Appendix

Strombolian Eruptions and Scoria Cones In Reference to Volcanic Consequence Analysis at Yucca Mountain

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The tremendous variety of volcanic eruptions and the volcanic landforms that they produce has led to a large and sometimes confusing nomenclature. Alas, I believe this has befallen some of the literature and discussions about the consequences of a volcanic dike intersecting drifts of the proposed high-level radioactive waste repository beneath Yucca Mountain, Nevada. I have attempted to clarify the nomenclature for you and me.

A good place to start is the measure of volcanic eruption magnitude called the Volcanic Explosivity Index (VEI, Table 1 below) as described by Simkin and Siebert (1994, p. 23, Table 4)[1]. Simkin and Siebert summarize the problem with developing a quantitative scale for eruption magnitudes:

The reported size, or "bigness" of historical eruptions depends very much on both the experience and vantage point of the observer. Volcanology, unfortunately, has no instrumentally determined magnitude scale, like that used successfully by seismologists for earthquakes, so it is easy to understand why one observer's "major" eruption might be another observer's "moderate" or even "small" event.

The VEI scale attempts to add quantitative meaning to otherwise subjective descriptions[2]. Note in Table 1 that there is considerable overlap between Strombolian and Hawaiian eruptions on the low end, and of Strombolian and Vulcanian on the high end of measures of eruption magnitude. Terms commonly used for supposed large Crater Flat eruptions are "intense Strombolian", a term of uncertain meaning.

At a recent meeting a column height of 35 km was mentioned in the context of Strombolian eruptions. Note that in Table 1 such an elevation has been mentioned as a possibility (>25 km is given as the highest eruption cloud) in only the most intense eruptions: Plinian and Ultra-Plinian. There is a rough but real direct correlation between the eruption magnitude and volcanic edifice size. Strombolian eruptions have a small VEI, between 1 to 2, and build the smallest volume cones, particularly for scoria cones produced by a single eruption episode.

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[1] Simkin, T. and Siebert, L., 1994, Volcanoes of the World, Second Edition, 1994, Geoscience Press, Inc., Tucson, Arizona. See pages 23-

[2] Newhall, C.G. and Self, S., 1982. The volcanic explosivity index (VEI): an estimate of explosive magnitude of historical eruptions. Jour. Geophys. Res., 87: 1231-38.

Note that the bottom row in Figure 1 shows that Strombolian eruptions are by far the most abundant type of historical eruption. Volcanoes characterized by Strombolian eruptions are common at the term's namesake volcano: Stromboli in the Mediterranean.

	0	1	2	3	4	5	6	7	8
General Description	Non-Explosive	Small	Moderate	Moderate-Large	Large	Very Large			
Volume of Tephra (m^3)		1×10^4	1×10^6	1×10^7	1×10^8	1×10^9	1×10^{10}	1×10^{11}	1×10^{12}
Cloud Column Height (km) Above crater / Above sea level	<0.1	0.1-1	1-5	3-15	10-25	>25 →			
Qualitative Description	"Gentle,"	"Effusive"	← "Explosive" →		← "Cataclysmic," / "Severe,"	"paroxysmal," / "violent,"	"colossal" → / "terrific" →		
Eruption Type (see fig. 6)	← Hawaiian →	← Strombolian →	← Vulcanian →	← Plinian →		← Ultra-Plinian →			
Duration (continuous blast)	← <1 hour →		← 1-6 hrs →	← 6-12 hrs →	← >12 hrs →				
CAVW max explosivity (most explosive activity listed in CAVW)	Lava flow / Dome or mudflow	← Explosion or Nuee ardente → / ← Phreatic → - - →							
Tropospheric Injection	Negligible	Minor	Moderate	Substantial →					
Stratospheric Injection	None	None	None	Possible	Definite	Significant →			
Eruptions (total in file)	699	845	3477	869	278	84	39	4	0

Table 1. The Volcanic Explosivity Index for Eruptions termed Strombolian. Note that maximum column height for these is about 5 km, and maximum volume of .01 km^3 (10^7 m^3).

Hawaiian and Strombolian eruption types[3] are commonly associated. Both involve eruption of low-viscosity basaltic magmas with some dissolved gases, mainly H_2O and much less CO_2 along with small amounts of S, Cl and F species. Their eruptions are intensified by the near surface expansion and explosive disruption of gas bubbles. Hawaiian eruptions typically involve breaching of the surface by a dike followed by eruptions of spectacular "curtains" of fire that characterize most of the initial phases of the eruptions of Kilauea and Mauna Loa Volcanoes, Hawaii. At a lesser scale, they probably initiated many if not all of the Crater Flat cones.

Eventually, the activity along the dike focuses at one or at the most a few places, building centralized scoria cones characterized by Strombolian eruptions. Scoria are small (usually fist-sized but can be much larger or smaller) quenched magma parcels containing bubbles that are on the order of a few millimeters, but can be much larger or

[3] See pages 321, 447, and 483 in the *Encyclopedia of Volcanoes*, 2000, H. Sigurdsson, Editor, Academic Press, New York, for more information on Strombolian eruptions, scoria cones and their eruptive products.

smaller. They form from the high velocity disruption and ejection of magma explosively from a central vent or fissure.

The scoria cones produced by Strombolian eruptions are the most common volcanoes on earth. Most, but not all, are produced during a single eruptive episode. This is the case of the Lathrop Wells scoria cone, which formed about 75,000 years ago, the last eruptive episode in the Yucca Mountain region.

Lava fountaining is a typical part of Strombolian eruptions, driven to by rising magma that is rapidly expanding as gases, again mainly water, exsolve due to drop on pressure in the rising magma column. At times, both degassed lava and Strombolian eruptions occur simultaneously (Figure 1).

Figure 1. 1968 Strombolian eruption of Cerro Negro Volcano, Nicaragua. In the foreground is a small crater that is emitting fire fountains that are feeding a lava flow during the central crater's Strombolian eruption. Diameter of base is about 1.5 km. Photo by Robert Citron

Hawaiian eruptions typically begin with ground fissuring accompanied by swarms of propagating earthquakes. Vents develop along the lengthening fissure and an almost continuous wall of magma, a curtain of fire, may extend over more than a kilometer. Gradually the "curtains" shrink to a single portion of the vent, forming towering fountains that rapidly build a scoria cone. About 50-1000 m3/s is emitted during a fountaining episode, reaching heights of 100-500 m and even higher. Izu-Oshima volcano, Japan, produced fountains to 1600 m during its 1986-87 eruption[4]. These values are for eruptions located, first, above the extremely active Hawaiian thermal plume (hot spot) and, secondly, in Japan, in above a highly active subduction zone. The same can be said for the relatively intense eruptions of Tolbachik in Kamchatka, often refrrred to as a good analogy for future Yucca Mountain eruptions. Tolbachik is a large-volume volcanic

[4] From Vergniolle, S. and Mangan, M., 2000, Hawaiian and Strombolian eruptions, p. 447, Encyclopedia of Volcanoes.

complex above another zone of rapid subduction, that beneath Kamchatka. The high-volume-eruption rates that produced the intense fountaining and Strombolian eruptions in these environments are less likely to be associated with future Yucca Mountain region eruptions based the comparatively low volume, small scoria cones so far erupted there and the intraplate, non-hotspot tectonic environment.

Strombolian eruptions are commonly initiated by a Hawaiian-style fissure eruption that withdraws to single vent, as noted above. In some cases, they may begin with a vent-clearing explosion. Strombolian magmas may be slightly more viscous than those of Hawaiian eruptions, because of lower eruption temperatures and/or differing compositions. Strombolian explosive eruptions can involve by episodic bursting of an accumulation of gas in a conduit cavity that may form a gas-filled "blister" several meters in diameter that explodes with an intense "roar", lasting 1 to 10 seconds and ejecting gas and centimeter to millimeter largely angular fragments of the disrupted "lid".

Scoria cones (also called cinder or tephra cones) commonly occur in groups or fields, such as in Crater Flat. Crater Flat is a relatively small cinder cone field; some contains hundreds of cones. Scoria cones may include a hydromagmatic (also termed phreatomagmatic) deposits formed by interaction of ascending magma with groundwater.

Scoria cones are found distributed in fields like Crater Flat in many areas the southwestern U.S., a tectonic setting involving extensional faulting associated with over-riding of the East Pacific Rise spreading center by the North American plate. They can occur too in association with hot-spot volcanism, such as those in the Craters of the Moon cluster associated with the Yellowstone hotspot and those above the Hawaiian and Iceland hotspots. They are common too behind many of the major giant composite volcanic belts that mark the landward side of continental-oceanic lithosphere subduction zones such as the Cascade, Mexican, Central American, and Andes volcanic belts. Island arcs of oceanic-oceanic lithosphere convergence are also rich in scoria cones. The magmas that produce them are mainly basaltic and derived from depths on the order of 100 km, that is, in the asthenosphere. The type Strombolian eruptions of Stromboli in the Mediterranean are derived from the slow convergence of the African and Eurasian Plates.