion, but estimates of total mass in the jets can be used instead (Chouet et al., 1974; Ripepe et al., 1993). These sources list masses of between 8 kg and 33,000 kg for discrete explosions.

Time-averaged mass discharge rates can be calculated using the duration of the explosions and the erupted mass (Table 1). These range from 5×10^2 kg s^{-1} to 4×10^4 kg s^{-1} (equivalent to 0.5–40 m^3 s^{-1}). By comparison, high Hawaiian fountains have time-averaged discharge rates of 6×10^3 kg s^{-1} to 1.5×10^6 kg s^{-1} (e.g., Wolfe 1988), and two 21st century Strombolian paroxysms have rates of 2.1×10^6 kg s^{-1} (Pistolesi et al., 2011) and 1.1×10^7 kg s^{-1} (Rosi et al., 2006).

CLASSIFICATION OF EXPLOSIVE ERUPTIONS

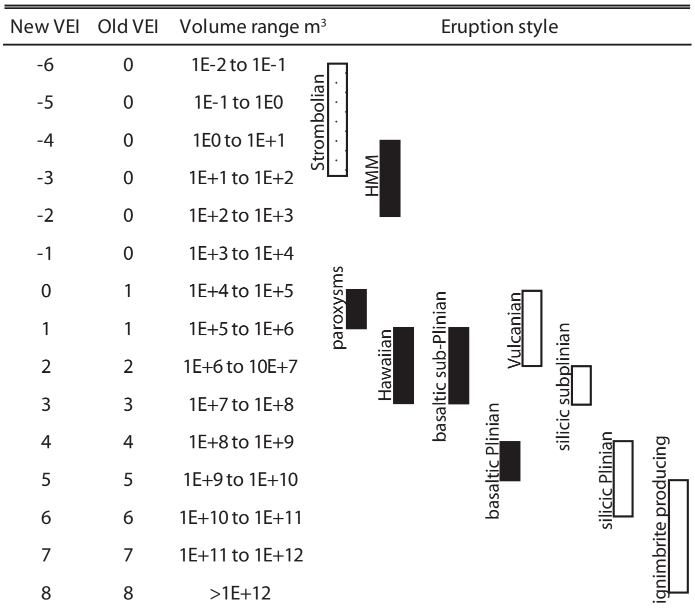
There is no simple way to accommodate the 2008 Halema‘uma‘u deposits in existing classifications of explosive eruptions. They were not phreatomagmatic, because no external water phase was involved; there was no surface water at the vent and the free surface for the explosions was 400–500 m above the water table. The explosions and their products plot at the low-volume, low-intensity end of a range of mostly basaltic eruption styles called Hawaiian and Strombolian. Both styles form cones of locally dispersed ejecta dominated by juvenile scoria. Hawaiian eruptions are sustained fountains of pyroclasts and gas on time scales of hours to days (e.g., Wolfe, 1988). Strombolian activity consists of successions of impulsive, transient, discrete explosions with durations of seconds to tens of seconds, spaced minutes to hours apart. Taddeucci et al. (2012a) showed that each explosion can be resolved into a series of even shorter pulses.

The 2008 events were clearly not Hawaiian; they were not sustained, they produced jets and plumes rather than fountains, and their deposits are much richer in conduit and vent wall rock than classic Hawaiian products. The Halema‘uma‘u explosions have durations more than two orders of magnitude less than Hawaiian fountains (Wolfe, 1988), and have durations similar to paroxysms at Stromboli (Pistolesi et al., 2011), but were clearly much weaker. In volume and duration the 2008 explosions were similar to Strombolian events (Chouet et al., 1974; Ripepe et al., 1993; Taddeucci et al., 2012a, 2012b); however, they are rich in wall rock and detailed studies show a different triggering mechanism that is not related to the rise of large gas slugs, but is instead linked to the instability of the vent walls (Orr et al., 2012).

VEI

The VEI is being increasingly used as a measure of eruptive magnitude especially in the context of the source term for modeling of tephra plumes. The Newhall and Self (1982) scale is logarithmic, with each interval on the scale representing a tenfold increase in tephra volume, with the exception of VEI 0 (<10^4 m^3 tephra), and VEI 1 (10^4–10^6 m^3 tephra). The category VEI 0 is described as nonexplosive, yet the 2008 eruptions at Halema‘uma‘u were entirely explosive. Typical Strombolian explosions would also be classified as nonexplosive on this basis. We suggest redefining VEI 1 to make it consistent with VEI 2 and above, and then extending the defined classes on the VEI scale, following Pyle (1995), such that an eruption of bulk volume $A \times 10^i$ m^3, where $1.0 < A < 10.0$, has a VEI classification of VEI = $i - 4$ (i = 0, 1, …).

On this basis, the eruptions described here are within VEI classes of –2 to –4 (Fig. 5), in comparison to VEI 0–1 for Strombolian paroxysms and 2–3 for Hawaiian fountains. In this way the scale is internally consistent (entirely logarithmic), and the important physical and social implications of small explosive eruptions are not overlooked.



New VEI	Old VEI	Volume range m^3
-6	0	1E-2 to 1E-1
-5	0	1E-1 to 1E0
-4	0	1E0 to 1E+1
-3	0	1E+1 to 1E+2
-2	0	1E+2 to 1E+3
-1	0	1E+3 to 1E+4
0	1	1E+4 to 1E+5
1	1	1E+5 to 1E+6
2	2	1E+6 to 10E+7
3	3	1E+7 to 1E+8
4	4	1E+8 to 1E+9
5	5	1E+9 to 1E+10
6	6	1E+10 to 1E+11
7	7	1E+11 to 1E+12
8	8	>1E+12

Figure 5. Suggested extension of categories within Volcanic Explosivity Index (VEI) scale. Categories are unchanged for deposits of volume >10^5 m^3. All deposits that would have been formally classified in category 0 of Newhall and Self (1982) are now classified by extension of Pyle (1995) formula used for category 1 and above. Columns on right indicate common values derived for volumes of deposits for variety of basaltic (black) and silicic (white) eruption styles using data from Newhall and Self (1982), Wolfe (1988), Pyle (1989), Bonadonna et al. (2002), Cole et al. (2005), Thordarson and Larsen (2007), Andronico et al. (2008), and Pistolesi et al. (2011). HMM are 2008 Halema‘uma‘u deposits described here. "Ignimbrite producing" refers to large caldera-forming eruptions cited by Newhall and Self (1982). Shown for comparison (stippled) is range for typical Strombolian explosions, derived not from deposits but from estimated mass of ejecta in Strombolian jets (after Chouet et al., 1974; Ripepe et al., 1993).

CONCLUSIONS

The 2008 eruptions of Halemaʻumaʻu at Kīlauea produced the smallest pyroclastic fall deposits yet documented, with commensurately restricted dispersal. They show simple exponential thinning, permitting accurate measurement of dispersal parameters and erupted volumes. Extending the categories within the VEI scale by six orders of magnitude incorporates both the 2008 deposits and the products of typical explosions at Stromboli (Chouet et al., 1974; Ripepe et al., 1993). Newly published data obtained at Stromboli, via a high-speed camera (Taddeucci et al., 2012b), suggest that, ultimately, even the smallest and shortest Strombolian events will be subdivided into multiple pulses with VEI values as small as −7. This revision permits more accurate inputs for tephra and hazard models and allows volcanologists to communicate effectively relative hazard over an extended range of explosivity.

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