Estimating plumes from seismic data: What we can and cannot do

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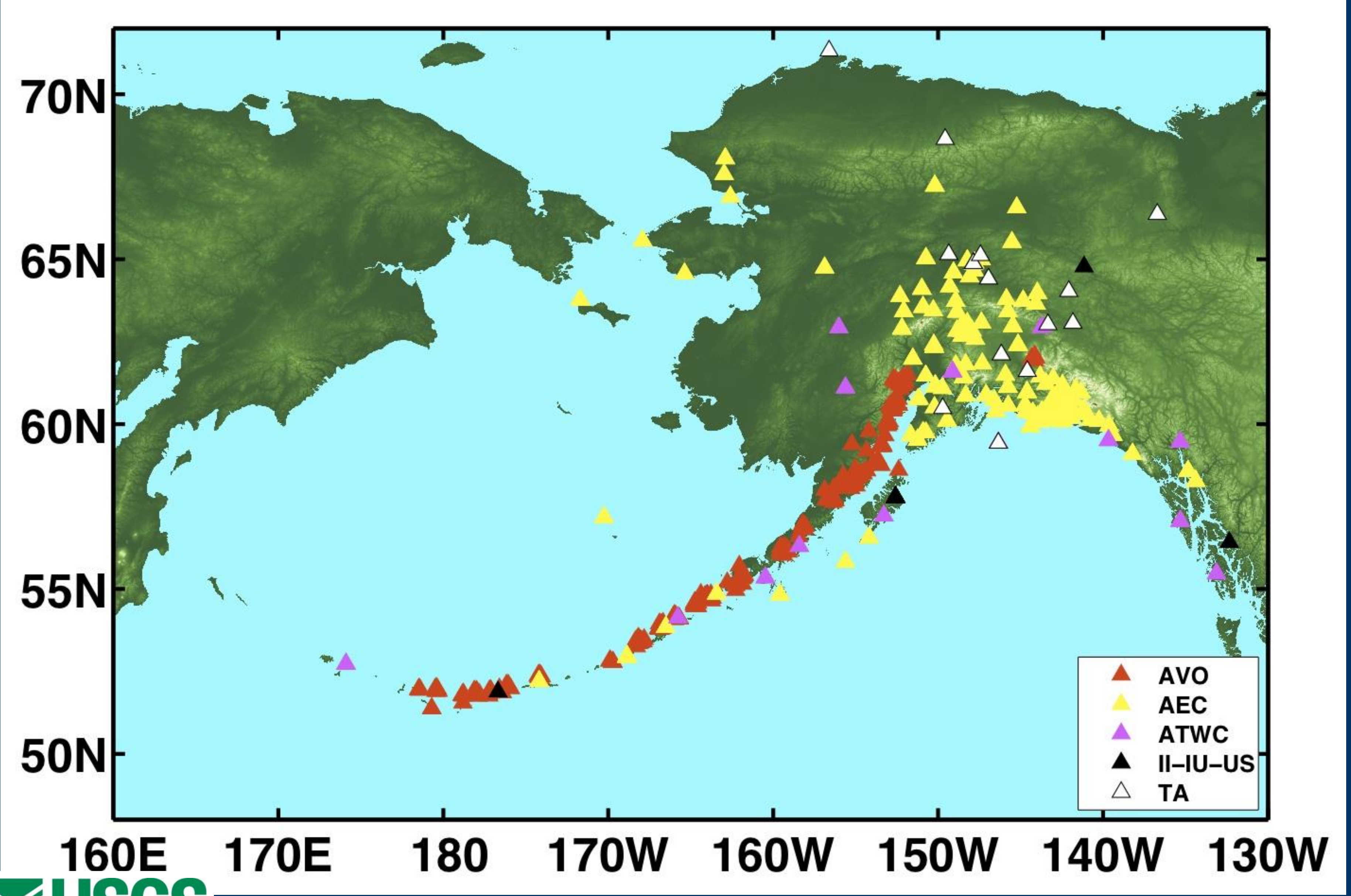
Seismic monitoring in Alaska



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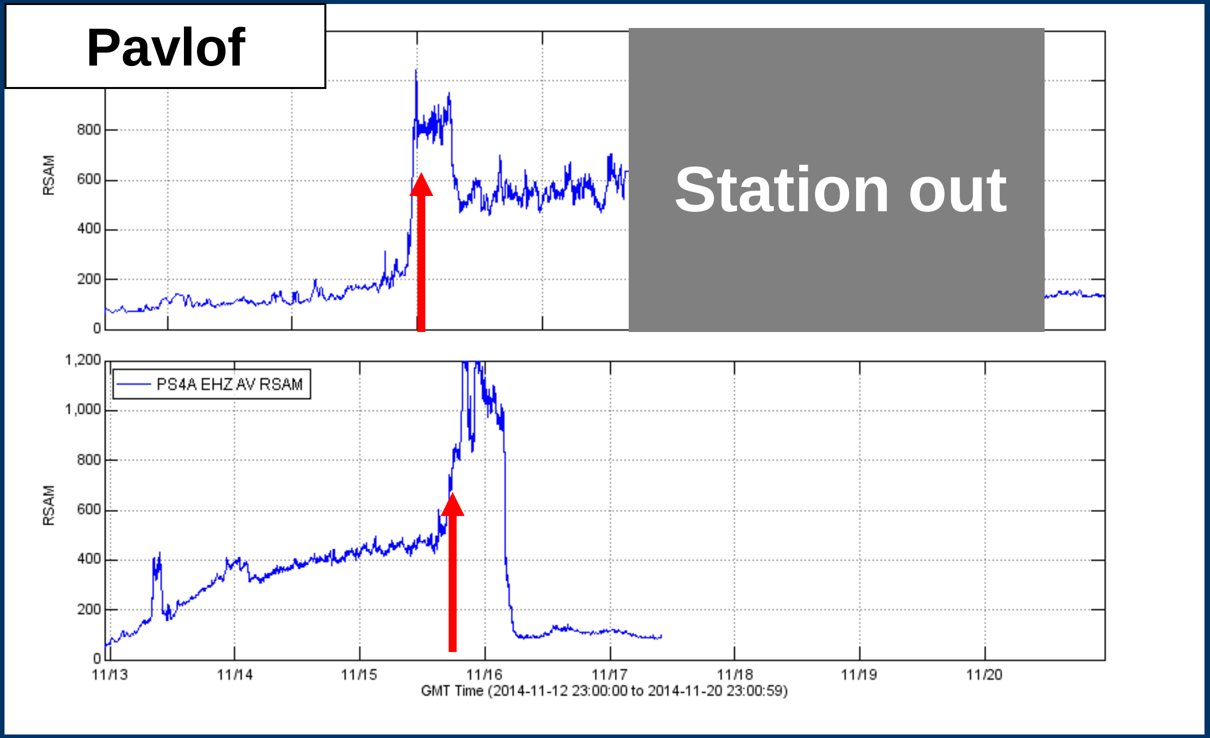
Outline

- 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

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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

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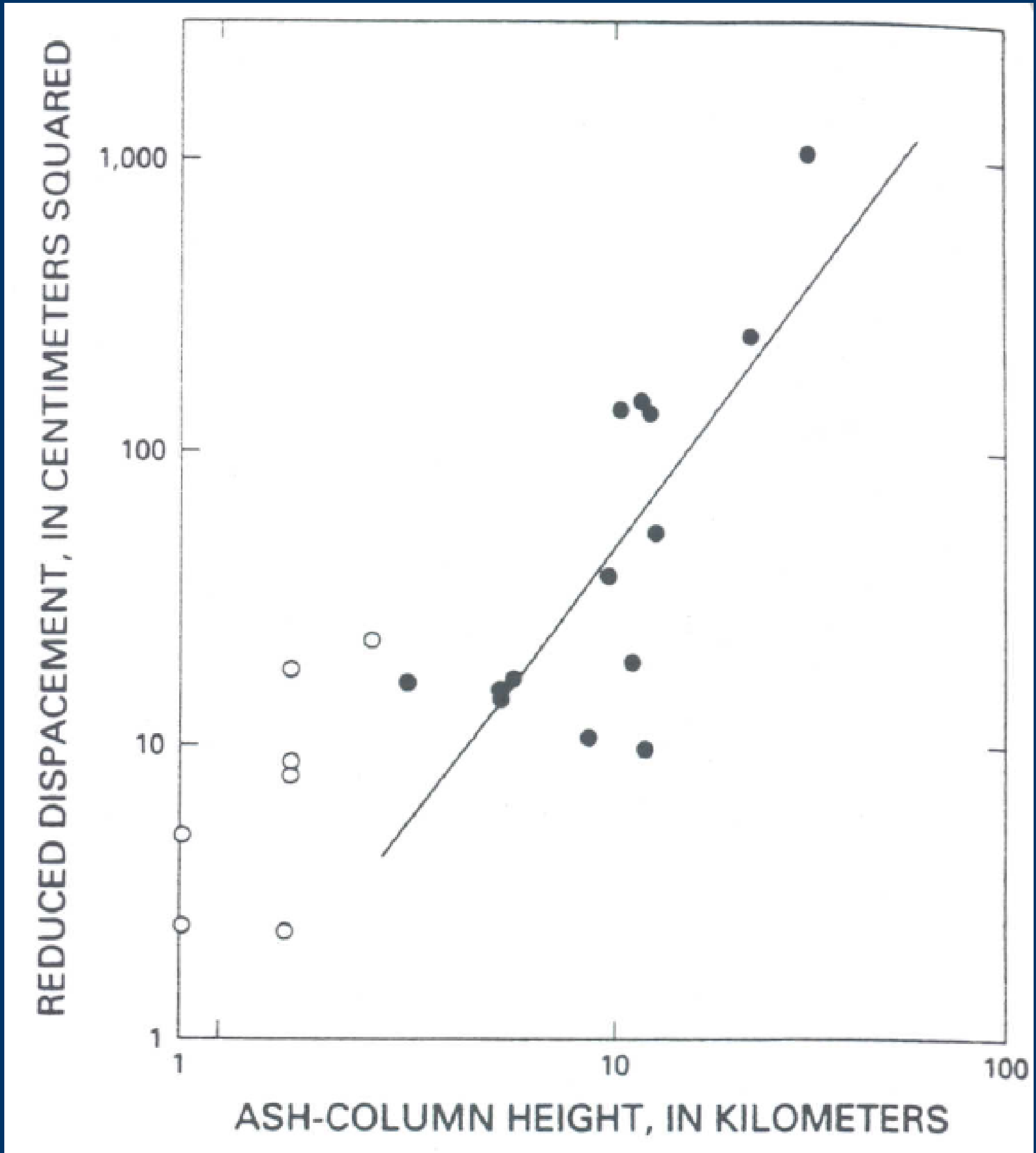
Plume Height vs. D_R

McNutt (1994)



$$\log10(D_R) = 1.80\,\log10(H) - 0.08$$

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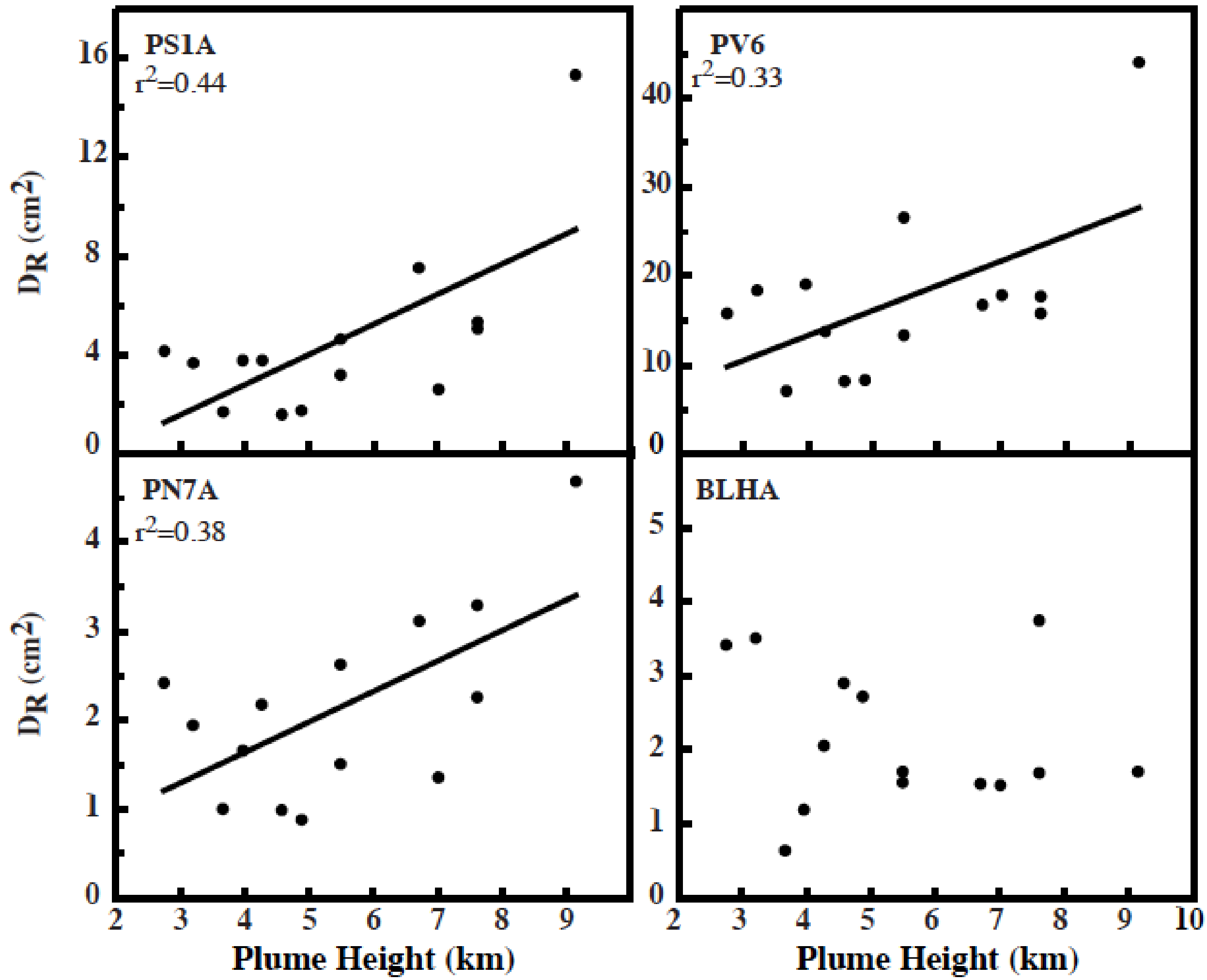
Fig. 13 Comparison of reduced displacement (D_R) and reported plume heights. Plume heights generally increase with reduced displacement; the effect is most apparent on stations PS1A and PN7A. Station PV6, on the other hand, had continually high levels of tremor associated with a debris or mud flow in 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



Roach *et al*. (2001) *Bull. Volc.*

Senyukov et al. (2013)

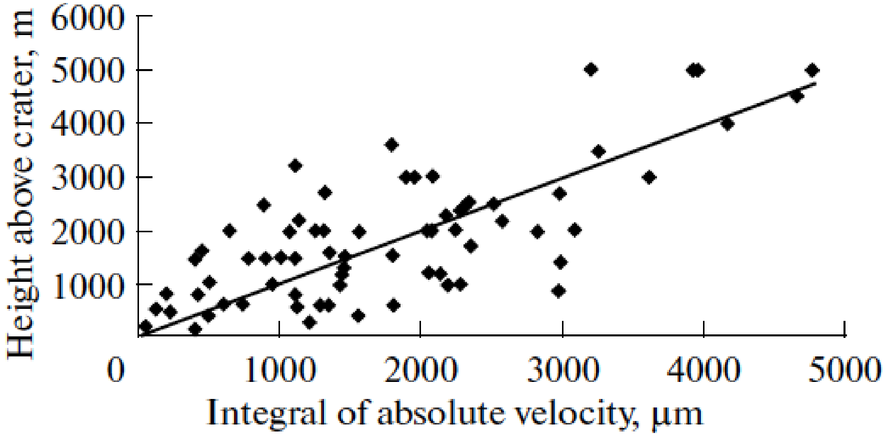


Fig. 3. The correlation between the height of ash plumes on Karymskii Volcano and the integral of absolute velocity as observed at the KRY station for 70 cases recorded by visual, photographic, and video observations in 2004–2007.

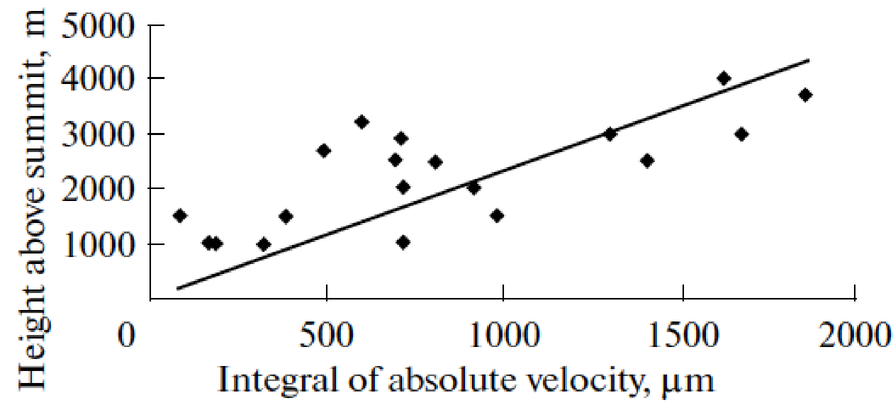


Fig. 4. The correlation between the height of ash emissions on Kizimen Volcano and the integral of absolute velocity as observed at the KZV station for 19 cases recorded by visual, photographic, and video observations in 2011.

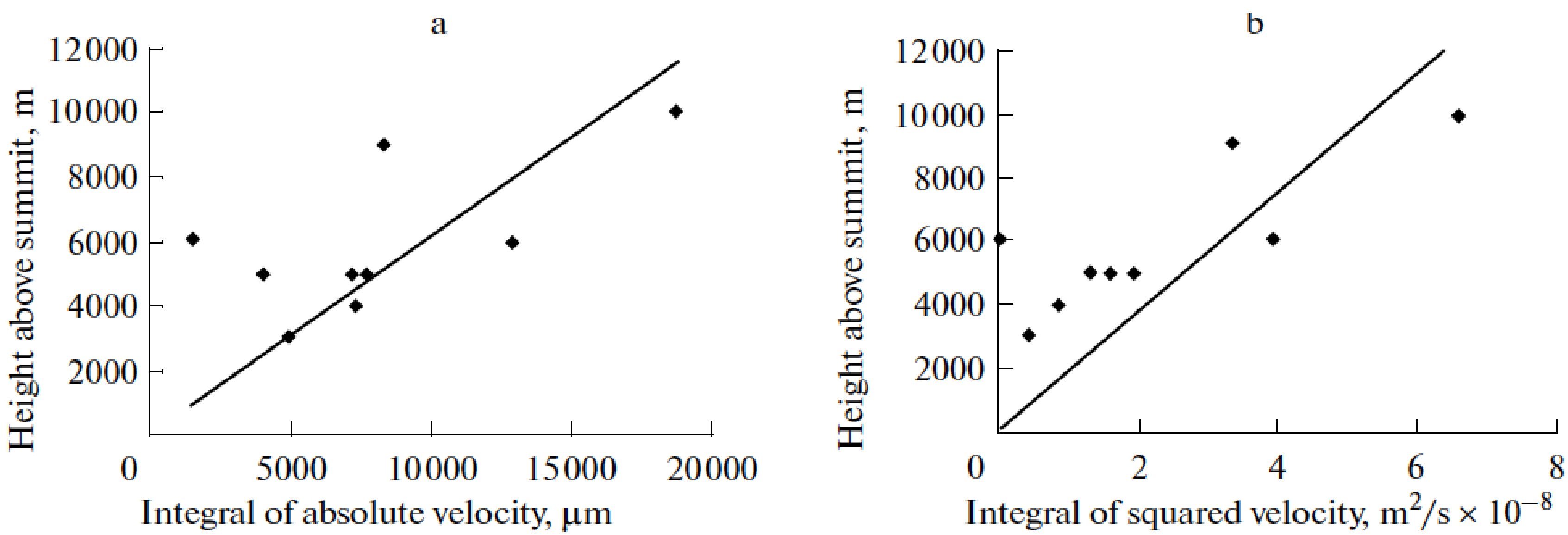
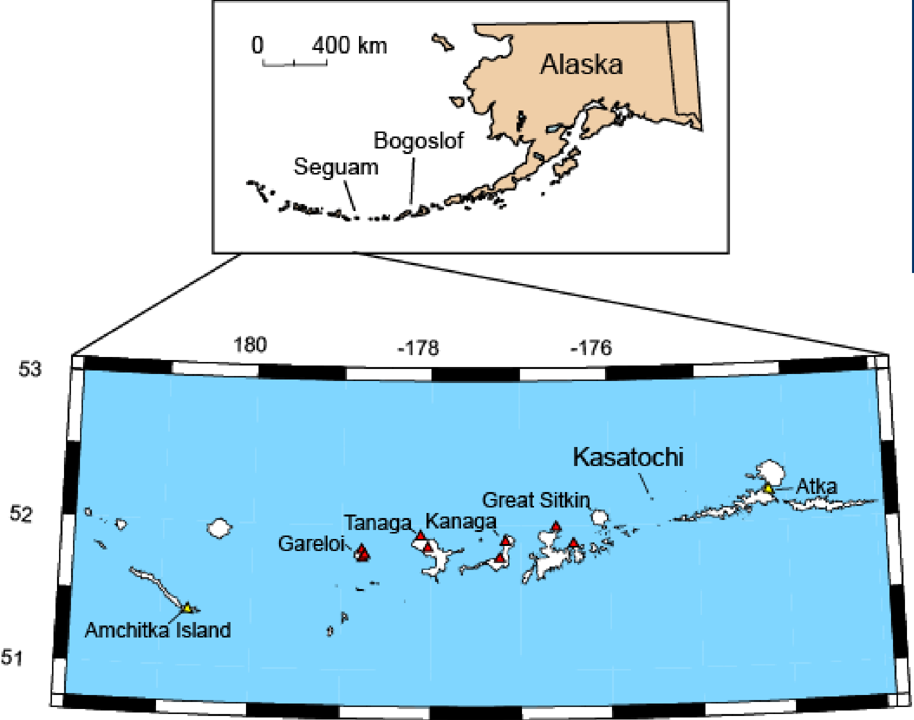


Fig. 5. The correlation of the height of ash plumes on Bezymyannyi Volcano: (a) with the integral of absolute velocity, (b) with the integral of squared velocity. The analysis involved records of the LGN station for nine cases recorded by visual, photographic, and video observations.

Prejean and Brodsky (2011) *JGR*



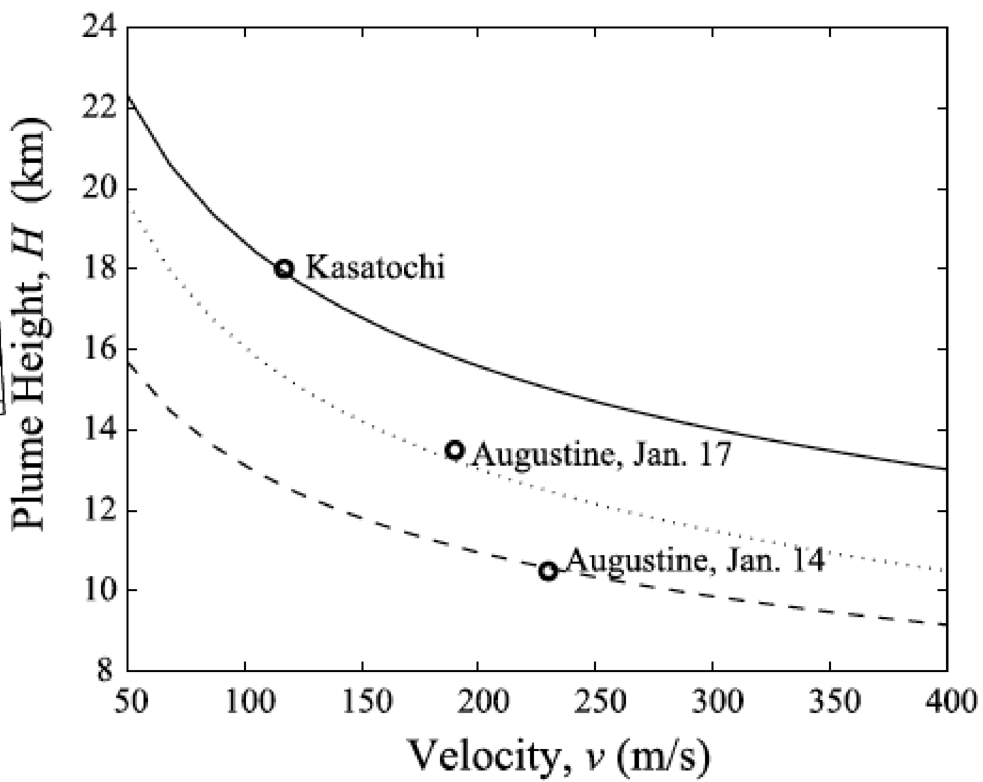


Figure 8. Calculated plume heights, H, for a possible range in v given measured displacement, u, for explosions at Kasatochi Volcano on 8 August 2008 (solid line), Augustine Volcano on 14 January 2006 (dashed line), and Augustine Volcano on 17 January 2006 (dotted line). Observed plume heights, H, and inferred preferred velocities, v, are indicated by circles.

- Force source model
- Far-field Rayleigh waves
- Used Sparks *et al.* (1997) relation:

$$H \sim q^{1/4}$$

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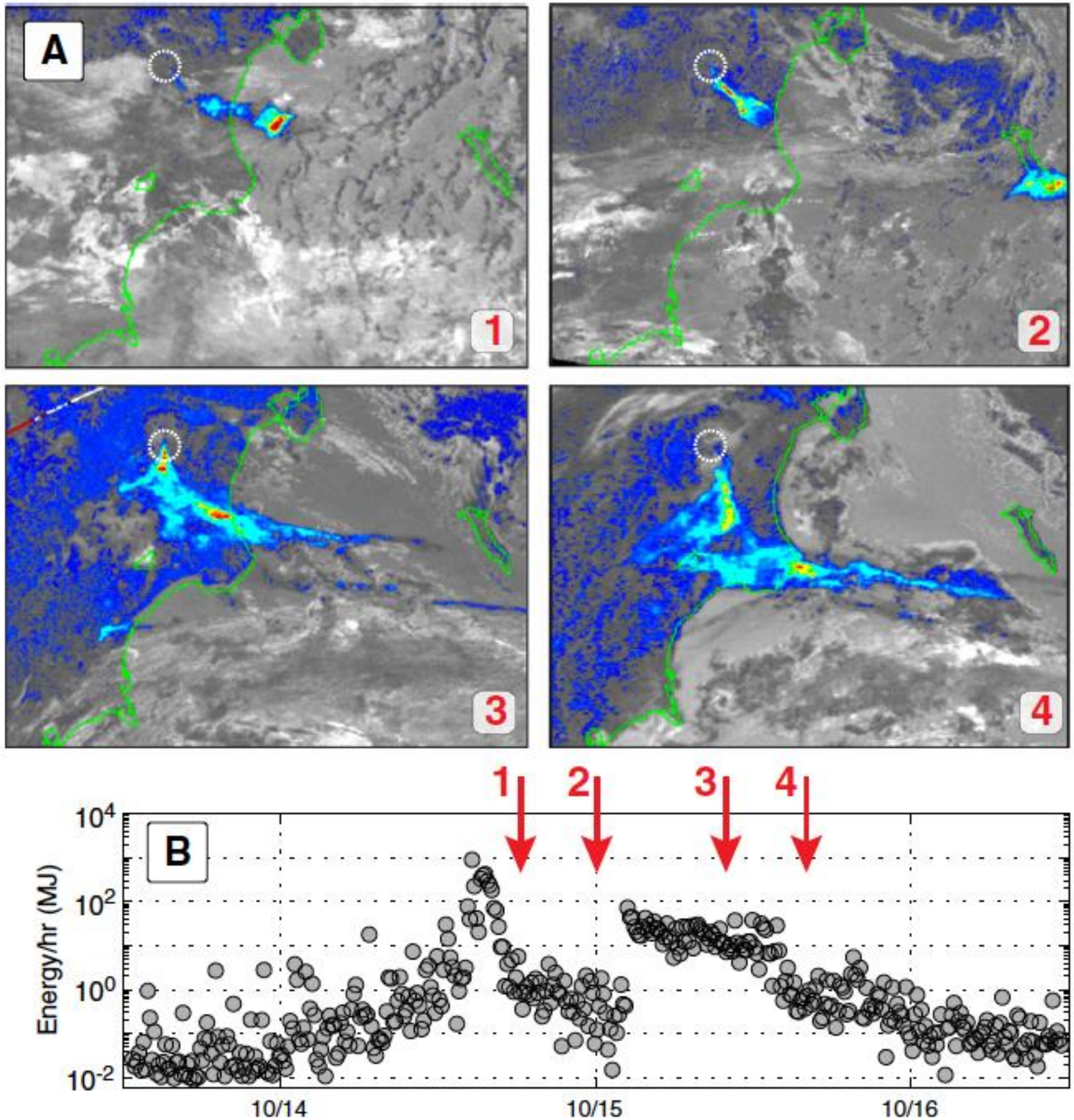
West (2013)
JVGR



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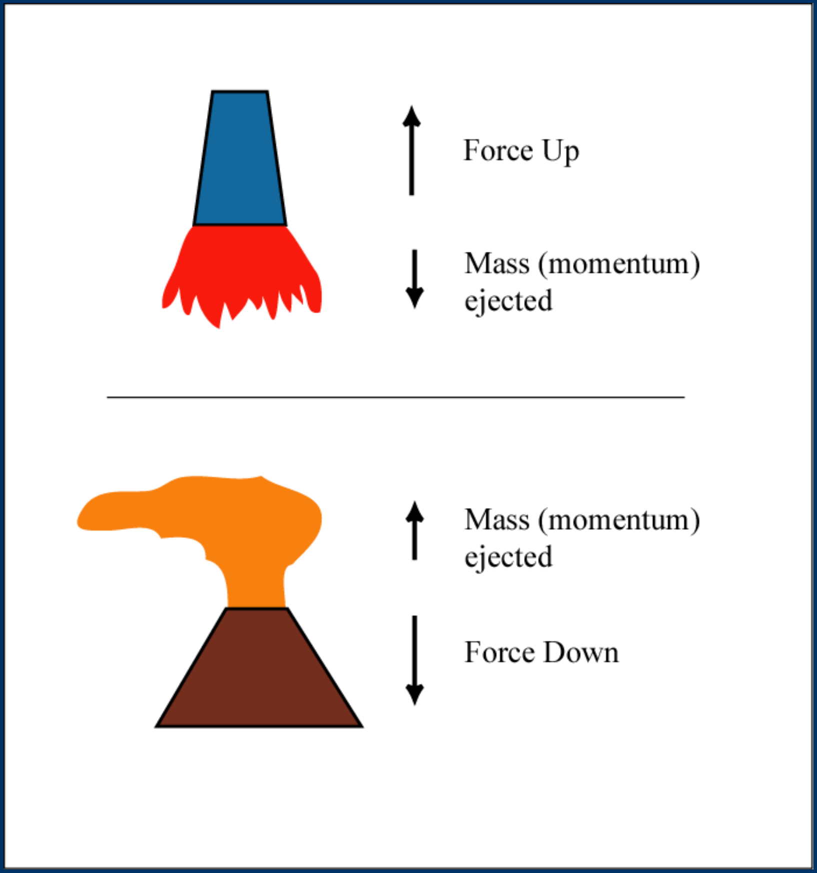
Assumptions in plume seismology

- 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

Force source model

Prejean and Brodsky (2011) *JGR*:



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

$$F = q\rho V$$

ρ	**Plume density**
q	**Volume eruption rate**
V	**Exit velocity**

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Scaling: Radiated seismic power

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

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

ρ	Plume density
A	Area of vent
V	Exit velocity
V_p	P-wave velocity
ρ_s	Earth density

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Scaling: Acoustic analogy

Empirical constant or fudge factor

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

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

Woulff and McGetchin (1976)

Dipole sound radiation model

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Scaling: Vent area and plume height

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

Square root scaling with vent area

$$D_R \sim \sqrt{W} \sim \sqrt{A}$$

Rewriting in terms of volume eruption rate

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

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

$$D_R \sim \sqrt{W} \sim H^2$$

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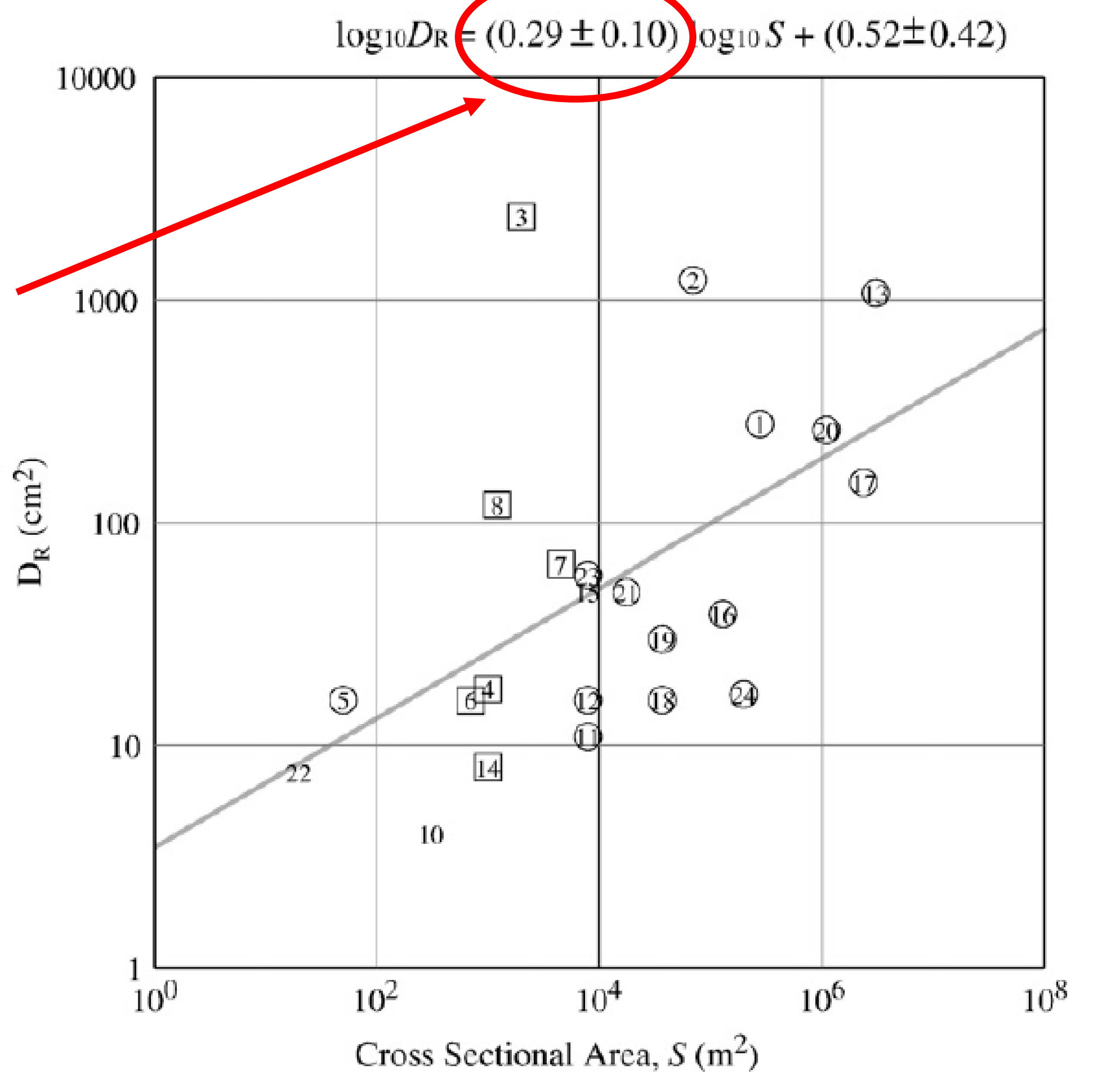
McNutt and Nishimura (2008)

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 …"



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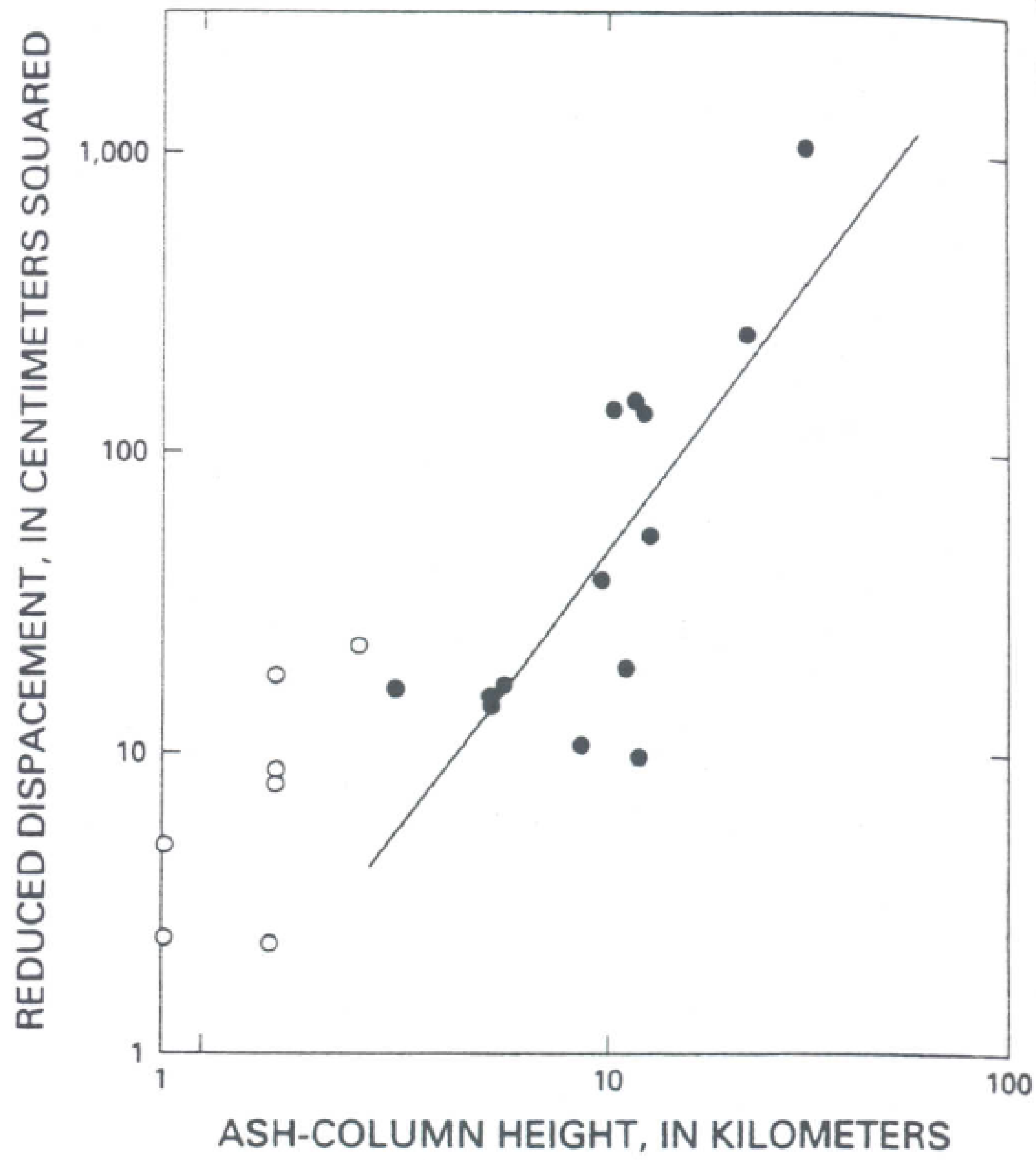
McNutt (1994) revisited

$\log10(D_R) =$
$1.80 \log10(H) - 0.08$

Close to scaling prediction of 2



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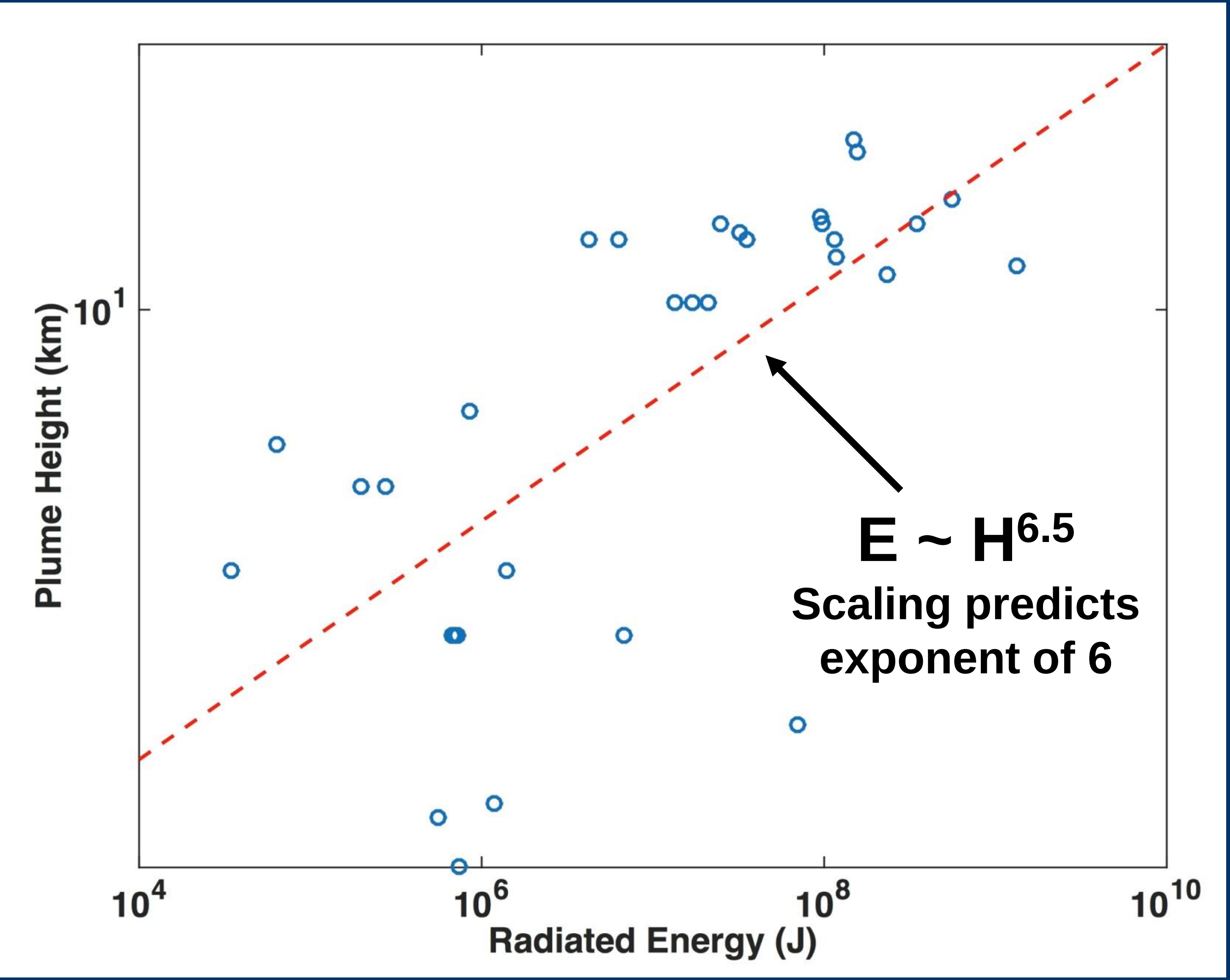
Redoubt 2009 explosive events

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



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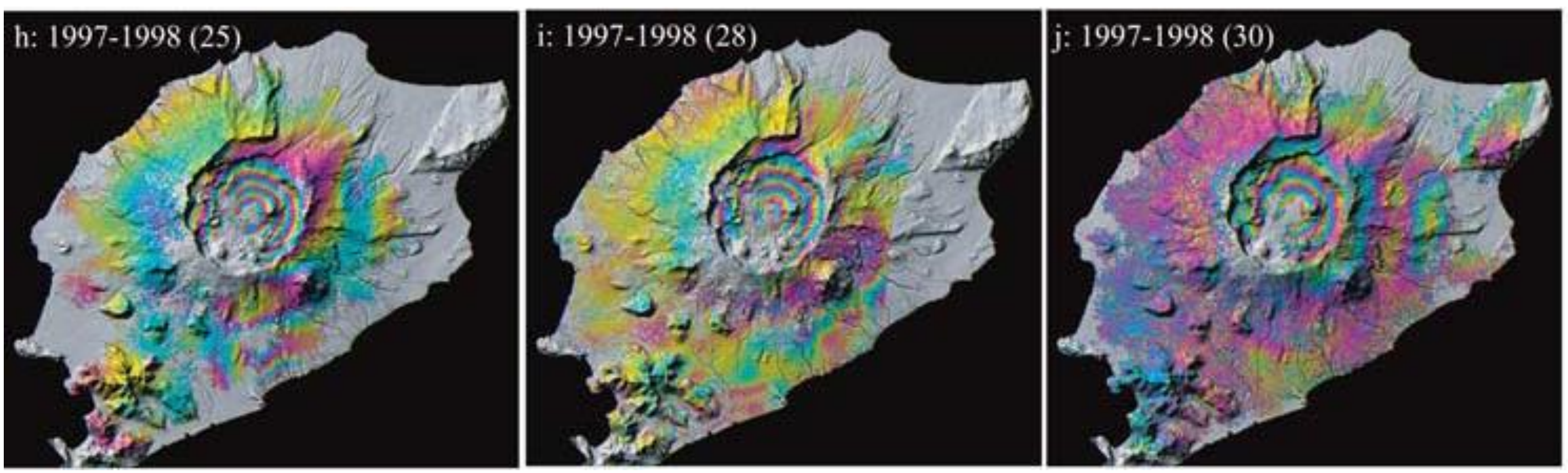
Okmok Volcano: A counter-example



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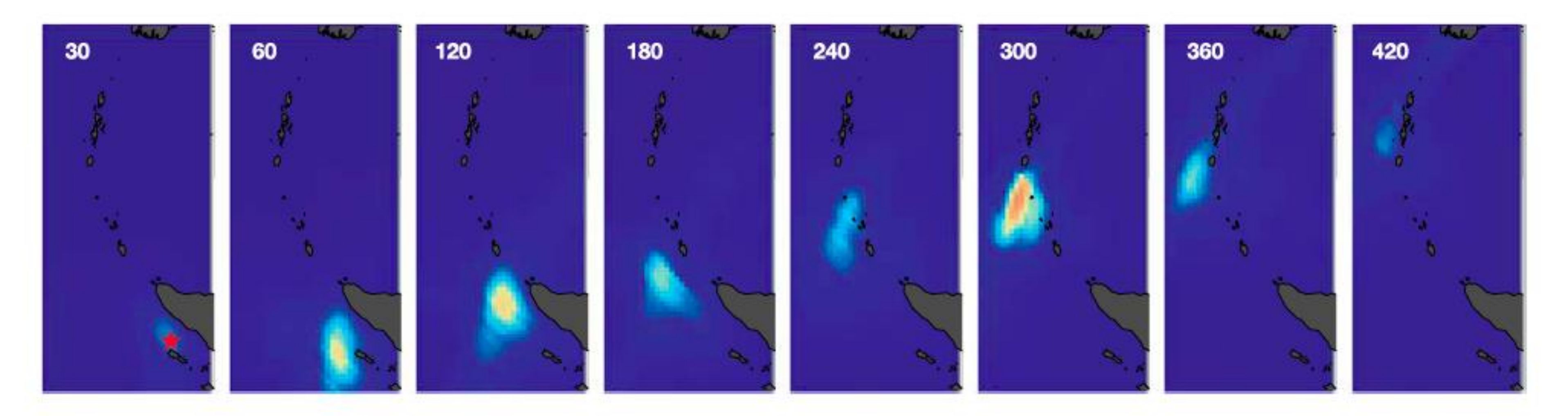
Lu *et al*. (2005) *JGR*

Backprojection Method

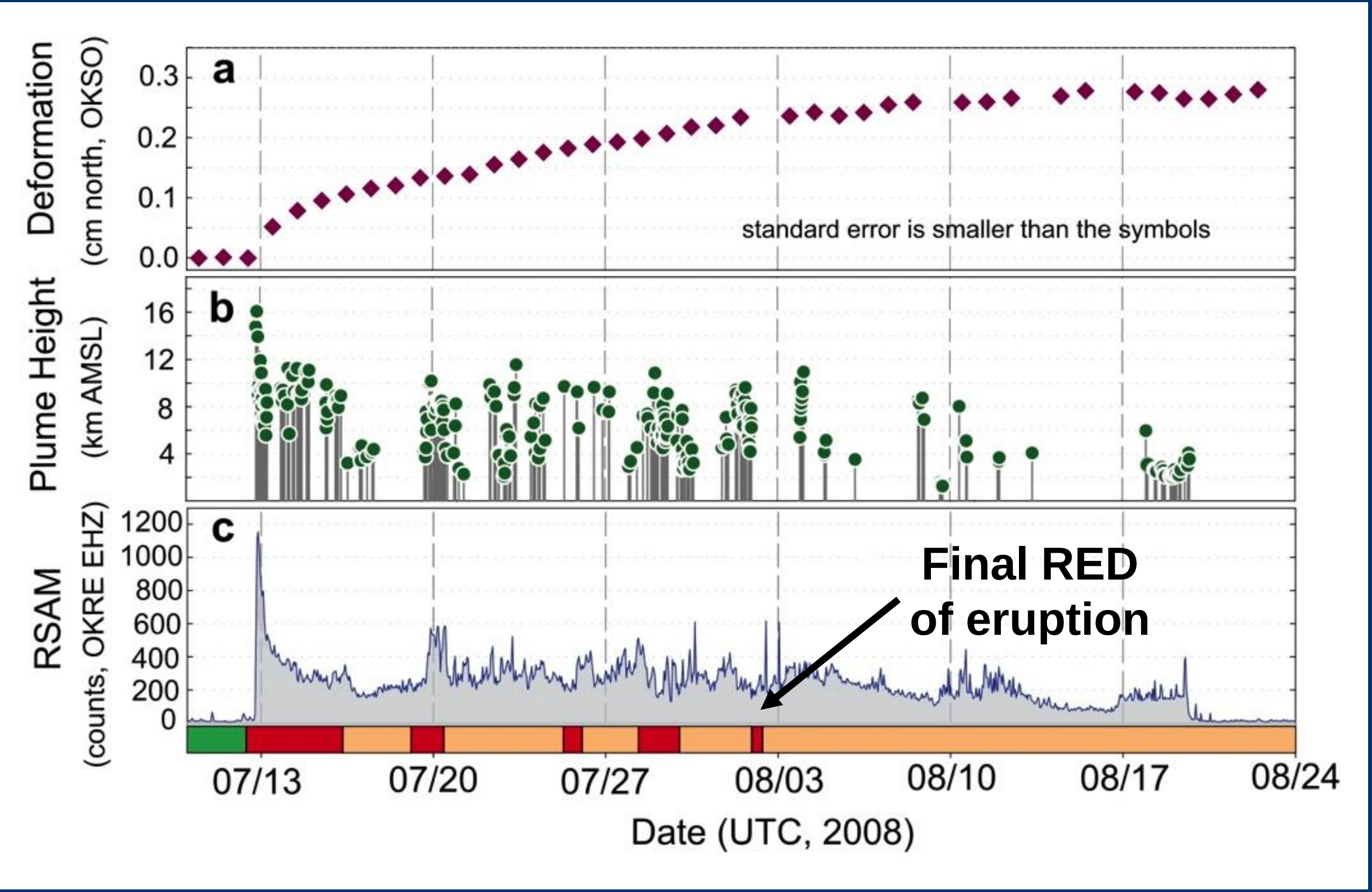
- **Illuminating the source by summing over stations**

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



Ishii *et al*. (2005) *Nature*

2008 eruption of Okmok



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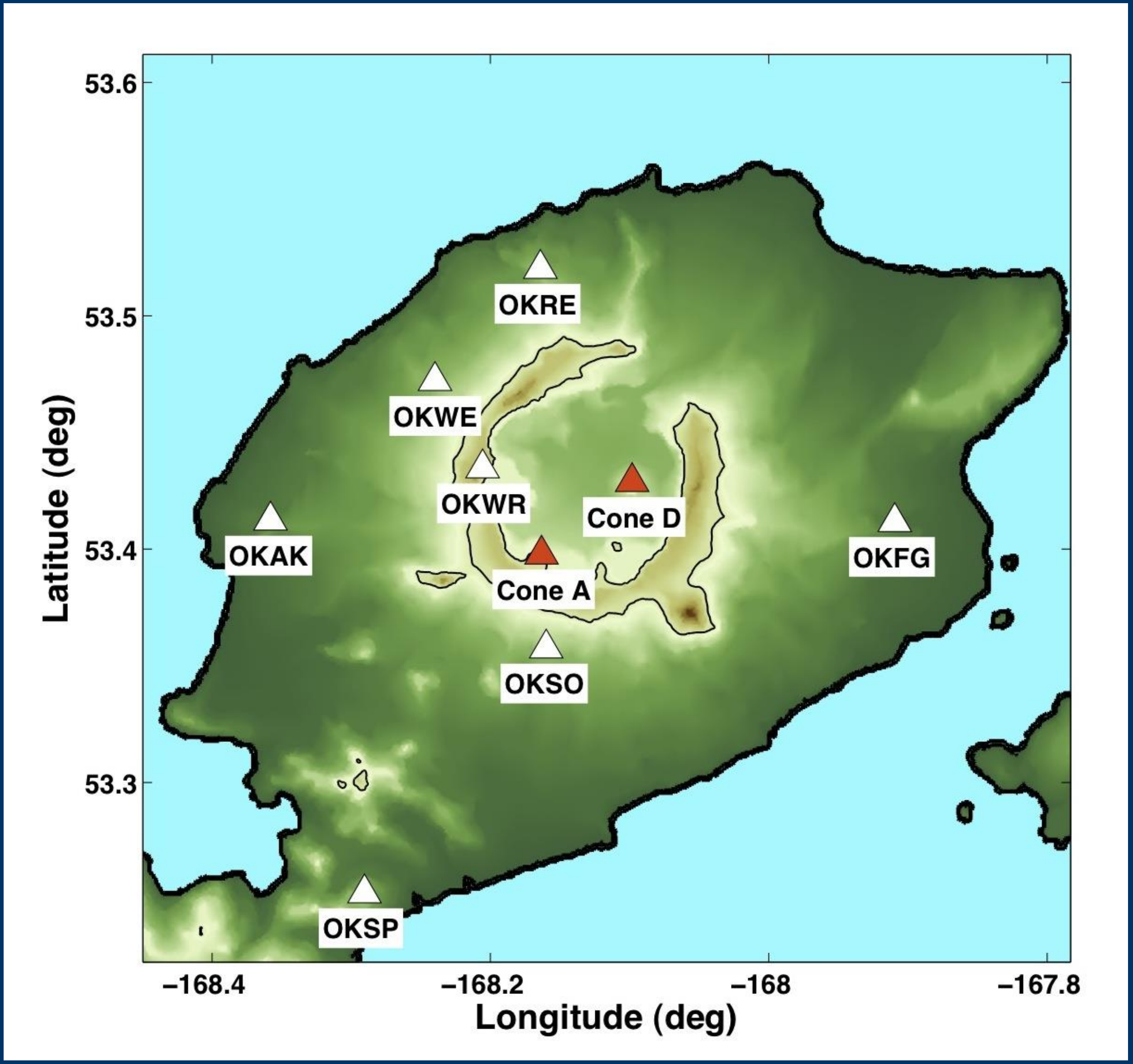
Larsen *et al*. (2009) *EOS*

Okmok seismic stations

2 broadbands: OKSO, OKFG

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

Several other stations damaged by eruption



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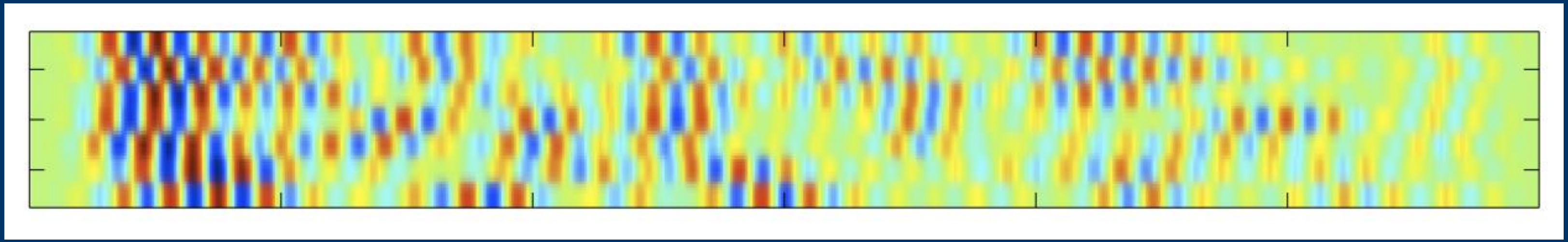
Backprojection methodology

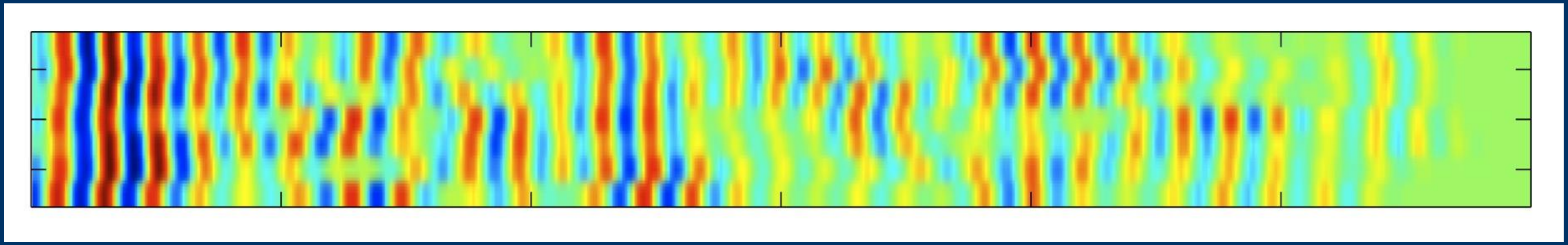
- Spectral whitening, time shift, and compute stack power for candidate source locations

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

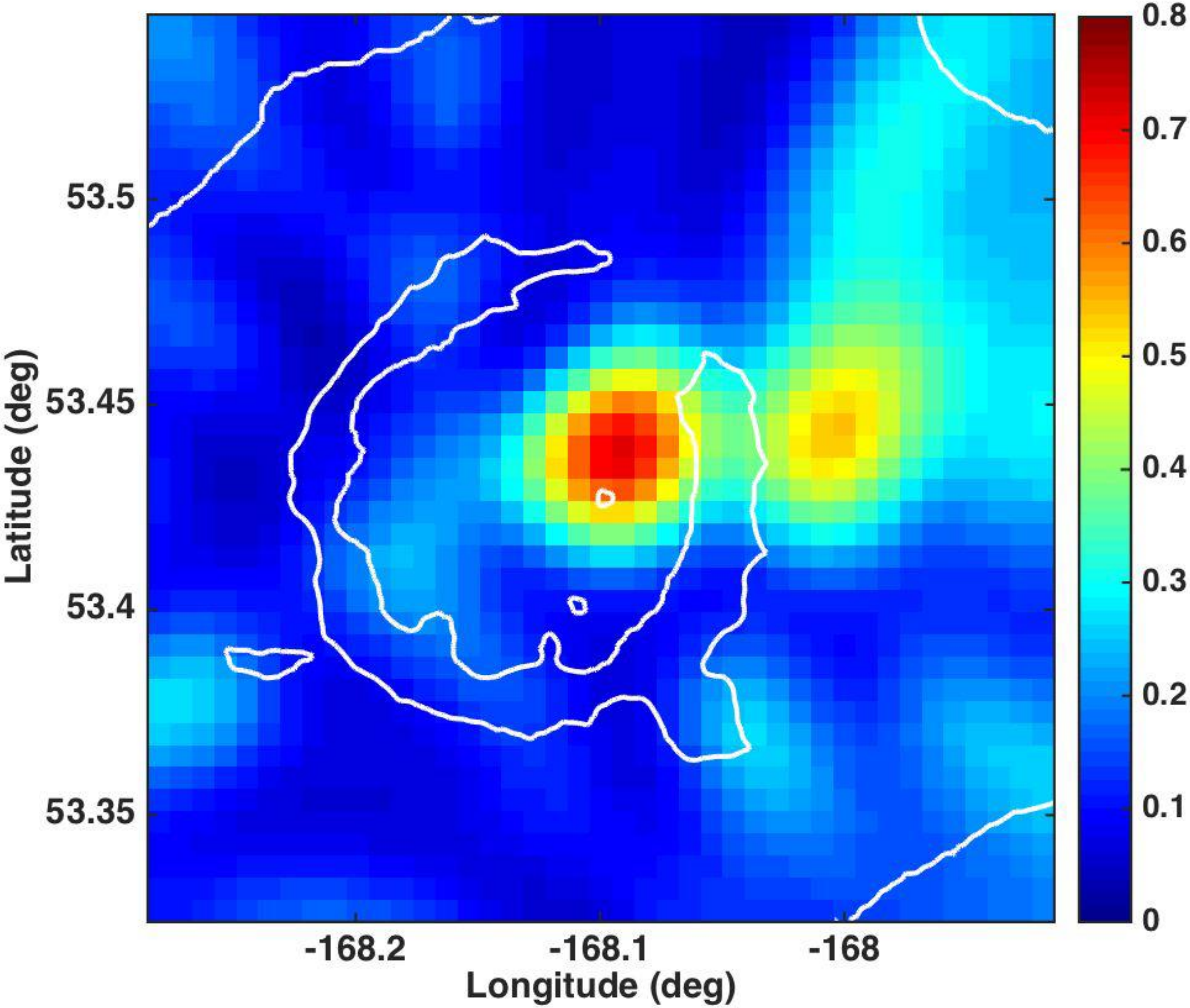
- Time shifting based on a homogeneous surface wave velocity model of 2.7 km/s (Masterlark *et al*., 2010)



Raw seismograms



Seismograms shifted at tremor location


Latitude (deg)
53.5
53.45
53.4
53.35
-168.2
-168.1
-168
Longitude (deg)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

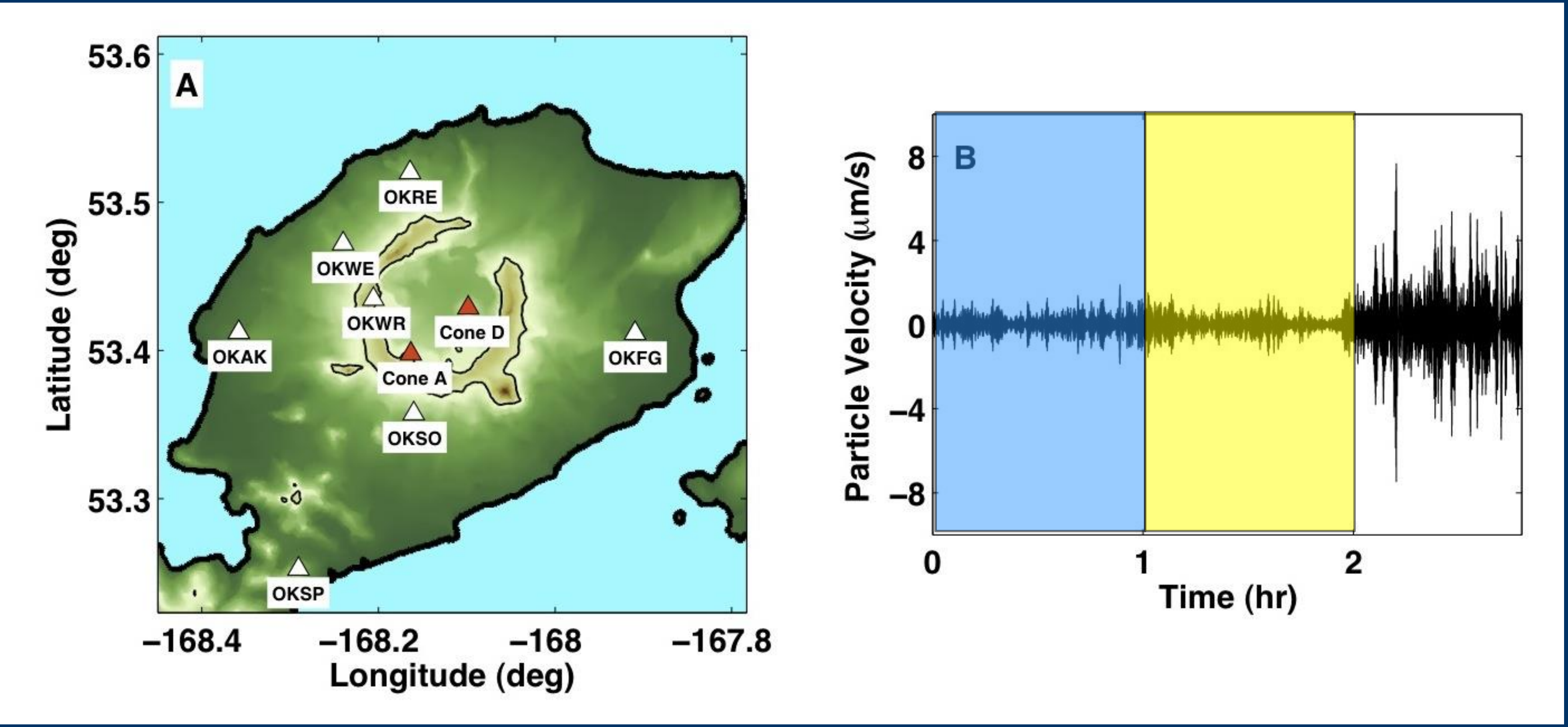
Array Deconvolution

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

- Solution: Remove impulse response by deconvolution

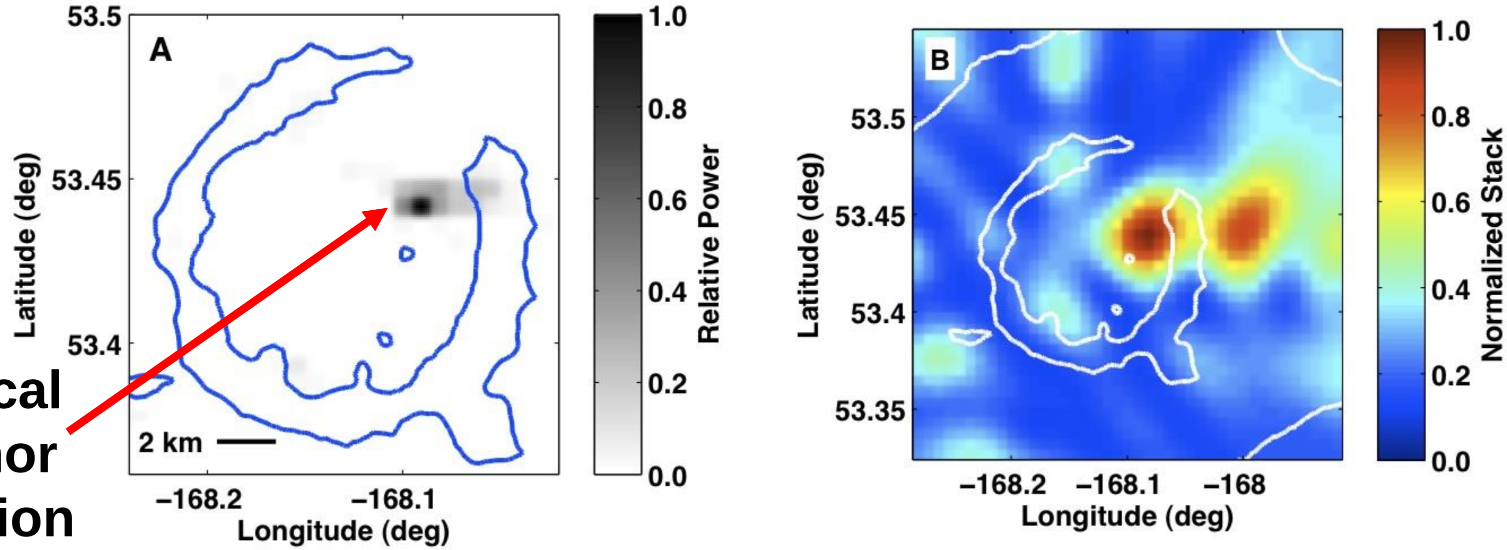
- Two possible methods:
  - Richardson-Lucy, Nishida *et al*. (2008) *GRL*
  - Non-Negative Least Squares

August 2, 2008 tremor episode



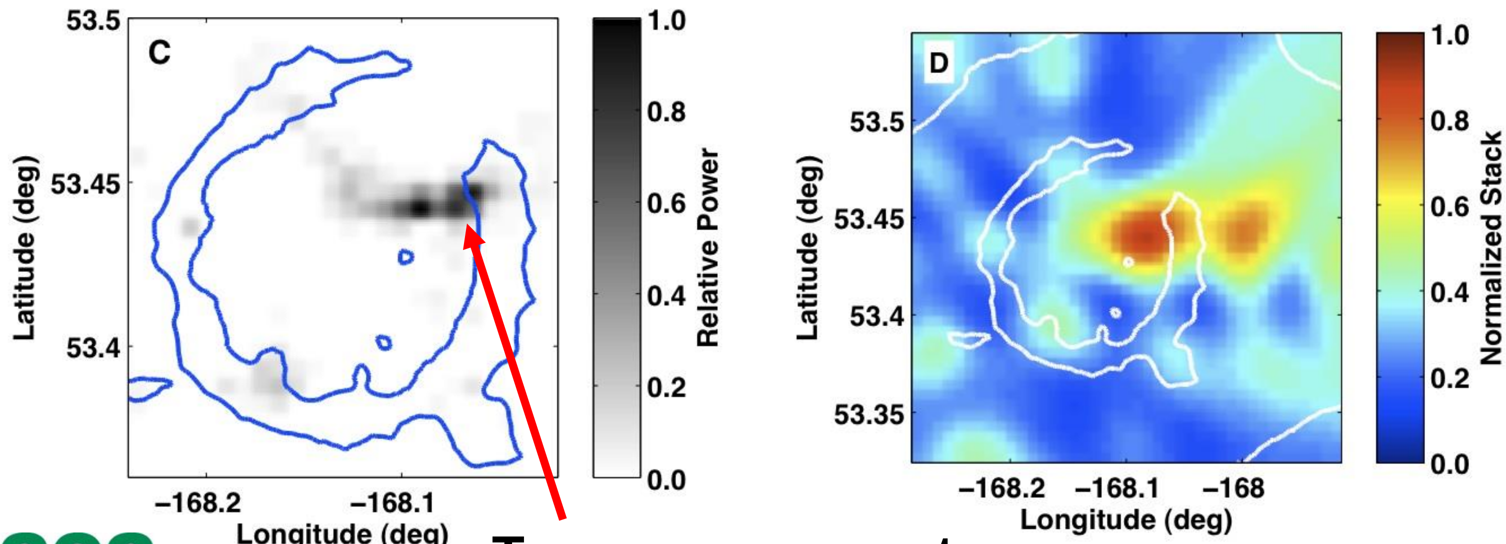
Haney (2014) *GRL*

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

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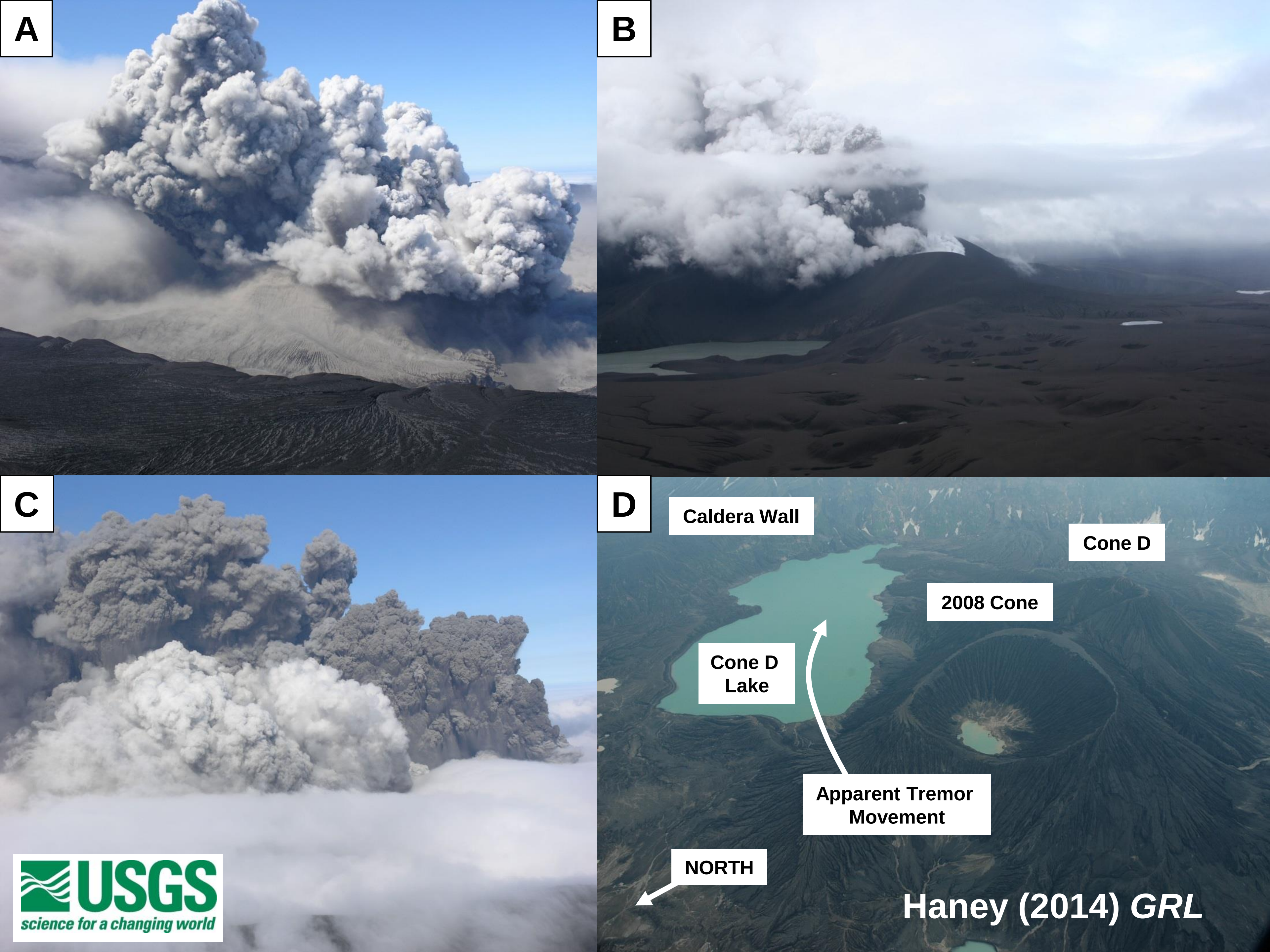
Haney (2014) *GRL*


A
B
C
D
Caldera Wall
Cone D
2008 Cone
Cone D
Lake
Apparent Tremor
Movement
NORTH
Haney (2014) *GRL*
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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

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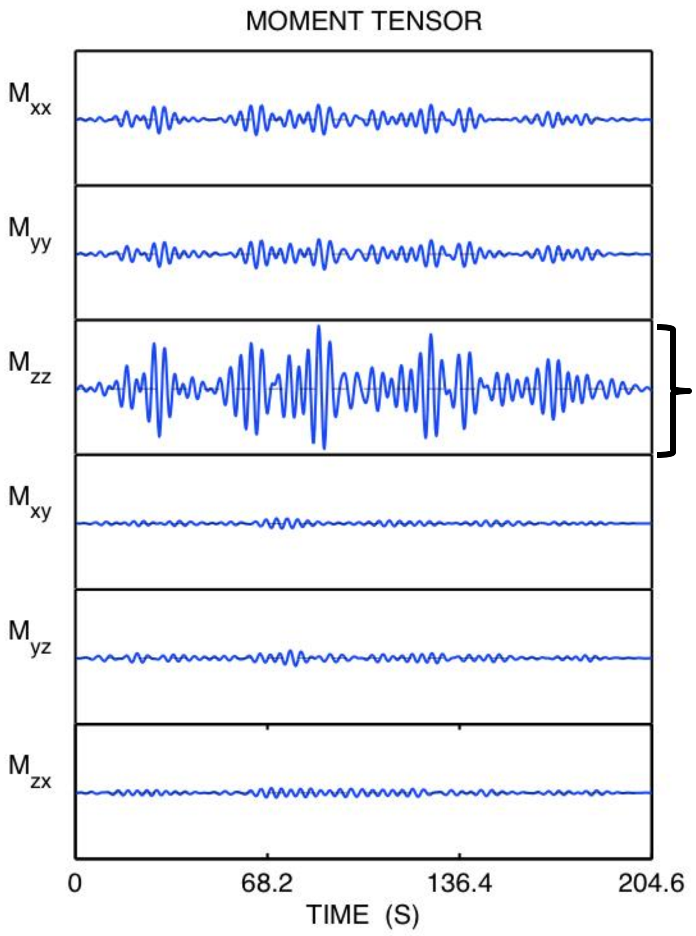
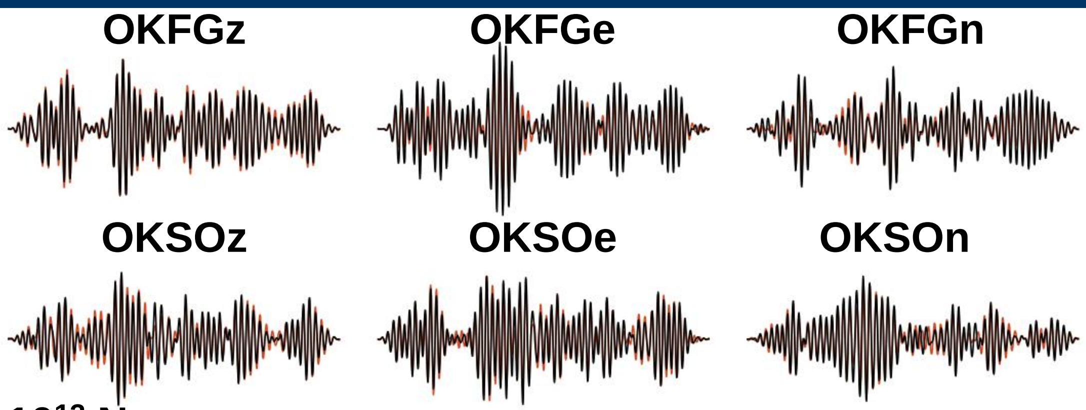
Waveform inversion of tremor





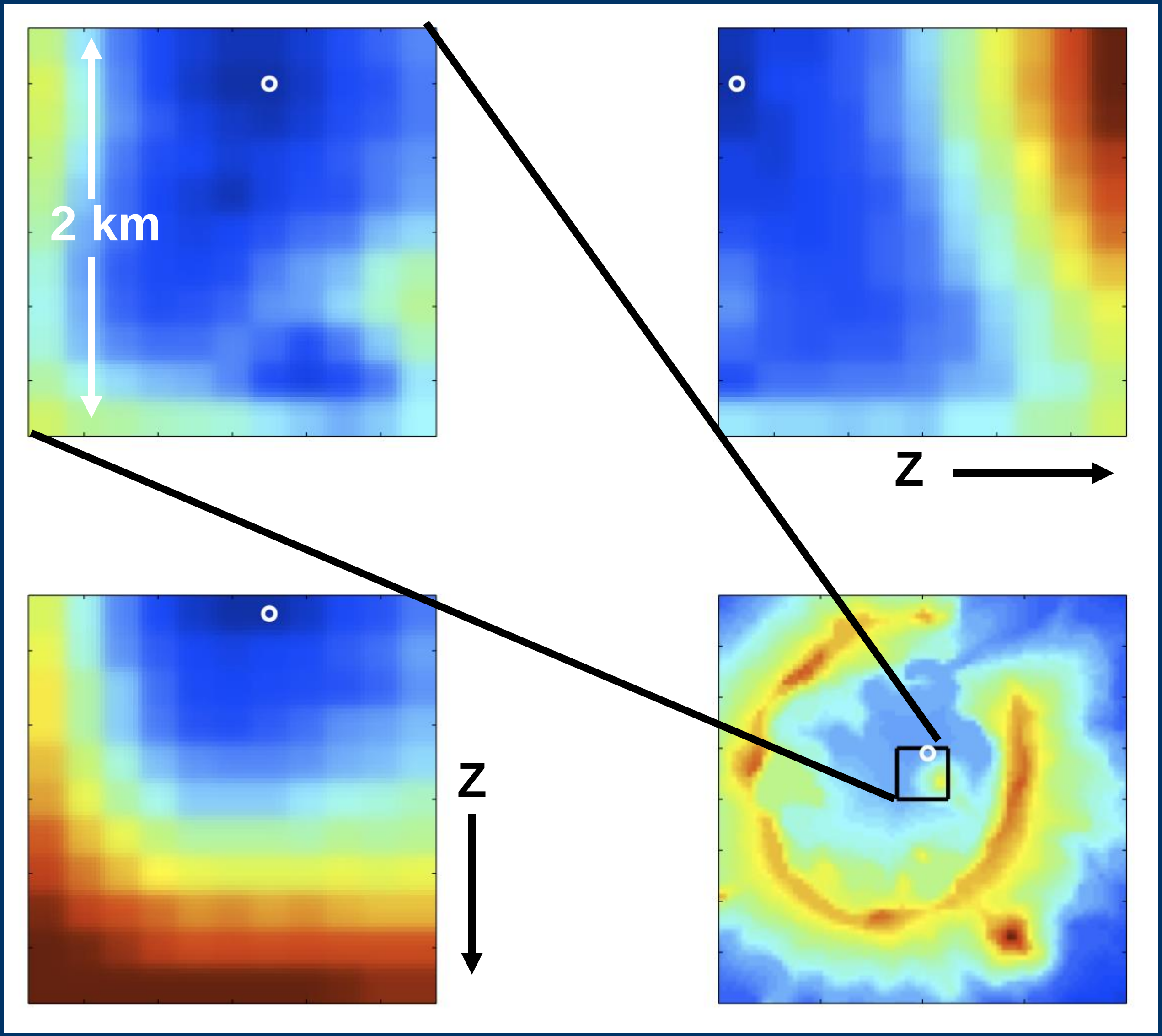
- Finite difference modeling/inversion code by Chouet, Dawson, and Ohminato
- Moment-only solution dominated by Mzz

E1 = 100 x Var(Misfit)/Var(Data) = 17%

Location from waveform inversion

Error volume slices: blue = less error

Tremor at shallow depth, < 1 km



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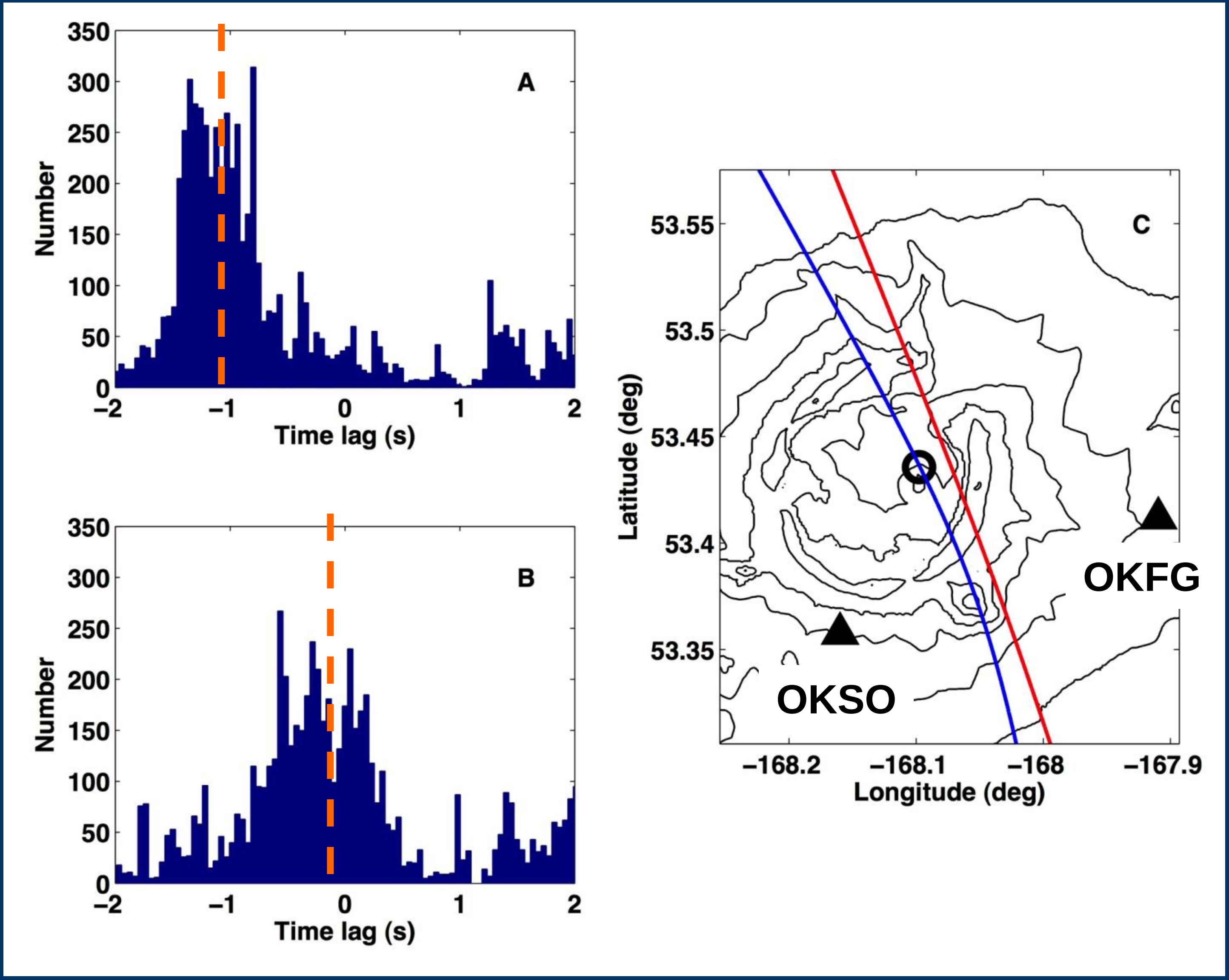
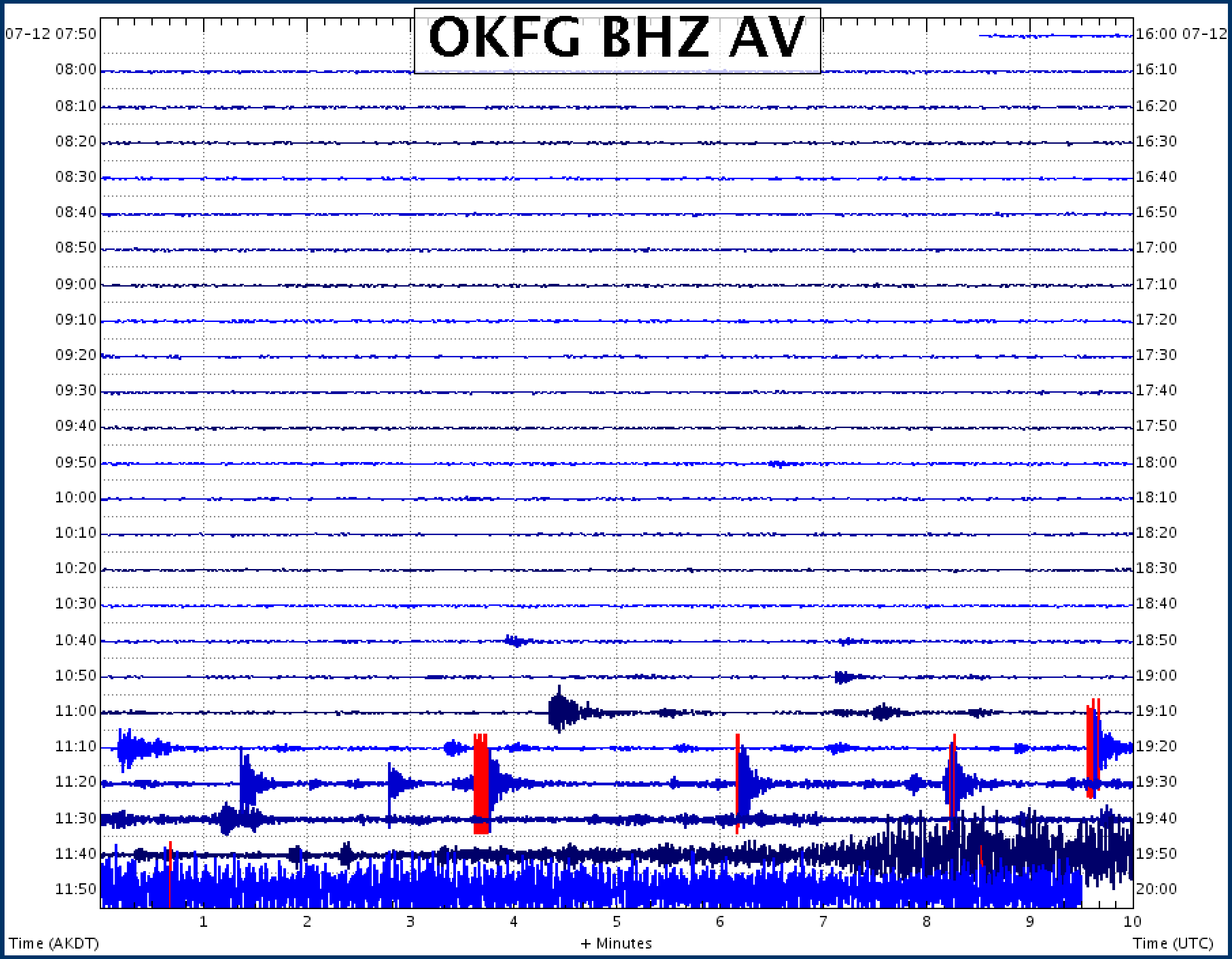
Interstation times during escalation

1-2 hours prior to escalation

During tremor escalation



Precursory seismicity at Okmok



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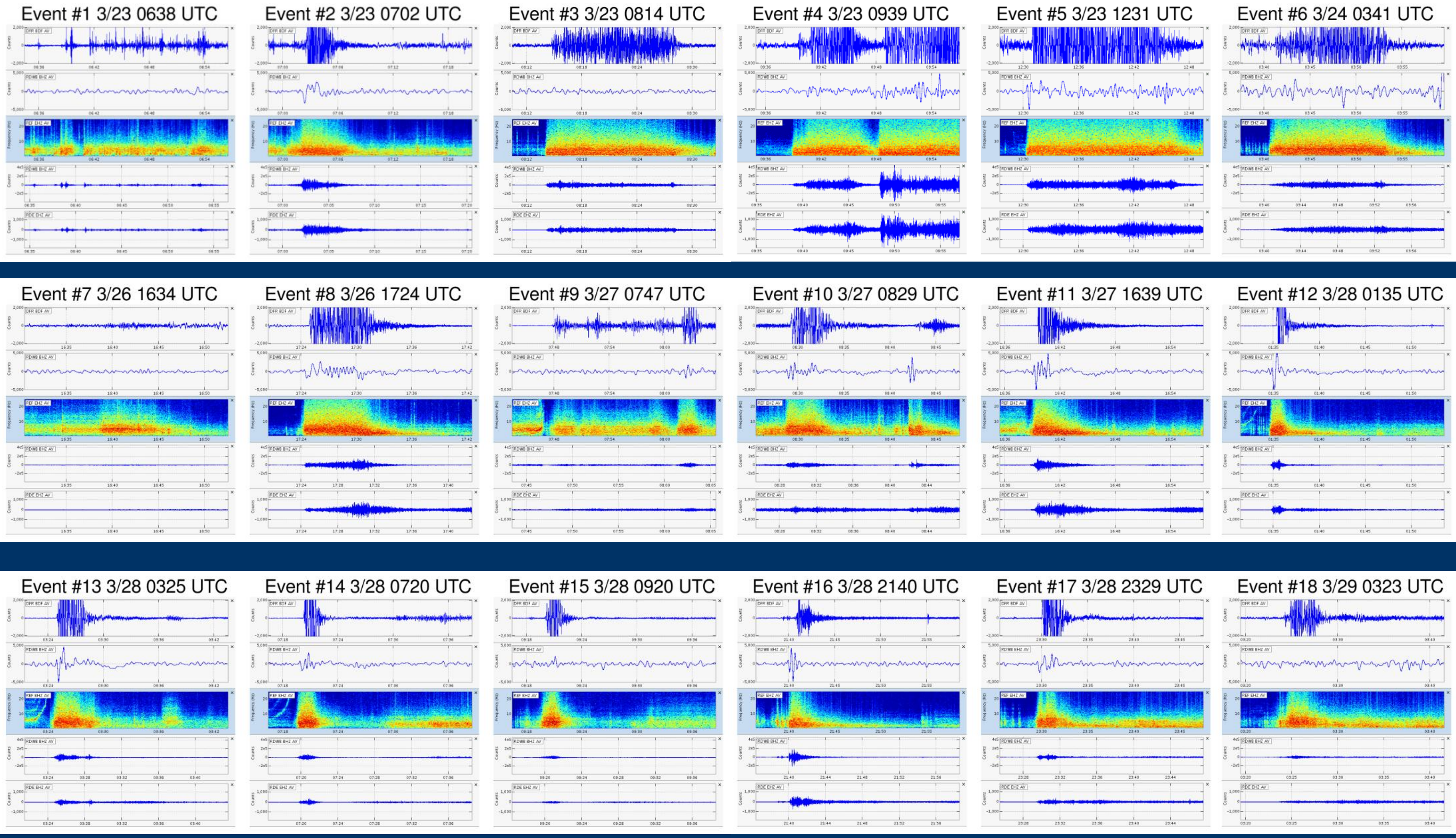

First 18 preliminary events of the 2009 Redoubt erruption

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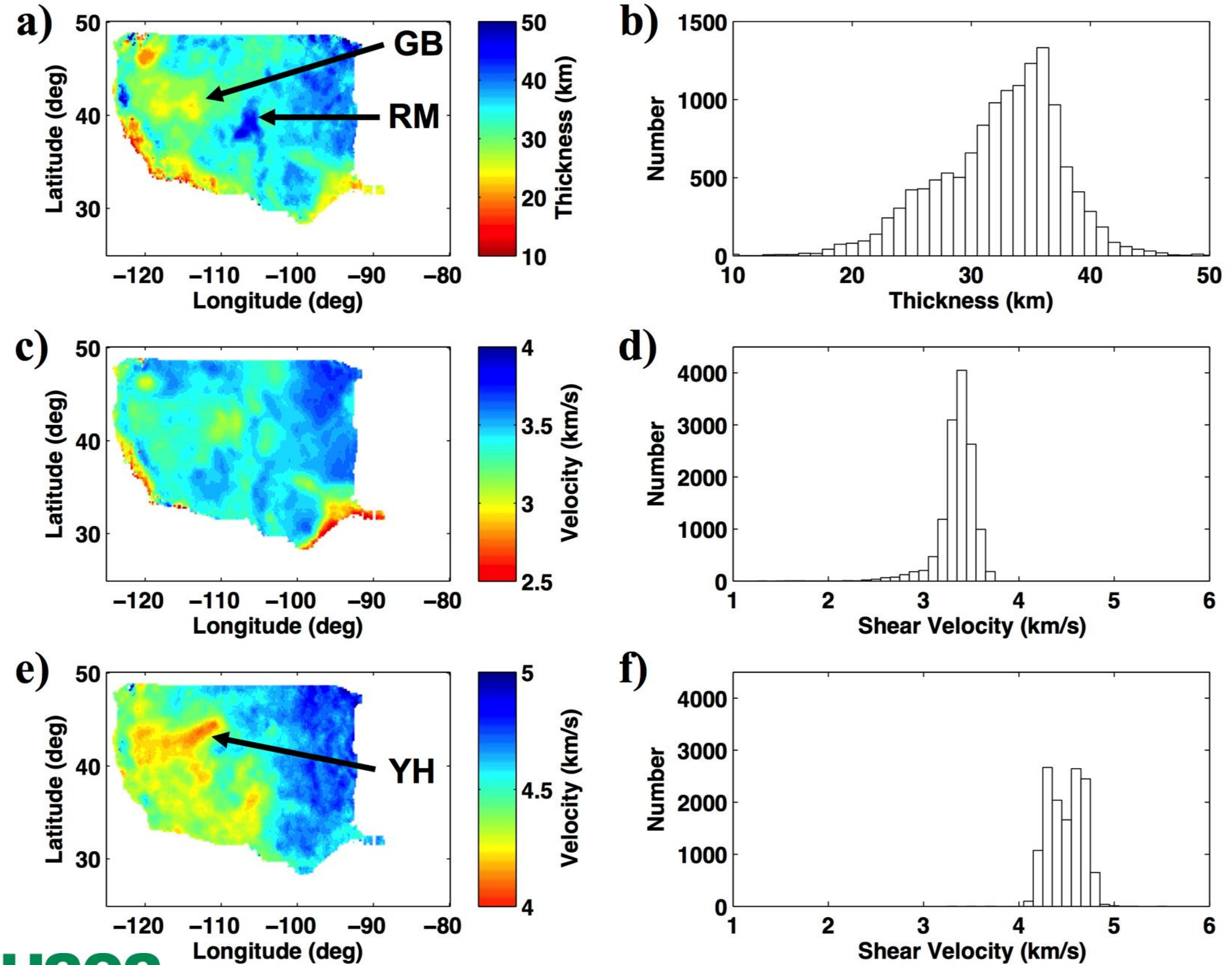


Haney and Tsai (2015) *Geophysics*

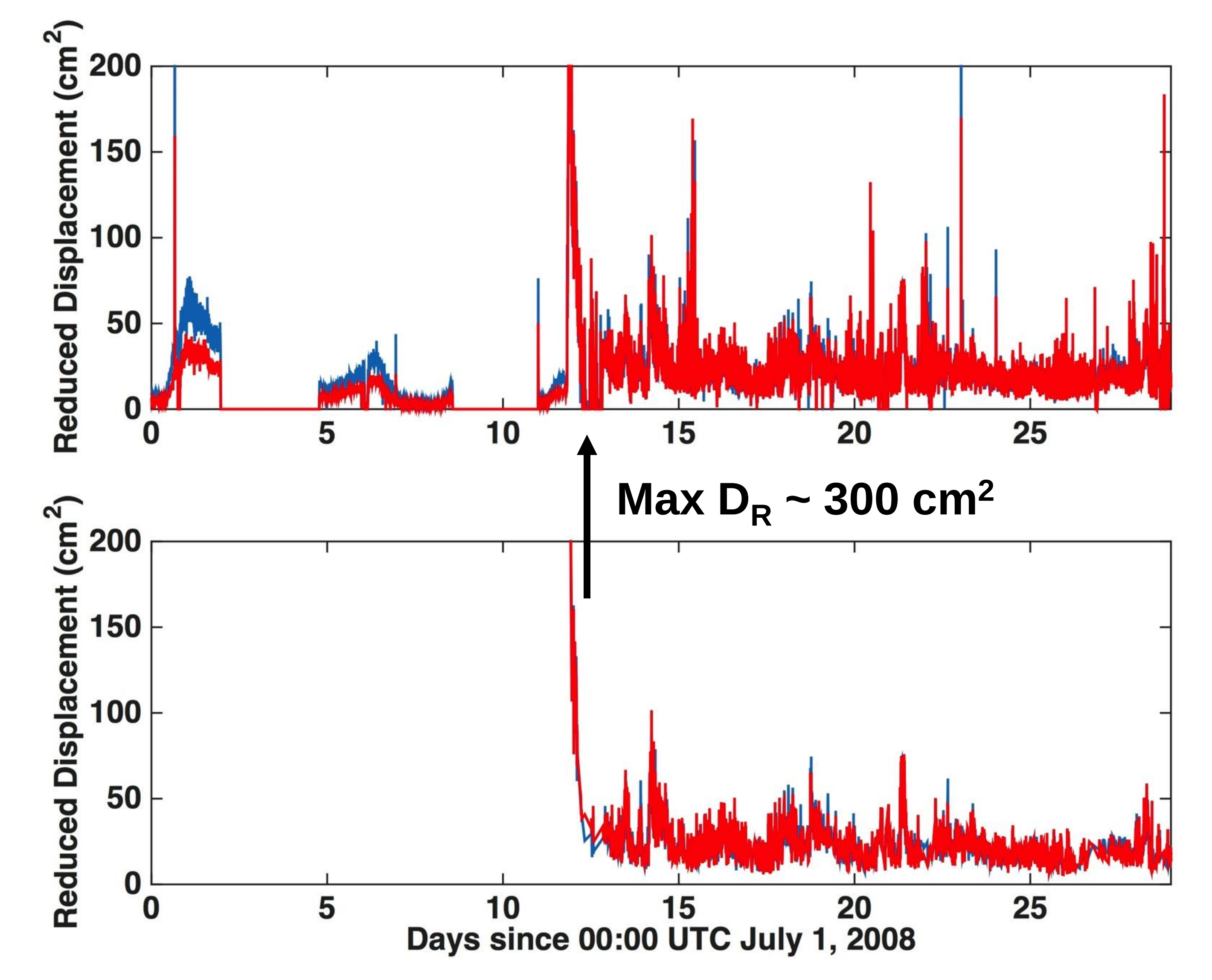
Reduced Displacement 0.2-0.3 Hz

Izu Ooshima ~ 1230-2380 cm^2

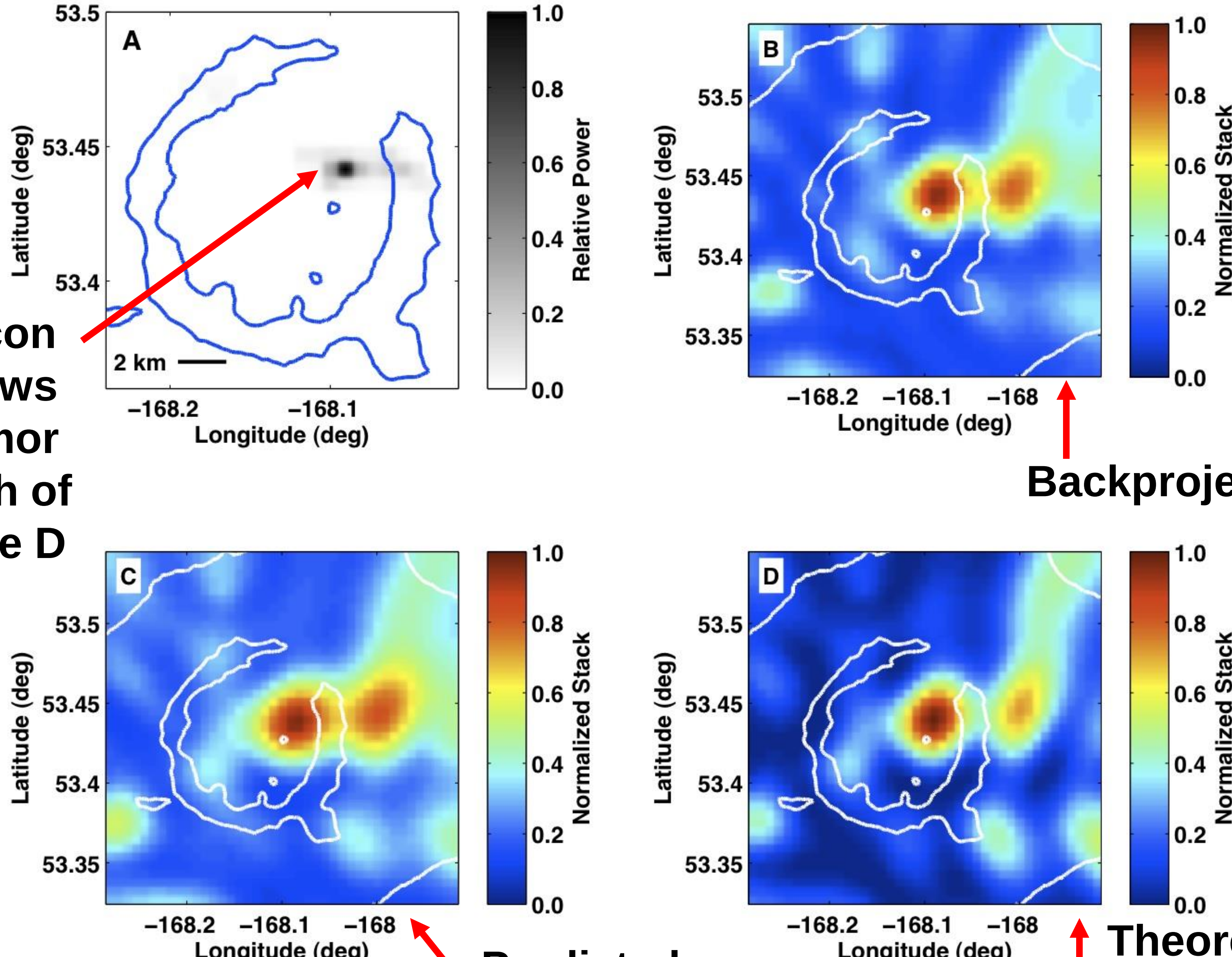
Pinatubo ~ 1070 cm^2

MSH ~ 260 cm^2

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

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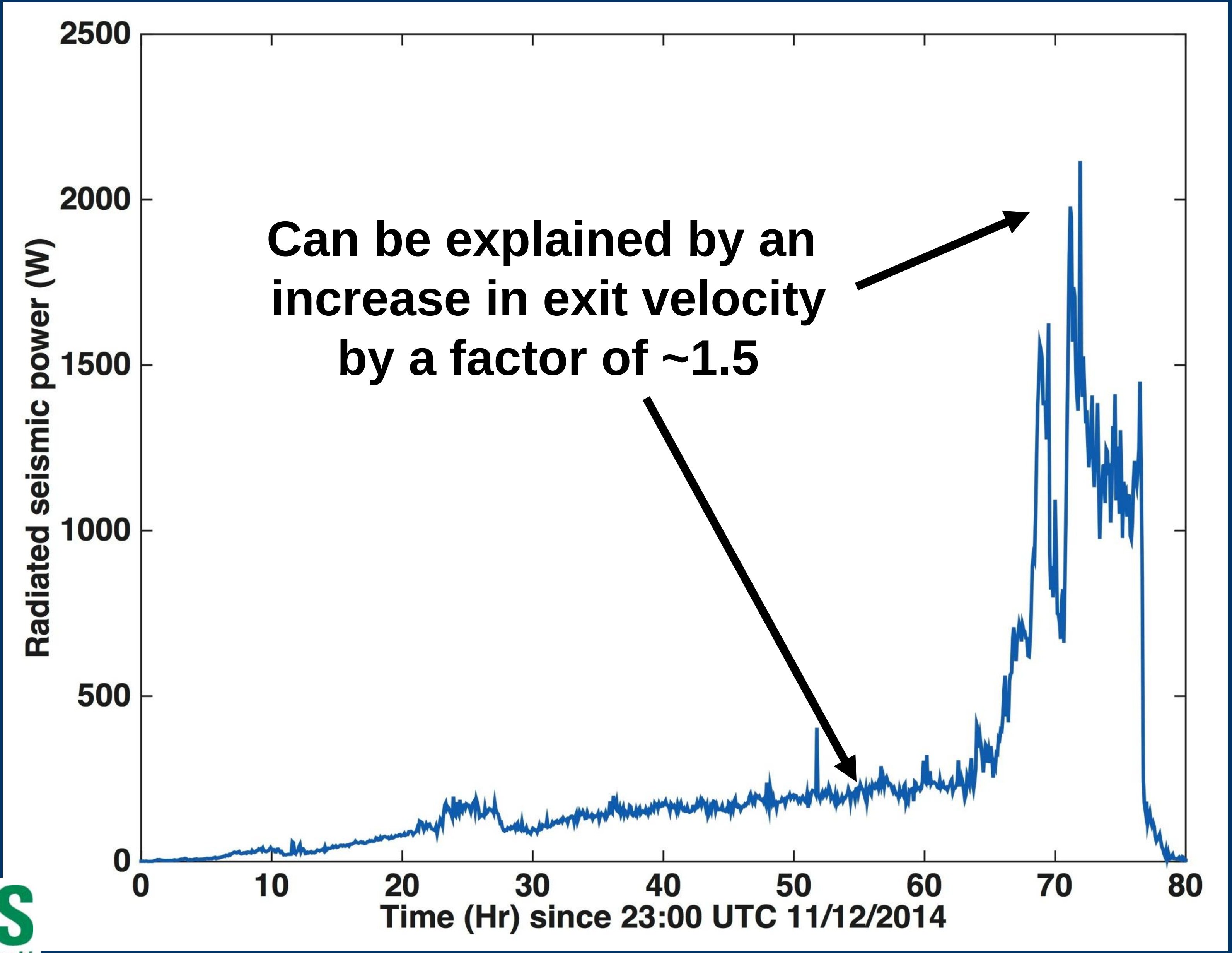
November 2014 Pavlof Eruption



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**