Estimating plumes from seismic data: What we can and cannot do
Seismic monitoring in Alaska
Outline

- Review of plume seismology
- Force source seismic model
- Scaling arguments
- Counter-example: Okmok 2008
Real-time seismic amplitude (RSAM)

May-June 2014

November 2014

Color code changes based in large part on increase in RSAM
Reduced displacement ($D_R$)

- Ground displacement multiplied by distance from source - physical dimensions of displacement squared
- In principle should be the same at all stations
- Analogous to scattering cross section in radiative transfer
- Alternatives are RSAM and radiated energy
Plume Height vs. $D_R$  

McNutt (1994)

$$\log_{10}(D_R) = 1.80 \log_{10}(H) - 0.08$$

![Graph showing the relationship between plume height and reduced displacement](image.png)
Fig. 13 Comparison of reduced displacement ($D_R$) and reported plume heights. Plume heights generally increase with reduced displacement; the effect is most apparent on stations PS1A and PN7A. Station PV6, on the other hand, had continually high levels of tremor associated with a debris or mud flow in a nearby gully; note the scale difference on the graph for PV6. Reduced displacement at station BLHA, located at 33 km, shows no relationship with plume height.

Fig. 3. The correlation between the height of ash plumes on Karymskii Volcano and the integral of absolute velocity as observed at the KRY station for 70 cases recorded by visual, photographic, and video observations in 2004–2007.

Fig. 4. The correlation between the height of ash emissions on Kizimen Volcano and the integral of absolute velocity as observed at the KZV station for 19 cases recorded by visual, photographic, and video observations in 2011.

Fig. 5. The correlation of the height of ash plumes on Bezymyannyi Volcano: (a) with the integral of absolute velocity, (b) with the integral of squared velocity. The analysis involved records of the LGN station for nine cases recorded by visual, photographic, and video observations.
- Force source model
- Far-field Rayleigh waves
- Used Sparks et al. (1997) relation:

\[ H \sim q^{1/4} \]
Assumptions in plume seismology

- Seismic signals from the plume dominate
  - Seismicity not at depth in the Earth
  - Not ground-coupled airwaves

- Wave type known: P, S, or Rayleigh wave

- Distortion from path effects unimportant

- Amplitude proportional to plume height

- Applies for plumes higher than 5 km
Prejean and Brodsky (2011) *JGR*:

A volcanic plume source acts as an inverted rocket engine, imparting force on the Earth:

\[ F = q \rho V \]

- \( \rho \): Plume density
- \( q \): Volume eruption rate
- \( V \): Exit velocity
Scaling: Radiated seismic power

Prejean and Brodsky (2011) source model leads to above scaling relation for seismic power $W$

$$W \sim \frac{\rho A V^6}{V_p^3} \left( \frac{\rho}{\rho_s} \right)$$

- $\rho$: Plume density
- $A$: Area of vent
- $V$: Exit velocity
- $V_p$: P-wave velocity
- $\rho_s$: Earth density
Scaling: Acoustic analogy

\[ W \sim \frac{\rho AV^6}{V_p^3} \left( \frac{\rho}{\rho_s} \right) \]

\[ P_D = K_D \frac{\rho_0 A_D V^6}{a_0^3} \]

Empirical constant or fudge factor

Woulff and McGetchin (1976)

Dipole sound radiation model
Scaling: Vent area and plume height

Rewriting in terms of volume eruption rate

\[ W \sim \frac{\rho AV^6}{V_p^3} \left( \frac{\rho}{\rho_s} \right) \]

Together with Sparks et al. (1997) relation gives quadratic scaling w/plume height

\[ D_R \sim \sqrt{W} \sim \sqrt{A} \]

Square root scaling with vent area

\[ W \sim \frac{\rho q V^5}{V_p^3} \left( \frac{\rho}{\rho_s} \right) \]

\[ D_R \sim \sqrt{W} \sim H^2 \]
Close to scaling prediction of 0.5

“We infer that the maximum reduced displacement is approximately proportional to the square root of the area of vents …”
\[ \log_{10}(D_R) = 1.80 \log_{10}(H) - 0.08 \]

Close to scaling prediction of 2
Redoubt 2009 explosive events

Radiated energy and plume height data from McNutt et al. (2013)

\[ E \sim H^{6.5} \]

Scaling predicts exponent of 6
Okmok Volcano: A counter-example
Backprojection Method

- Illuminating the source by summing over stations

$$s_j(t) = \sum_k \left( \frac{p_k}{A_k} \right) u_k \left( t - t_{jk} + \Delta t_k \right)$$

Ishii et al. (2005) Nature
2008 eruption of Okmok

Larsen et al. (2009) EOS
Okmok seismic stations

2 broadbands: OKSO, OKFG

5 short-periods: OKAK, OKSP, OKWE, OKWR, OKRE

Several other stations damaged by eruption
Backprojection methodology

- Spectral whitening, time shift, and compute stack power for candidate source locations

- At Okmok, virtually no path effects in the 0.2-0.3 Hz band (Haney, 2010)

- Time shifting based on a homogeneous surface wave velocity model of 2.7 km/s (Masterlark et al., 2010)
Raw seismograms

Seismograms shifted at tremor location
Array Deconvolution

- Problem: Impulse response of modest 7 station network lacks sharp resolution

- Solution: Remove impulse response by deconvolution

- Two possible methods:
  - Richardson-Lucy, Nishida et al. (2008) *GRL*
  - Non-Negative Least Squares
August 2, 2008 tremor episode

Haney (2014) GRL
1-2 hours prior to tremor escalation at Okmok Volcano, 2008

Typical tremor location

0-1 hours prior to tremor escalation

Tremor movement toward caldera wall

Haney (2014) GRL
Conclusions

- What we cannot do:
  - Reliably predict the fudge factor $K_d$ at a volcano
  - Strictly speaking, untangle the combination of parameters controlling radiated energy

- What we can do:
  - Roughly predict plume heights from seismic based on previous eruption observations
  - Use time-varying seismic amplitude as a proxy for changes in exit velocity
Waveform inversion of tremor

- Finite difference modeling/inversion code by Chouet, Dawson, and Ohminato
- Moment-only solution dominated by $M_{zz}$

$$E_1 = 100 \times \frac{\text{Var(Misfit)}}{\text{Var(Data)}} = 17\%$$
Location from waveform inversion

Error volume slices: blue = less error

Tremor at shallow depth, < 1 km
Interstation times during escalation

1-2 hours prior to escalation

During tremor escalation
Precursory seismicity at Okmok
First 18 preliminary events of the 2009 Redoubt eruption
Reduced Displacement 0.2-0.3 Hz

Izu Ooshima ~ 1230-2380 cm²
Pinatubo ~ 1070 cm²
MSH ~ 260 cm²

Max $D_R \sim 300$ cm²

McNutt and Nishimura (2008)
1 hour of typical tremor at Okmok: July 23, 2008

Decon shows tremor north of Cone D

Backprojection

Predicted backprojection

Theoretical backprojection for single source
November 2014 Pavlof Eruption

Can be explained by an increase in exit velocity by a factor of ~1.5
Conclusions

- Advances in location methods and use of infrasound can provide information on whether tremor observed during eruptions originates from vent.

- Scaling gives a rough picture, but more modern approaches exist for characterizing jets (Matoza et al., 2013) and methods based on first principles are needed.