



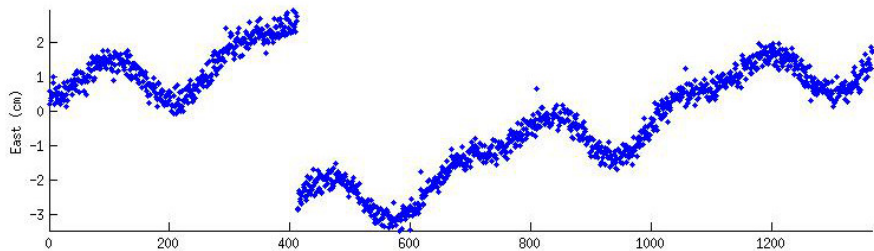
ERTH 491-01 / GEOP 572-02
Geodetic Methods

– Lecture 26: Modeling - Volcano Deformation –

Ronni Grapenthin
rg@nmt.edu
MSEC 356
x5924

November 18, 2015

On modeling ...

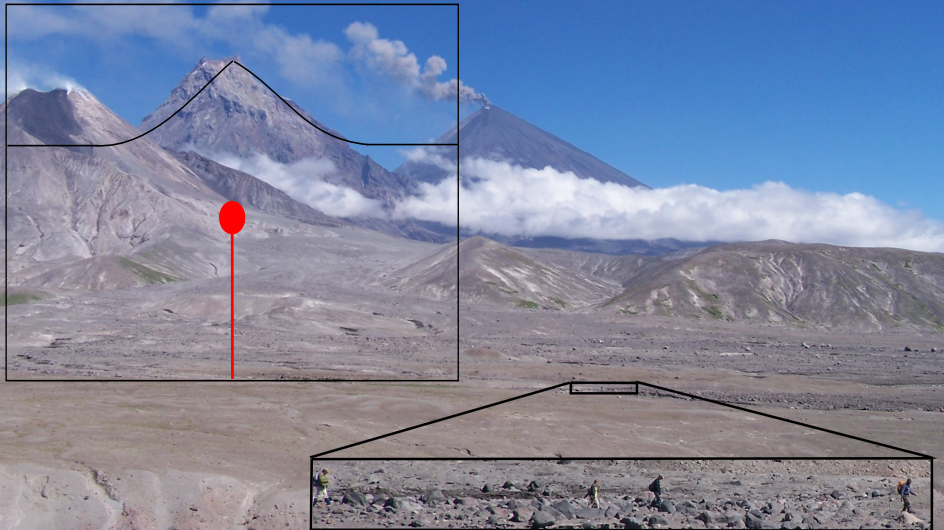


... time (days) ...

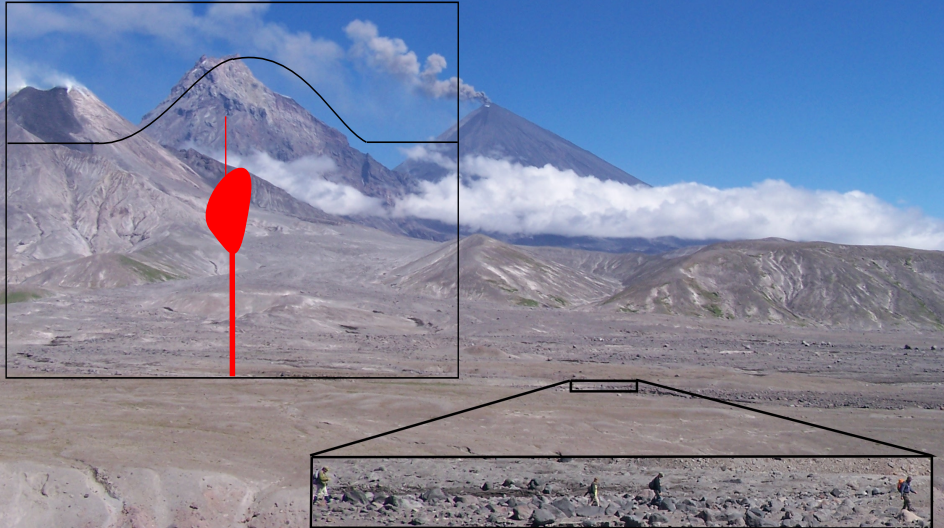
1. Plumbing: How does GPS help?



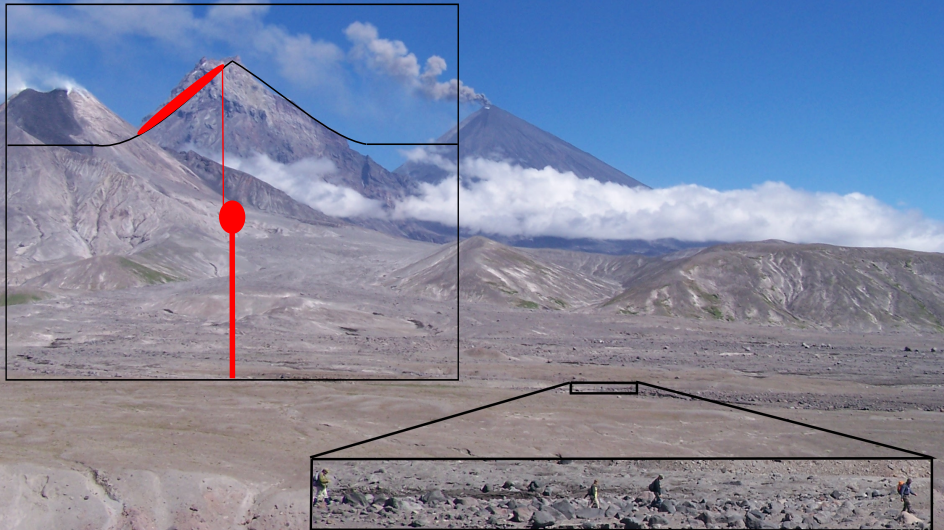
1. Plumbing: How does GPS help?



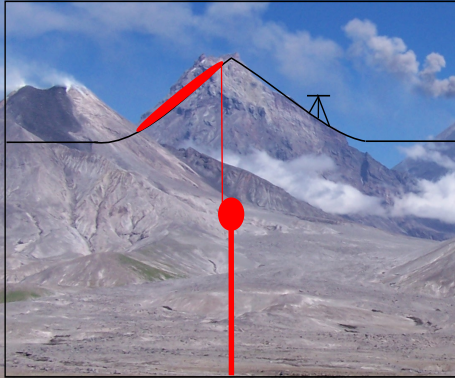
1. Plumbing: How does GPS help?



1. Plumbing: How does GPS help?



1. Plumbing: How does GPS help?

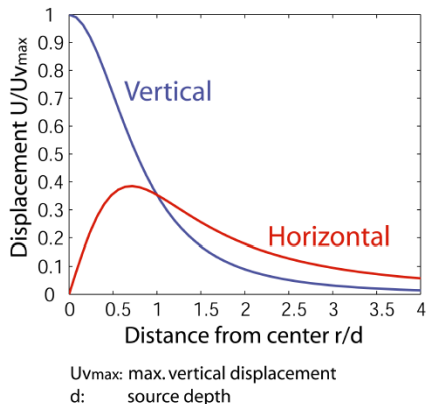
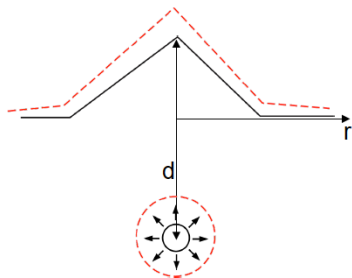


- Geodetic tools measure deformation: GPS, InSAR, ...
- Analytical models link deformation to volcano source characteristics



Source Models: Mogi (1958)

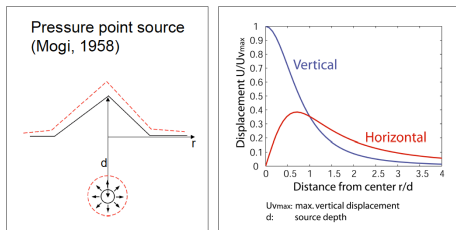
Pressure point source
(Mogi, 1958)



Jeff Freymueller

Model parameters: lat, lon, depth, source strength

Source Models: Mogi (1958)



Jeff Freymueller

- r - radial distance from source
- d - source depth
- ν - Poisson's ratio (0.25)
- $C = \frac{(1-\nu)\Delta V}{\pi}$ - source strength

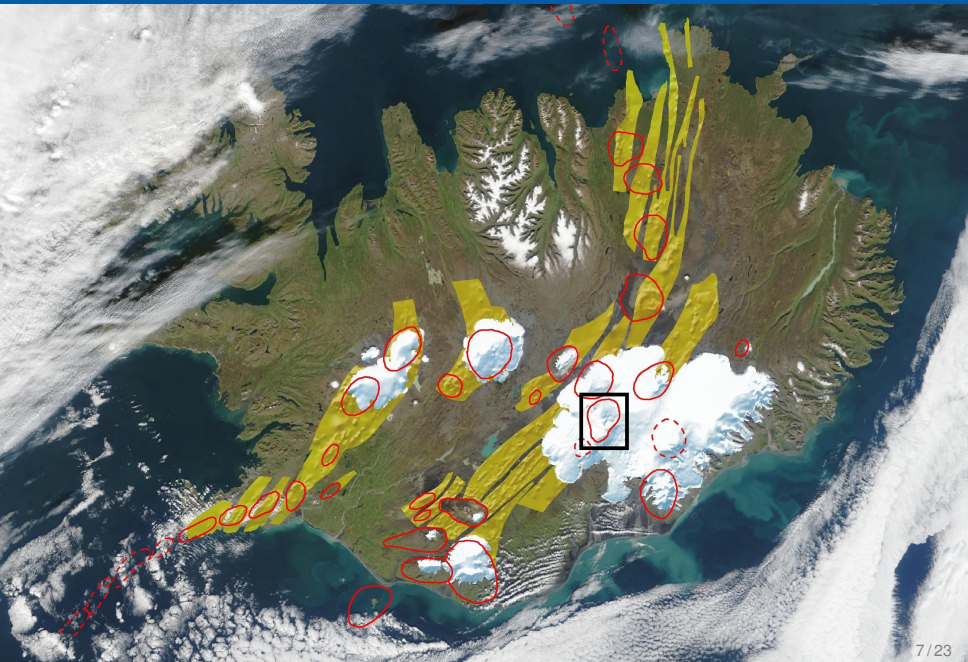
$$u_z = \frac{(1-\nu)\Delta V}{\pi} \frac{d}{(r^2 + d^2)^{3/2}}$$
$$u_r = \frac{(1-\nu)\Delta V}{\pi} \frac{r}{(r^2 + d^2)^{3/2}}$$

- $\Delta V = \frac{\pi \rho a^3}{\mu}$ - source volume change (see later!)
- ρ - pressurization
- a - source radius
- μ - shear modulus

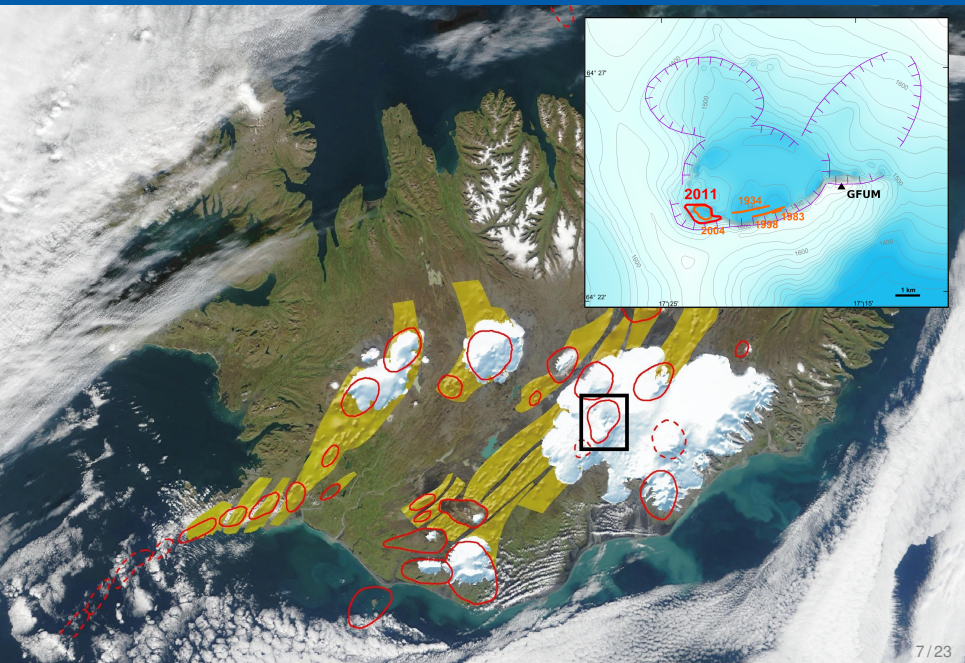
Source Models: Mogi (1958)

- ΔV is volume change of the chamber \neq magma volume change
- equivalent to scaled pressure change in cavity
- doesn't consider magma compressibility (more compressible the more gases are exsolved)
- volume is function of pressure and mass
- point source approximation means $a \ll d$, in practice good approx. for $a < 0.5d$

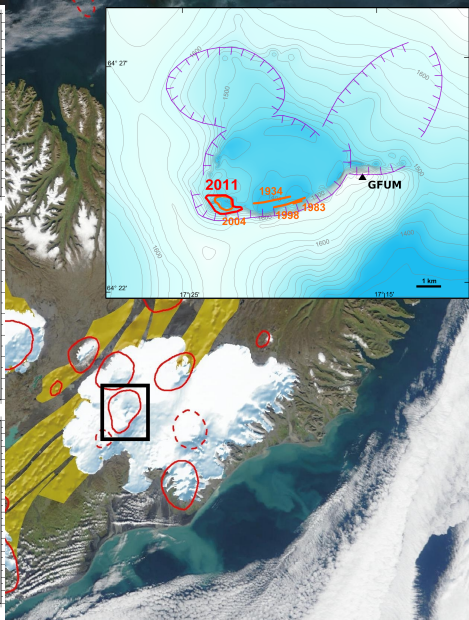
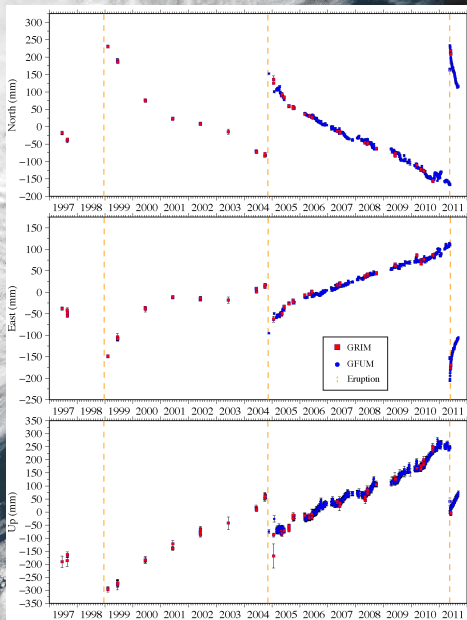
2011 Grímsvötn



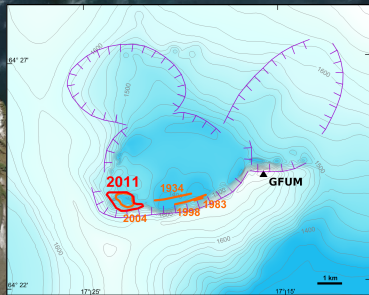
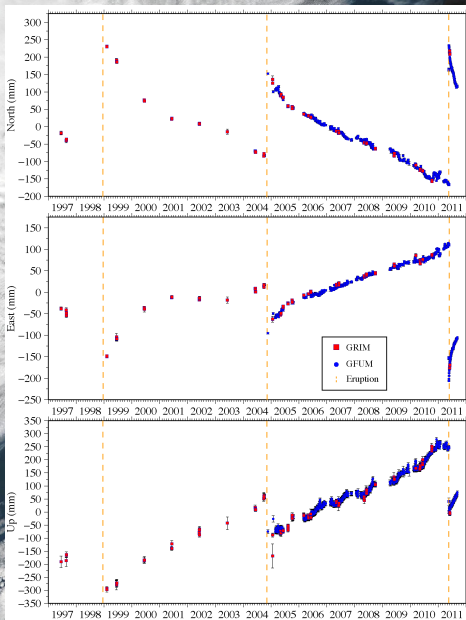
2011 Grímsvötn



2011 Grímsvötn

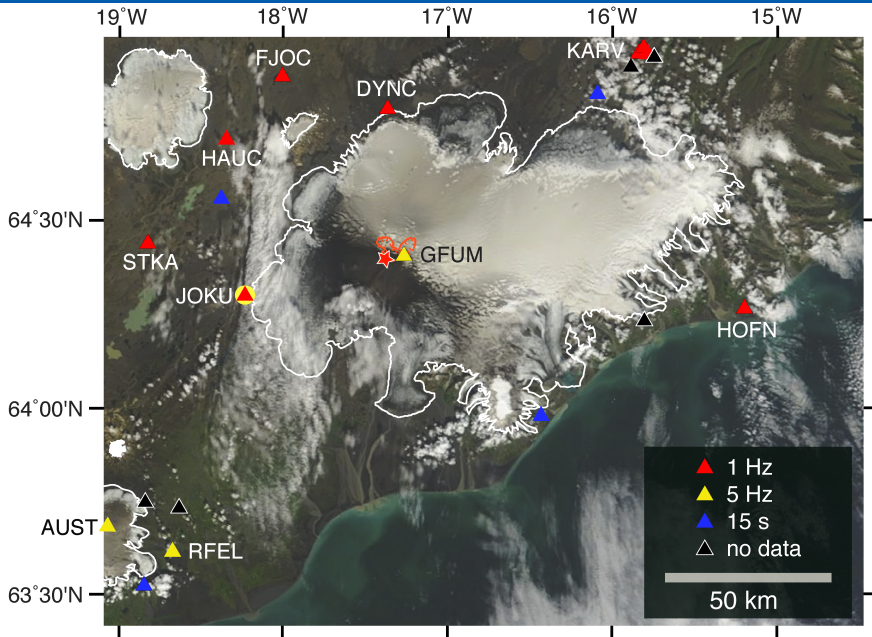


2011 Grímsvötn



- explosive eruption
21-28 May 2011
- plumes > 20 km
- continuous inflation,
gradual increase in
seismicity

2011 Grímsvötn: Geodetic Network



2011 Grímsvötn: GPS Processing

1 Hz:

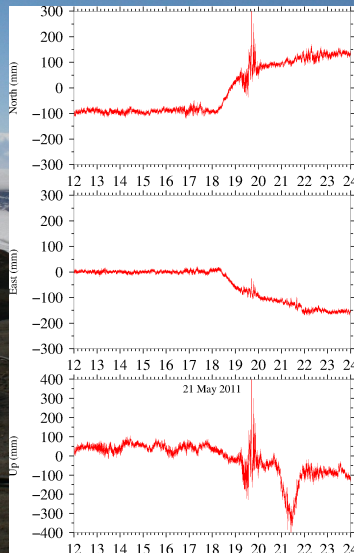
- Kinematic trajectories from track (GAMIT/GLOBK, MIT)
- Search for closest, unbiased sites
- 7 base stations about 50-100 km away
- Noise elimination: stacking of base lines
- Multi-path elimination with sidereal filtering: subtract pre-eruptive solutions shifted by 246 s
- more smoothing (15 s, 5 min windows)



2011 Grímsvötn: GPS Processing

1 Hz:

- Kinematic trajectories from track (GAMIT/GLOBK, MIT)
- Search for closest, unbiased sites
- 7 base stations about 50-100 km away
- Noise elimination: stacking of base lines
- Multi-path elimination with sidereal filtering: subtract pre-eruptive solutions shifted by 246 s
- more smoothing (15 s, 5 min windows)

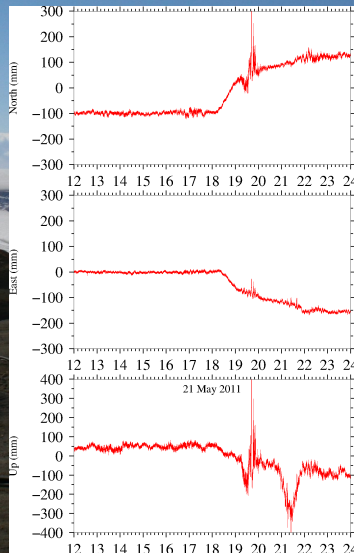


GFUM wrt JOKU

2011 Grímsvötn: GPS Processing

1 Hz:

- Kinematic trajectories from track (GAMIT/GLOBK, MIT)
- Search for closest, unbiased sites
- 7 base stations about 50-100 km away
- Noise elimination: stacking of base lines
- Multi-path elimination with sidereal filtering: subtract pre-eruptive solutions shifted by 246 s
- more smoothing (15 s, 5 min windows)

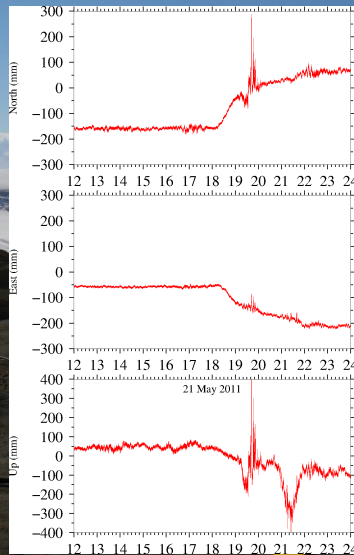


3 Station Stack

2011 Grímsvötn: GPS Processing

1 Hz:

- Kinematic trajectories from track (GAMIT/GLOBK, MIT)
- Search for closest, unbiased sites
- 7 base stations about 50-100 km away
- Noise elimination: stacking of base lines
- Multi-path elimination with sidereal filtering: subtract pre-eruptive solutions shifted by 246 s
- more smoothing (15 s, 5 min windows)

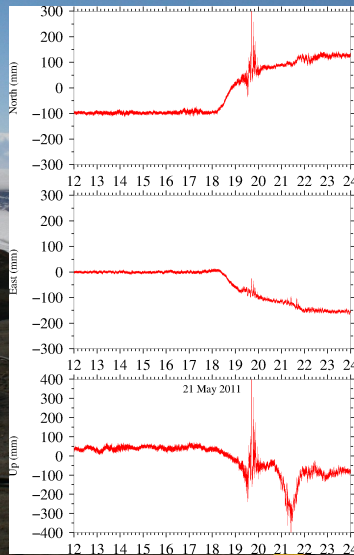


7 Station Stack

2011 Grímsvötn: GPS Processing

1 Hz:

- Kinematic trajectories from track (GAMIT/GLOBK, MIT)
- Search for closest, unbiased sites
- 7 base stations about 50-100 km away
- Noise elimination: stacking of base lines
- Multi-path elimination with sidereal filtering: subtract pre-eruptive solutions shifted by 246 s
- more smoothing (15 s, 5 min windows)

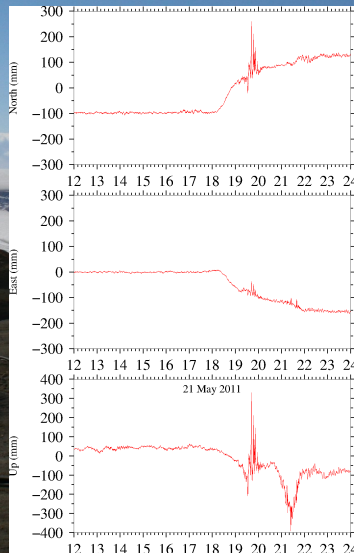


Sidereal Filtering

2011 Grímsvötn: GPS Processing

1 Hz:

- Kinematic trajectories from track (GAMIT/GLOBK, MIT)
- Search for closest, unbiased sites
- 7 base stations about 50-100 km away
- Noise elimination: stacking of base lines
- Multi-path elimination with sidereal filtering: subtract pre-eruptive solutions shifted by 246 s
- more smoothing (15 s, 5 min windows)

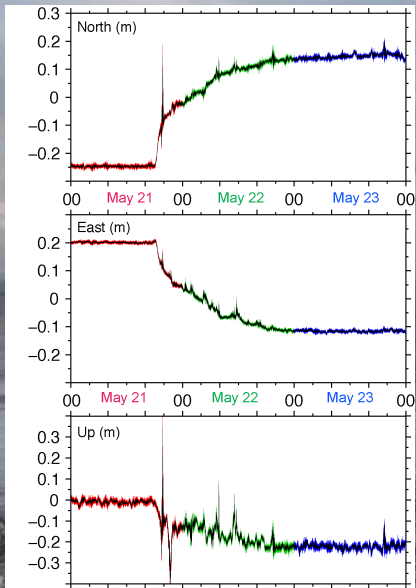


15 s Filter

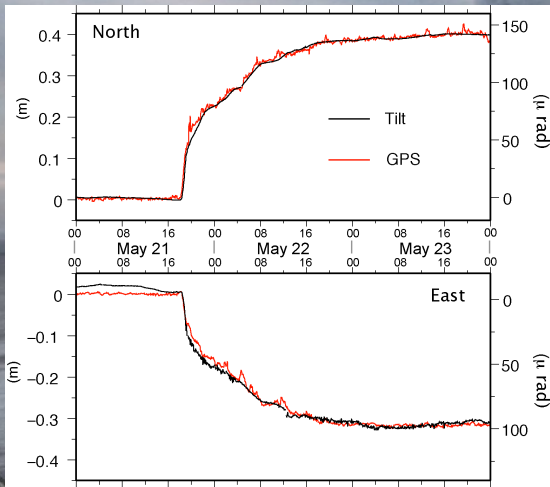
2011 Grímsvötn: Results



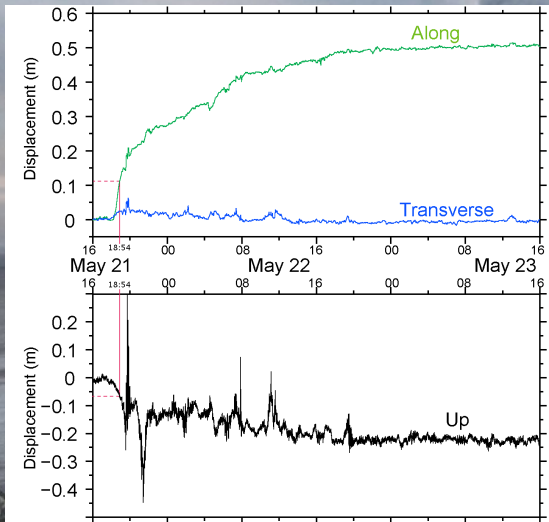
2011 Grímsvötn: Results



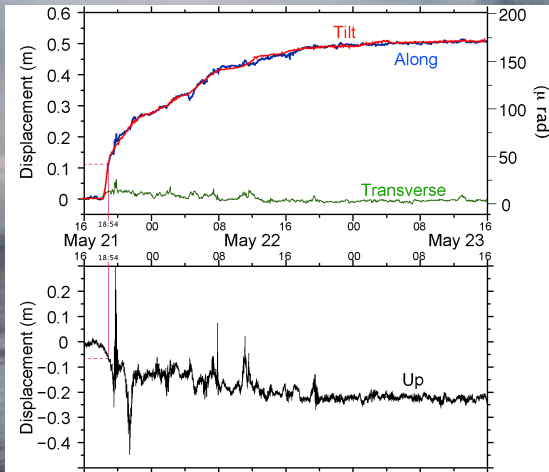
2011 Grímsvötn: Results



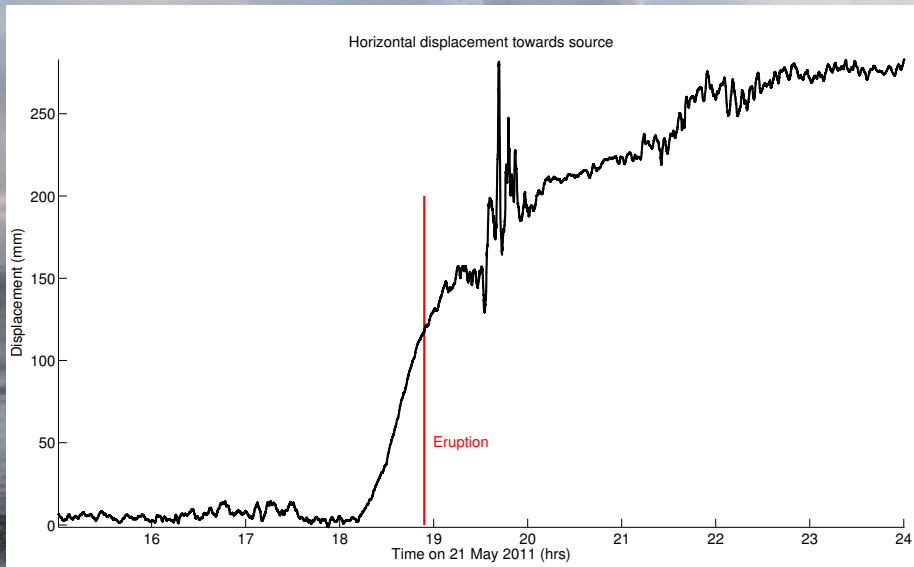
2011 Grímsvötn: Results



2011 Grímsvötn: Results



2011 Grímsvötn: Results



2011 Grímsvötn: Source Model

Measurements (Model given: Mogi 1958, Sigmundsson 2006):

$$\text{radial displacement} = u_r = C \frac{r}{(d^2 + r^2)^{3/2}} = \mathbf{51 \text{ cm N}38.5^\circ\text{W}}$$

$$\text{vertical displacement} = u_z = C \frac{d}{(d^2 + r^2)^{3/2}} = \mathbf{-25 \text{ cm}}$$

$$\text{tilt} = \delta = C \frac{-3dr}{(d^2 + r^2)^{5/2}} = \mathbf{171 \mu\text{rad}}$$

2011 Grímsvötn: Source Model

Measurements (Model given: Mogi 1958, Sigmundsson 2006):

$$\text{radial displacement} = u_r = C \frac{r}{(d^2 + r^2)^{3/2}} = \mathbf{51 \text{ cm N38.5}^\circ\text{W}}$$

$$\text{vertical displacement} = u_z = C \frac{d}{(d^2 + r^2)^{3/2}} = \mathbf{-25 \text{ cm}}$$

$$\text{tilt} = \delta = C \frac{-3dr}{(d^2 + r^2)^{5/2}} = \mathbf{171 \mu\text{rad}}$$

We derive (1σ uncertainties):

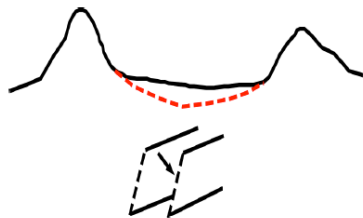
$$\text{distance} = r = \frac{u_r}{u_d} d = \mathbf{3.6 \pm 0.3 \text{ km}}$$

$$\text{depth} = d = -\frac{3u_z}{\delta} \frac{u_r/u_z}{1 + (u_r/u_z)^2} = \mathbf{1.8 \pm 0.2 \text{ km}}$$

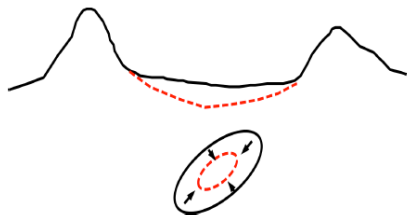
$$\text{strength} = C = 9 \frac{u_z^3 (u_r/u_z)^2}{\delta^2 \sqrt{1 + (u_r/u_z)^2}} = \mathbf{9 \pm 1 \times 10^6 \text{ m}^3}$$

Source Models: Okada (1985), Yang (1988)

Rectangular dislocation source (Okada, 1985)



Ellipsoidal pressure source (Yang, 1988)



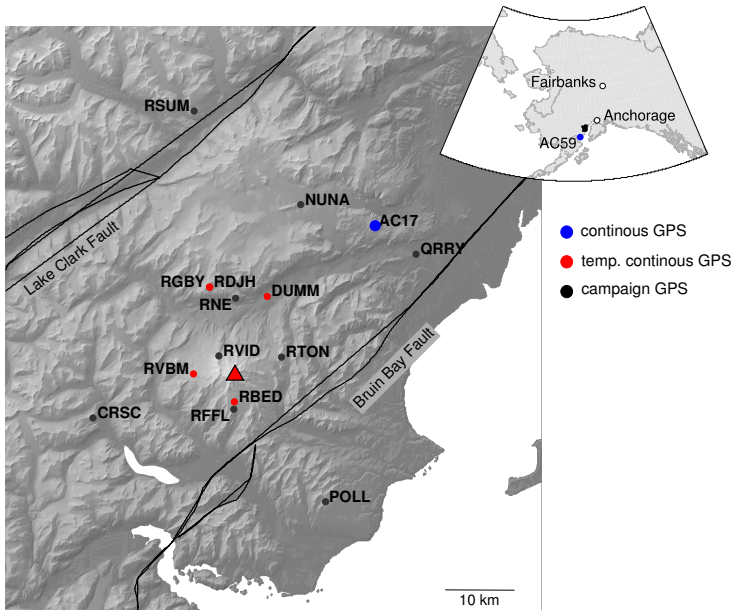
Jeff Freymueller

Model parameters: lat, lon, depth, length, width, dip, strike, source strength

Mt Redoubt, Alaska, 2009



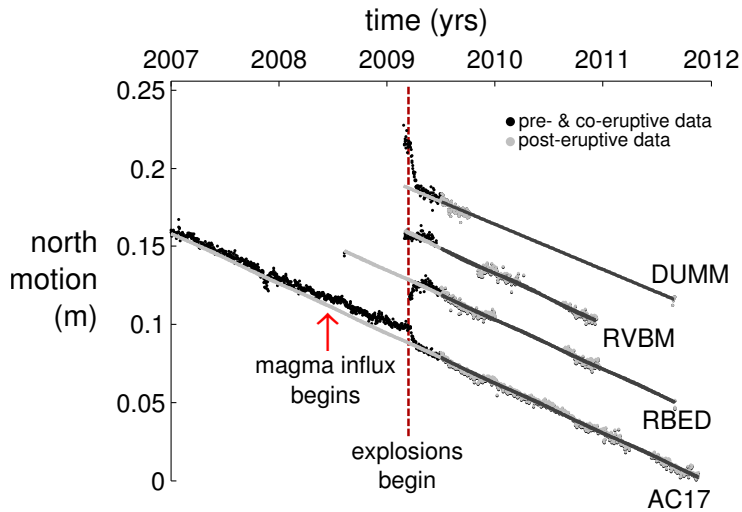
1. Weeks to Months: Mt. Redoubt Source Models



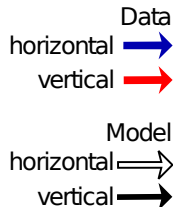
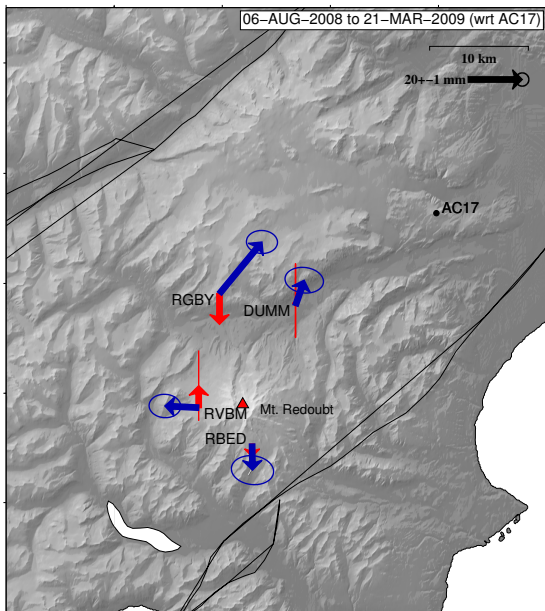
Source Estimation:

- Pressure Point Source (Mogi, 1958)
- degenerate prolate spheroid / conduit (Bonaccorso and Davis, 1999)
- general (prolate) spheroid (Yang 1986, Newman et al. 2006, Battaglia et al. 2012)
- Grid search over spatial domain (models non-linear in space)
- Least squares inversion for volume change

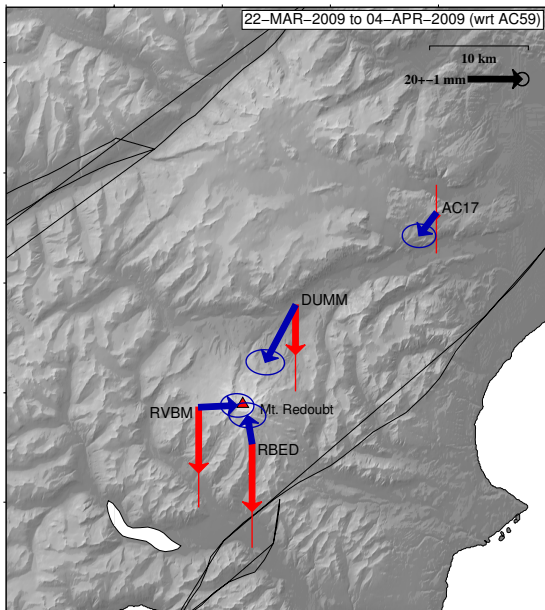
GPS Time Series relative to North America







Pre-eruptive Phase – Inflation



Explosive Phase – Deflation

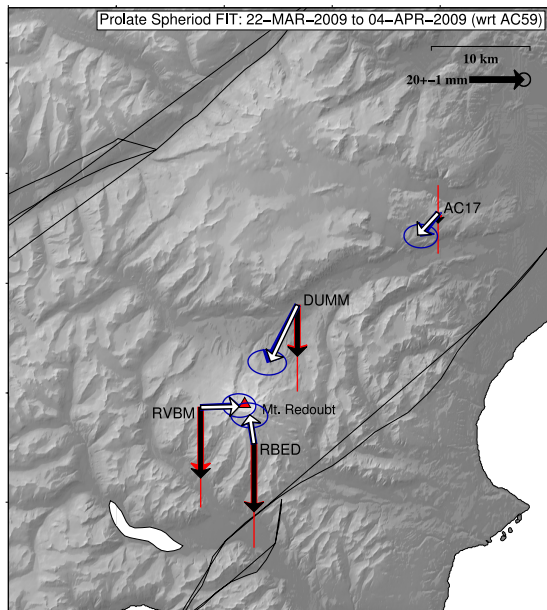


Data
horizontal 
vertical 

Model
horizontal 
vertical 

Explosive Phase – Deflation

Prolate Spheroid FIT: 22-MAR-2009 to 04-APR-2009 (wrt AC59)



General Spheroid:

$$r = 0.5 \text{ km E of dome}$$



$$d = 9.17 \begin{matrix} 6.92 \\ 15.17 \end{matrix} \text{ km}$$



$$a = 4.50 \begin{matrix} 1.25 \\ >10.00 \end{matrix} \text{ km}$$

$$b = 0.475 \begin{matrix} 0.3 \\ >4.00 \end{matrix} \text{ km}$$

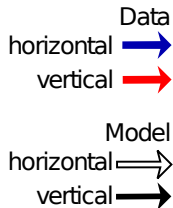
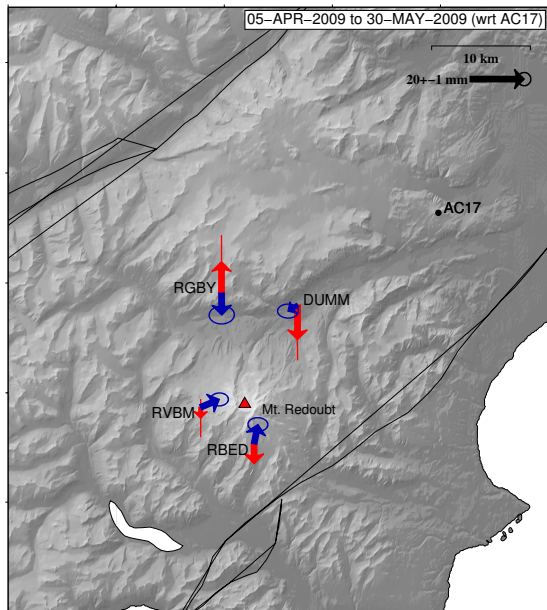
$$\Delta V = -(0.05 \begin{matrix} 0.028 \\ >0.1 \end{matrix}) \text{ km}^3$$

F-Test: Spheroid preferred.

Data
horizontal 
vertical 

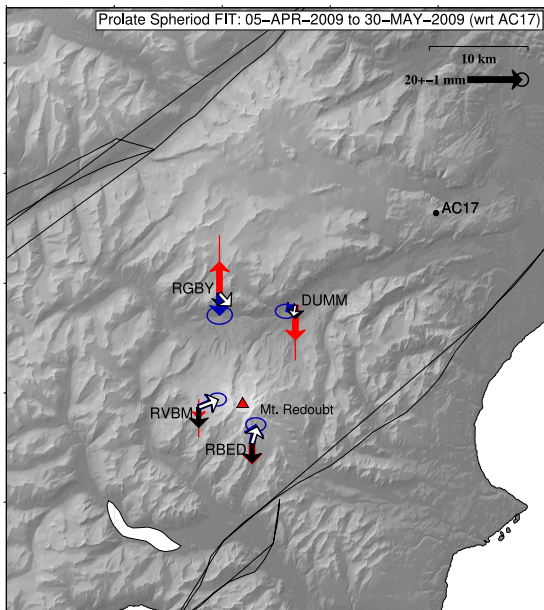
Model
horizontal 
vertical 

Effusive Phase – Deflation



Effusive Phase – Deflation

Prolate Spheroid FIT: 05-APR-2009 to 30-MAY-2009 (wrt AC17)

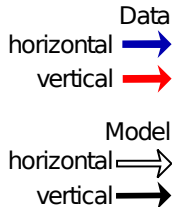


General Spheroid:

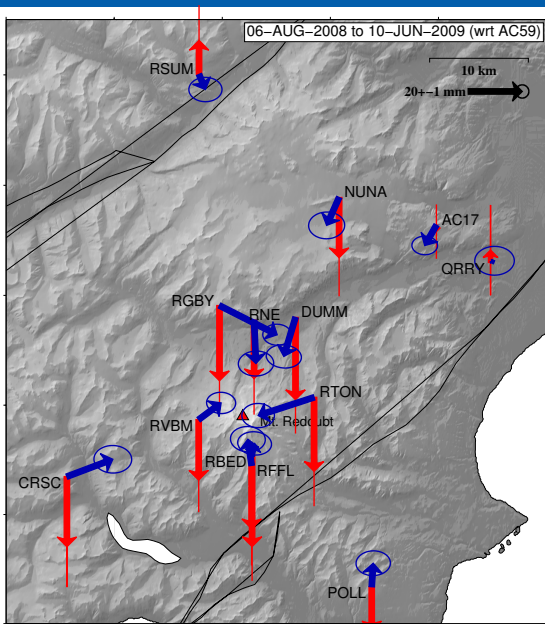
$$\Delta V = -(0.017 \begin{matrix} 0.011 \\ 0.023 \end{matrix}) \text{ km}^3$$

Mogi fits better

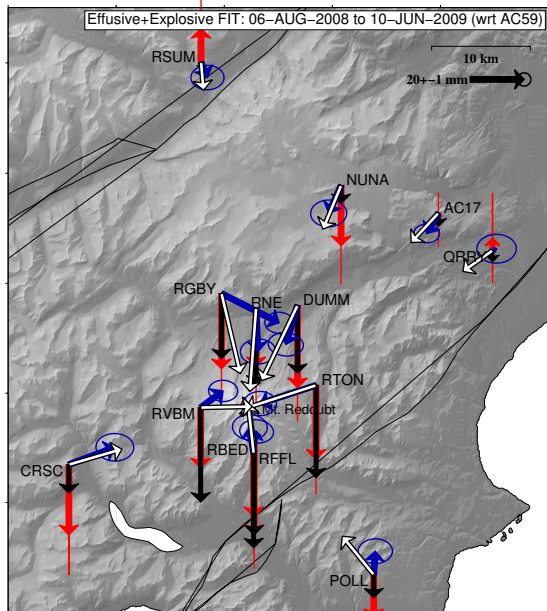
F-Test rejects Mogi



Full Eruption – Net Deflation



Full Eruption – Net Deflation



Explosive: Prolate Spheroid

$$r = 0.5 \text{ km E of dome}$$

$$d = 9.17^{6.92}_{15.17} \text{ km}$$

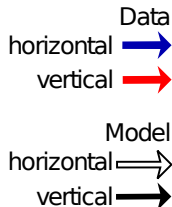
$$a = 4.50^{1.25}_{>10.00} \text{ km}$$

$$b = 0.475^{0.3}_{>4.00} \text{ km}$$

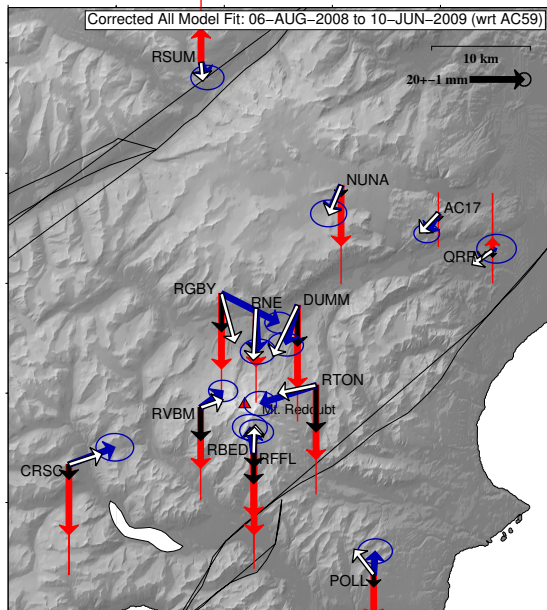
$$\Delta V = -(0.05^{0.028}_{>0.1}) \text{ km}^3$$

Effusive: same.

$$\Delta V = -(0.017^{0.011}_{0.023}) \text{ km}^3$$



Final Model



Explosive: Prolate Spheroid

$$r = 0.5 \text{ km E of dome}$$

$$d = 9.17^{6.92}_{15.17} \text{ km}$$

$$a = 4.50^{1.25}_{>10.00} \text{ km}$$

$$b = 0.475^{0.3}_{>4.00} \text{ km}$$

$$\Delta V = -(0.05^{0.028}_{>0.1}) \text{ km}^3$$

Effusive: same.

$$\Delta V = -(0.017^{0.011}_{0.023}) \text{ km}^3$$

Pre-eruptive: Mogi

$$r = 1.25 \text{ km S of dome}$$

$$d = 13.50^{10.17}_{17.33} \text{ km}$$

$$\Delta V = 0.0194^{0.0092}_{0.0340} \text{ km}^3$$

2009 Redoubt Source Evolution



2009 Redoubt Source Evolution

Main Results:

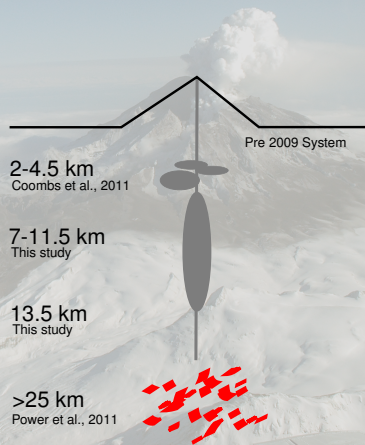
- pre-eruptive intrusion preceded seismic precursors
- dynamic change of source over weeks
- suggested process:



2009 Redoubt Source Evolution

Main Results:

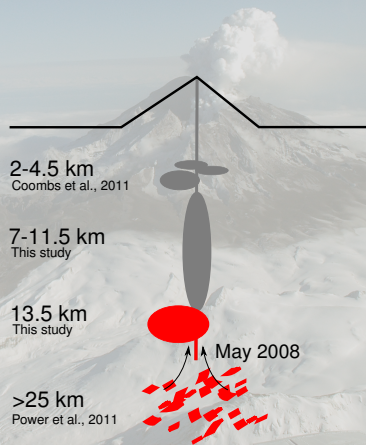
- pre-eruptive intrusion preceded seismic precursors
- dynamic change of source over weeks
- suggested process:



2009 Redoubt Source Evolution

Main Results:

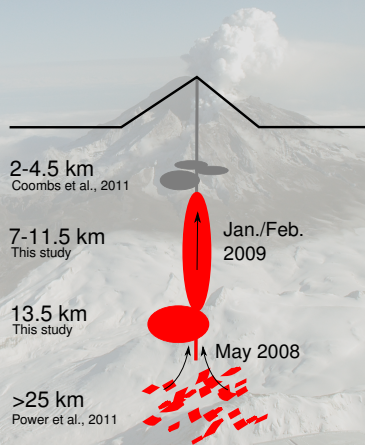
- pre-eruptive intrusion preceded seismic precursors
- dynamic change of source over weeks
- suggested process:



2009 Redoubt Source Evolution

Main Results:

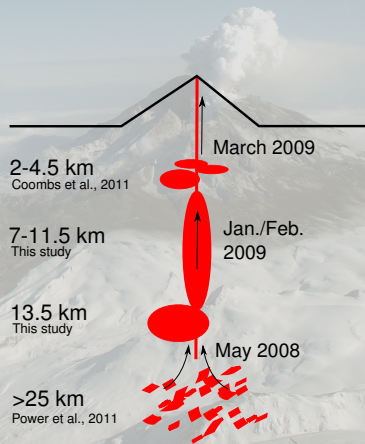
- pre-eruptive intrusion preceded seismic precursors
- dynamic change of source over weeks
- suggested process:



2009 Redoubt Source Evolution

Main Results:

- pre-eruptive intrusion preceded seismic precursors
- dynamic change of source over weeks
- suggested process:



2009 Redoubt Source Evolution

Main Results:

- pre-eruptive intrusion preceded seismic precursors
- dynamic change of source over weeks
- suggested process:

