From the ashes of VEI:
Decoding explosivity, mass eruption rate and hazards in real time

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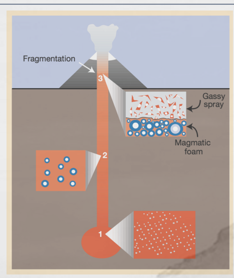
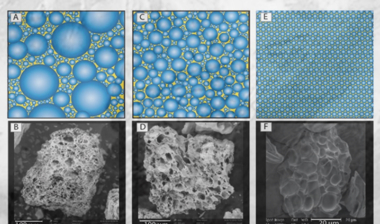
The Problem: The well-known Volcano Explosivity Index (VEI) has been used in the literature and popular media for decades but suffers from subjectivity and has fallen out of favor in the scientific community. Further, it is normally only assigned for major eruptions after the volume erupted has been measured, often long after eruption has ceased. Mass eruption rate (MER) better reflects eruption energy of interest to volcanologists.

Our Solution: Determine a measure for MER in real time for observed eruptions and from eruption products for ancient eruptions. The morphology of erupted ash establishes a threshold between low and high MER as well as VEI.

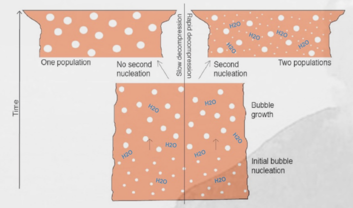
Background: VEI, established by Newhall and Self (1982), involves qualitative descriptions, volume of ejecta, column height, eruption duration, and several other descriptive factors. However, column height is not indicated beyond 25 km, or a VEI of 5 in the original VEI determination scheme. Beyond this, volume of ejecta to the nearest order of magnitude is the only basis for classification of eruptions. This and other factors that are difficult to measure render VEI less useful as an indicator of the eruption energy that drives Mass Eruption Rate. Consequently, we now prefer to use MER when describing explosive eruptions, so establishing convenient means for determining MER would be useful.



Bubbles nucleate at depth and grow during magma ascent by decompression and diffusion of dissolved volatiles (primarily water) into existing bubbles. This drives acceleration upward and if sufficiently rapid near the vent, can trigger a second phase of nucleation, creating a population of syn-eruptive bubbles with a much smaller modal size than the pre-eruptive bubbles that drove the eruption. Explosive decompression leads to fragmentation at or near the vent, converting a bubbly liquid into a gassy spray consisting of bubble wall and Plateau border fragments that cool to become simple and compound ash particles. The entire process is controlled by the distribution of nucleation sites, which highlights the critical importance of understanding nucleation mechanisms hat ultimately control Mass Eruption Rate.

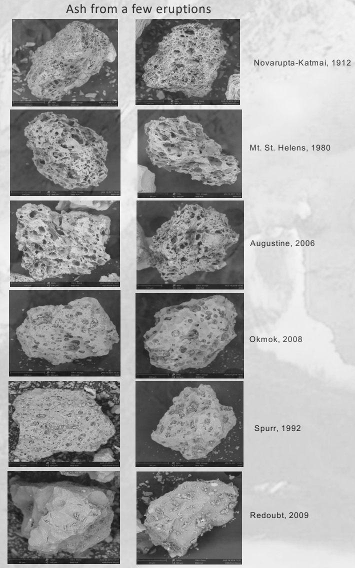


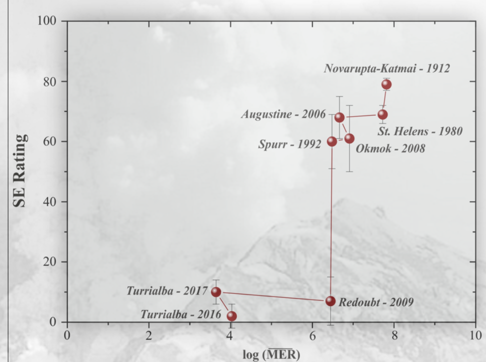
Nucleation controls the subsequent bubble growth that drives explosive eruptions. One would expect that the presence of microlites triggers heterogeneous nucleation at low oversaturation resulting in low bubble number density and broad bubble size distribution as in A,B above (Novarupta-Katmai ash). Homogeneous nucleation (C,D) should result in a more uniform spatial distribution of nucleation sites and thus narrower bubble size distribution (Augustine ash). Extreme oversaturation (only possible in the homogeneous case) leads to the most uniform spatial distribution (E,F) and thus bubble size distribution (Mt. St. Helens ash). In this case, bubble walls have sub-equal strength and thus break simultaneously (explosively) during fragmentation. We are testing these parameters on samples of known composition, water content and crystallinity in order to elucidate the mechanisms of nucleation in each case, and relate them back to ashes from natural eruptions.



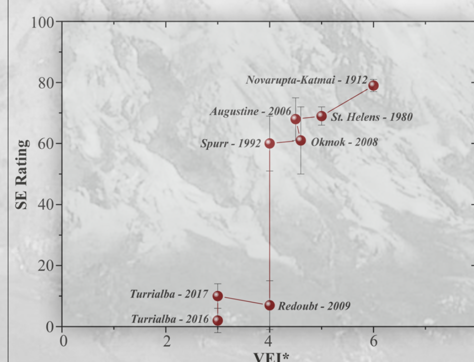
Magma ascent rates determine the degree of oversaturation of a decompressing magma. Pre-eruptive bubbles initially nucleate once an oversaturation threshold is exceeded, depending on presence of microlites and many other characteristics of the magma. Bubble growth by diffusion and decompression then accelerates ascent and further decompression. If decompression rate is sufficiently rapid, water oversaturation between bubbles can increase to the point that the nucleation threshold is again exceeded, and a second phase of nucleation occurs forming syn-eruptive bubbles. Upon fragmentation during ensuing explosive eruption, this leads to a bimodal bubble size distribution preserved in observable ash.

Ash from a few eruptions





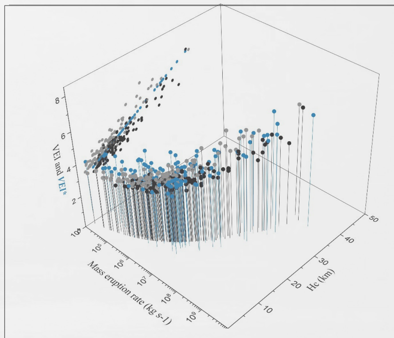
MER threshold above which syn-eruptive bubbles are nucleated. For eruptions that were not observed, asuch as ancient eruptions, MER can thus be constrained on the basis of ash morphology. If MER exceeds $5x10^6$ kg/s, syn-eruptive bubbles become common, and as MER increases beyond that there is some increase in SE rating, but the main threshold is at $5x10^6$ kg/s.



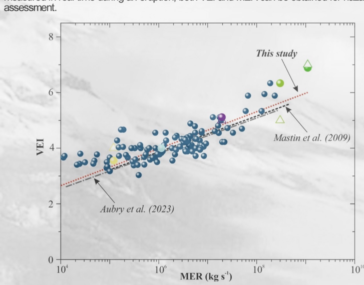
VEI threshold above which syn-eruptive bubbles are nucleated. VEI has fallen out of favor due to its subjectivity and weak association with eruption energy. Yet, I is commonly cited in the popular press and governmental organizations. The SE rating can also identify a sharp threshold at VEI = 4. Note that on the basis of total mass erupted, the "traditional" VEI for Redoubt is 3, but on the basis of column height, it is 4.

Eruption	Hc (km)	VEI	VEI*
Nevado del Ruiz (1985)	0.2	3	3
Fuego (Feb. 2002)	0.7	3	3
Asama (1783)	1	4	3
Pelee (1902)	1	4	3
Aoba (20118)	2	3	3
Dukono (1550)	3	3	3
Etna (2002)	4	3	3
Irazu (1963)	5	3	3
Montserrat (2004)	5	3	3
Sangay (1976)	6	3	3
Grimsvotn (1996)	6	3	3
Augustine (1883) 2006	7	3	4
Eyajallajokull (2010)	7	4	4
Kelud (1990)	7	4	4
Popocatepetl (1996)	8	3	4
Okmok (2008)	10	4	4
Spurr (1992)	10	4	4
Soufriere Hills (1999)	10	3	4
Sheveluch (2019)	10	4	4
Laki (June: 1783)	11	4	4
Raikoke (2019)	11	4	4
Calbuco (2015)	15	4	4
Redoubt (2009)	15	3	4
Fuji (1707)	16	4	5
Ulawun (2019)	16	4	5
El Chichon (1982)	19	5	5
Cerro Hudson (1991)	16	5	5
Agung (1963)	20	5	5
Mt. St. Helens (1980)	21	5	5
Galunggung (1822)	24	5	5
Askja (1875)	24	5	5
Pinatubo (1991)	29	6	6
Katmai (1912)	30	6	6
Krakatau (1883)	31	6	6
Vesuvius (1631)	34	5	6
Tambora (1815)	34	7	7
Lake Taupo (186 AD)	40	7	7
Toba (~73,000 BP)	48	8	8

Like MER, VEI can be estimated in real-time during an eruption merely on the basis of eruption column height for energetic eruptions (VEI>3) using $VEI = \frac{H_c+25}{9}$ Although this empirical formulation is not mechanistic, it works remarkably well for a wide range of eruptions.



Mass Eruption Rate can be calculated from eruption column height (e.g. Aubry et al. 2023). This 3-axis plot (above) illustrates the interconnection between VEI and MER through eruption column height. The projection onto the VEI-MER plane is below. Because eruption column height can be measured in real time during an eruption, both VEI and MER can be obtained for hazard assessment.



CONCLUSIONS

The ability to determine both VEI and MER in real time may enable better hazard management, particularly for air traffic. Although VEI has fallen out of favor amongst the volcanological research community (for some good reasons), it is still used by the general public, so being able to obtain both in real time during an eruption can be useful. For past eruptions whose column heights were not observed, ash morphology can partially constrain both MER and VEI on the basis of the SE rating reflecting the nucleation of syn-eruptive bubbles.

Acknowledgements

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