GEOS F493 / F693
Geodetic Methods and Modeling

– Lecture 11b: Modeling - Volcano Deformation –

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November 11, 2019

1. Plumbing: How does GPS help?

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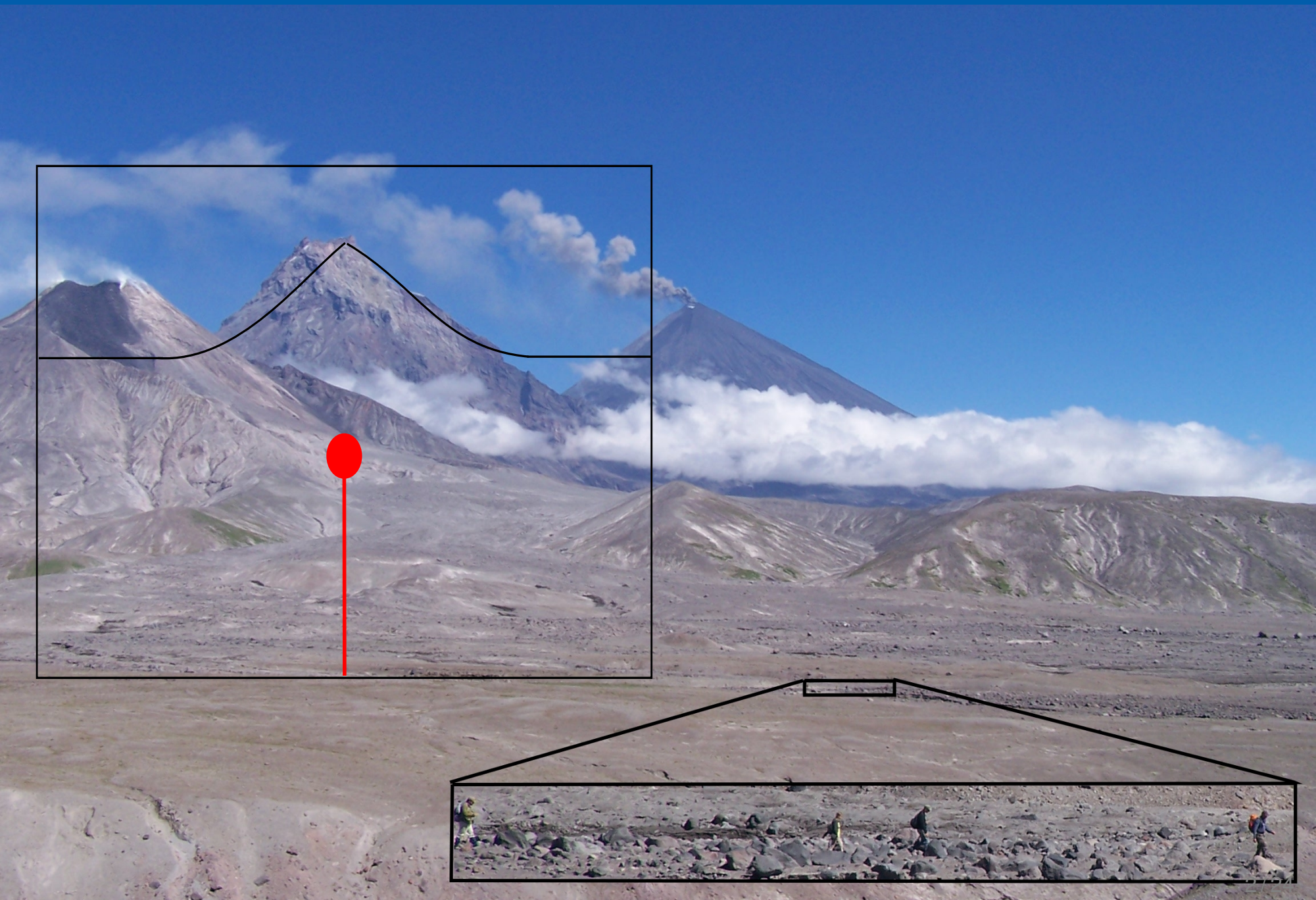

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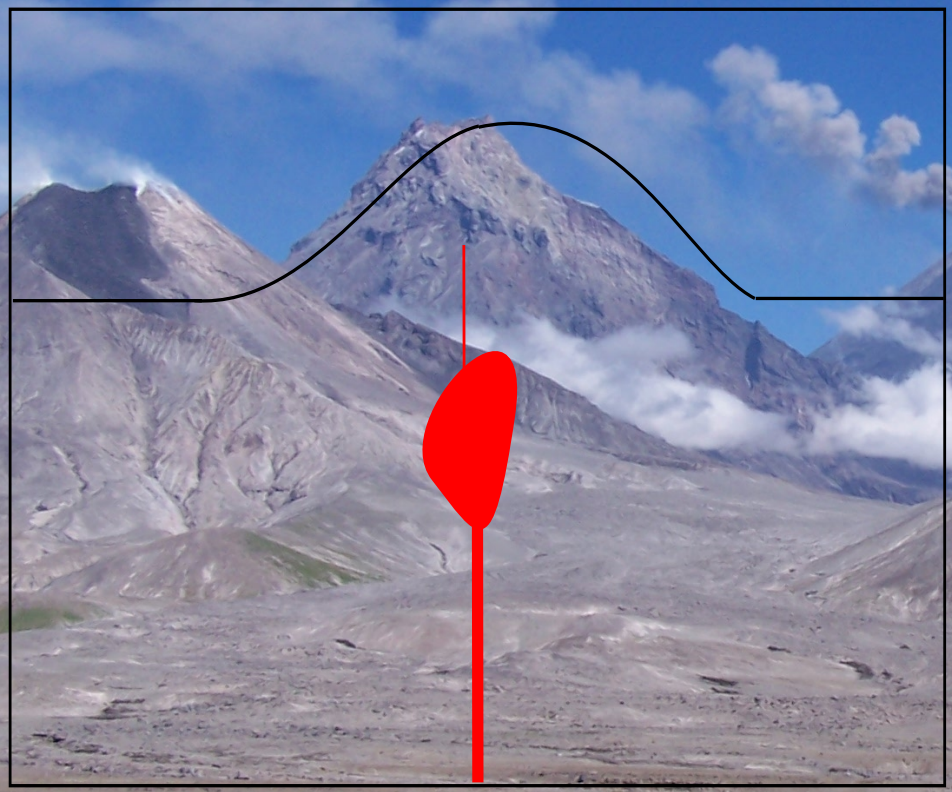

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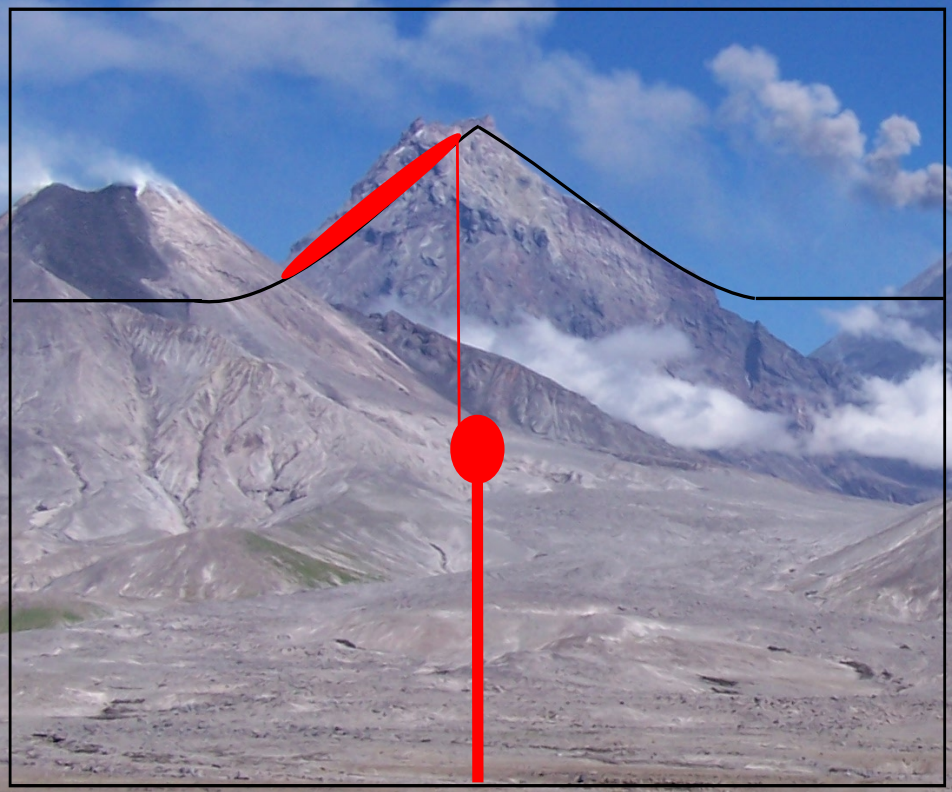

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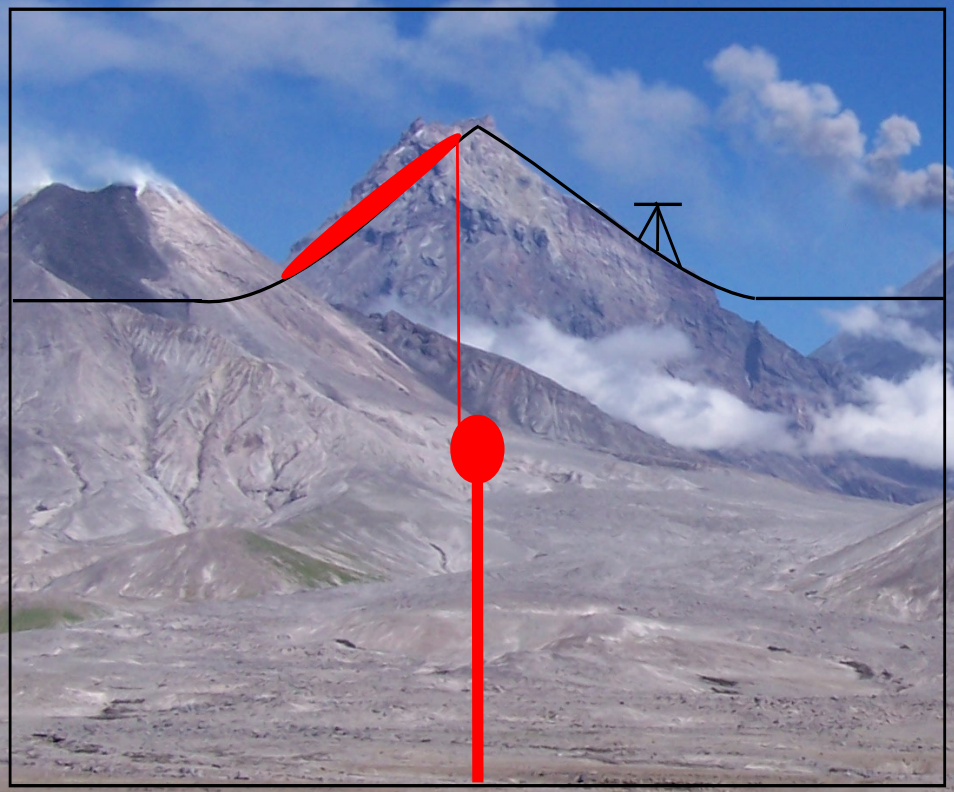
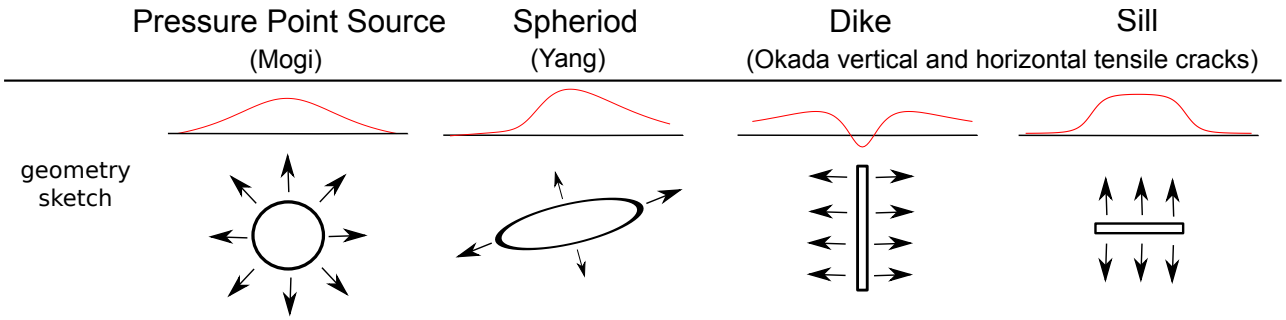
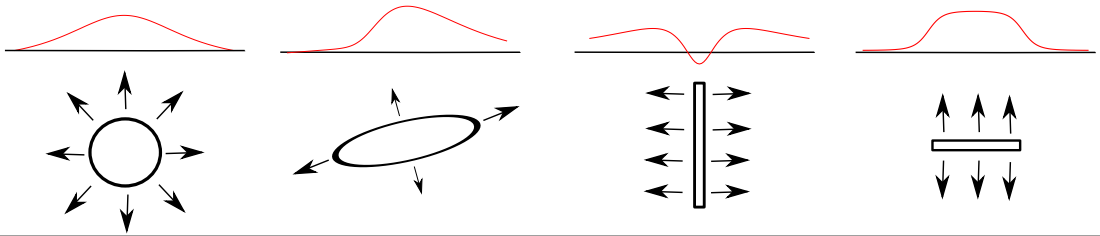


- Geodetic tools measure deformation: GPS, InSAR, . . .
- Analytical models link deformation to volcano source characteristics

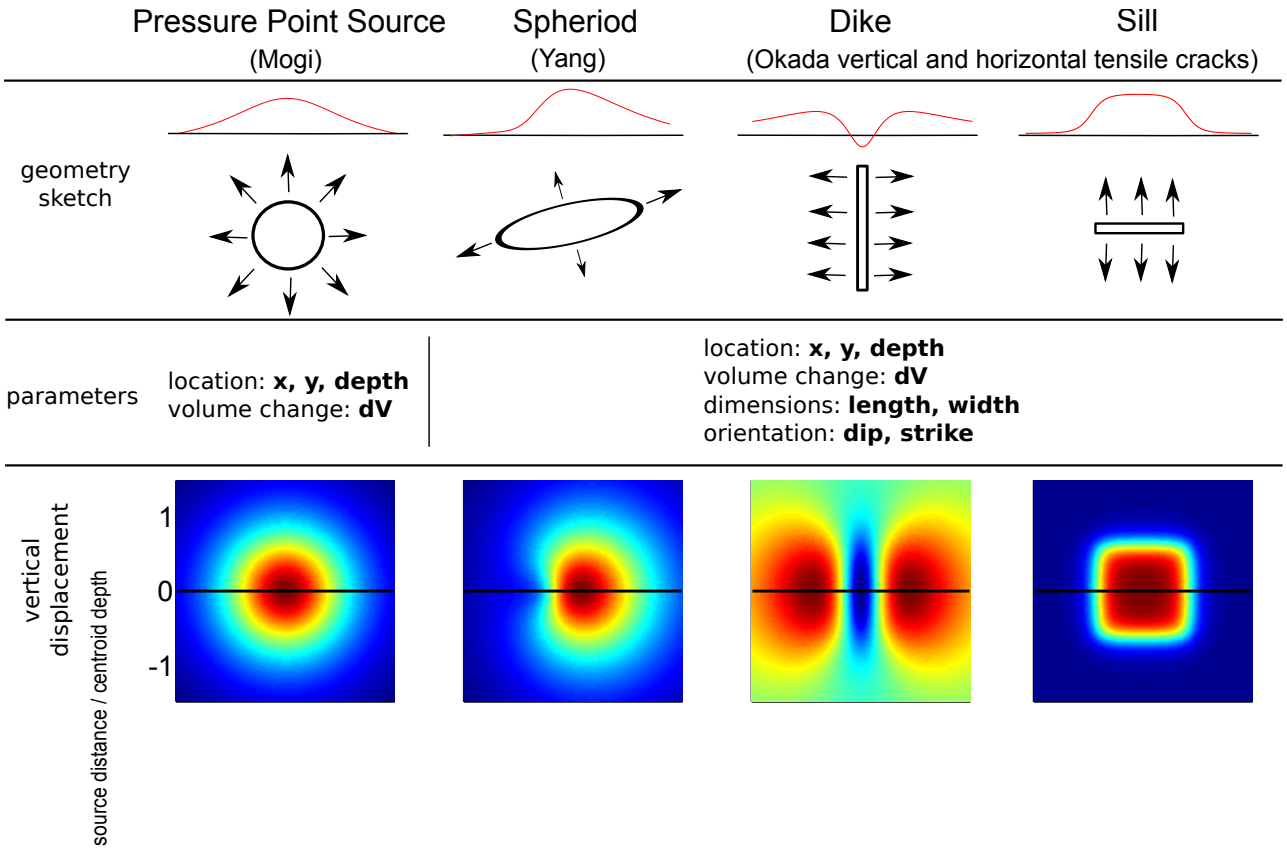
Source Models



Source Models

	Pressure Point Source (Mogi)	Spheriod (Yang)	Dike (Okada vertical and horizontal tensile cracks)	Sill
geometry sketch				
parameters	location: **x, y, depth** volume change: **dV**		location: **x, y, depth** volume change: **dV** dimensions: **length, width** orientation: **dip, strike**	

Source Models



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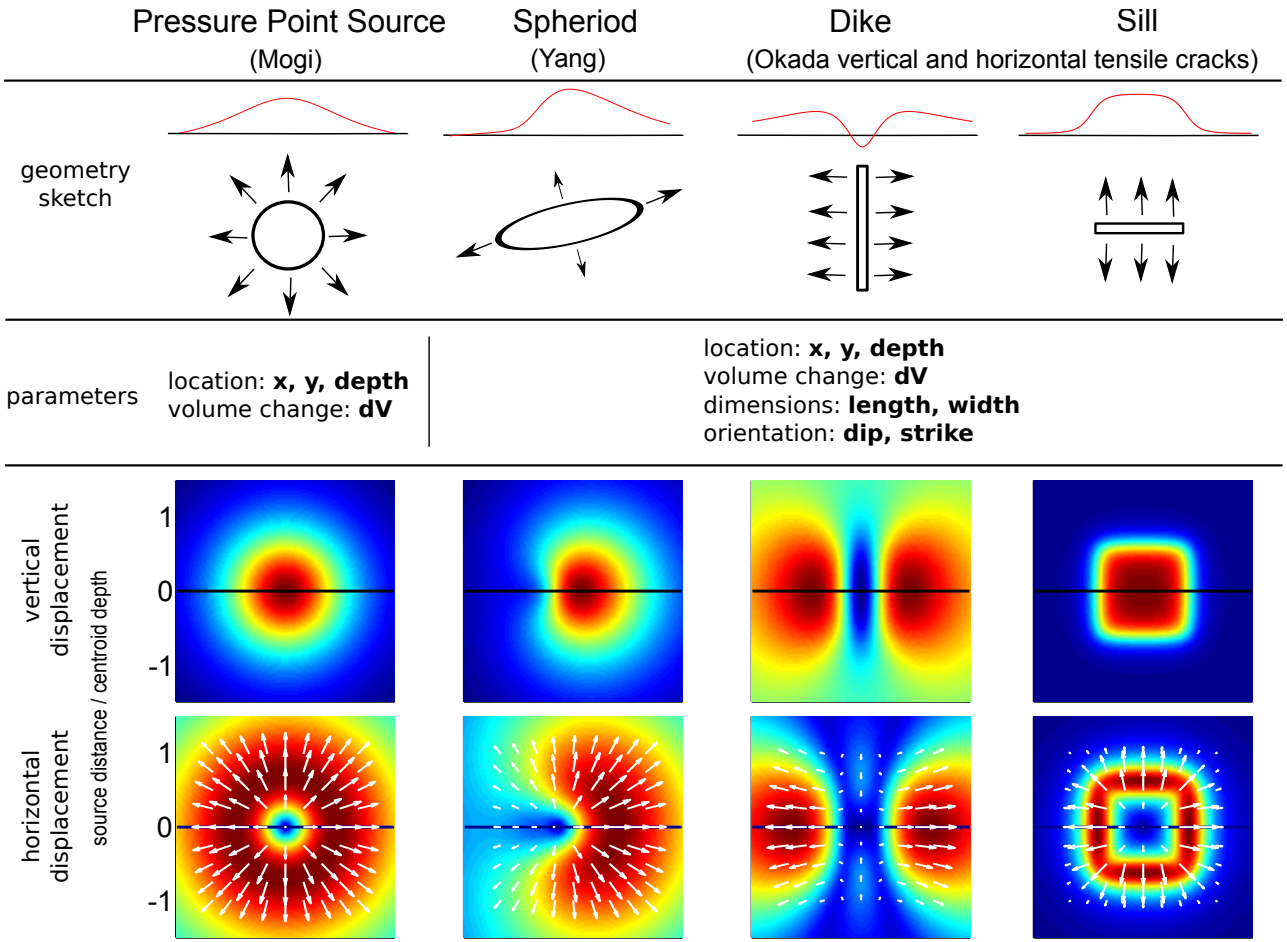
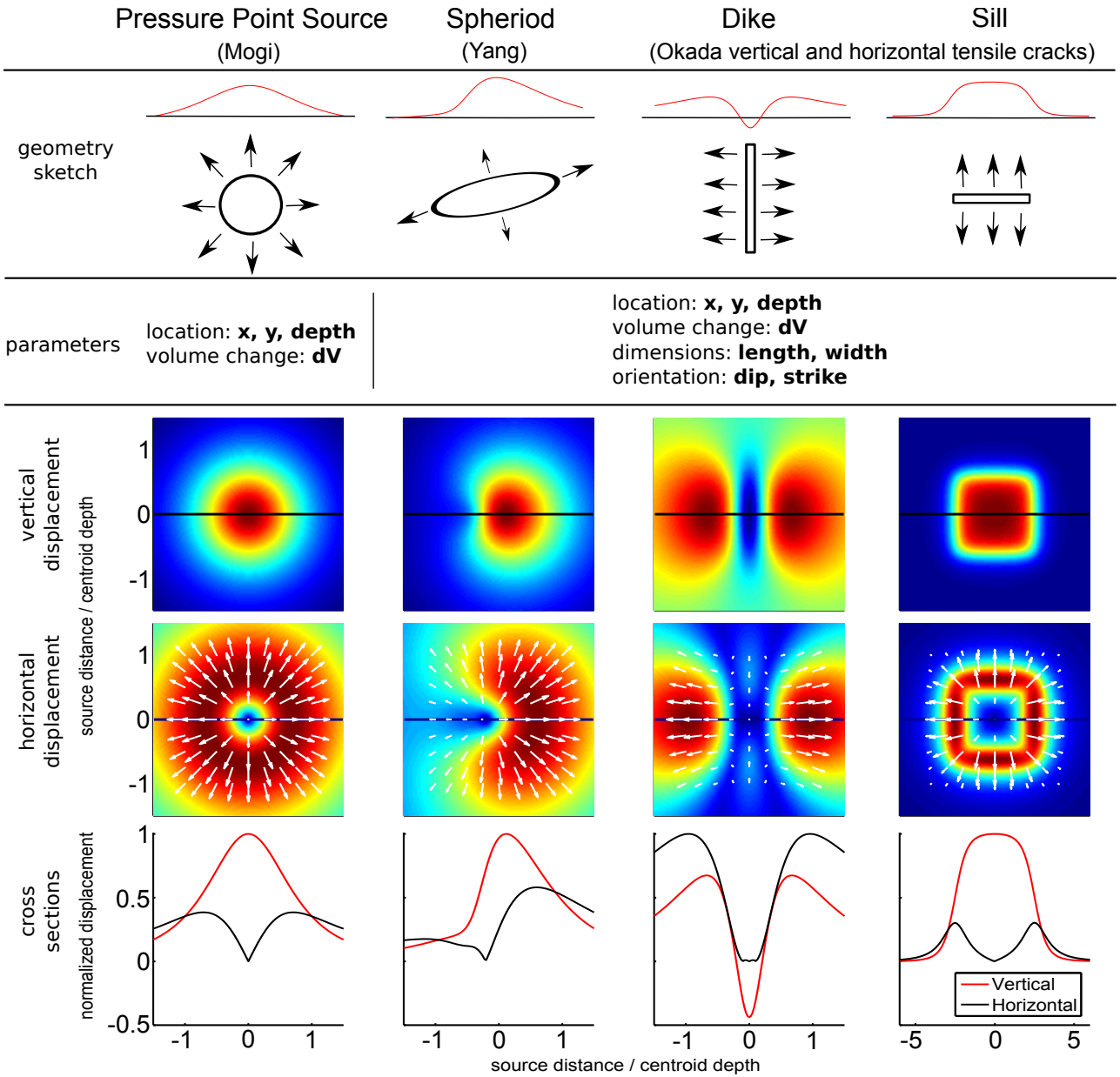


Source Models



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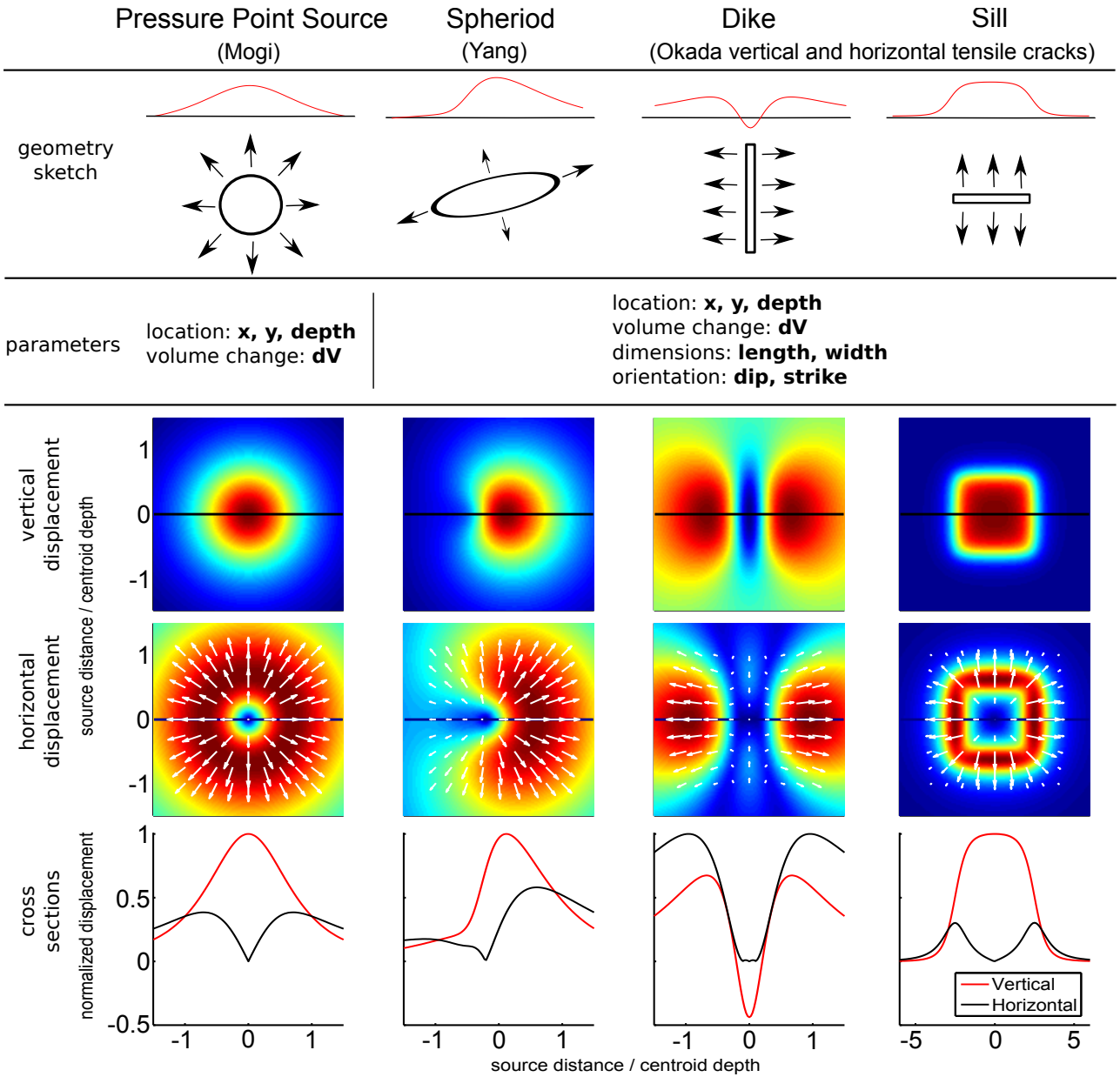
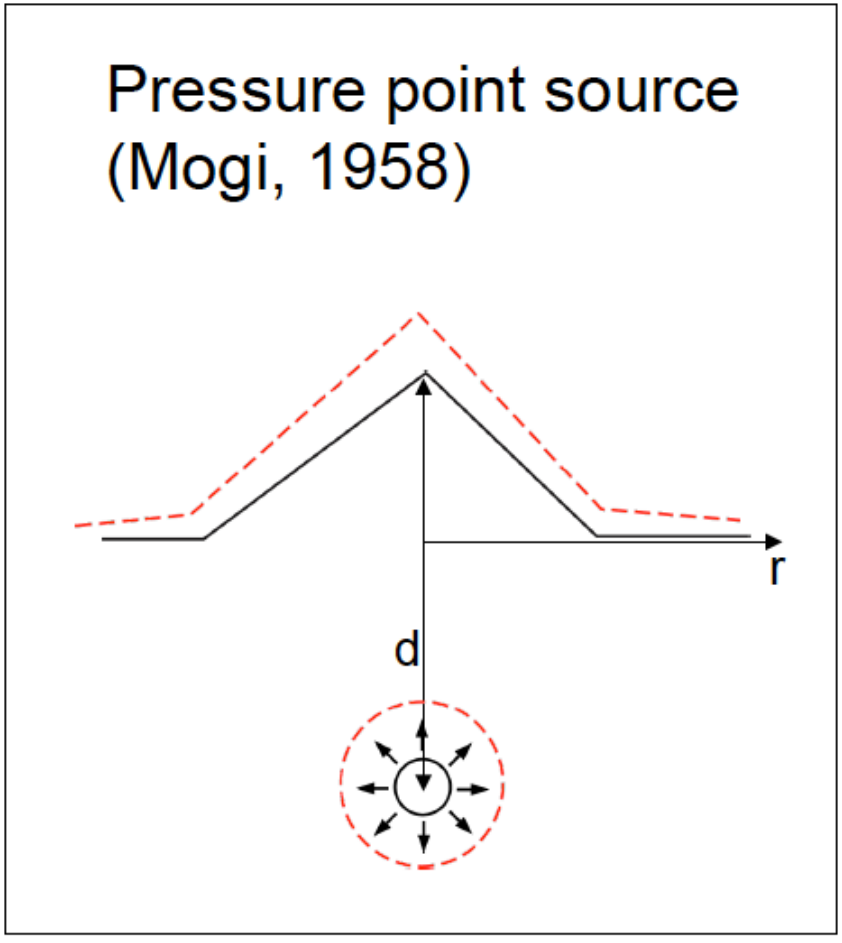
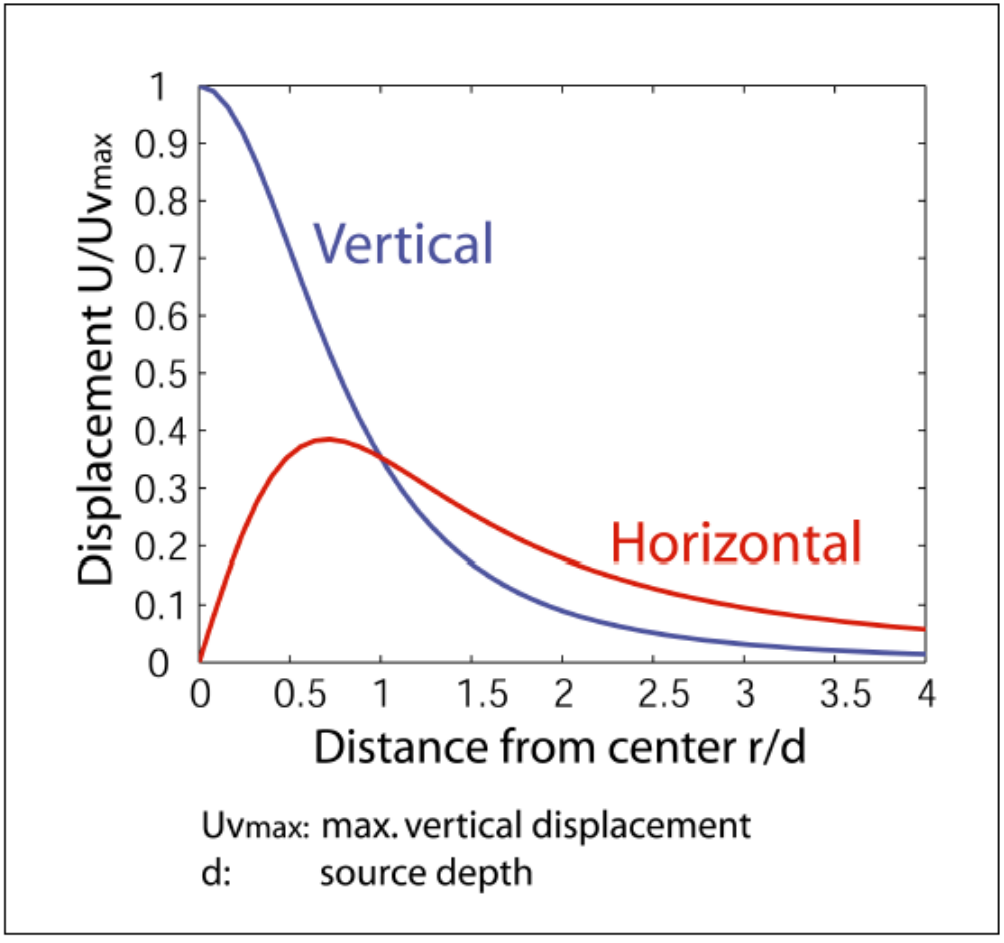


Source Models: Mogi (1958)

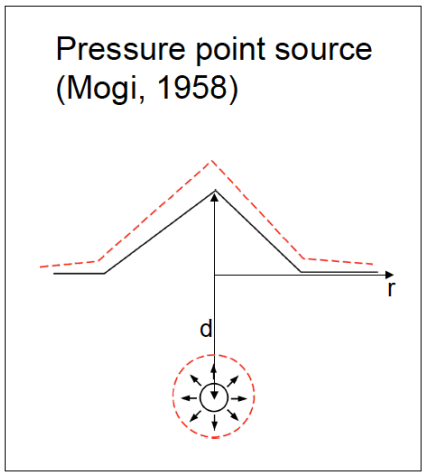


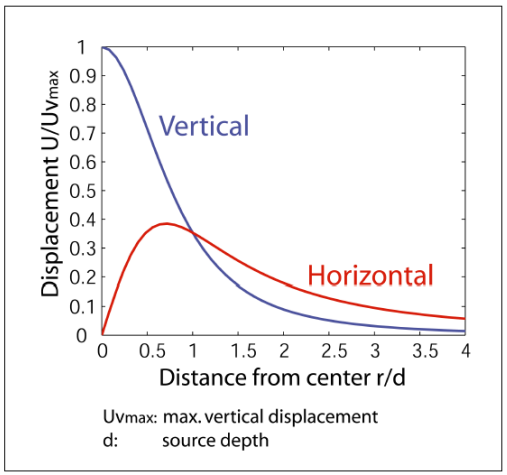


Jeff Freymueller

Model parameters: lat, lon, depth, source strength

Source Models: Mogi (1958)





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

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

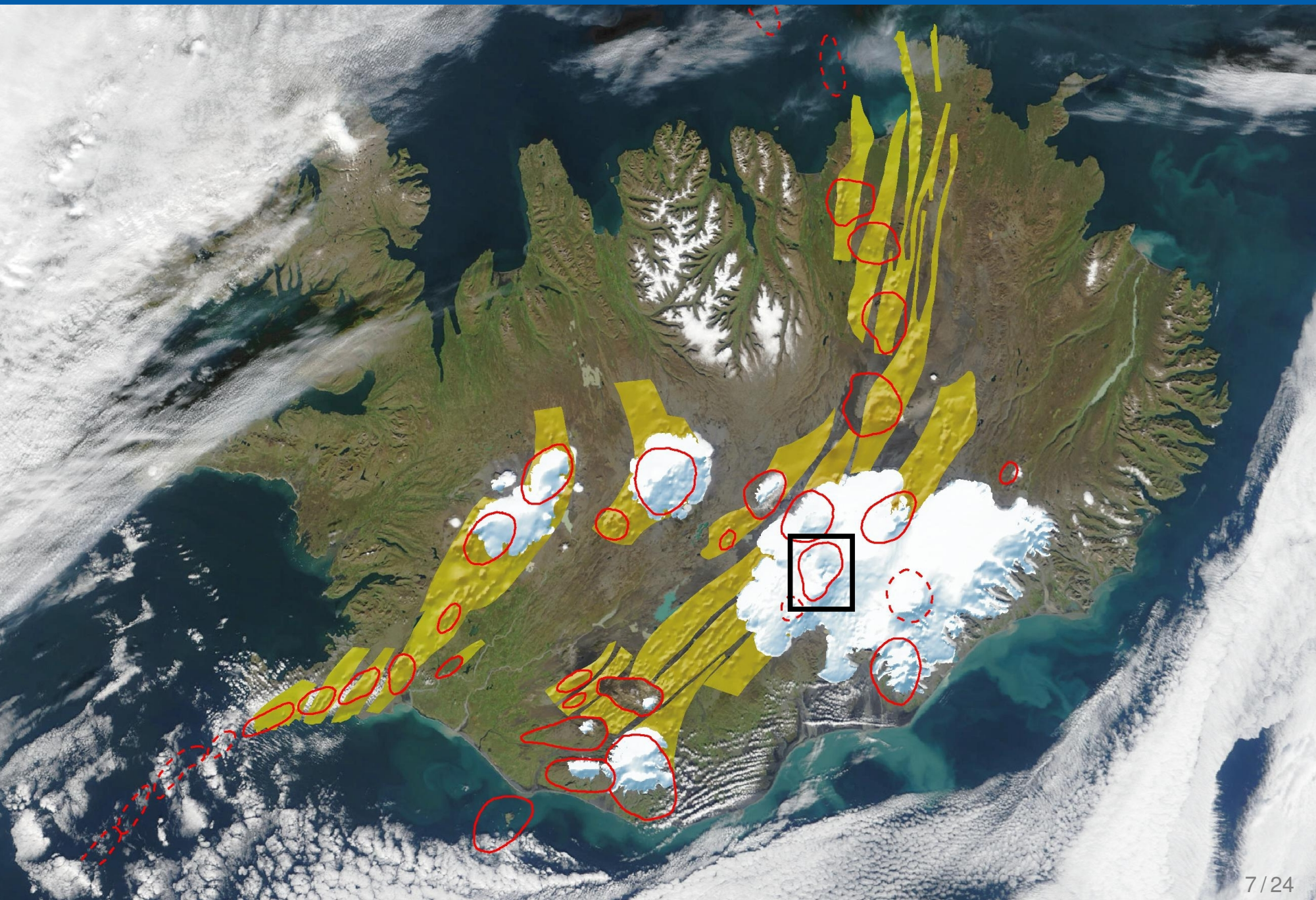
Jeff Freymueller

- r - radial distance from source
- d - source depth
- ν - Poisson's ratio (0.25)
- $C = \frac{(1-\nu)\Delta V}{\pi}$ - source strength
- $\Delta V = \frac{\pi p a^3}{\mu}$ - source volume change (see later!)
- p - 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 $a << d$, in practice good approx. for $a < 0.5d$

2011 Grímsvötn



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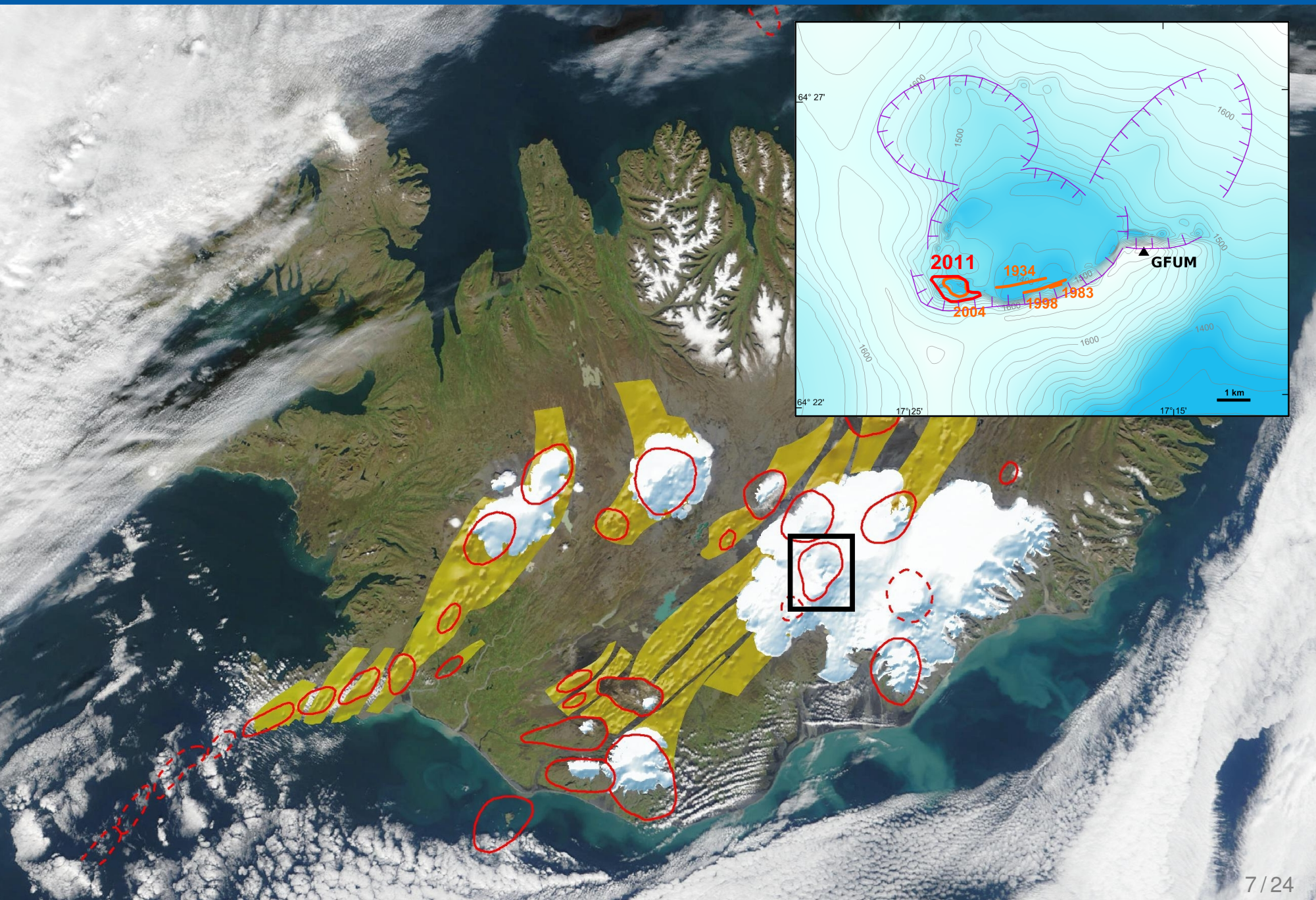

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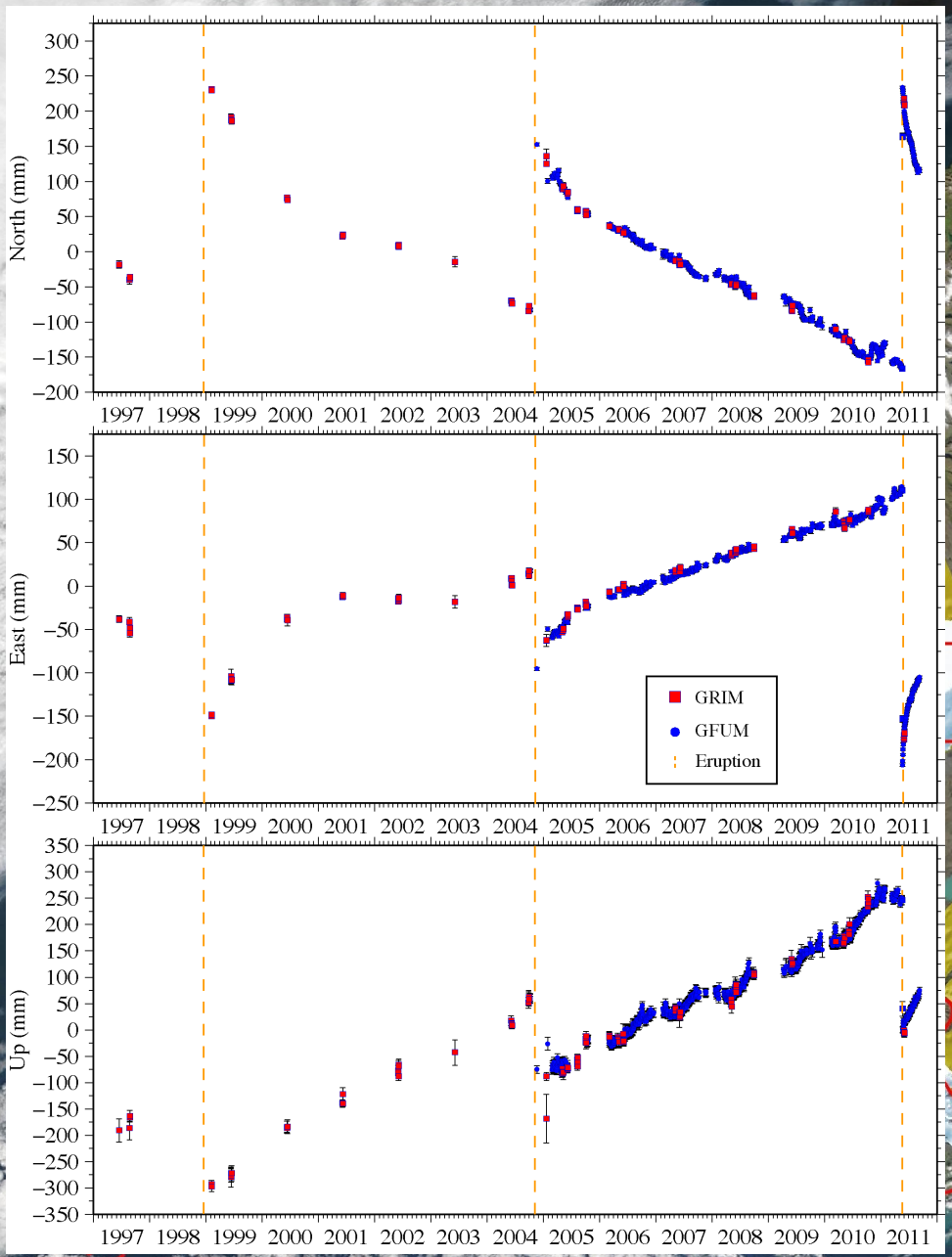

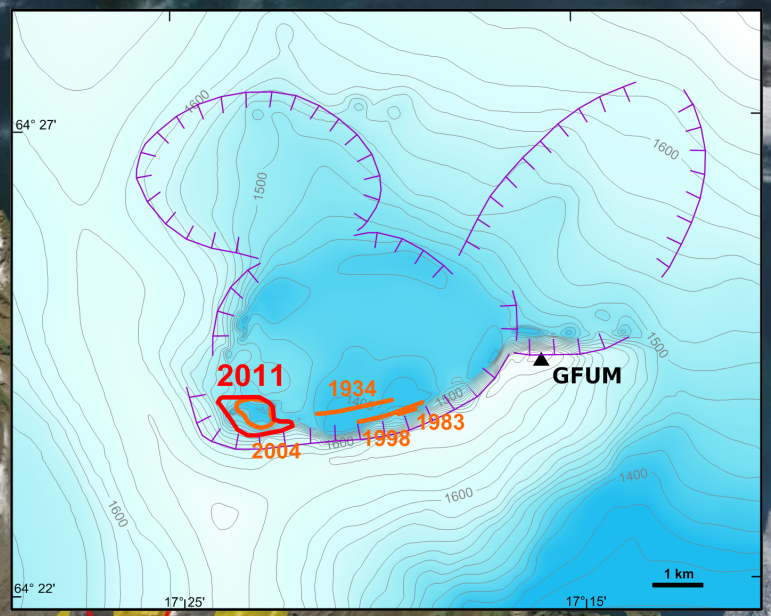

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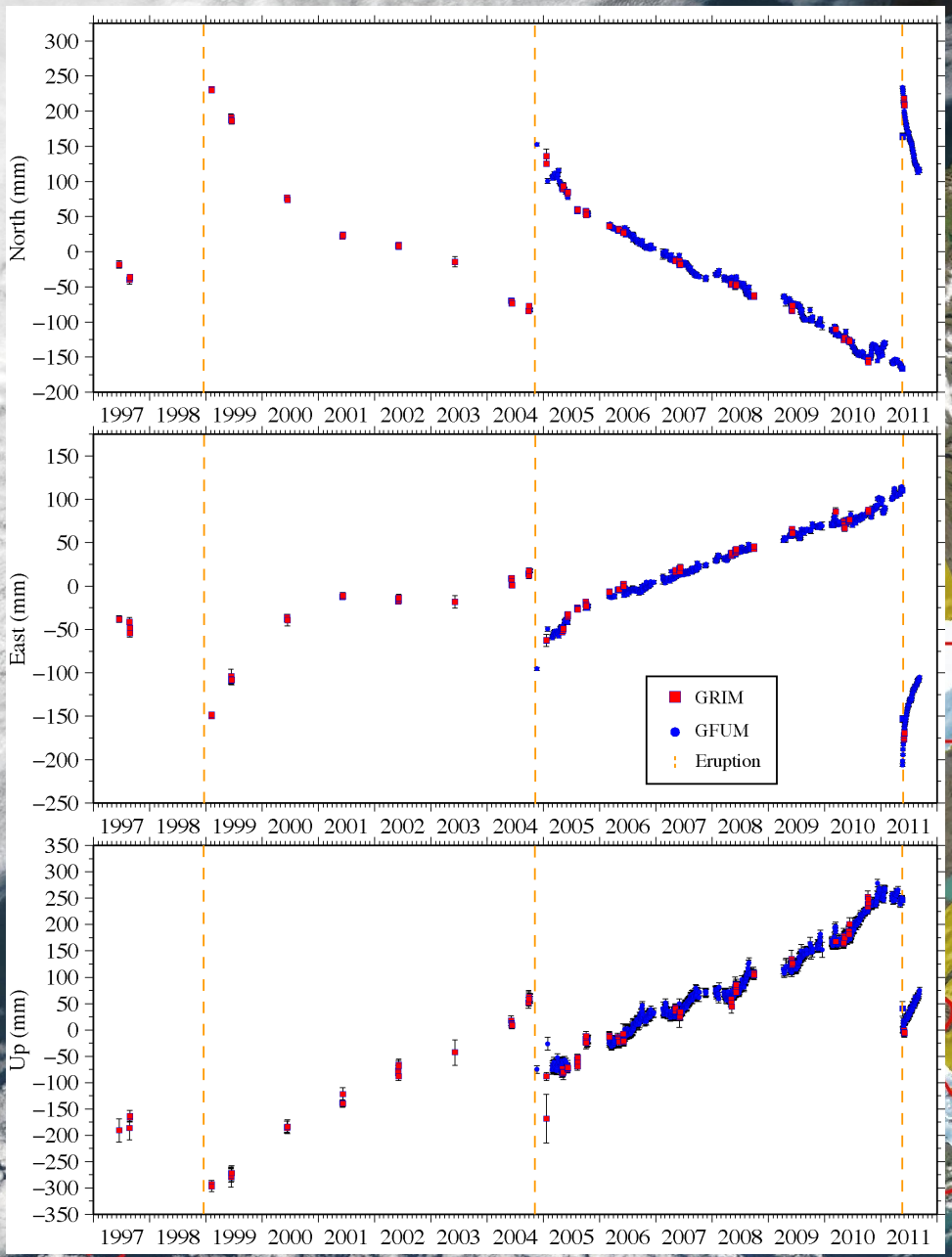
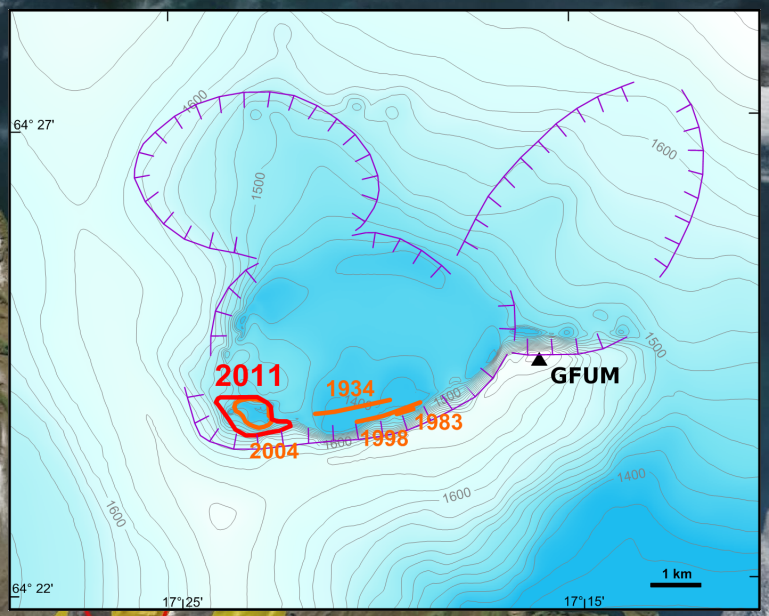
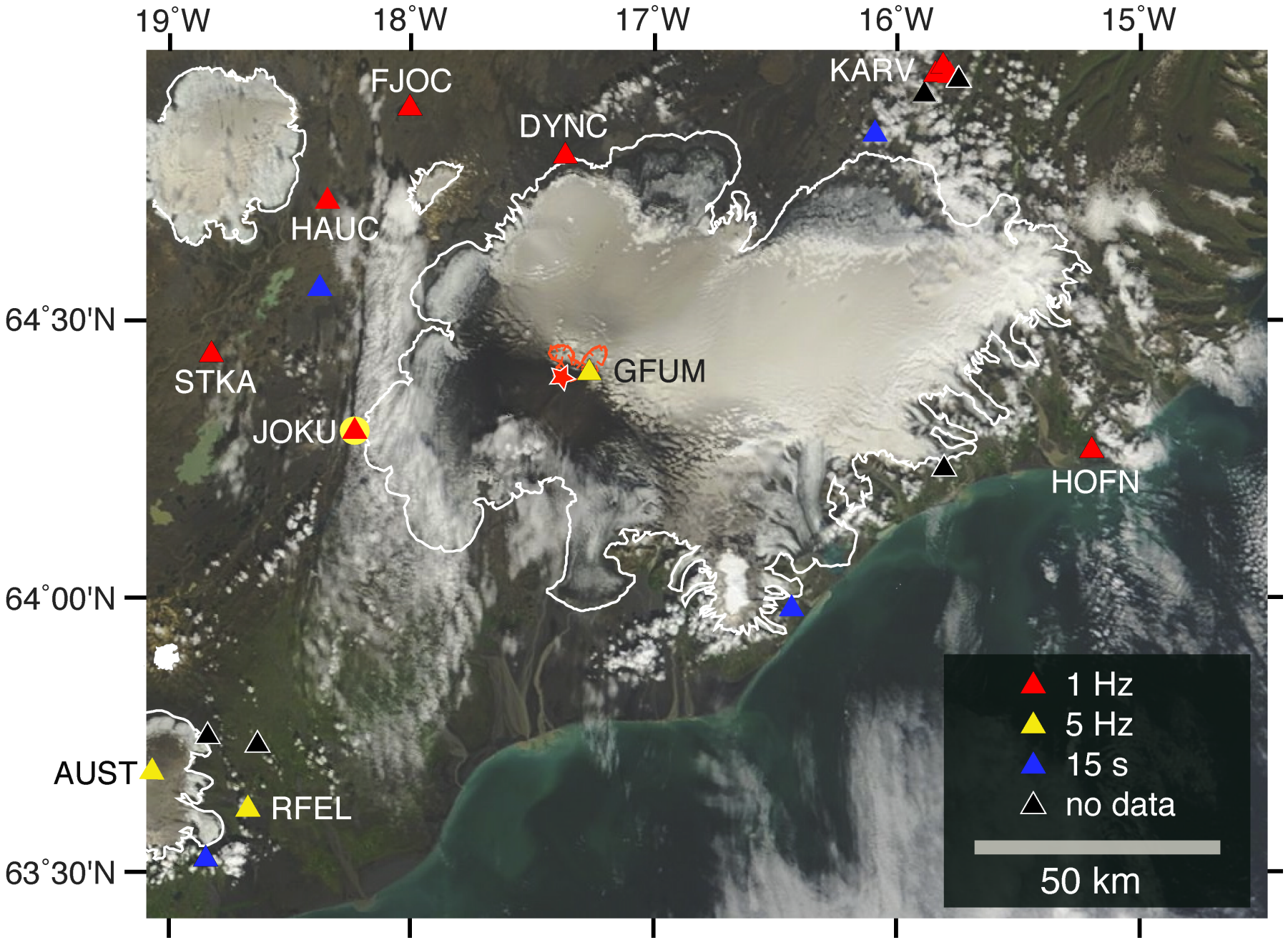




- explosive eruption 21-28 May 2011
- plumes $> 20\,km$
- continuous inflation, gradual increase in seismicity

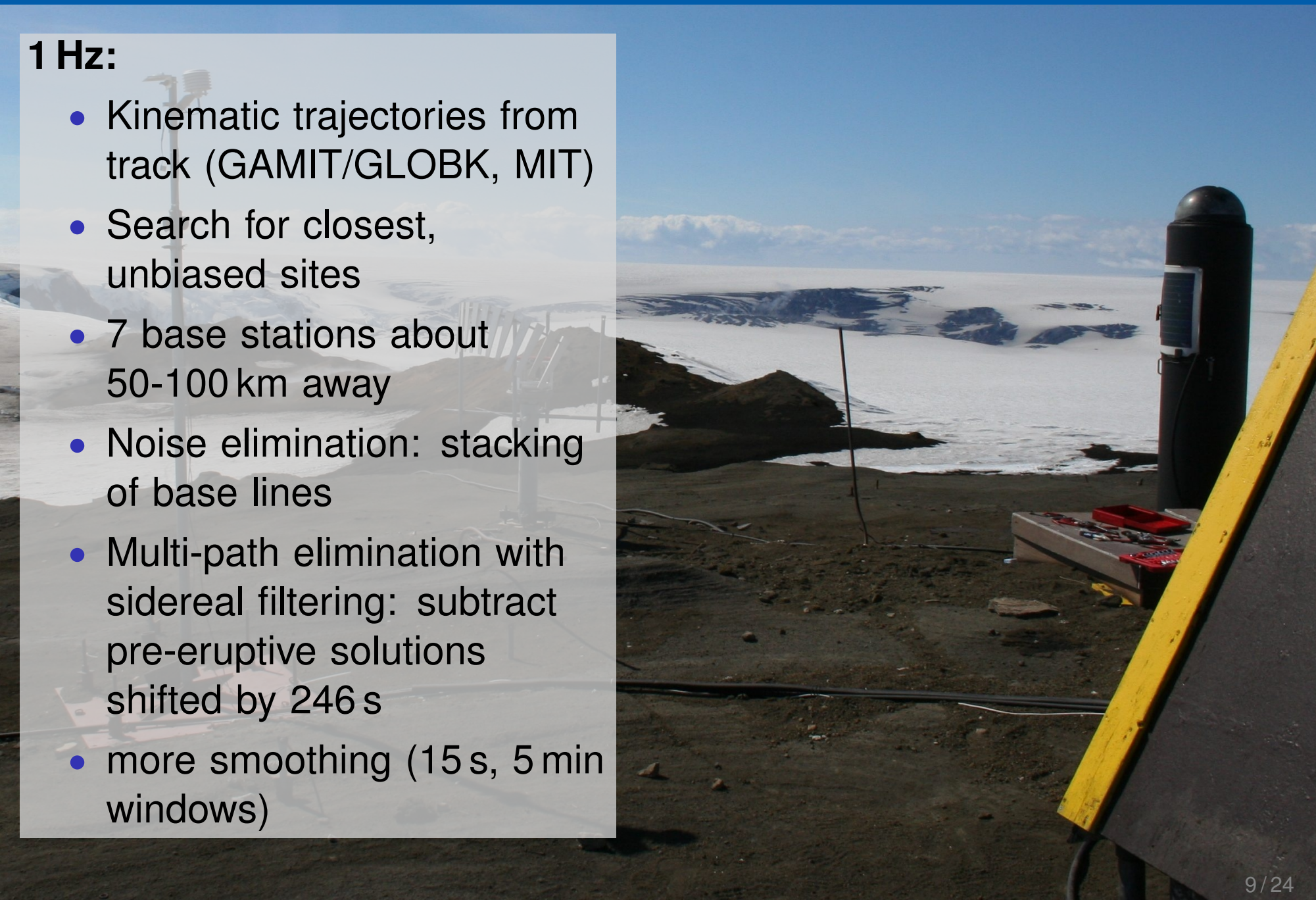
2011 Grímsvötn: Geodetic Network



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)



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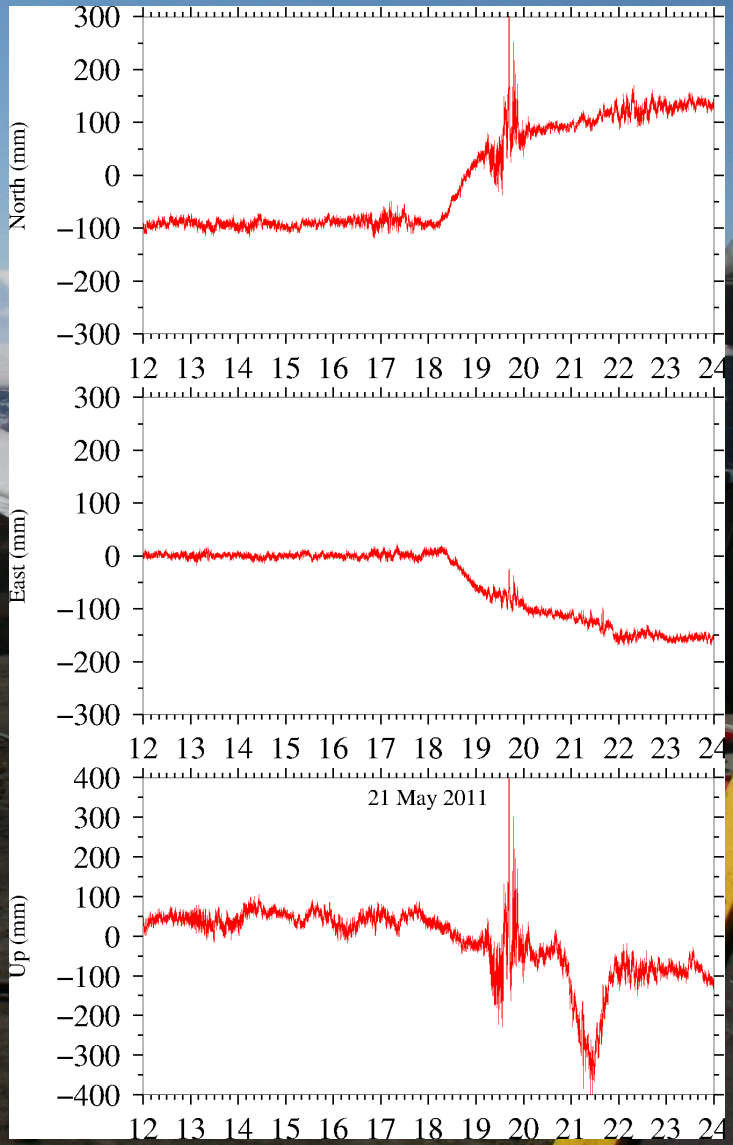

GFUM wrt JOKU

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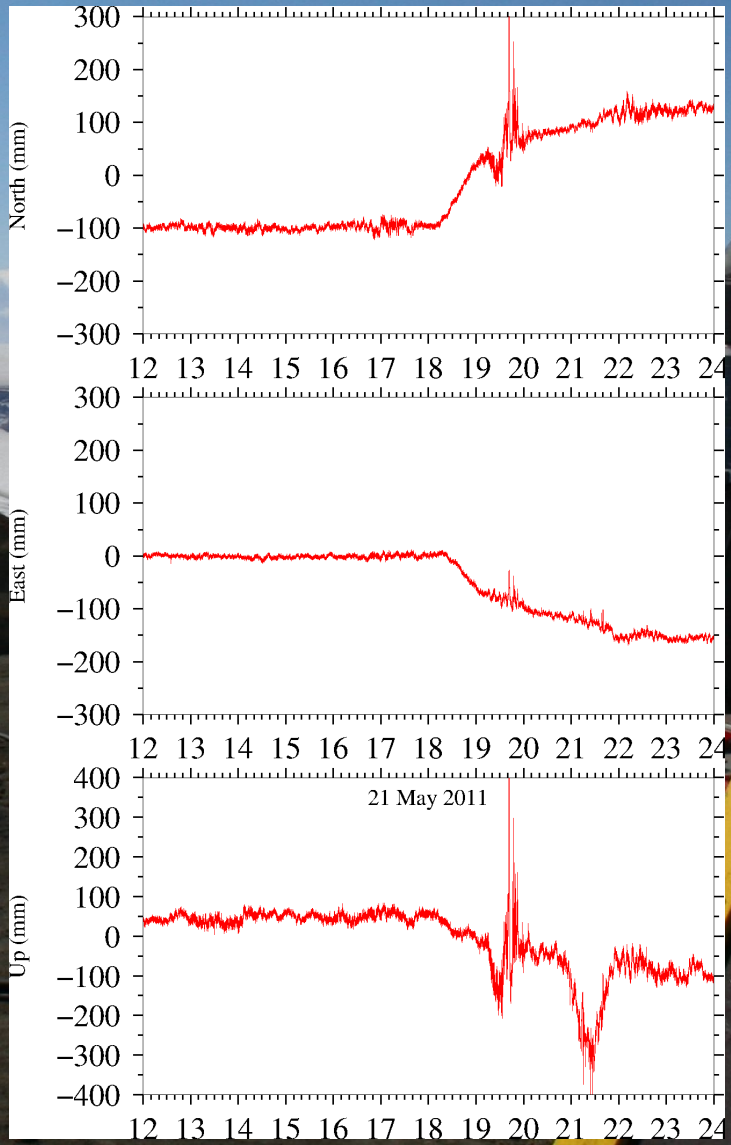

3 Station Stack

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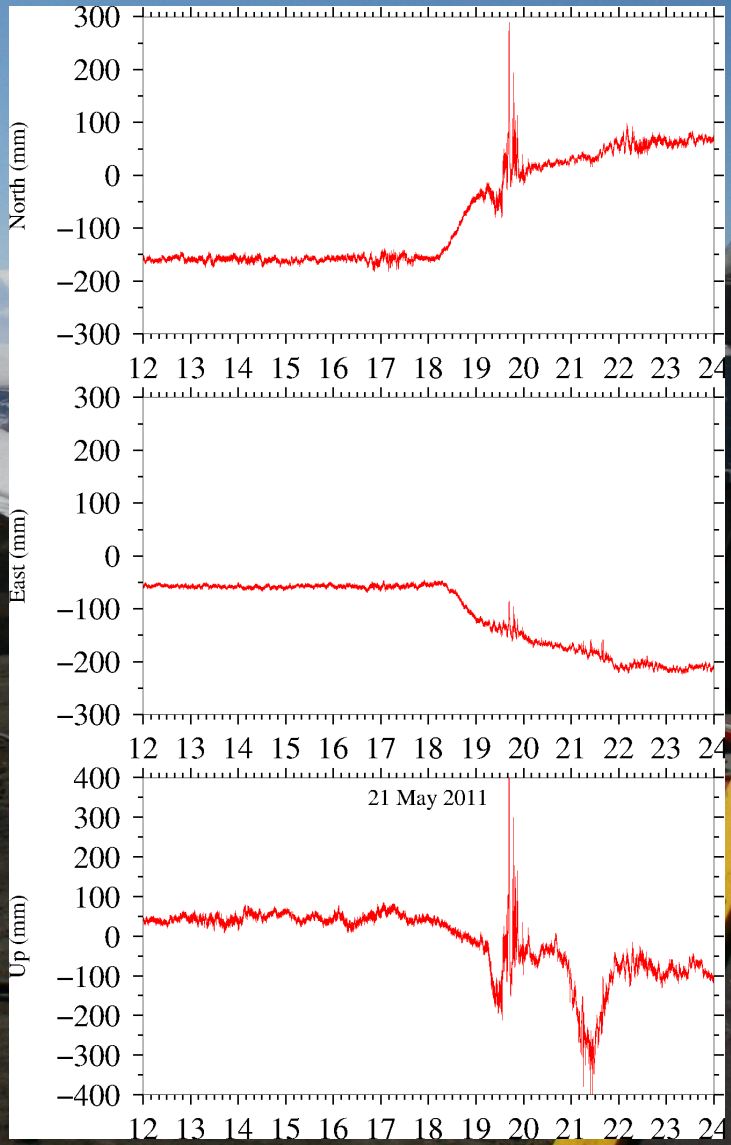

7 Station Stack

2011 Grímsvötn: GPS Processing

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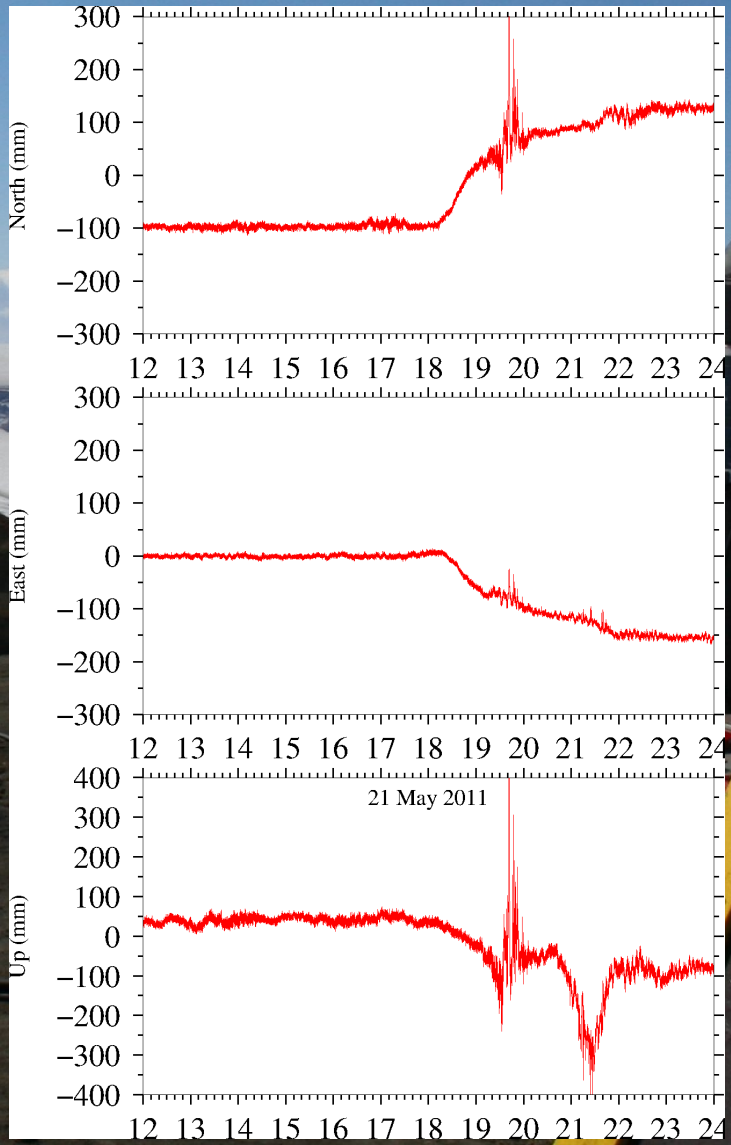

Sidereal Filtering

2011 Grímsvötn: GPS Processing

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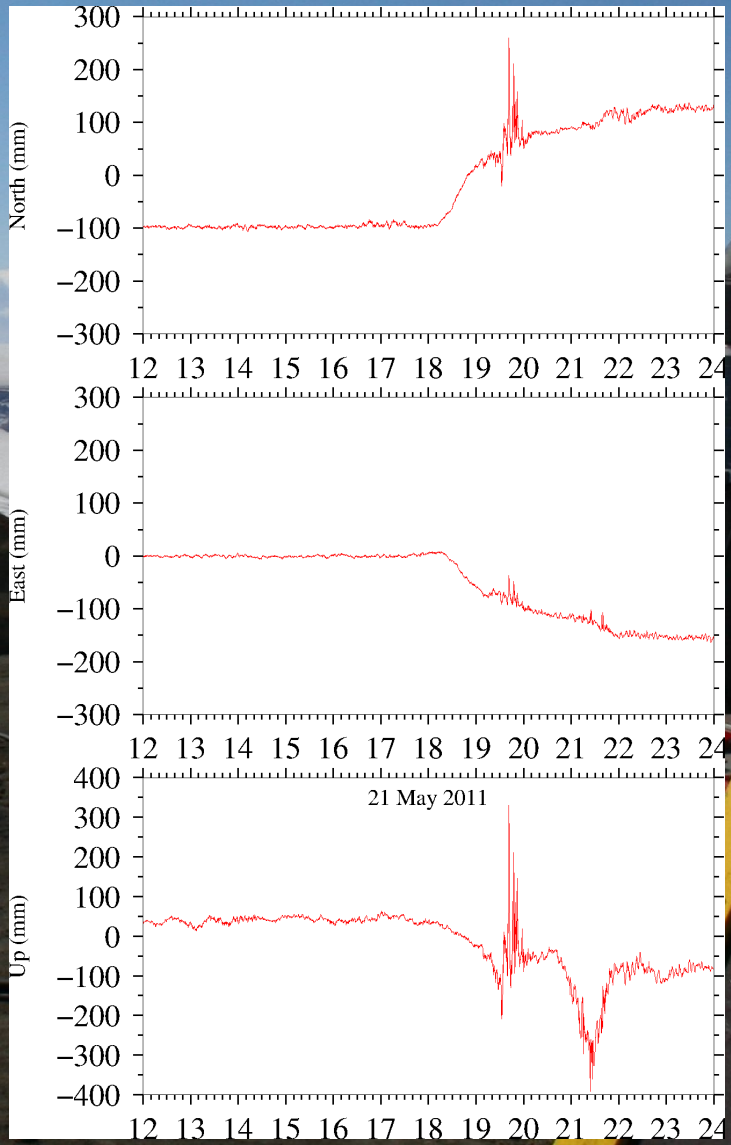
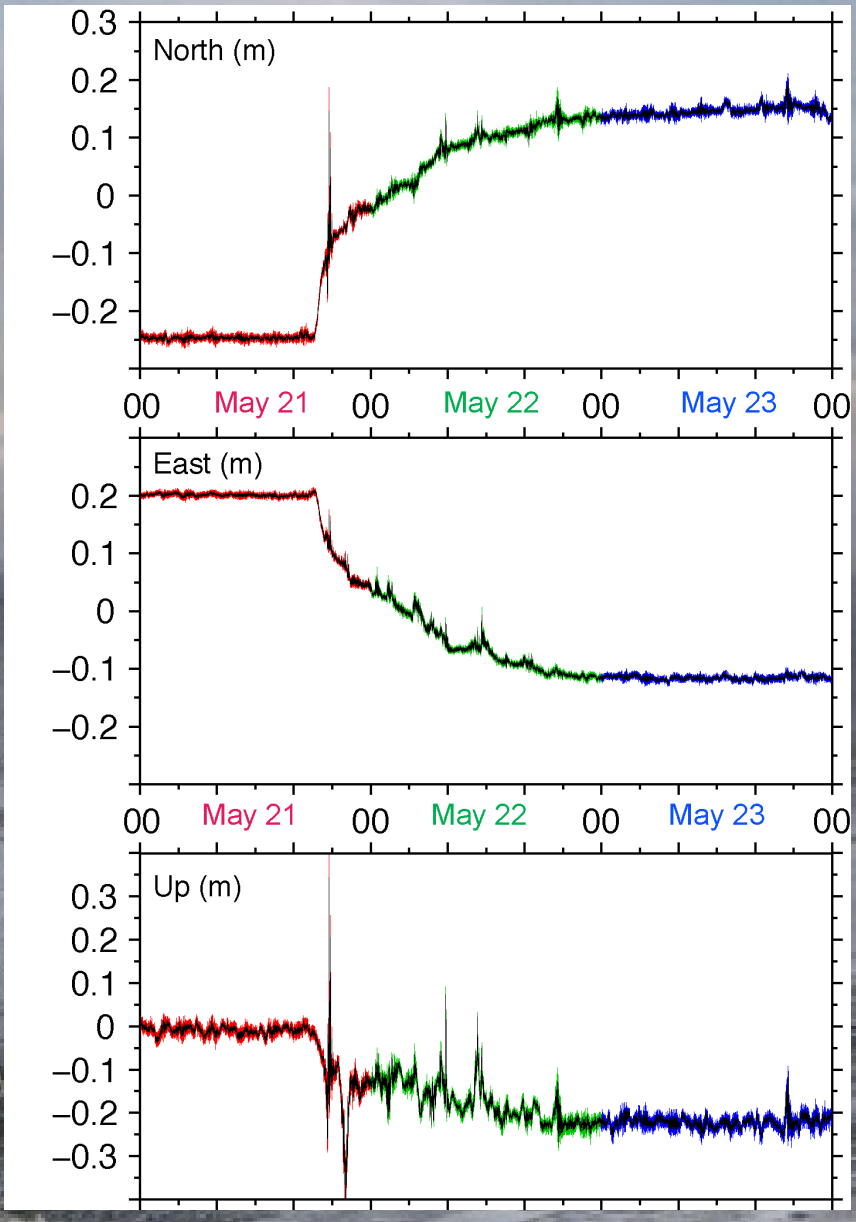


15 s Filter

2011 Grímsvötn: Results

2011 Grímsvötn: Results



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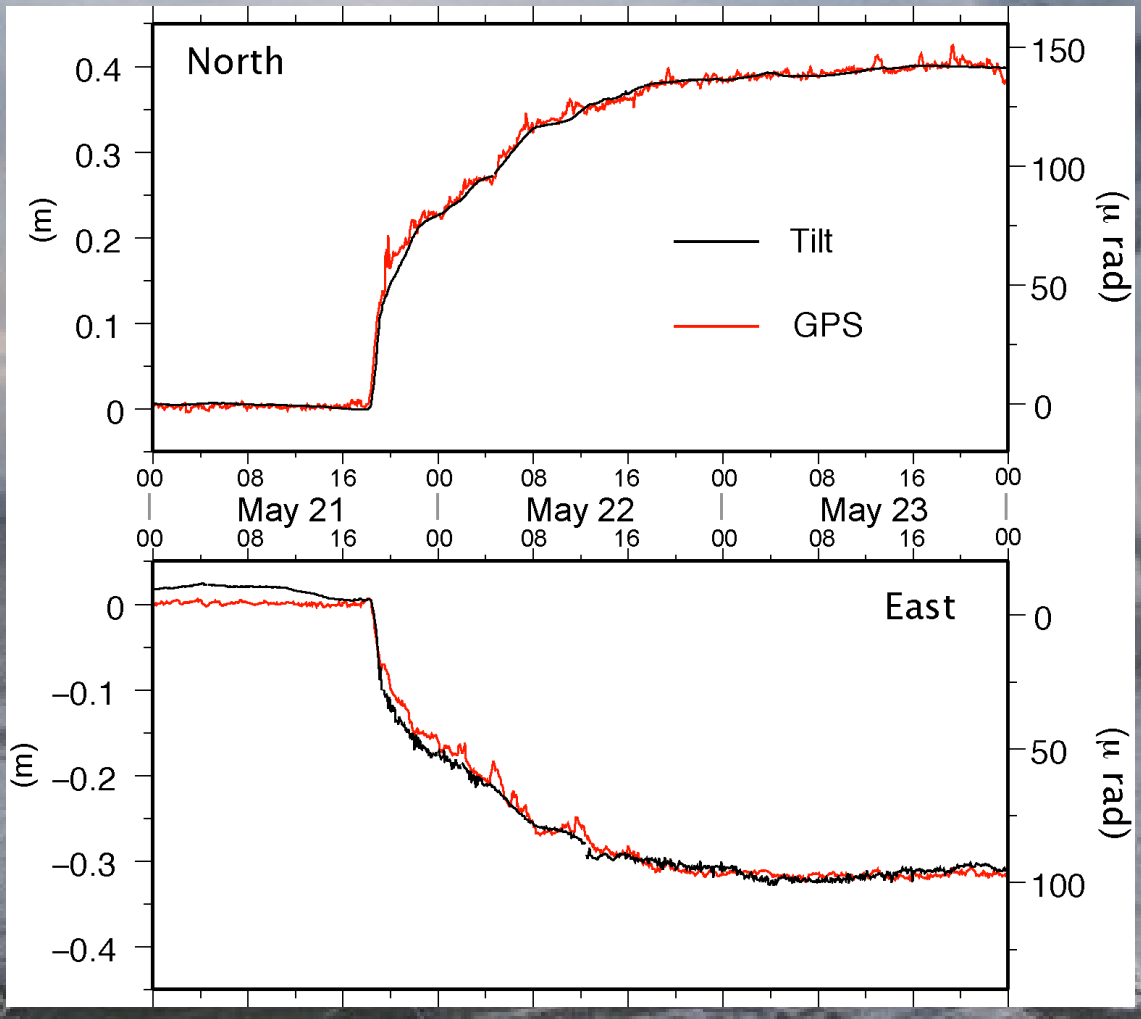

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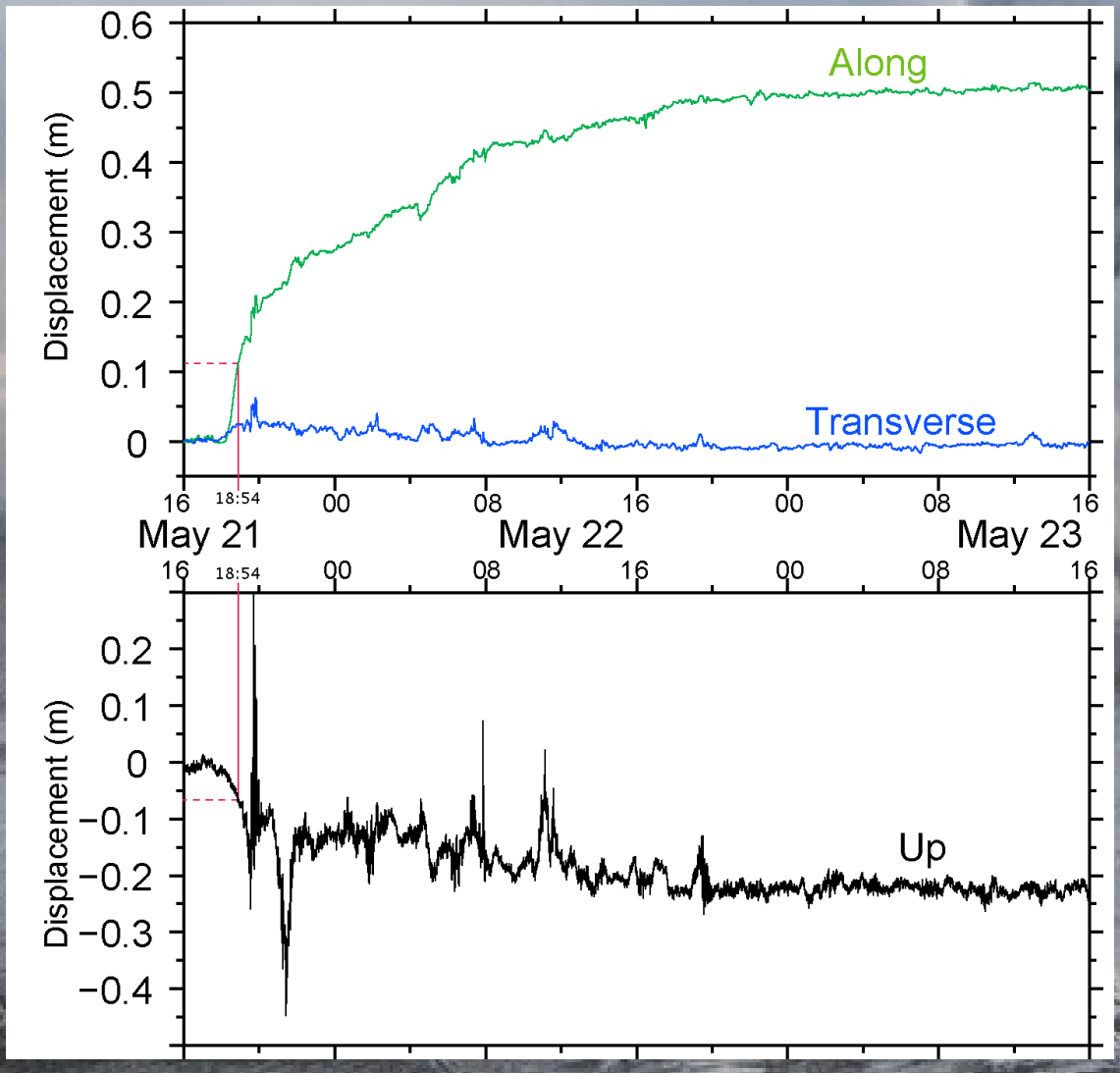

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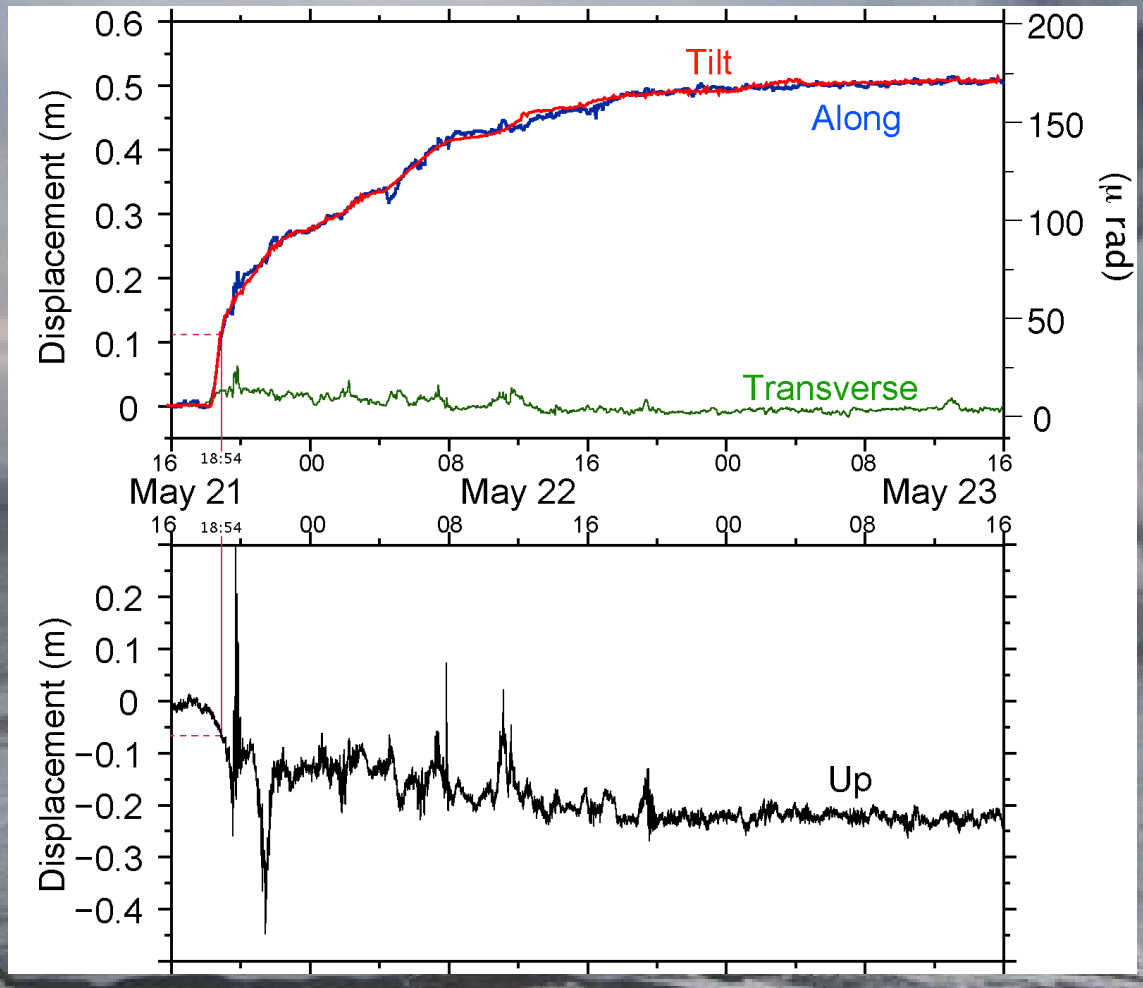

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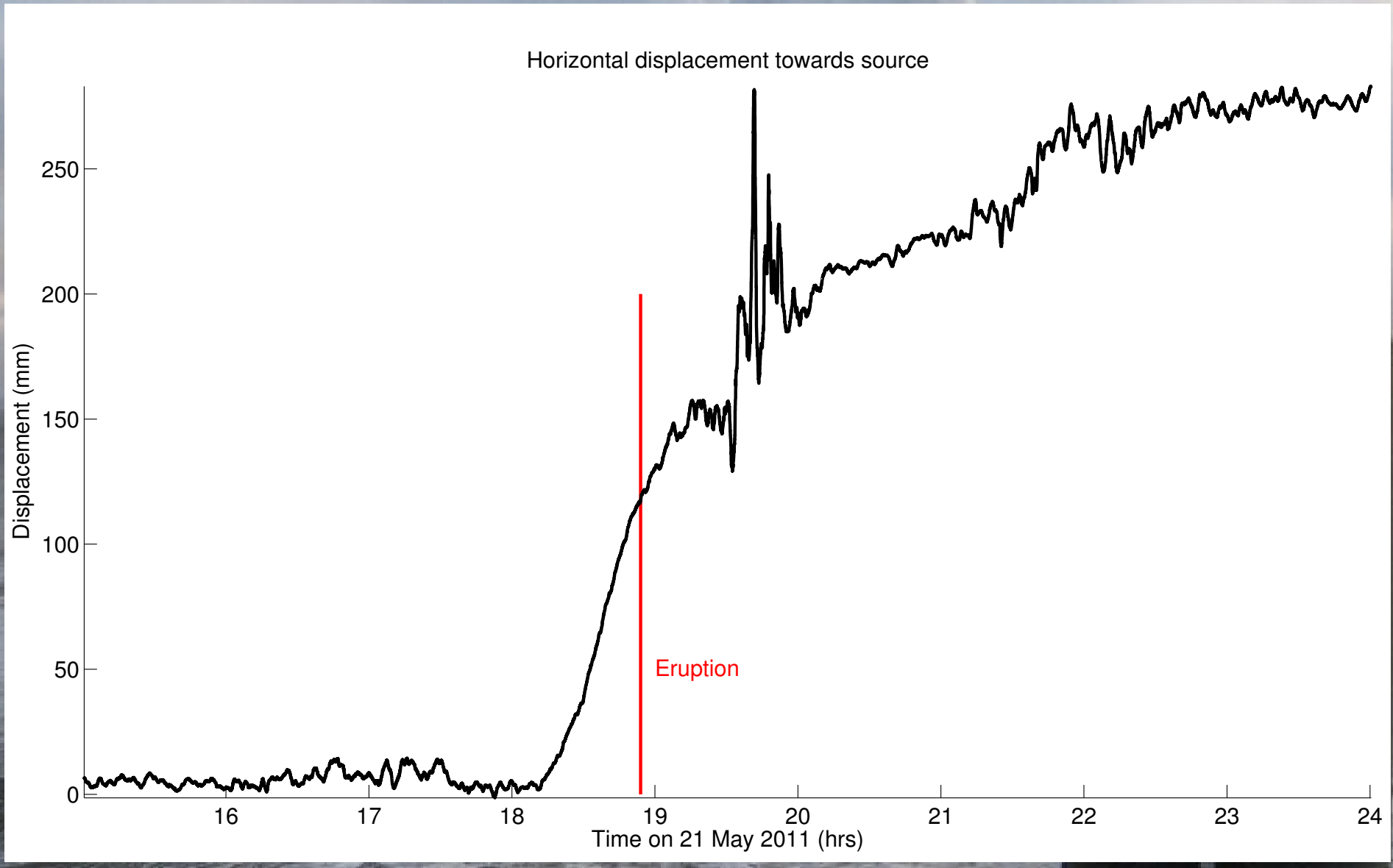

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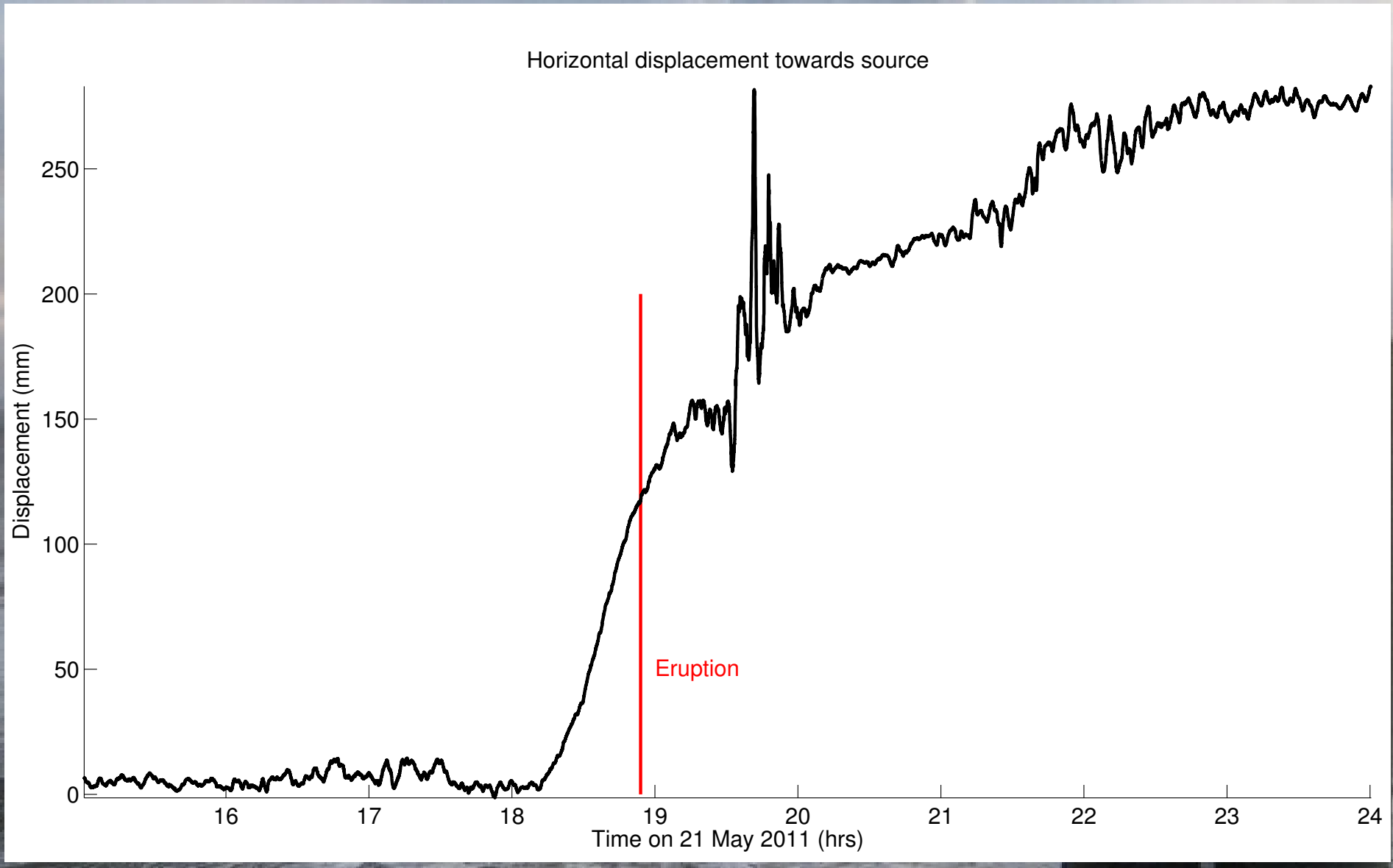

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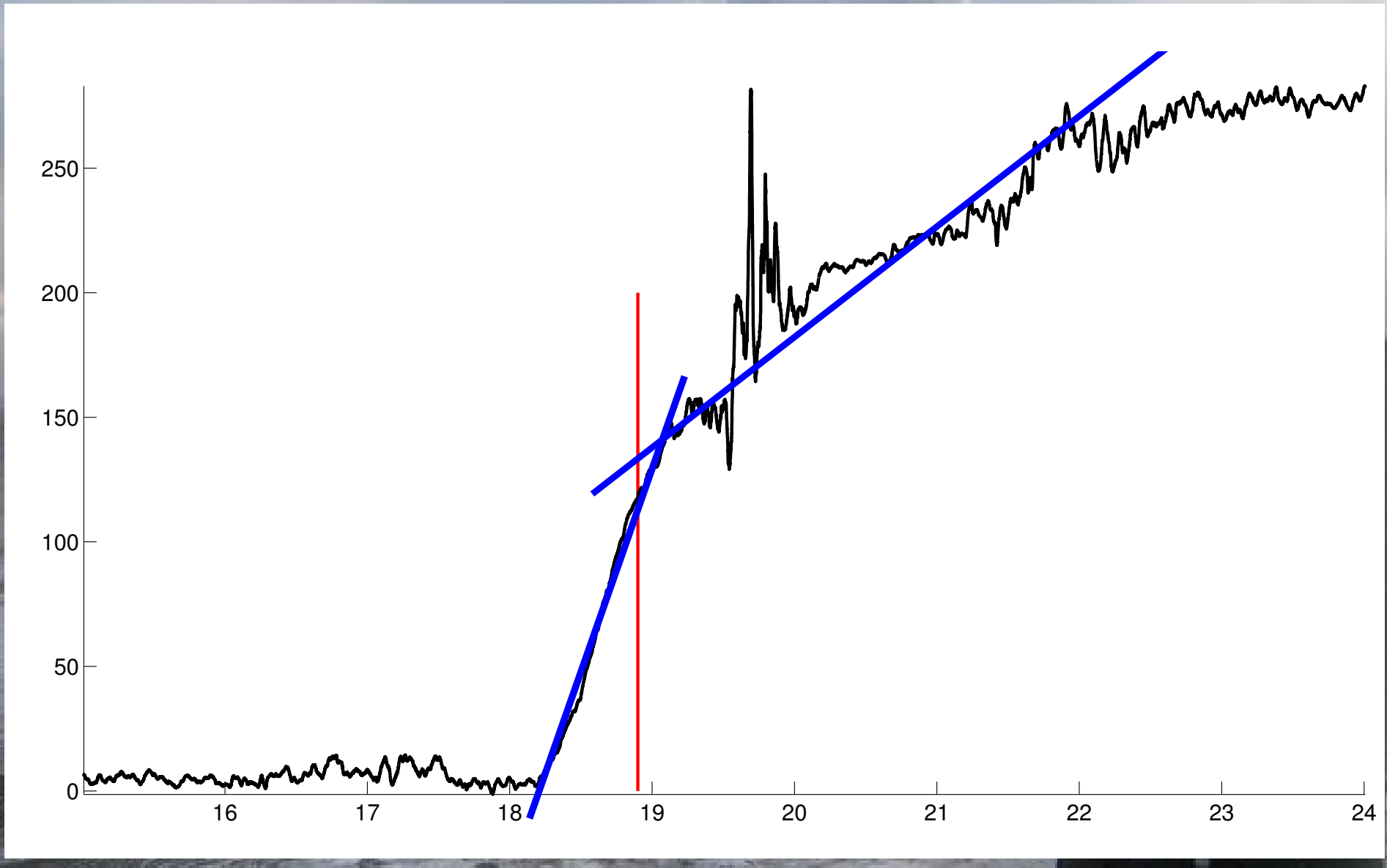

2011 Grímsvötn: Source Model

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

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

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

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

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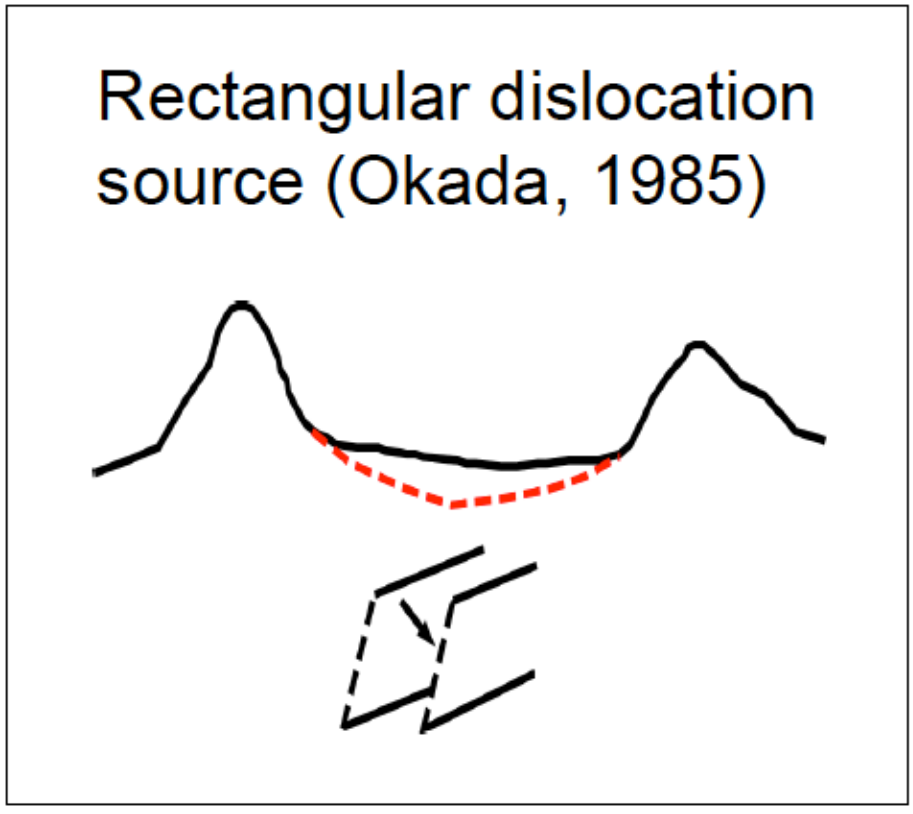
We derive (1σ uncertainties):

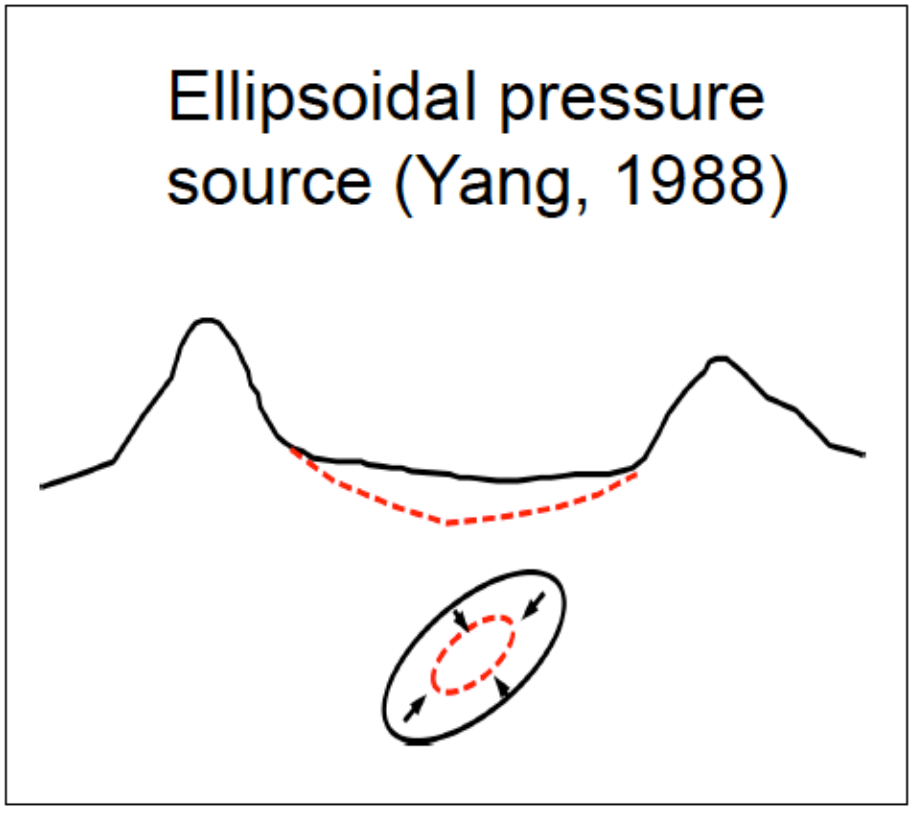
$$\textbf{distance} = r = \frac{u_r}{u_d}d = \textbf{3.6} \pm \textbf{0.3 km}$$

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

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

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





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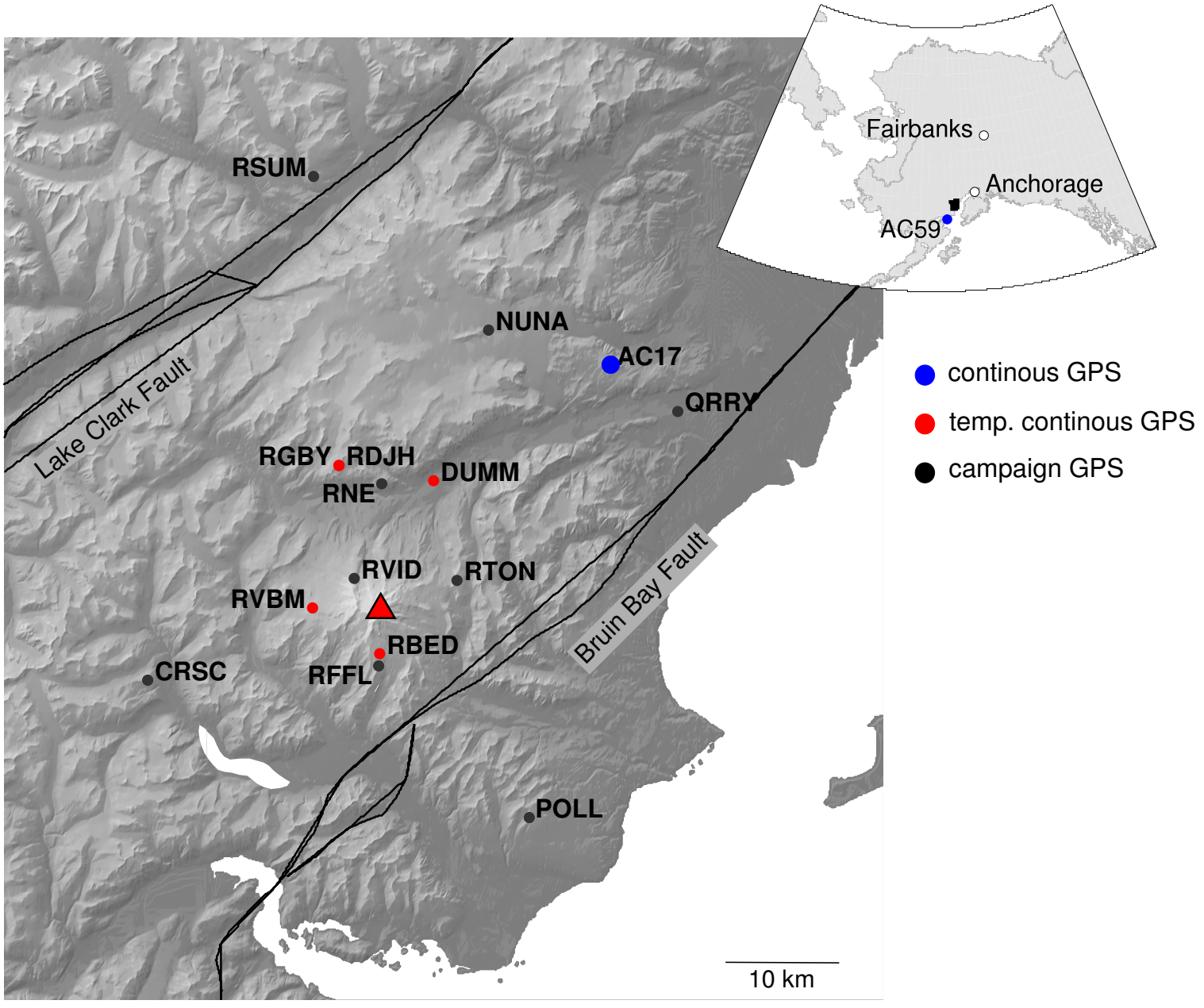
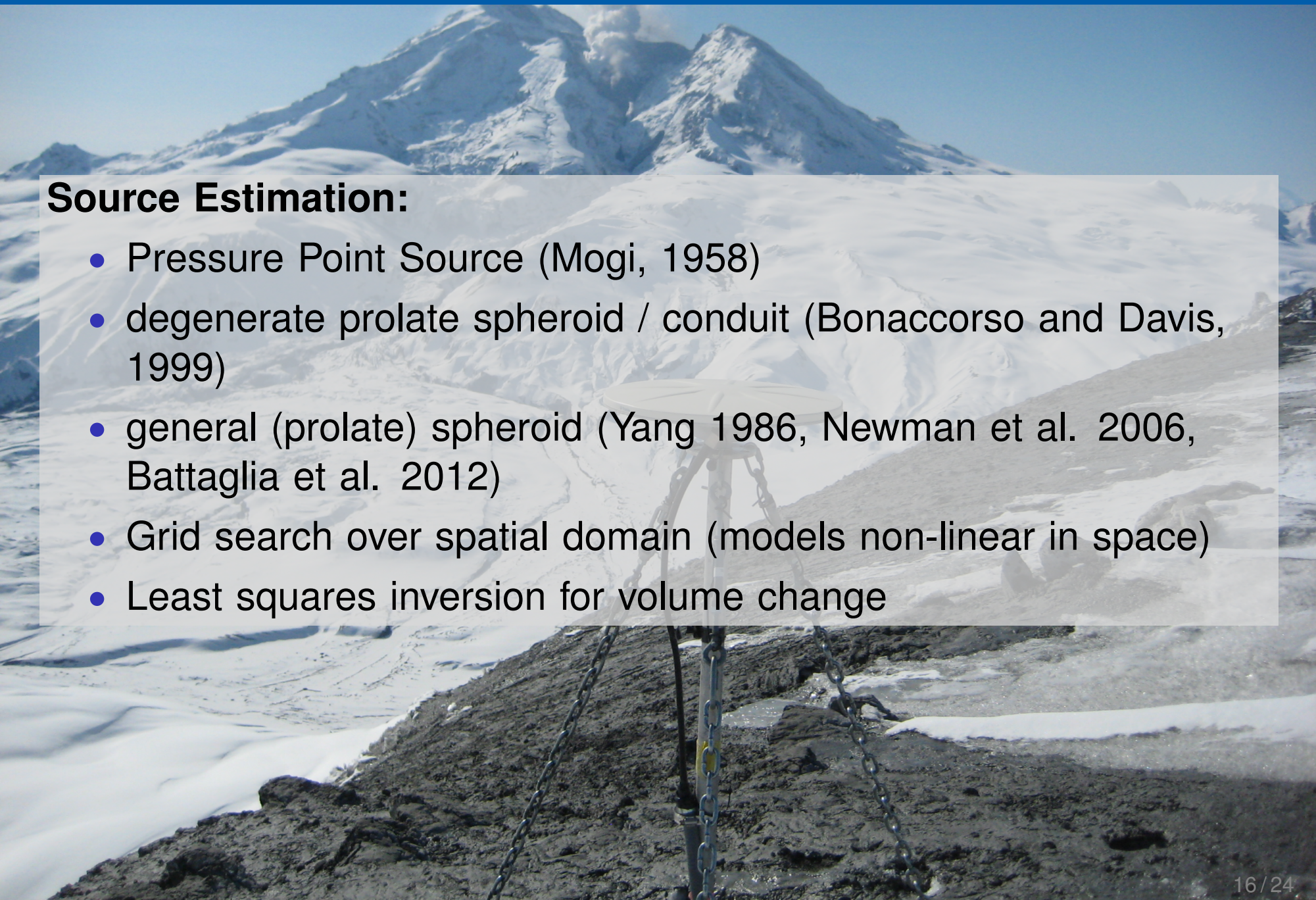
Model parameters: lat, lon, depth, length, width, dip, strike, source strength

Mt Redoubt, Alaska, 2009

1. Weeks to Months: Mt. Redoubt Source Models



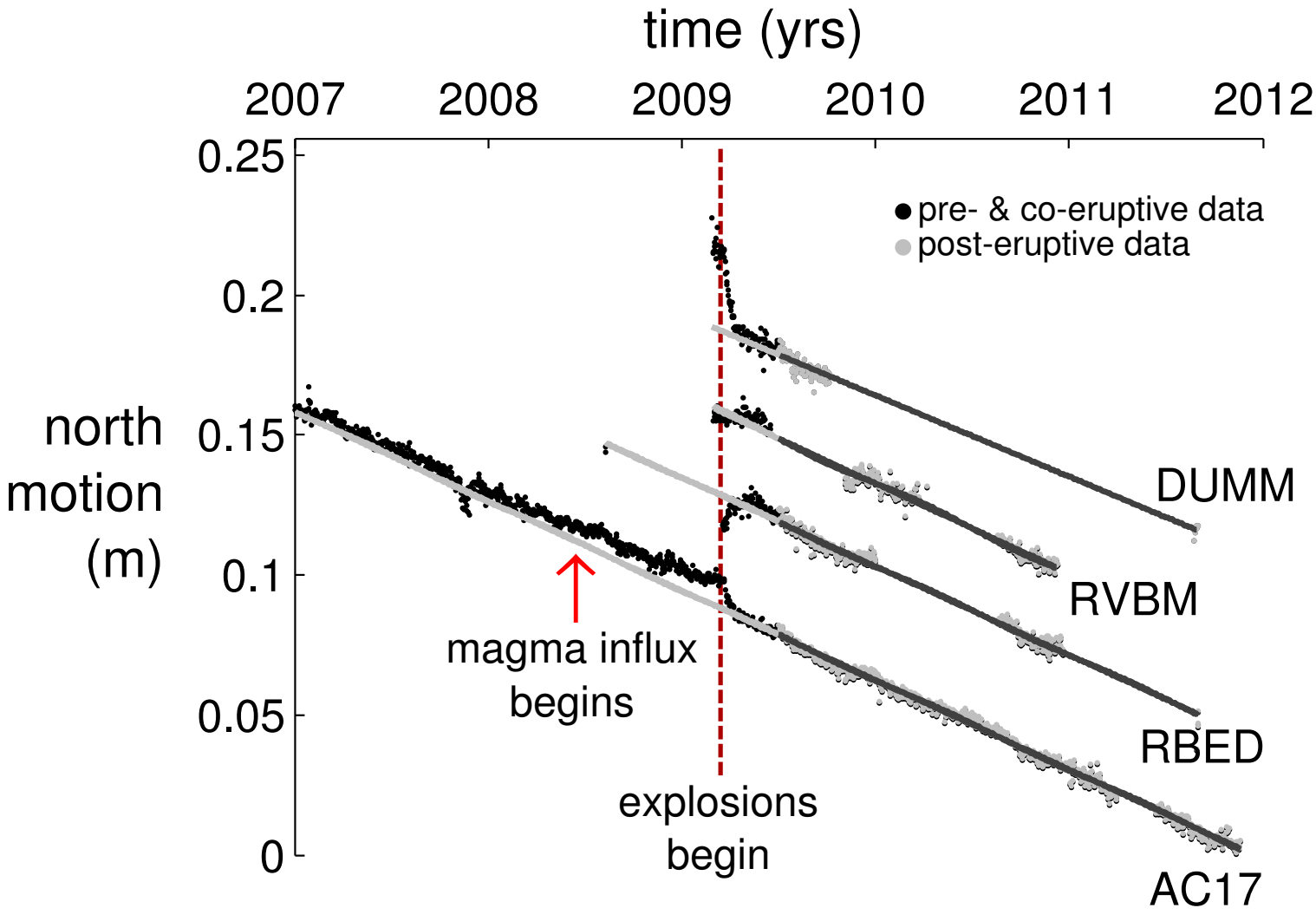
Redoubt 2009



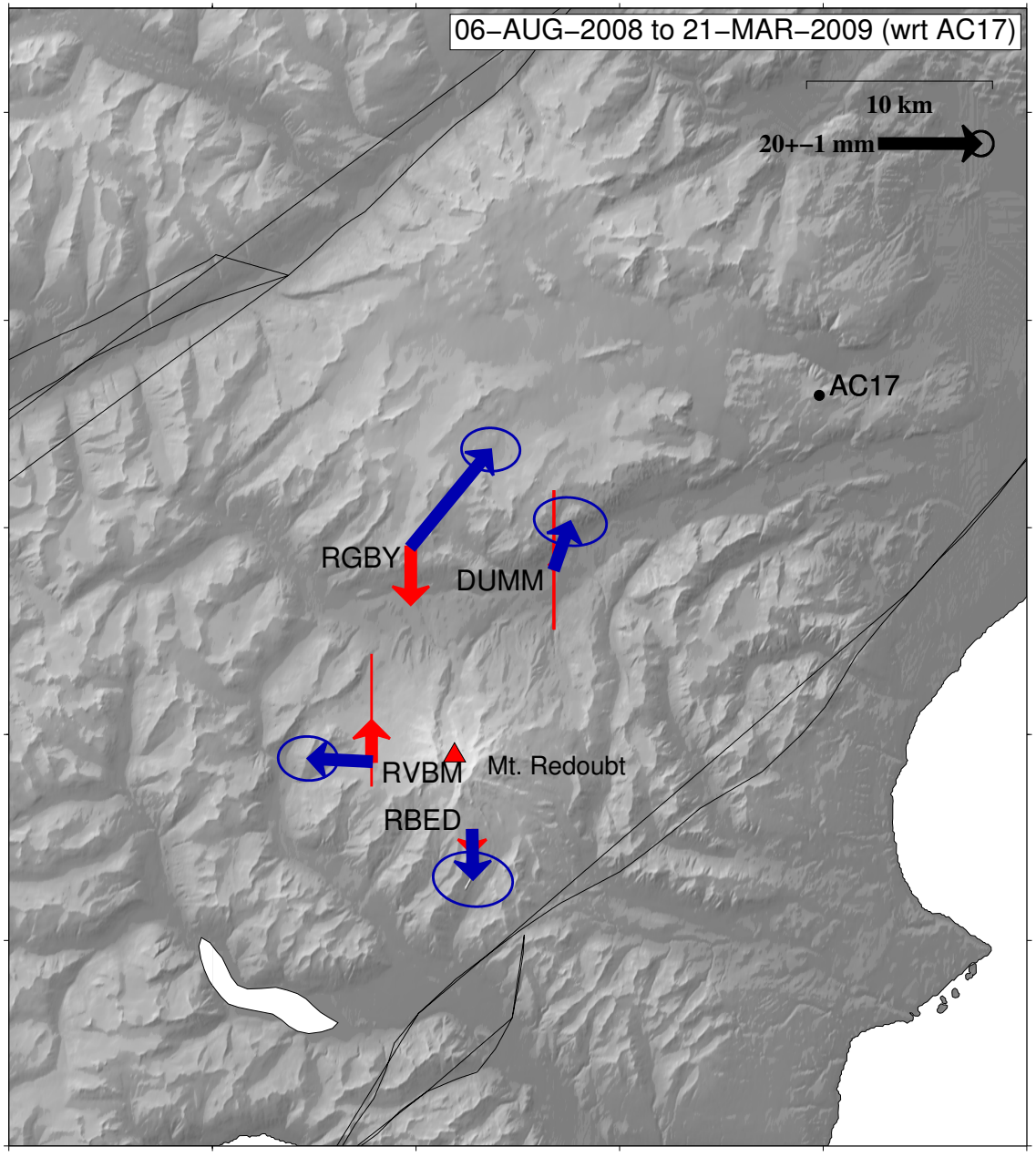
Source Estimation:

- 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



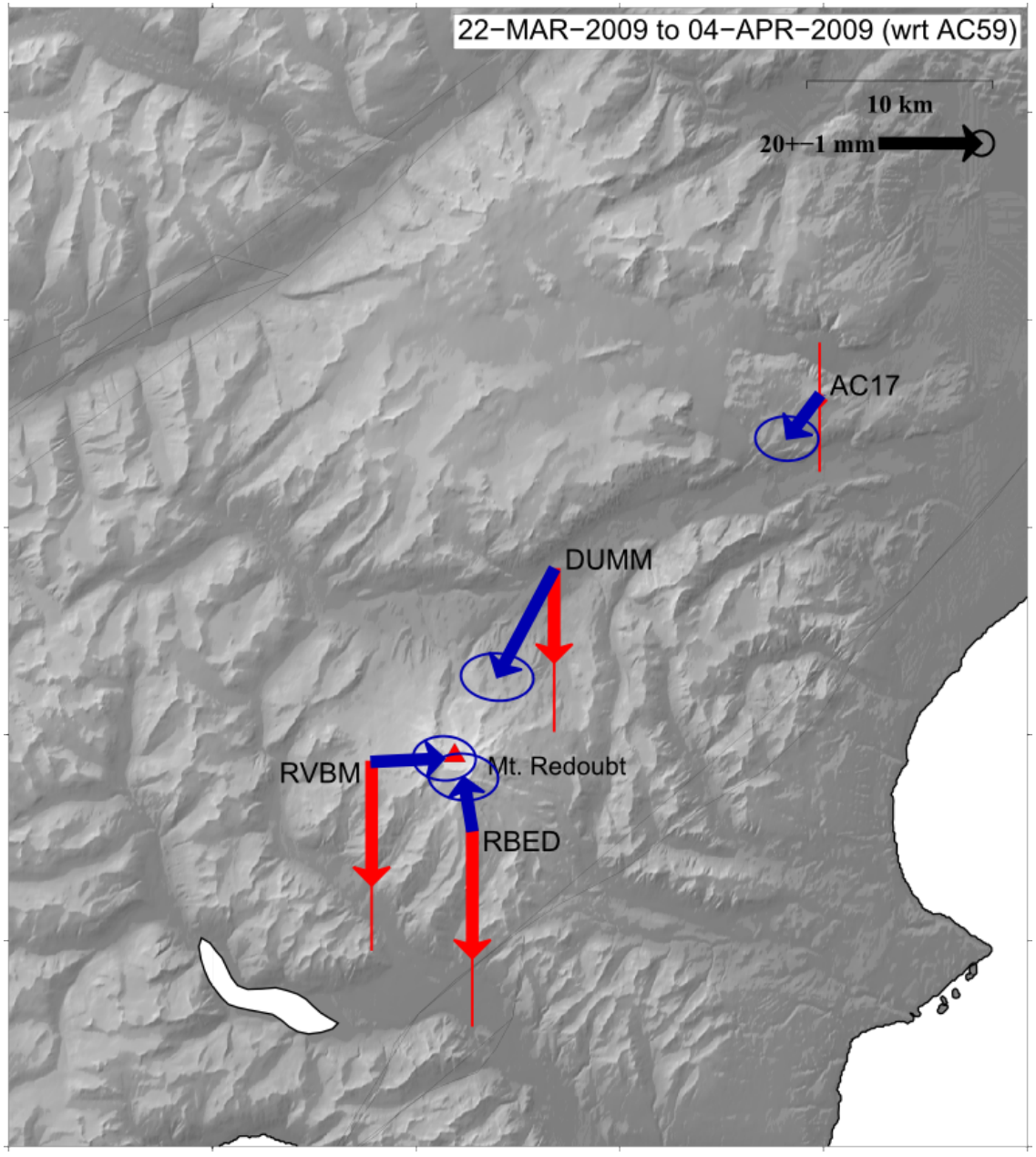
Pre-eruptive Phase – Inflation



Data
horizontal
vertical

Model
horizontal
vertical

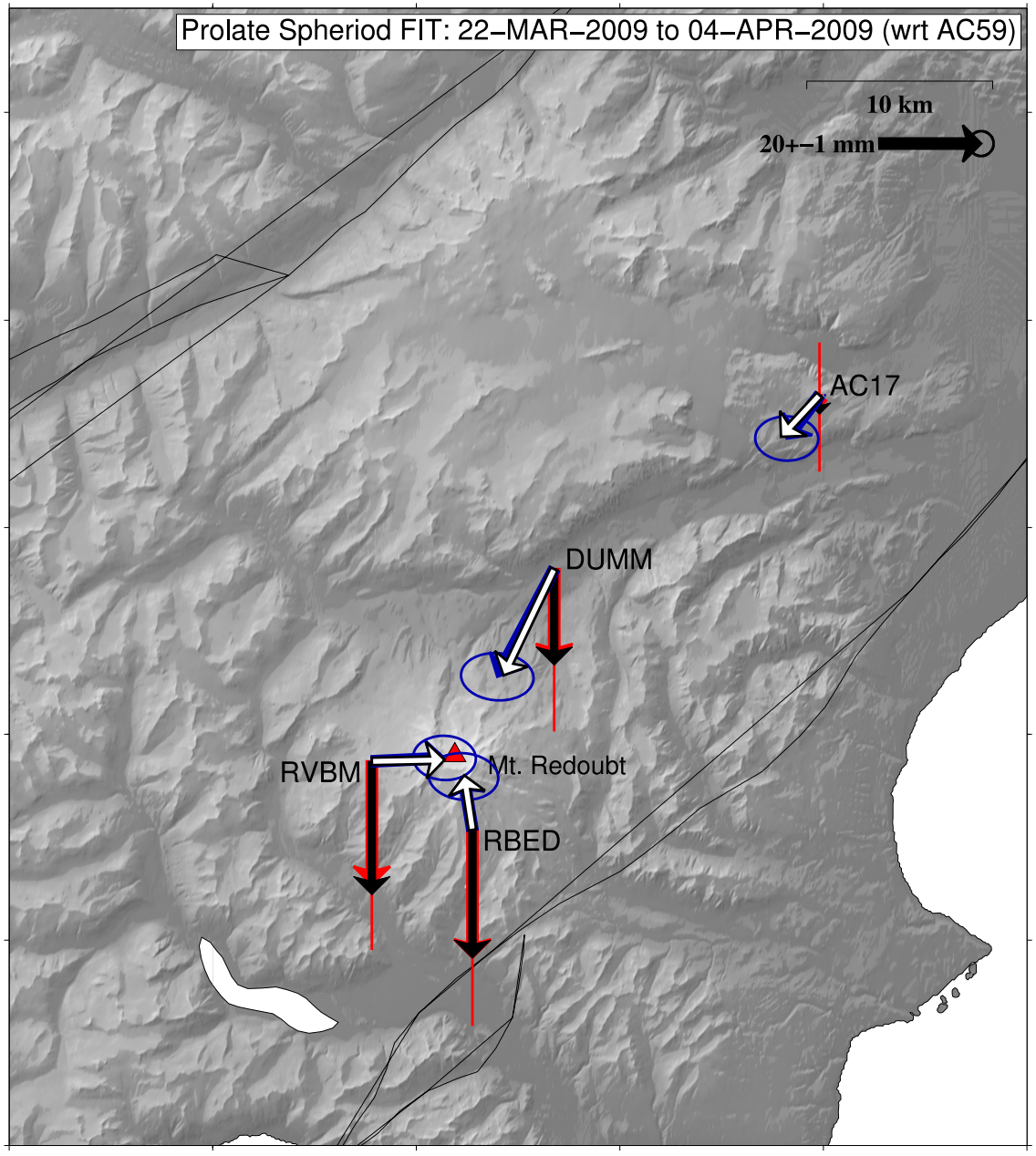
Explosive Phase – Deflation



Data
horizontal
vertical

Model
horizontal
vertical

Explosive Phase – Deflation



General Spheroid:

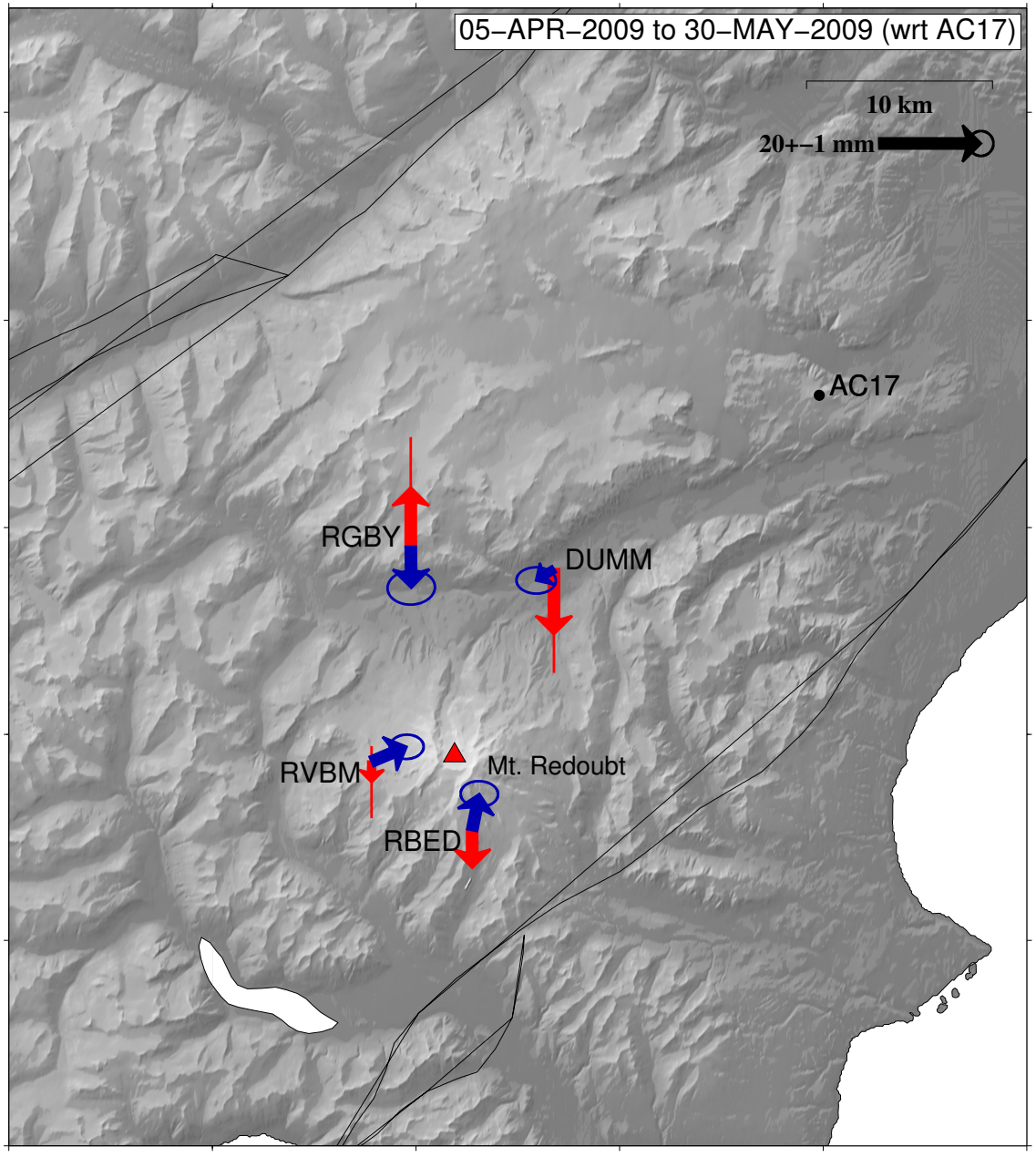
$$
\begin{aligned}
r &= 0.5\,km\,\text{E of dome} \\
d &= \mathbf{9.17}\ {}^{6.92}_{15.17}\,km \\
a &= \mathbf{4.50}\ {}^{1.25}_{>10.00}\,km \\
b &= \mathbf{0.475}\ {}^{0.3}_{>4.00}\,km \\
\Delta V &= -(\mathbf{0.05}\ {}^{0.028}_{>0.1})\,km^3
\end{aligned}
$$

F-Test: Spheroid preferred.

Data
horizontal
vertical

Model
horizontal
vertical

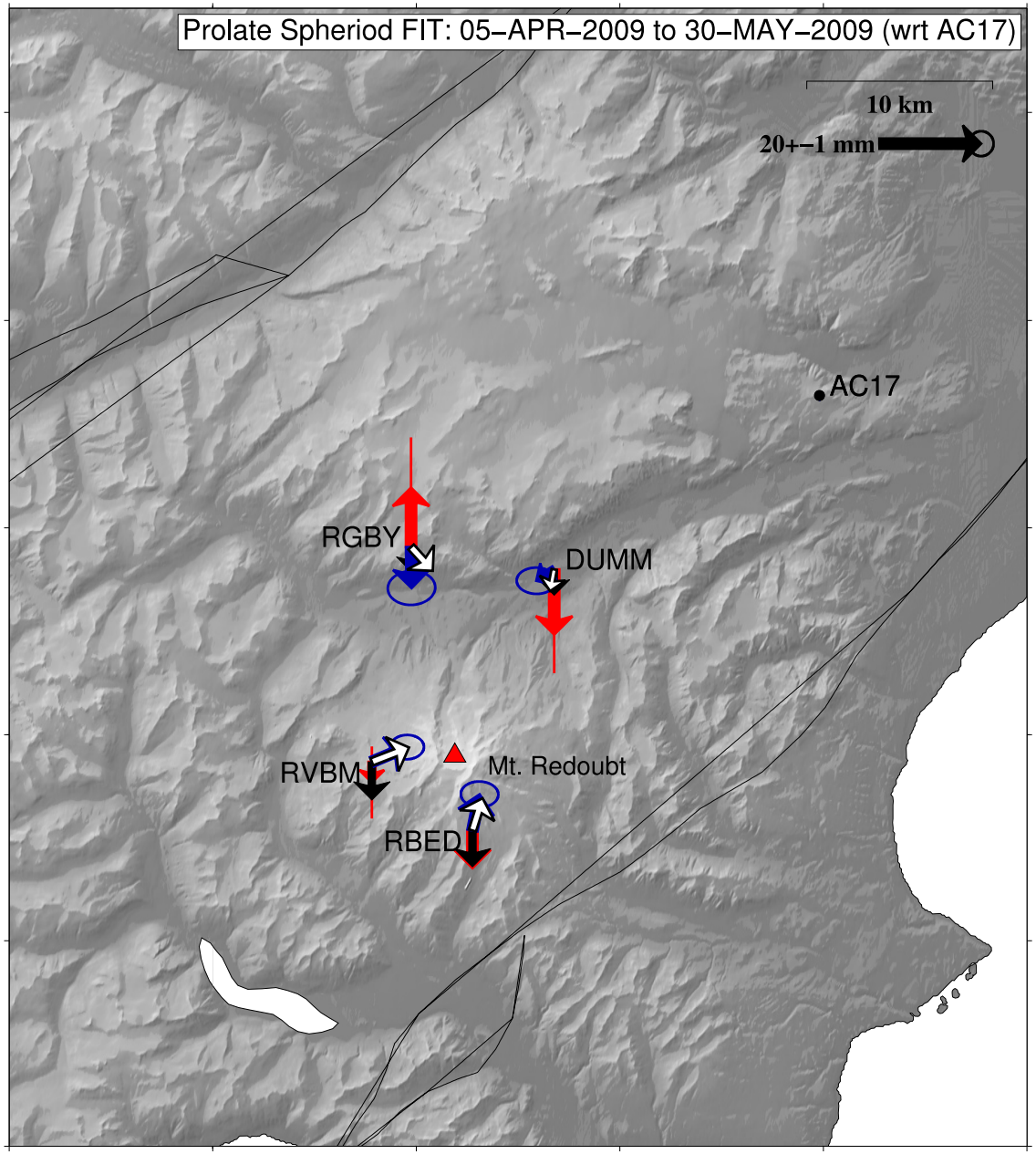
Effusive Phase – Deflation



Data
horizontal
vertical

Model
horizontal
vertical

Effusive Phase – Deflation



General Spheroid:

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

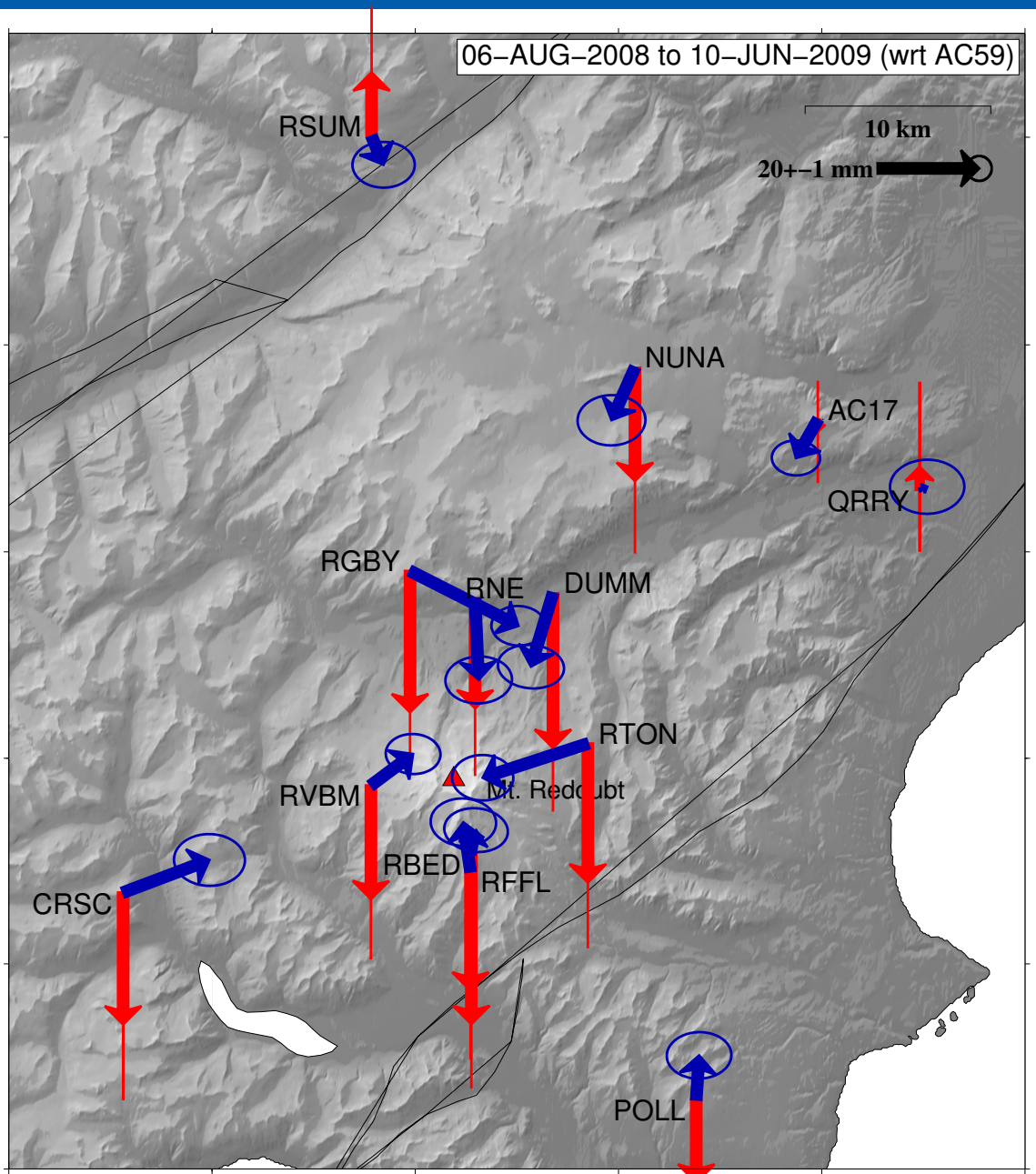
Mogi fits better

F-Test rejects Mogi

Data
horizontal
vertical

Model
horizontal
vertical

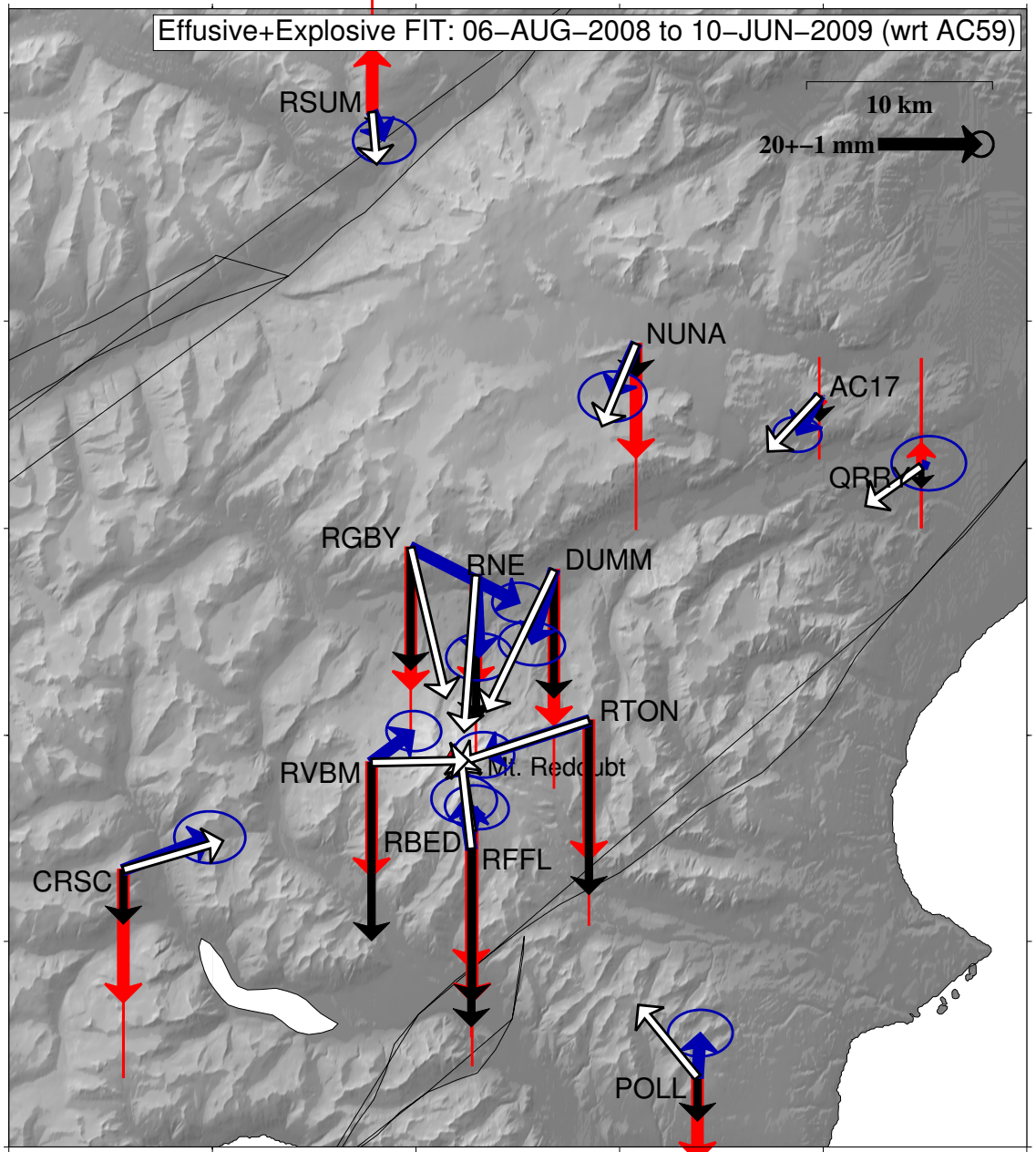
Full Eruption – Net Deflation



Data
horizontal
vertical

Model
horizontal
vertical

Full Eruption – Net Deflation



Explosive: Prolate Spheroid

$$
\begin{aligned}
r &= \mathbf{0.5}\ km\ \text{E of dome} \\
d &= \mathbf{9.17}\ {}^{6.92}_{15.17}\ km \\
a &= \mathbf{4.50}\ {}^{1.25}_{>10.00}\ km \\
b &= \mathbf{0.475}\ {}^{0.3}_{>4.00}\ km \\
\Delta V &= -(\mathbf{0.05}\ {}^{0.028}_{>0.1})\ km^3
\end{aligned}
$$

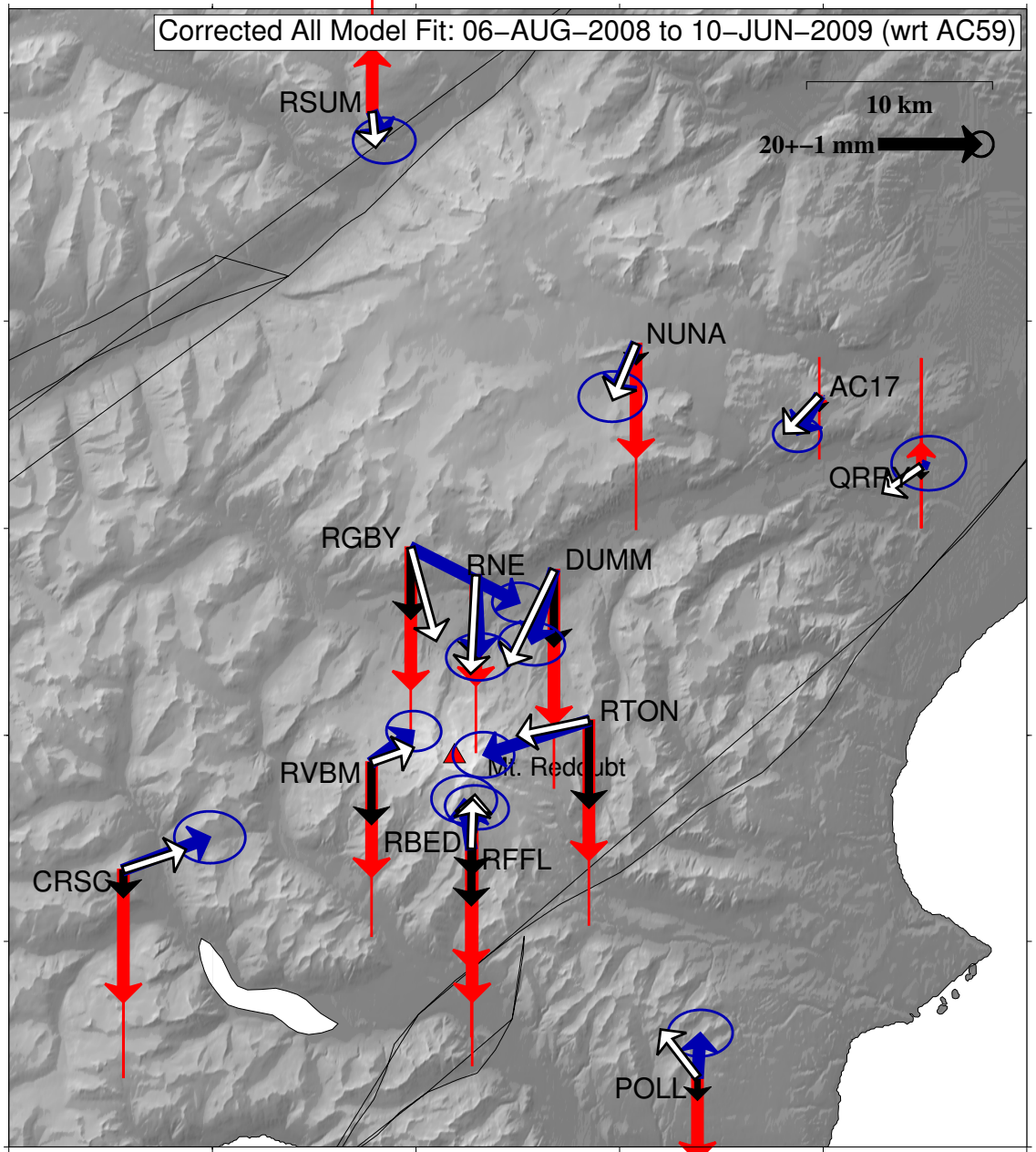
Effusive: same.

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

Data
horizontal →
vertical →

Model
horizontal ⇒
vertical →

Final Model



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Effusive: same.

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

Pre-eruptive: Mogi

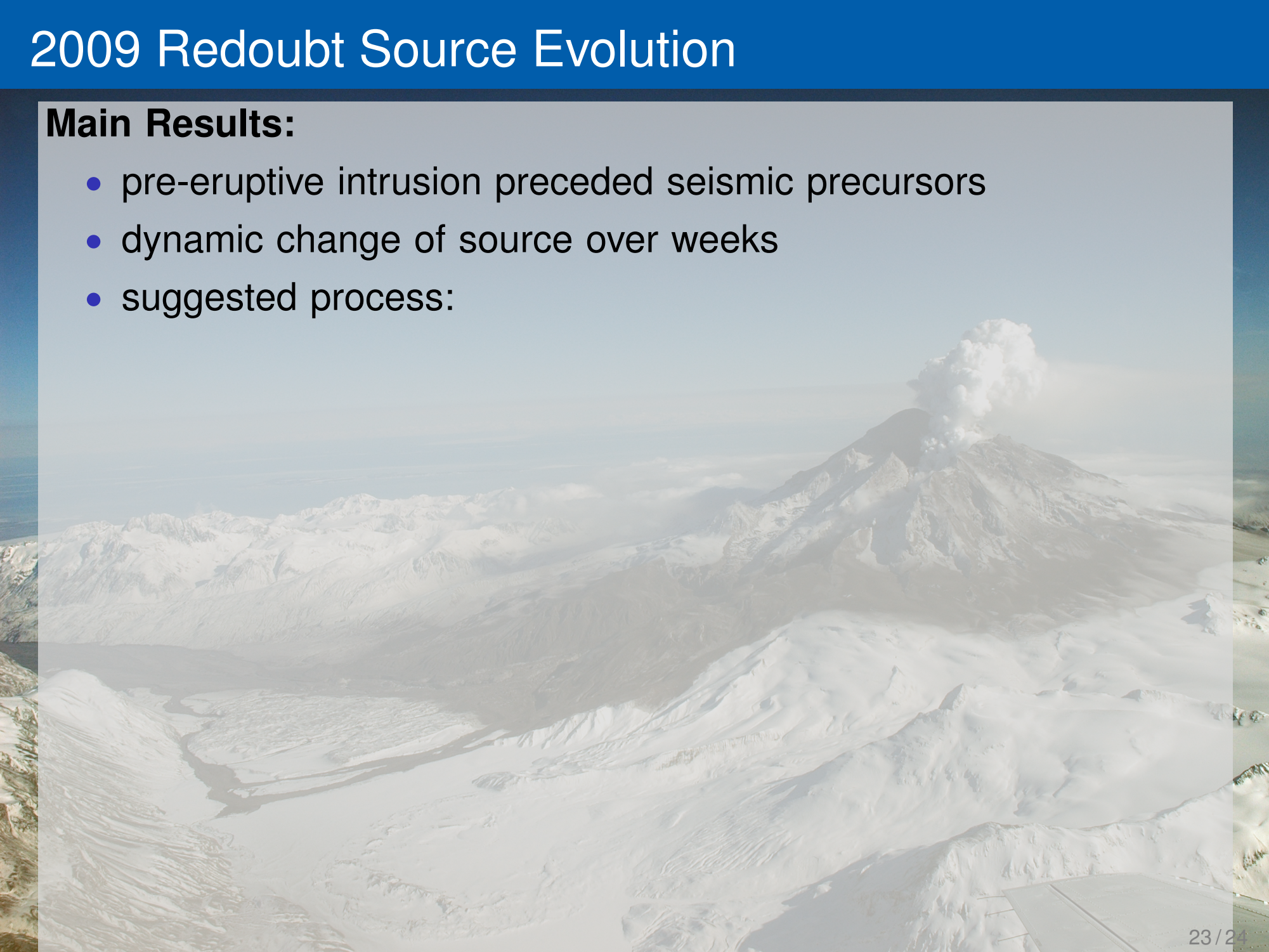
$$r = 1.25\,km\,\text{S of dome}$$
$$d = 13.50\ {}^{10.17}_{17.33}\,km$$
$$\Delta V = 0.0194\ {}^{0.0092}_{0.0340}\,km^3$$

2009 Redoubt Source Evolution

2009 Redoubt Source Evolution

Main Results:

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



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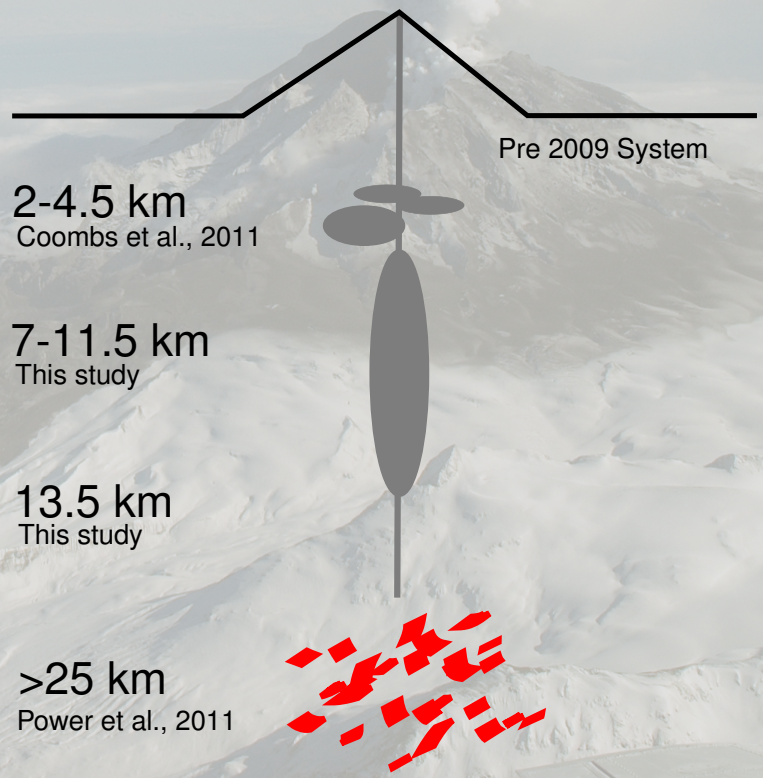

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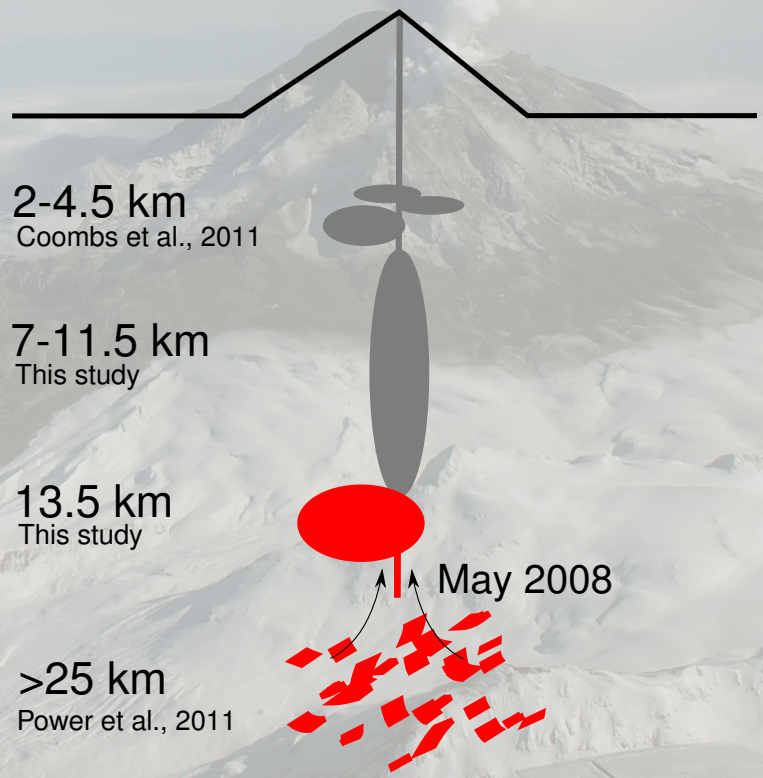

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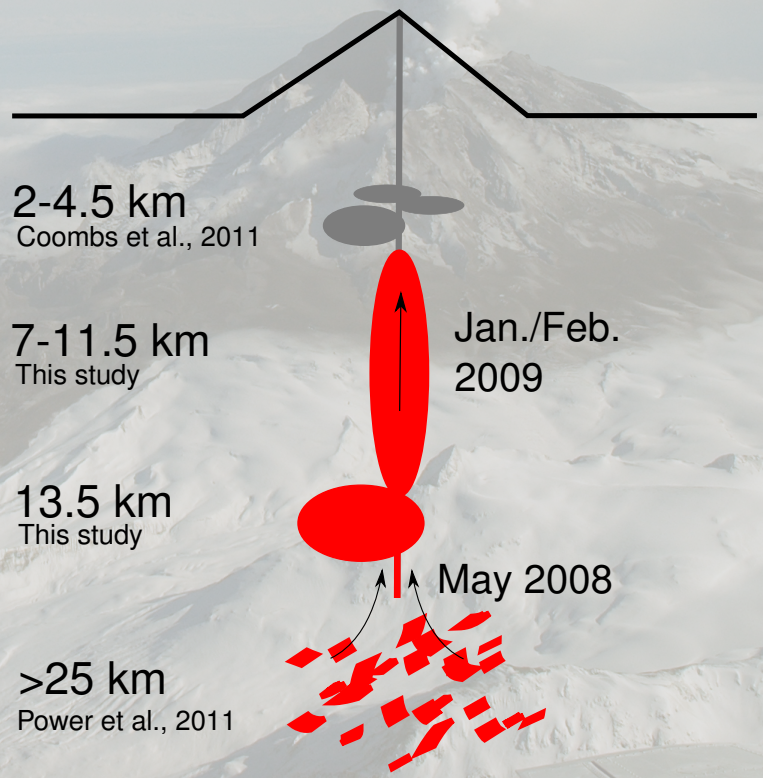

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