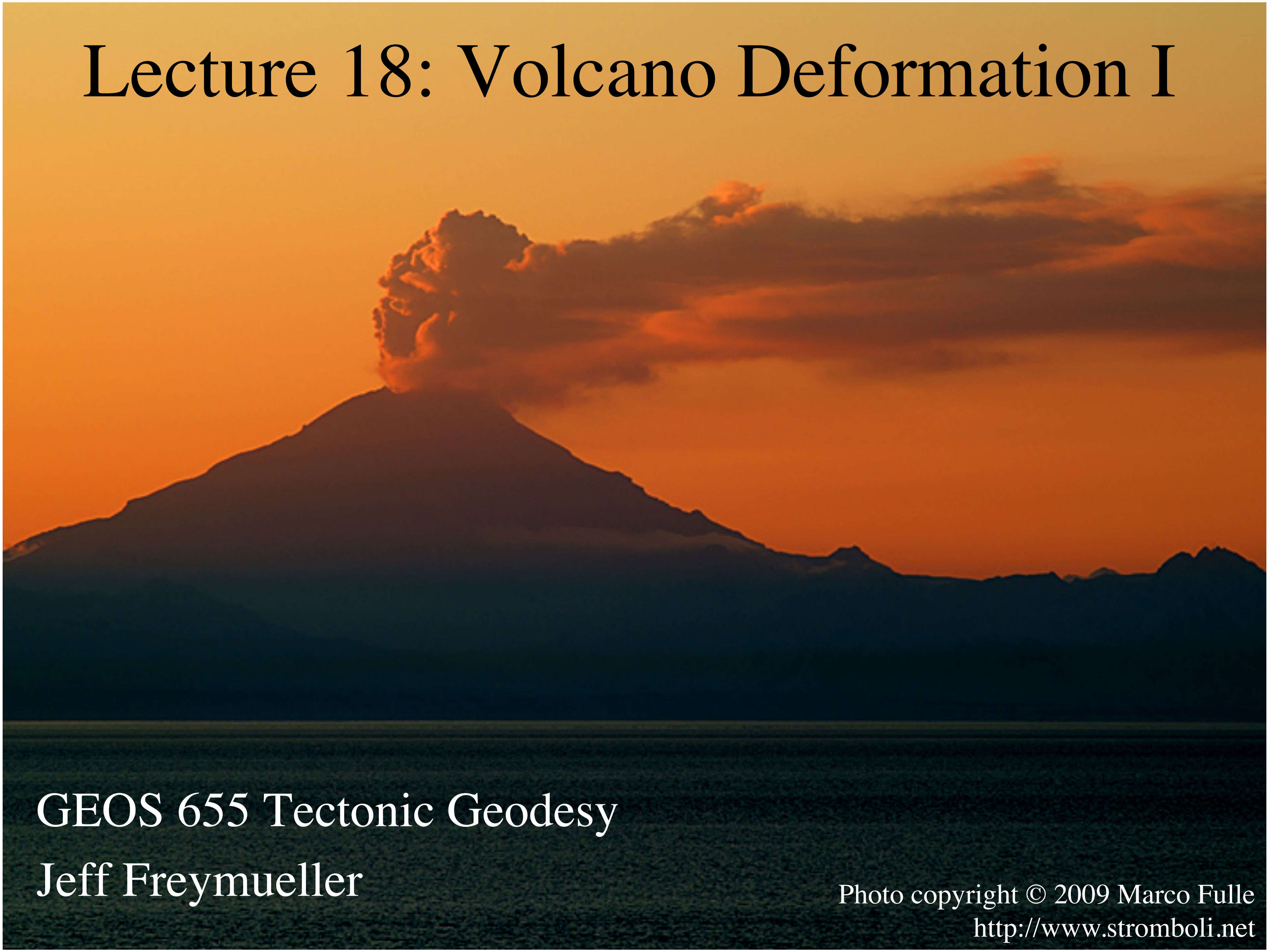
Lecture 18: Volcano Deformation I



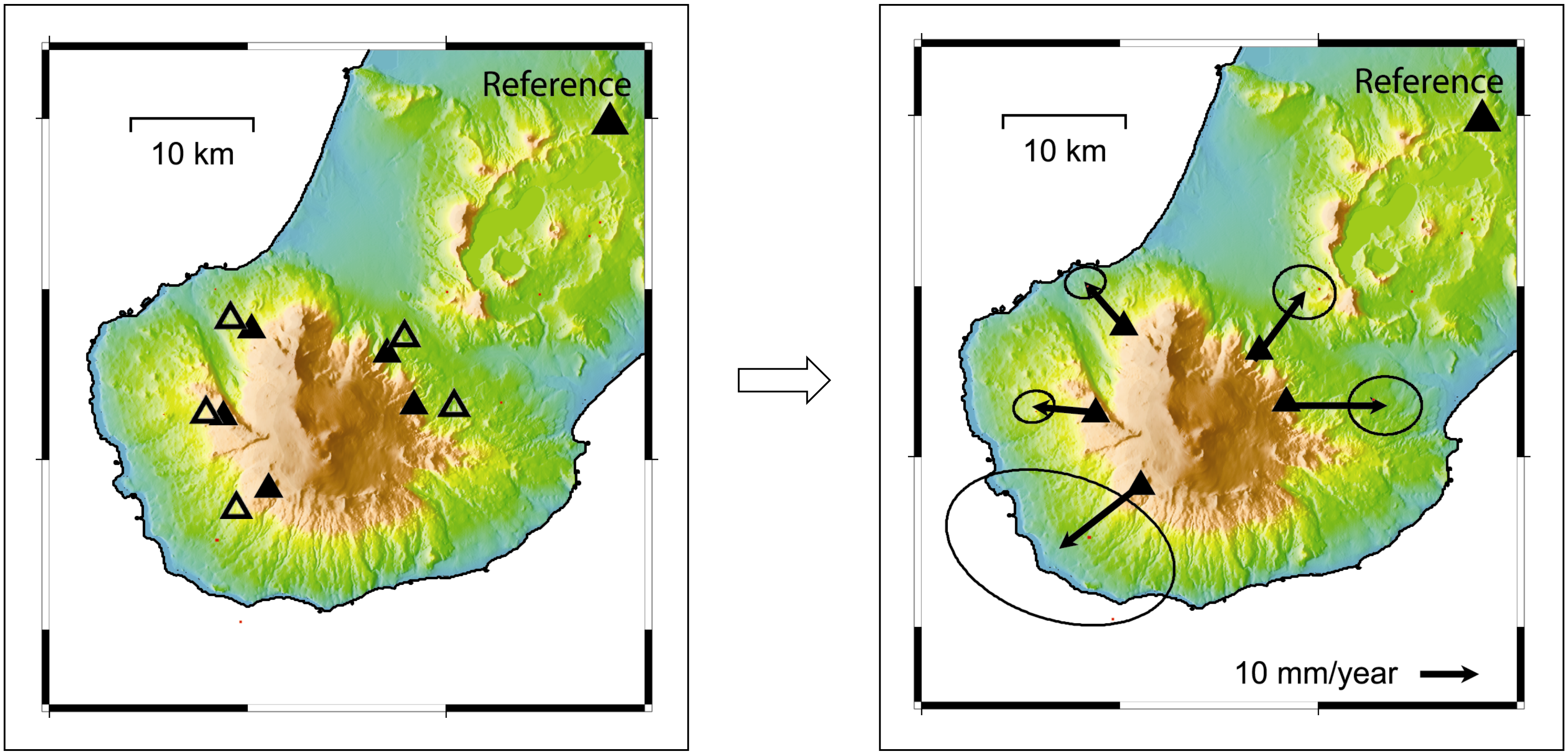
GEOS 655 Tectonic Geodesy

Jeff Freymueller

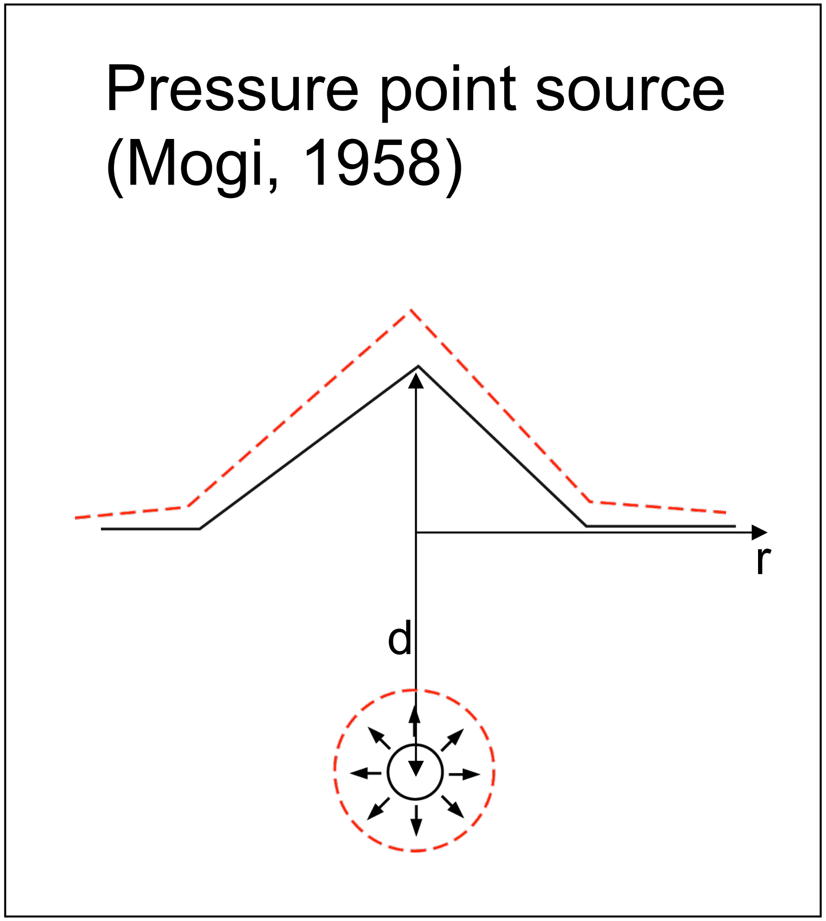
Cause of Volcano Deformation

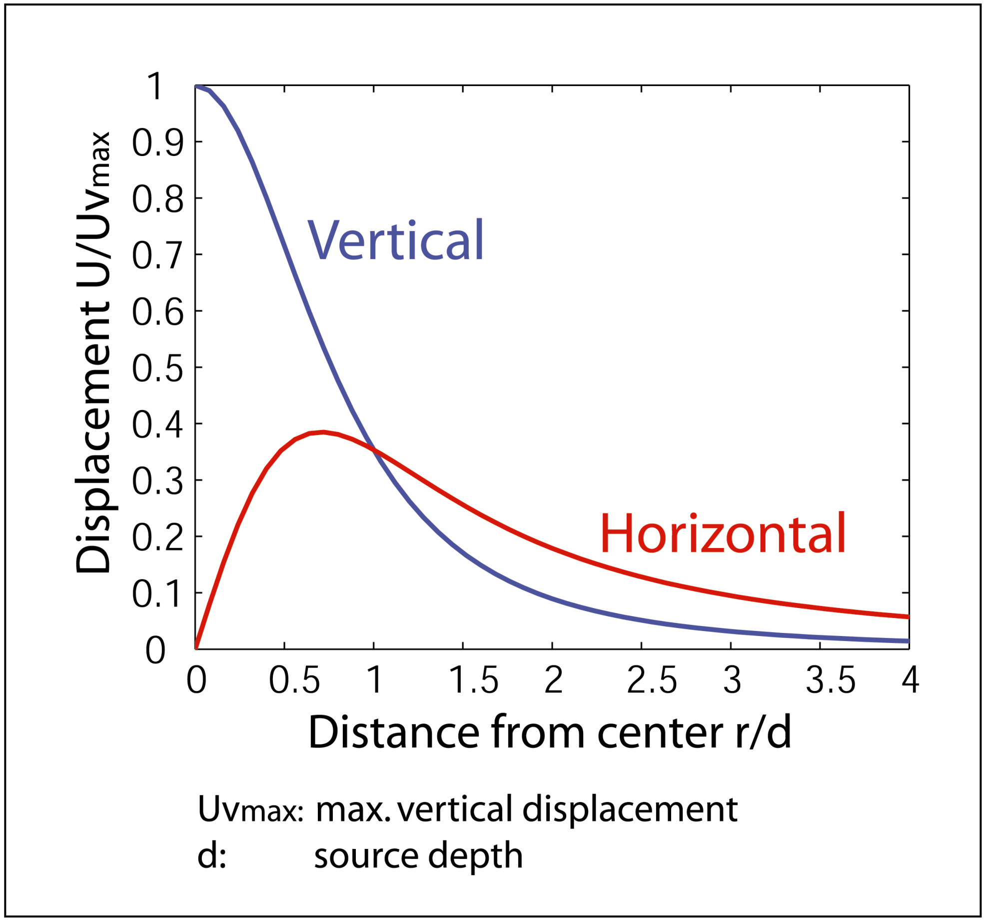
- Volcano deformation results from pressure changes caused by fluids.
  - Intrusions of magma in subsurface
  - Removal of magma to the surface during eruption
  - Pressure changes within hydrothermal systems
- Stresses and stressing rates from these sources can be very large.

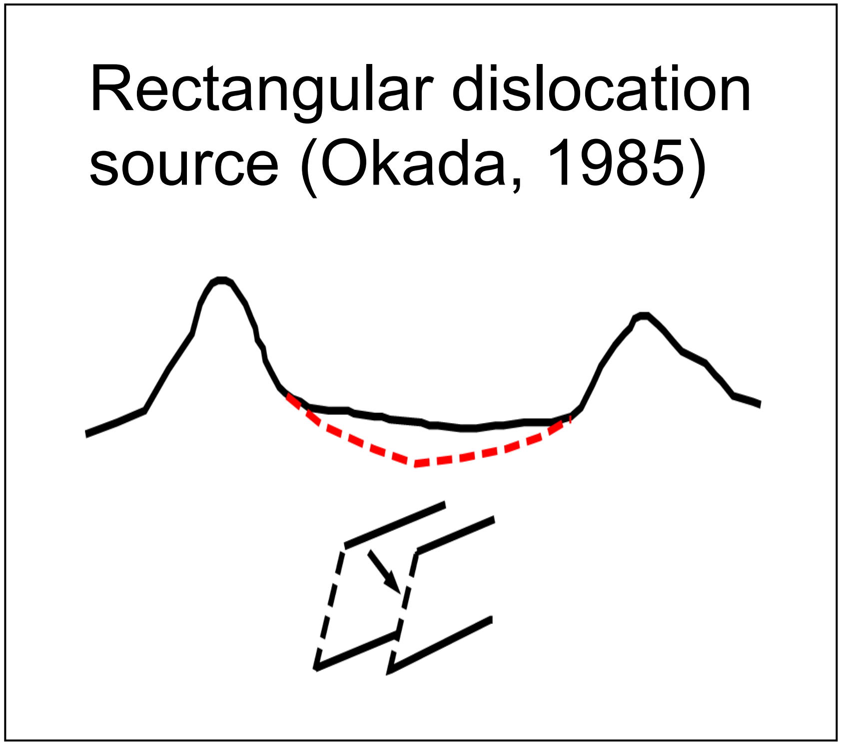
Example of Volcano Deformation (Westdahl, Aleutian Arc)

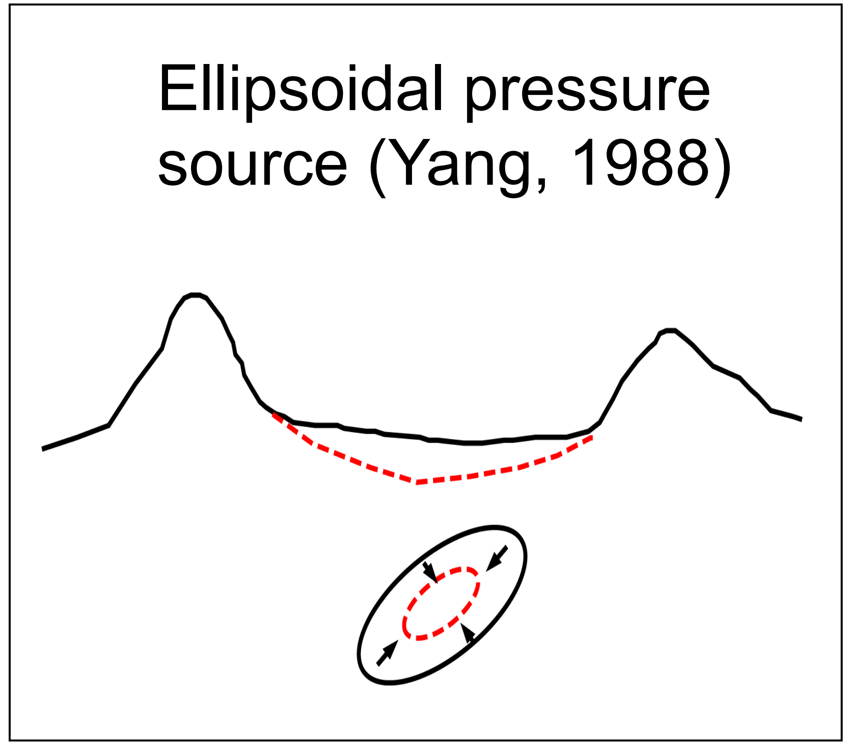


Volcanic source models









Dike or sill, expand or contract

Pressure release, degassing

Model parameters:
Location, depth, strength, length, width, dip, strike

Mogi model

Spherical pressure point source:

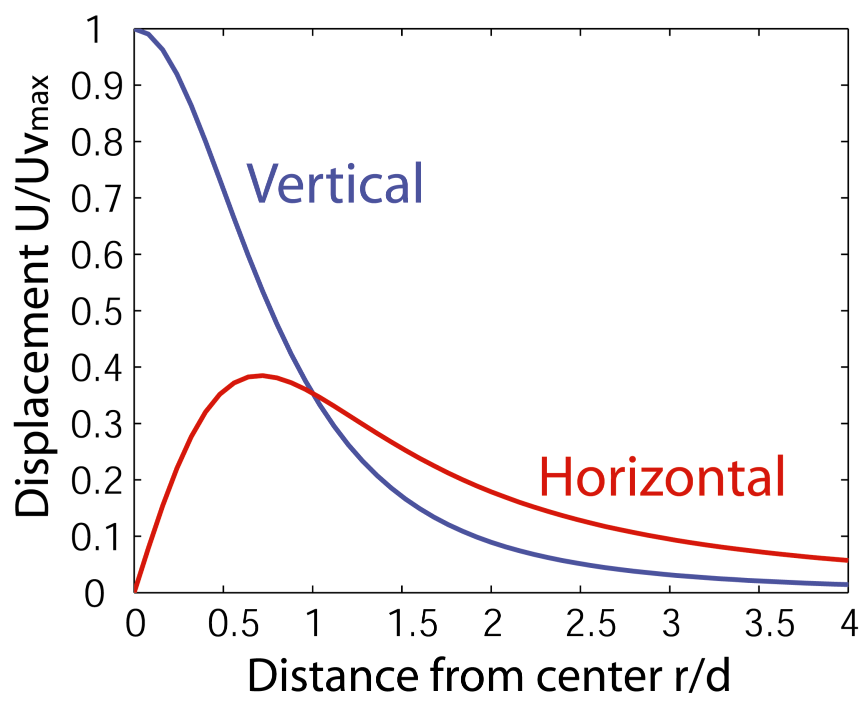
C

$$U_z = \frac{(1-\nu)pa^3}{\mu}\frac{d}{(r^2+d^2)^{3/2}}$$

$$U_r = \frac{(1-\nu)pa^3}{\mu}\frac{r}{(r^2+d^2)^{3/2}}$$

$$\Delta V = \pi pa^3/\mu$$

p = pressurization
a = radius of sphere
ΔV = volume change



Uvmax: max. vertical displacement
d: source depth

Notes on Mogi Model

- Radial and vertical displacements are like the sine and cosine of the 3D displacement vector
  - Because displacements at surface are radially outward from pressure source
  - This is not true at all depths
- Magnitude of (3D) displacement vector decreases as 1/distance from source
- The ΔV is volume change in the chamber.
  - Cannot exactly equate to change in mass because of compressibility of magma.

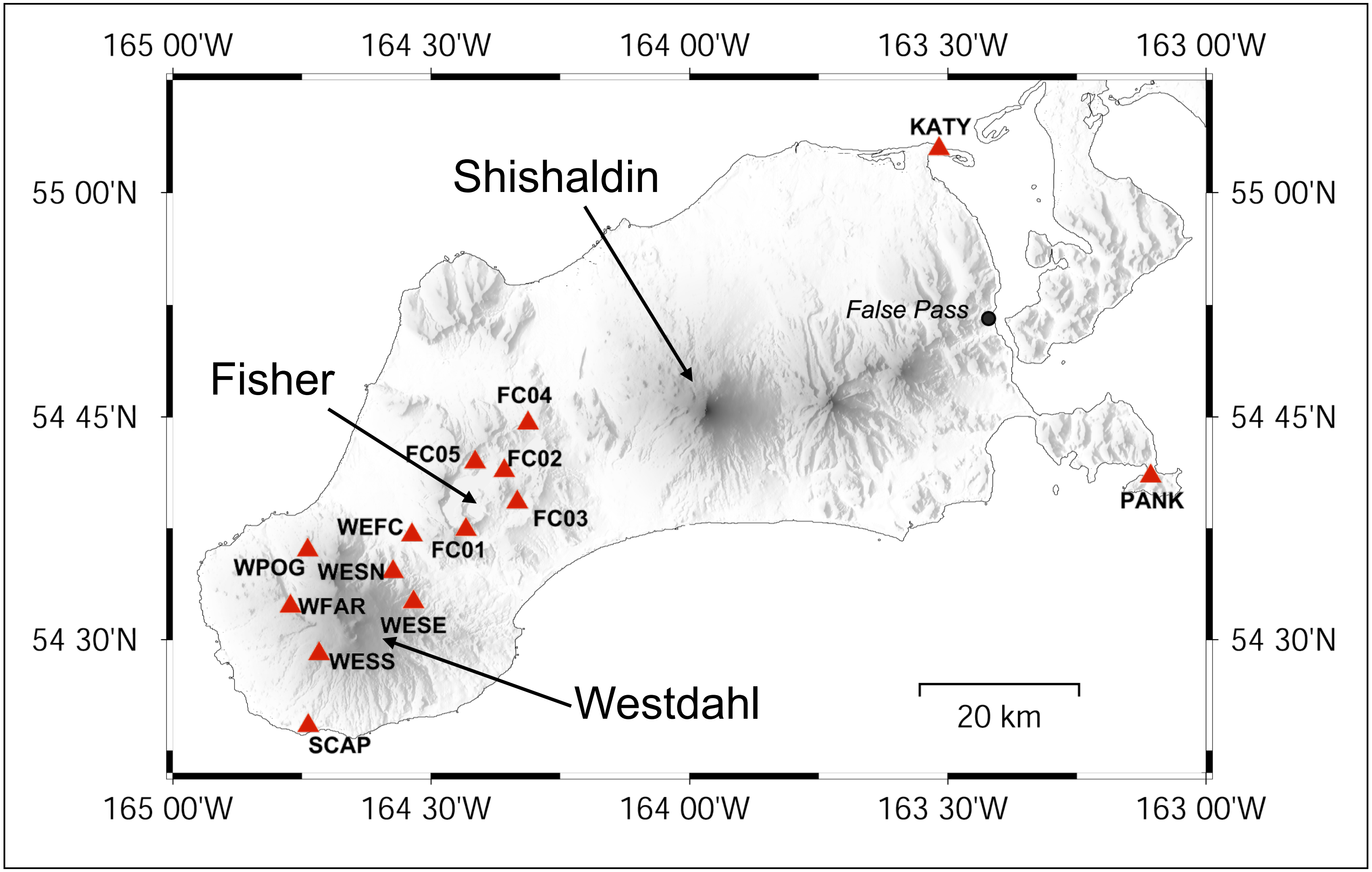
What is the ΔV?

- The ΔV in the previous slide is actually the volume change of the cavity, which is equivalent to a pressure change of the cavity.
- It may or may not reflect the volume of magma intruded
  - Incompressible magma: volume change of cavity equals volume change of magma
  - Compressible magma: what do you really mean by "volume" anyway? Volume is a function of pressure and mass
- Key points are that magma "volume" is model-dependent and also may or may not relate easily to mass of new magma

Derivation of Mogi Model

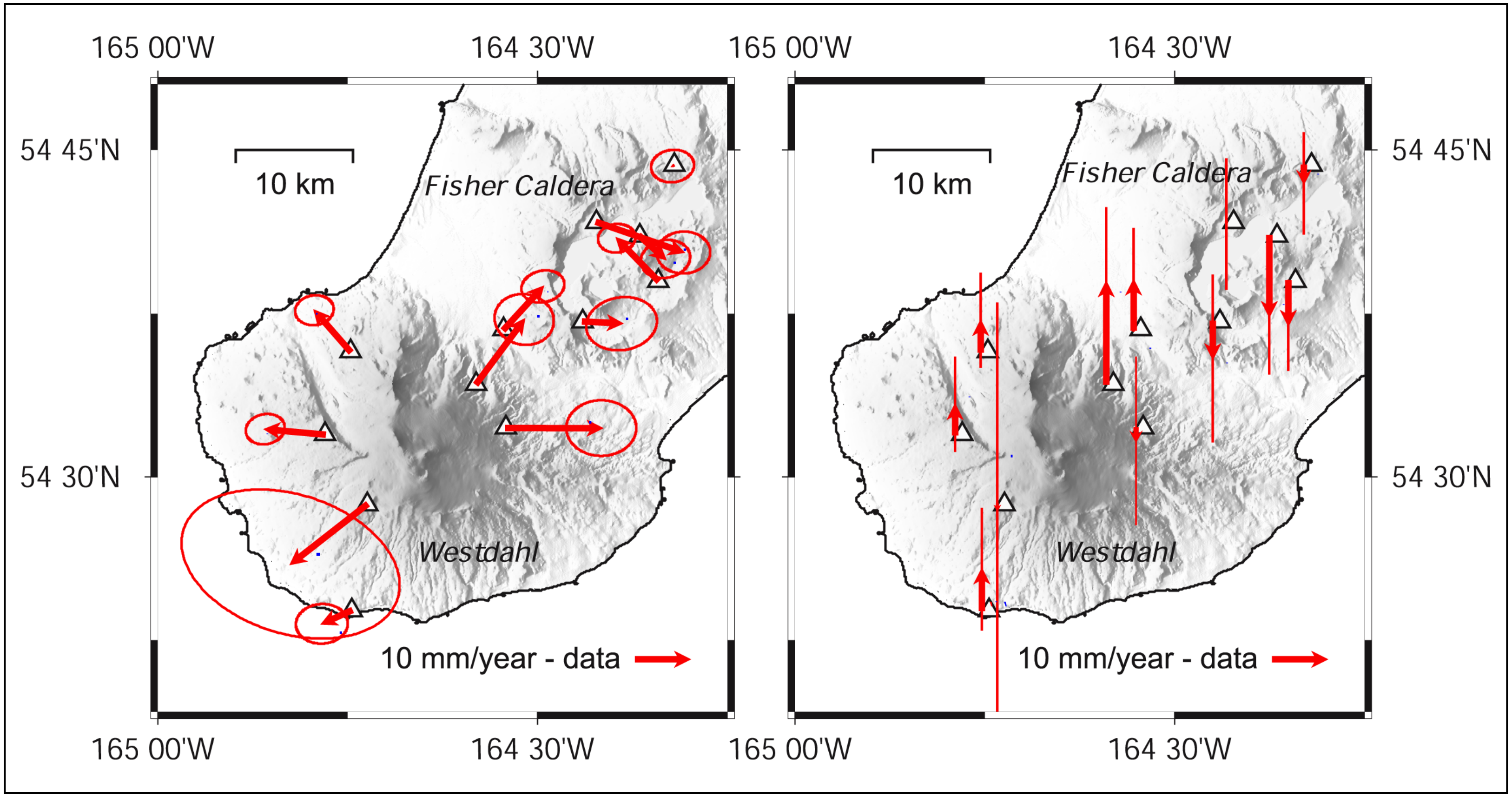
- Assume a spherical cavity of radius a
- Assume stress on walls of cavity is isotropic, corresponds to pressure p.
- Solve differential equation in terms of displacement
  - Impact of free surface means that an iterative approach to finding the solution is necessary (outlined in Segall, Chapter 7).
- Point source approximation means $a << d$
  - In practice, approximation is good for $a < 0.5d$

GPS network

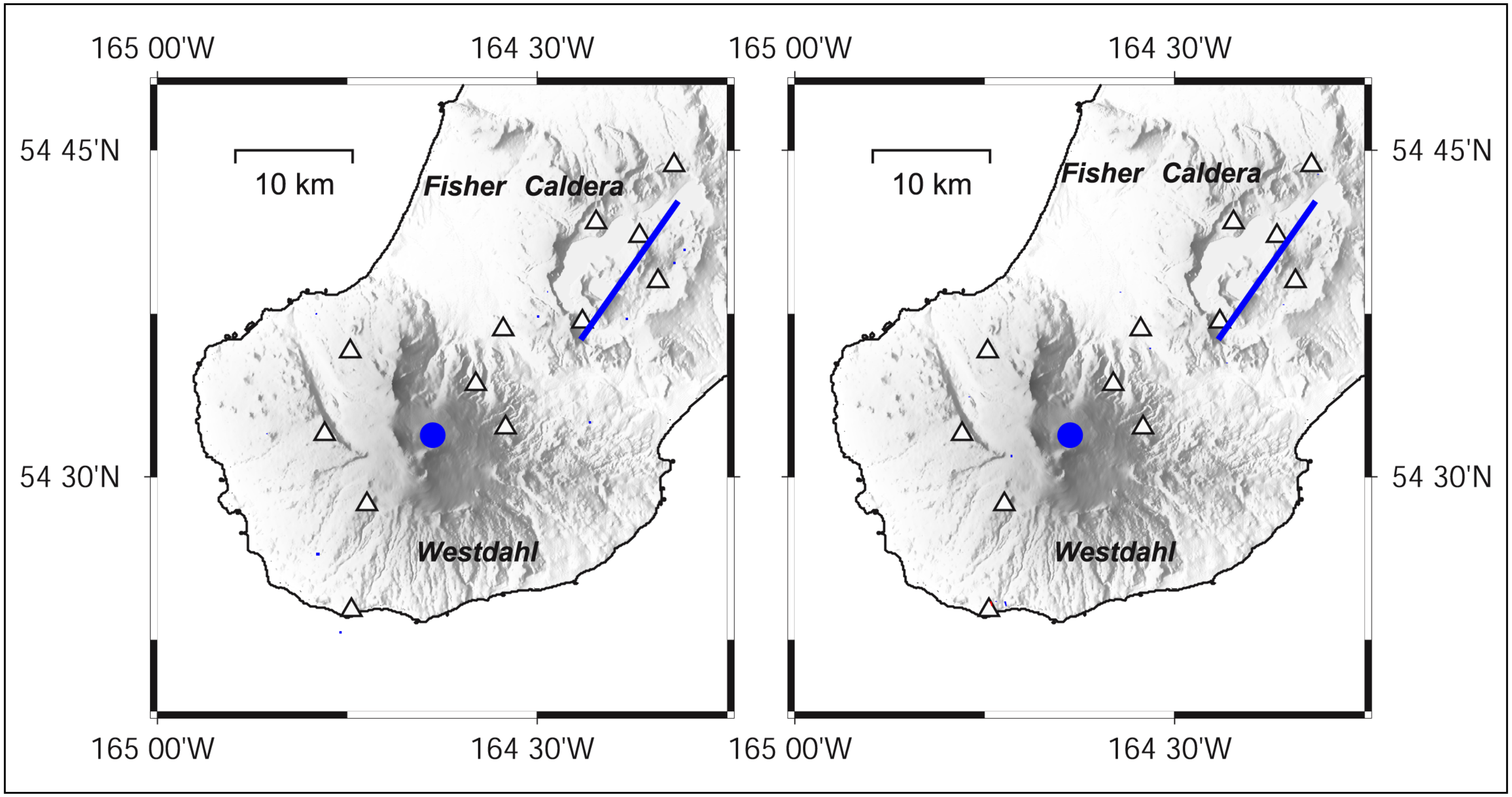


165 00'W
164 30'W
164 00'W
163 30'W
163 00'W
55 00'N
54 45'N
54 30'N
KATY
Shishaldin
False Pass
Fisher
FC04
FC05
FC02
FC03
FC01
WEFC
WPOG
WESN
WFAR
WESE
WESS
SCAP
PANK
Westdahl
20 km

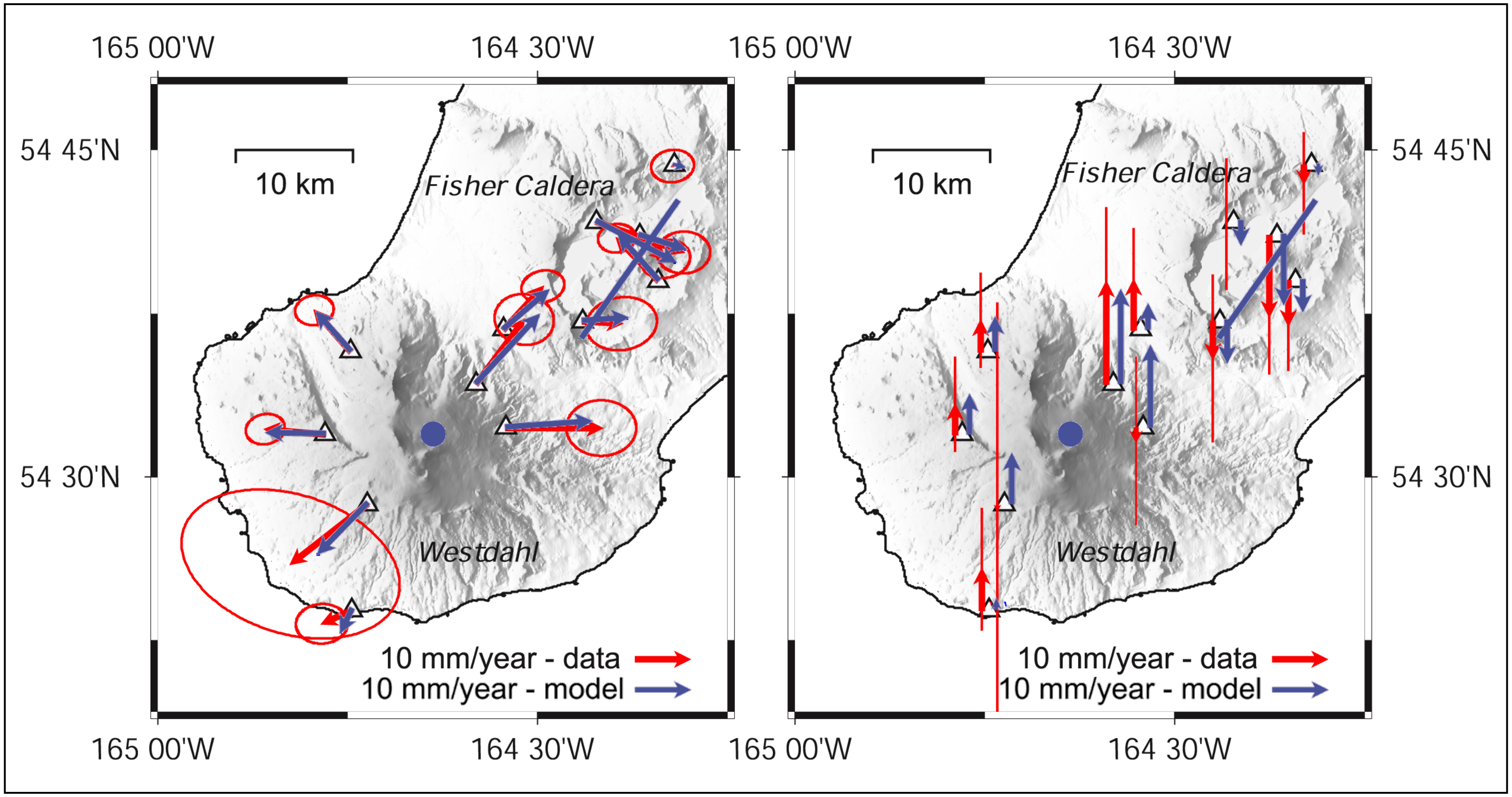
GPS data (1998-2001)



Model

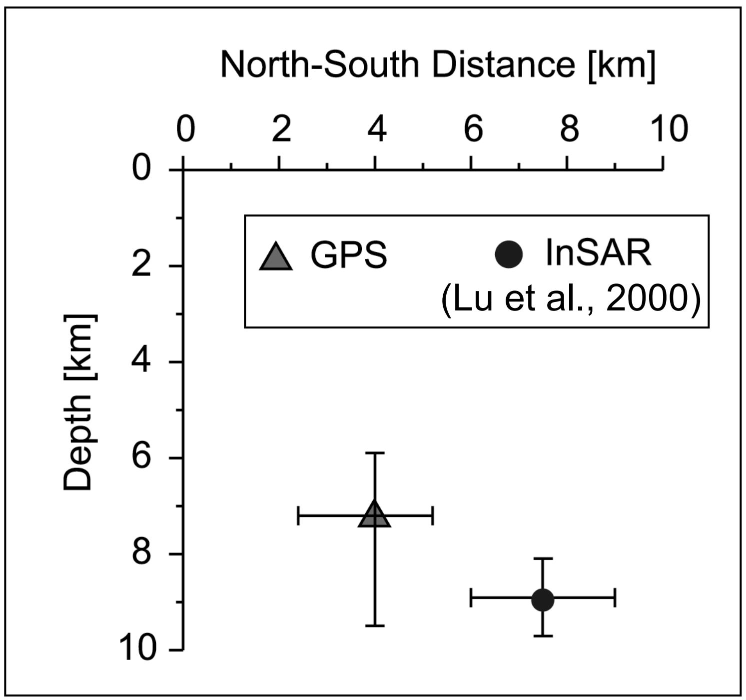

165 00'W
164 30'W
165 00'W
164 30'W
54 45'N
54 30'N
10 km
Fisher Caldera
Westdahl
10 km
Fisher Caldera
Westdahl
54 45'N
54 30'N
165 00'W
164 30'W
165 00'W
164 30'W

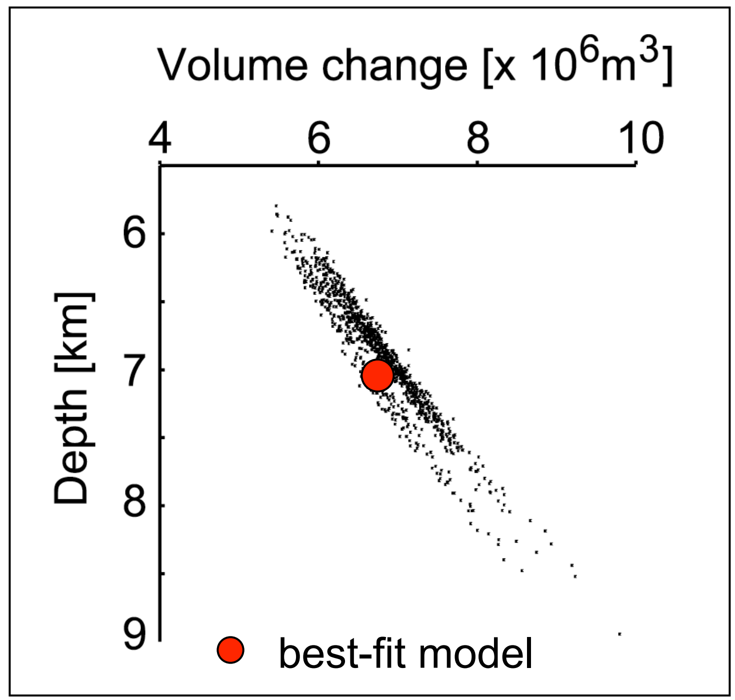
GPS data and model



Modeling results - Westdahl

- Point source east of Westdahl Peak
- Depth: 7.2 km (6 km below sea level)
- Volume change: 6.7 x 10^6 m^3/year



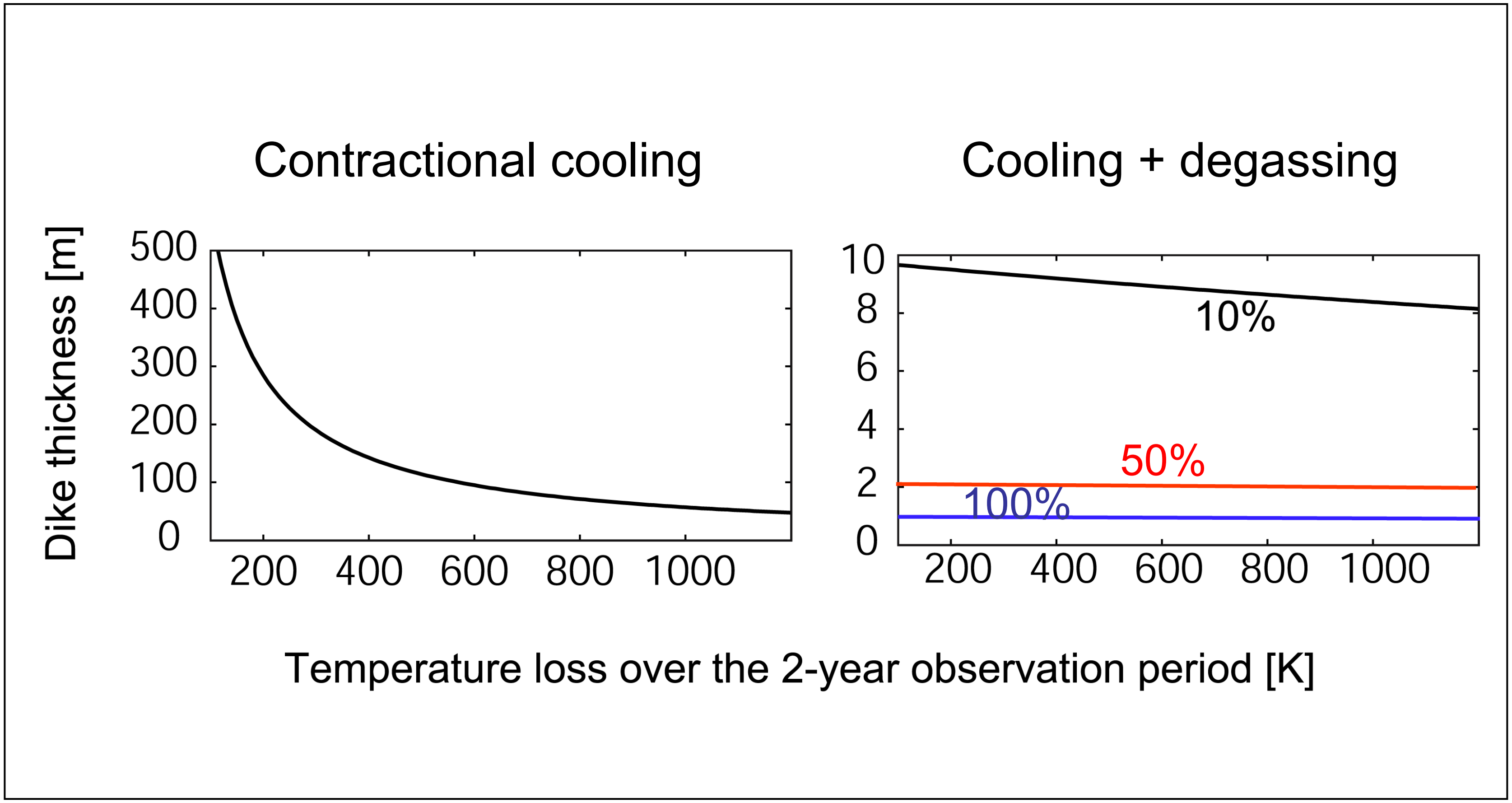


Modeling results - Fisher

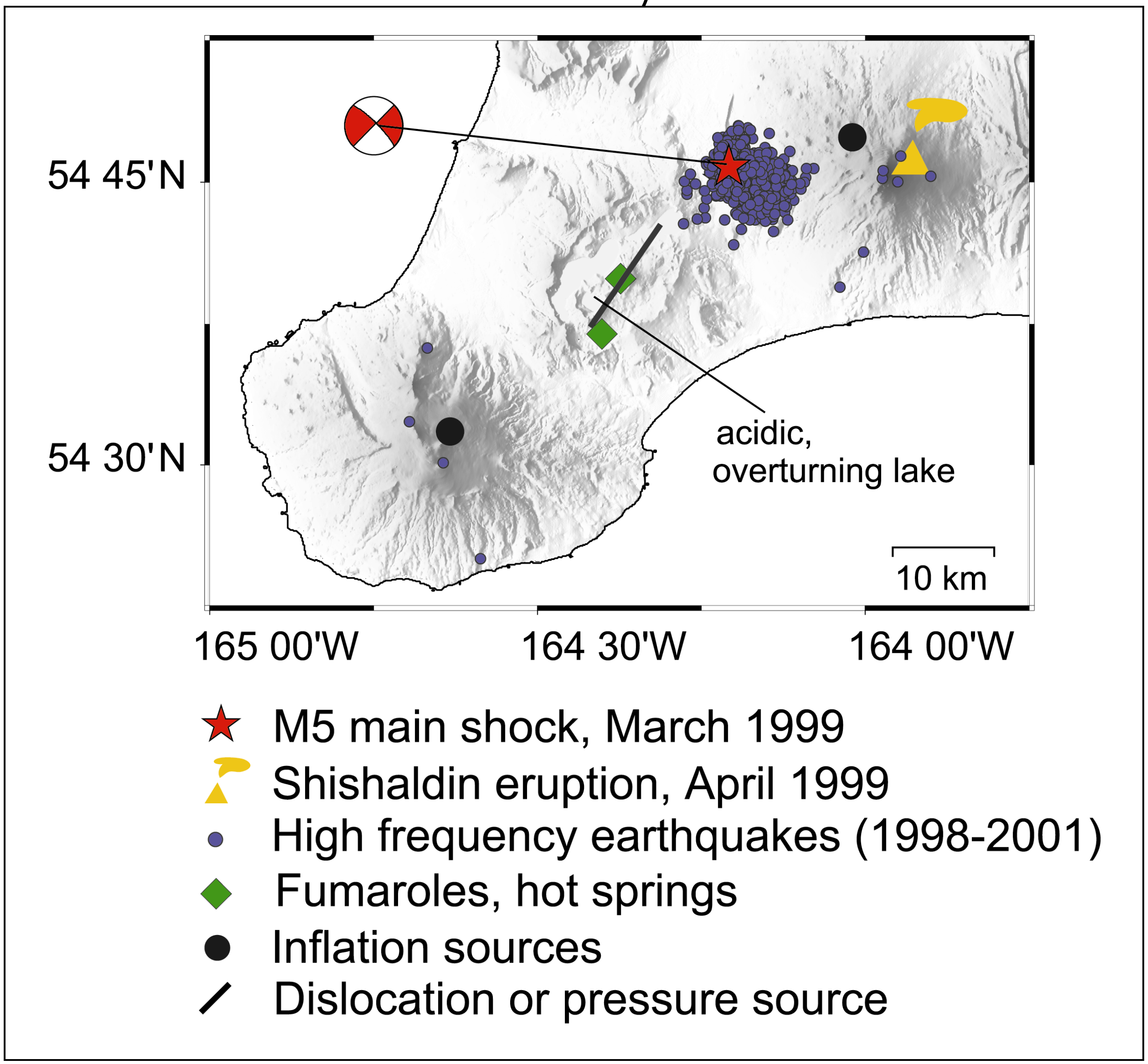
- Dike-like source along the long caldera axis

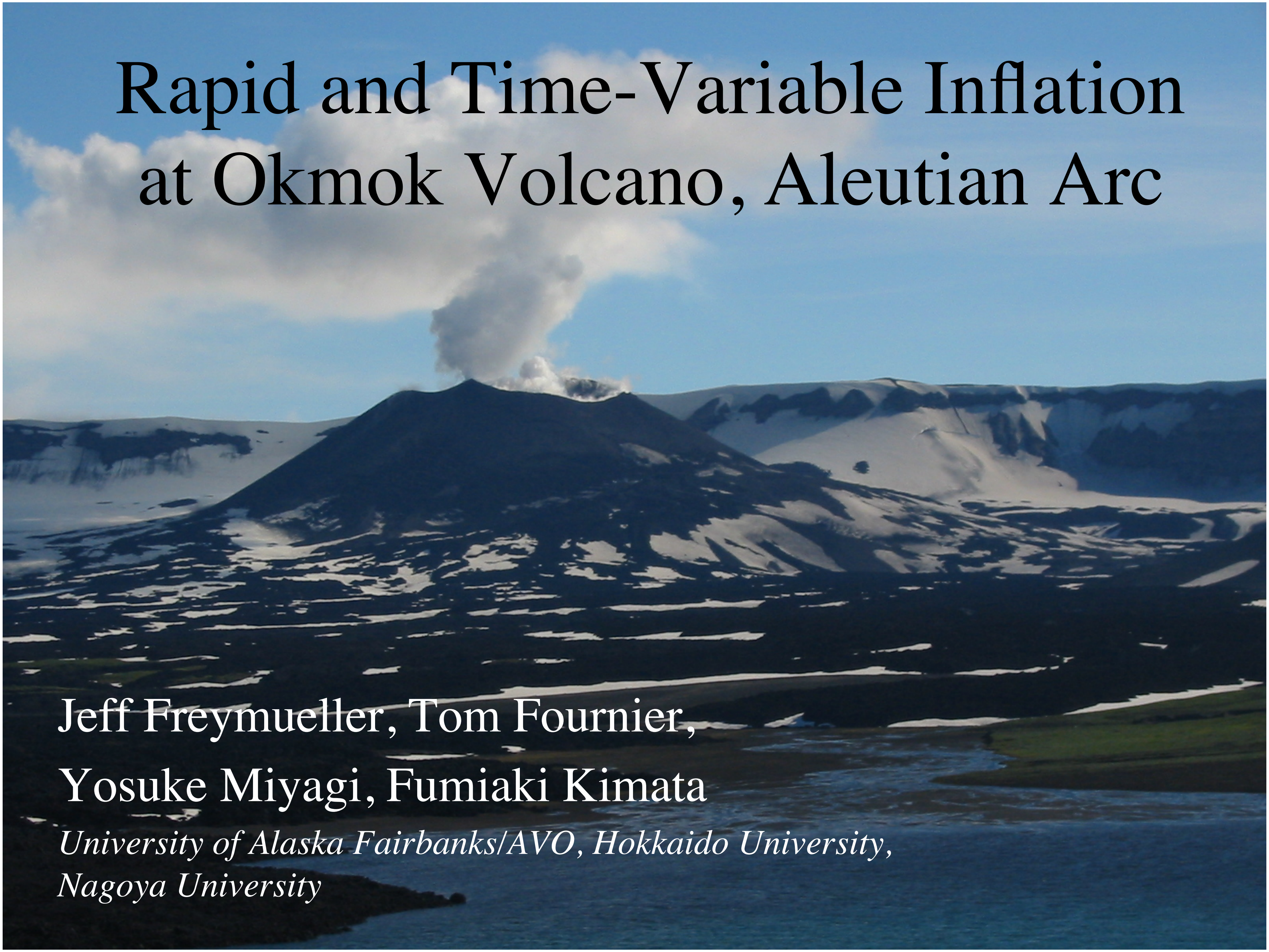
Depth (km)	Length (km)	Width (km)	Dip (°)	Strike (N°E)	Volume change (x 10^6 m^3 /year)
1.5	13	0.5	80	35	- 2.1

Dike cooling model



Volcanic, hydrothermal, and tectonic activity

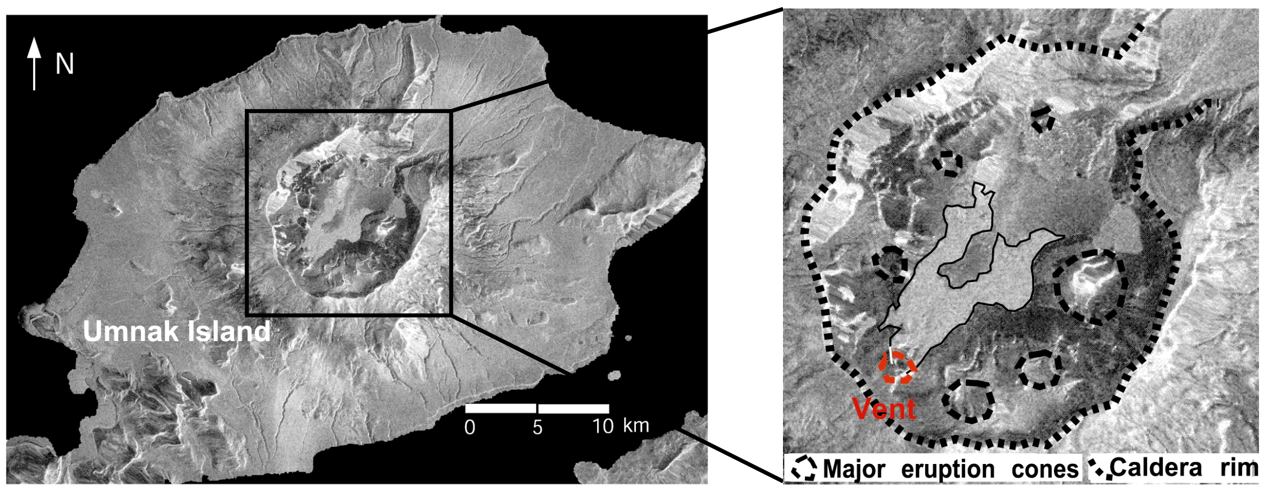




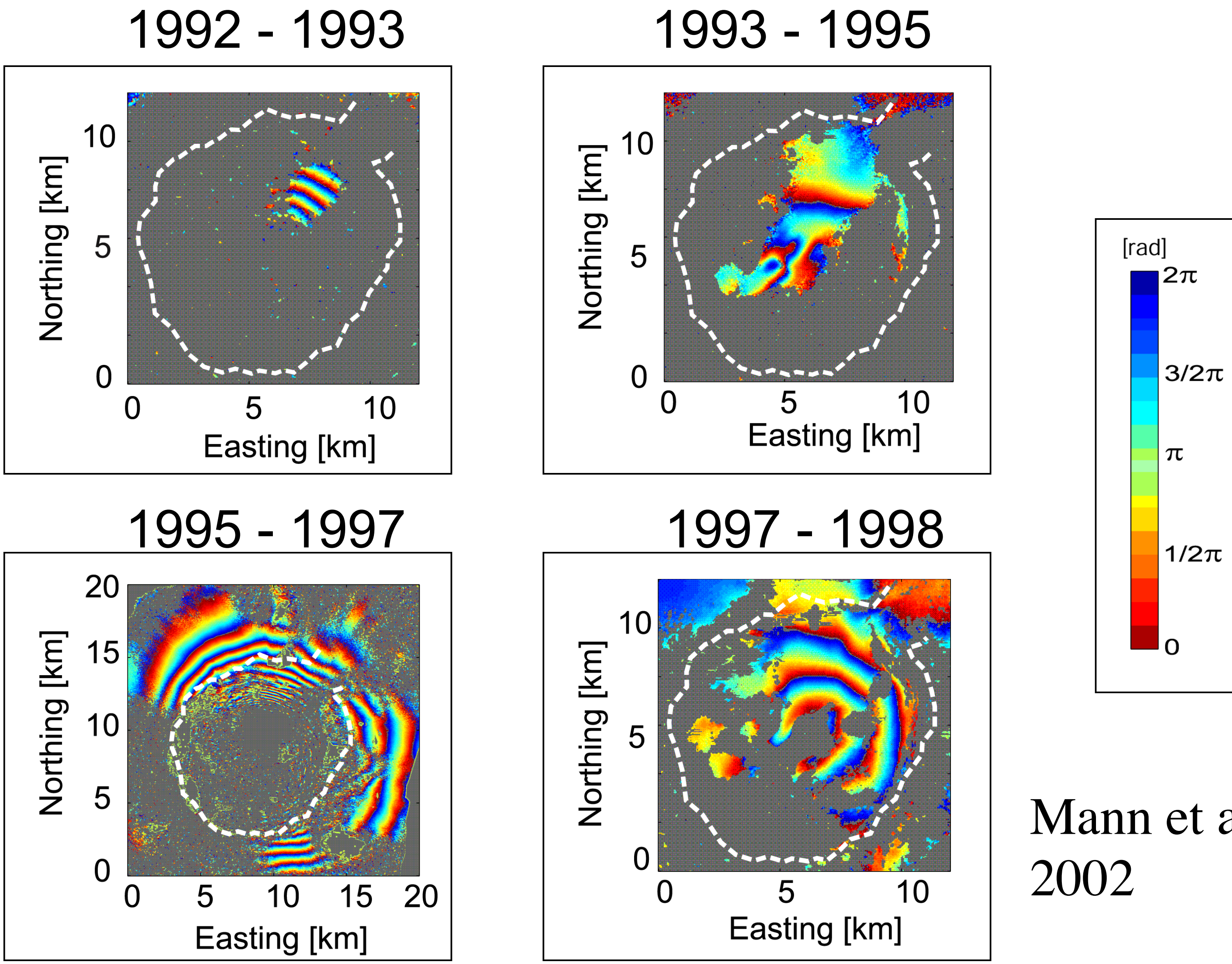
Rapid and Time-Variable Inflation at Okmok Volcano, Aleutian Arc

Jeff Freymueller, Tom Fournier,
Yosuke Miyagi, Fumiaki Kimata
University of Alaska Fairbanks/AVO, Hokkaido University, Nagoya University

Location

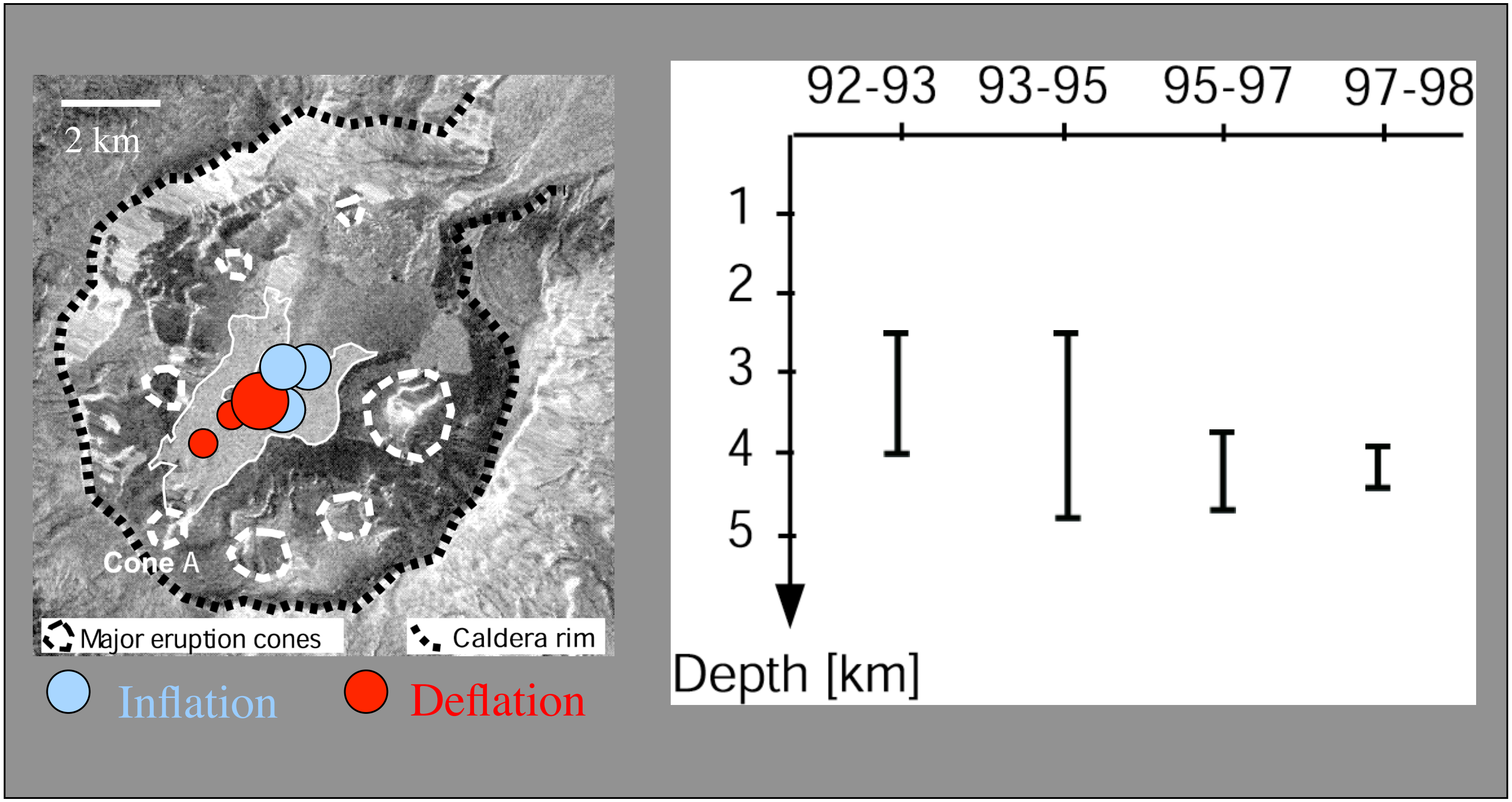

N
Umnak Island
0
5
10 km
Vent
Major eruption cones
Caldera rim

Deformation interferograms



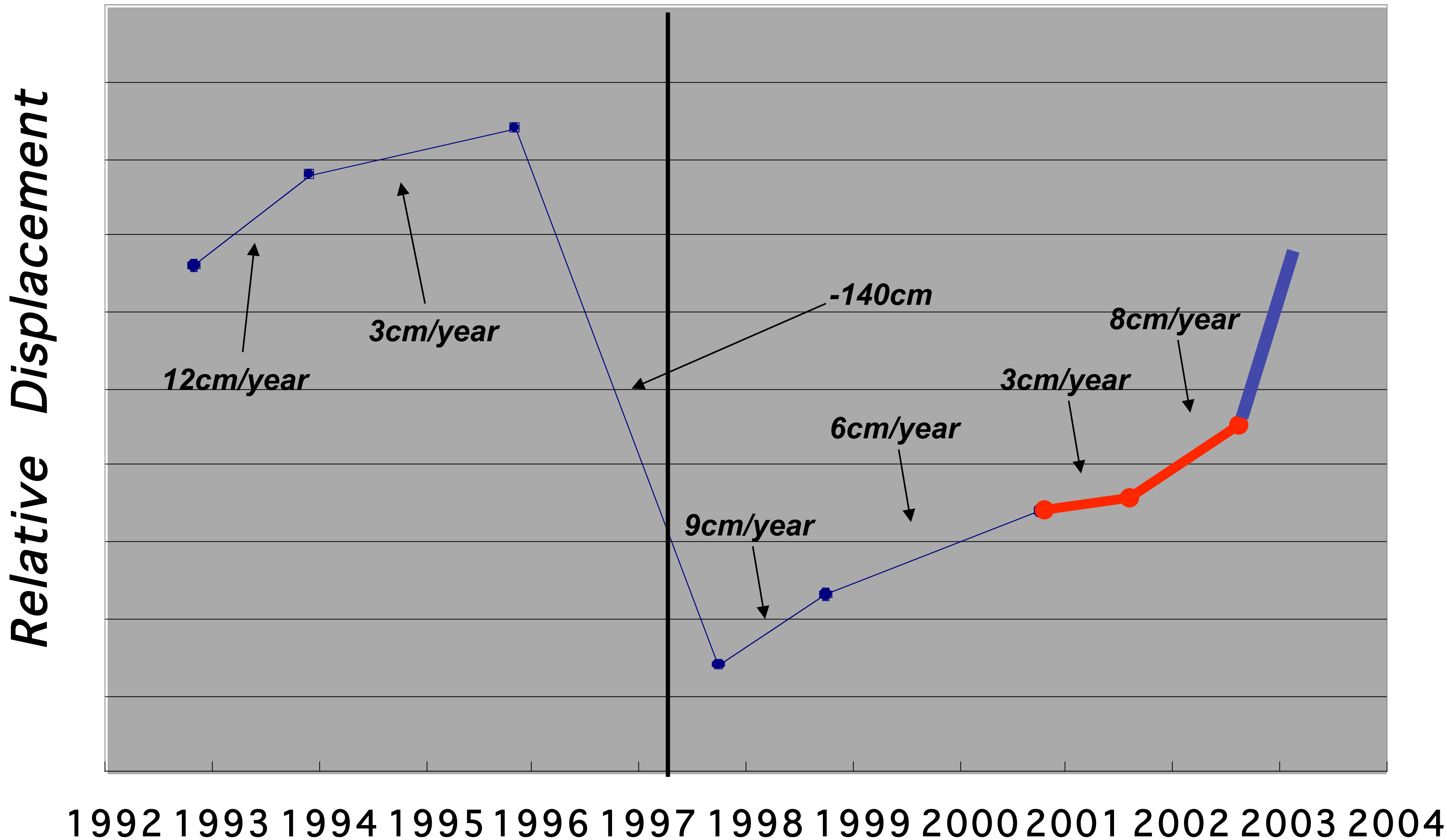
Mann et al., 2002

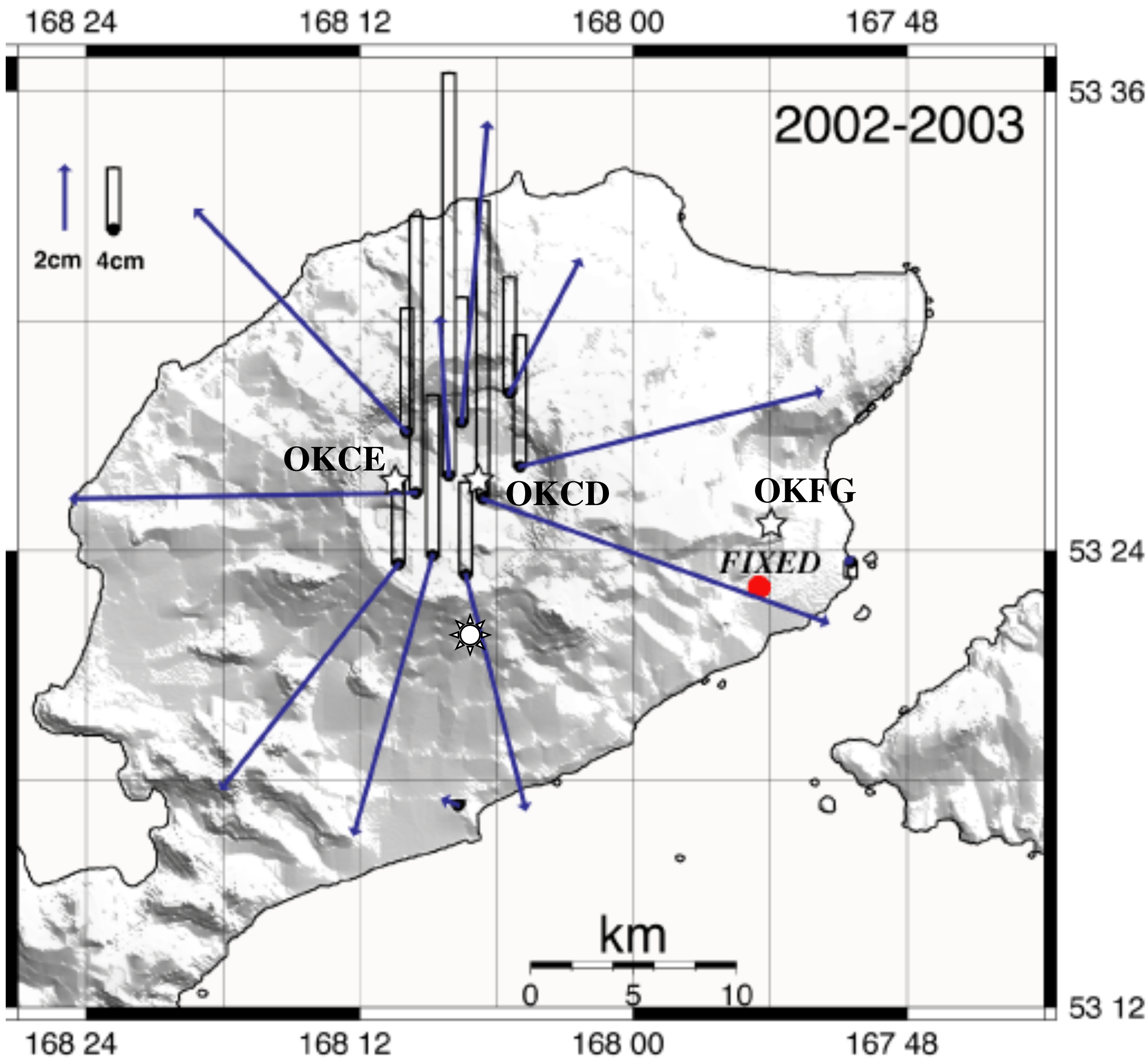
Source locations and depths



Mann et al., 2002

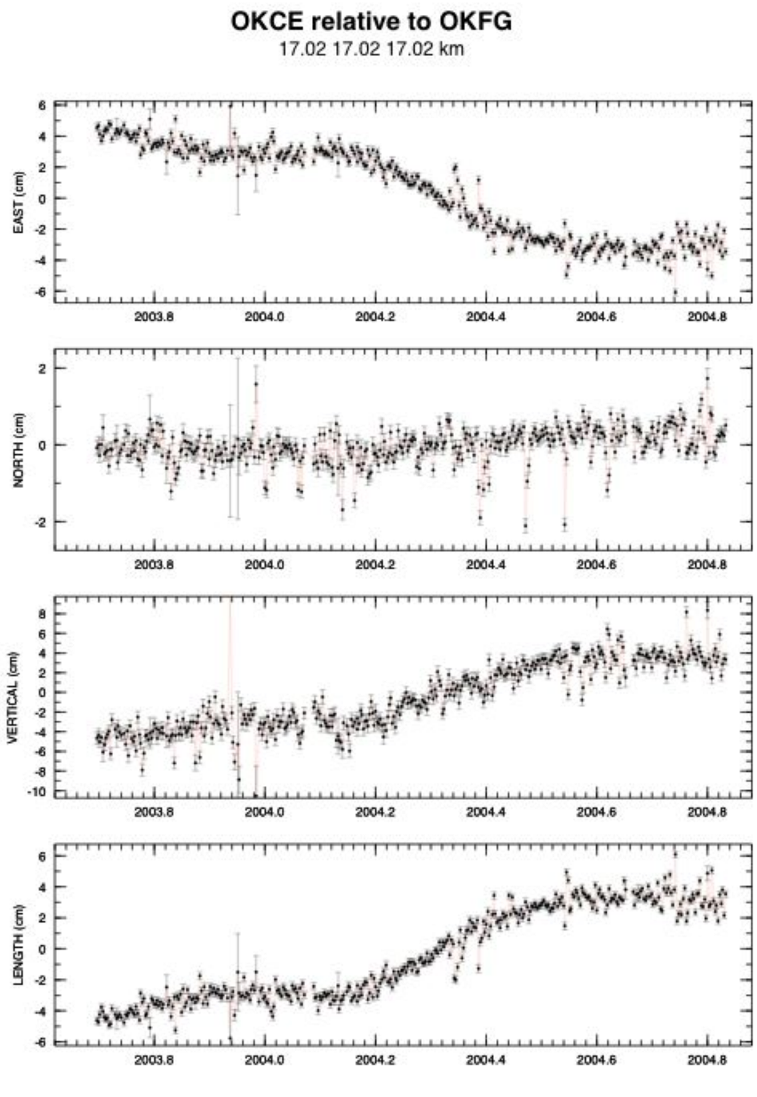
Uplift, Combined InSAR+GPS

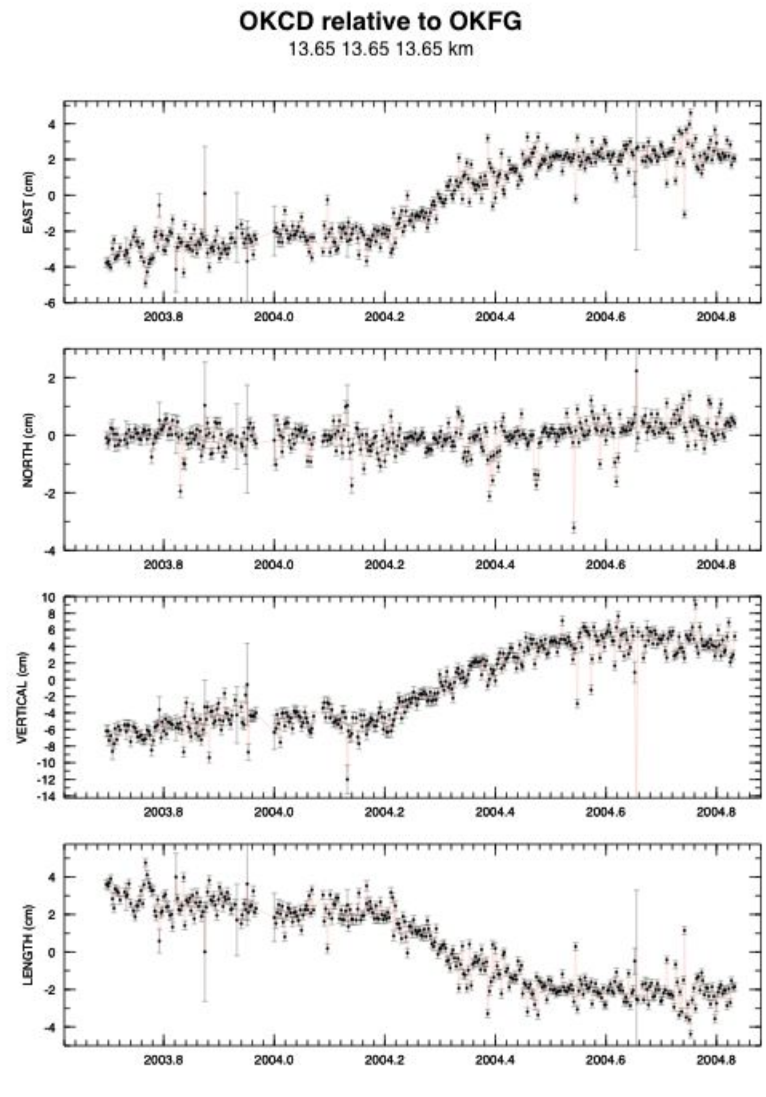




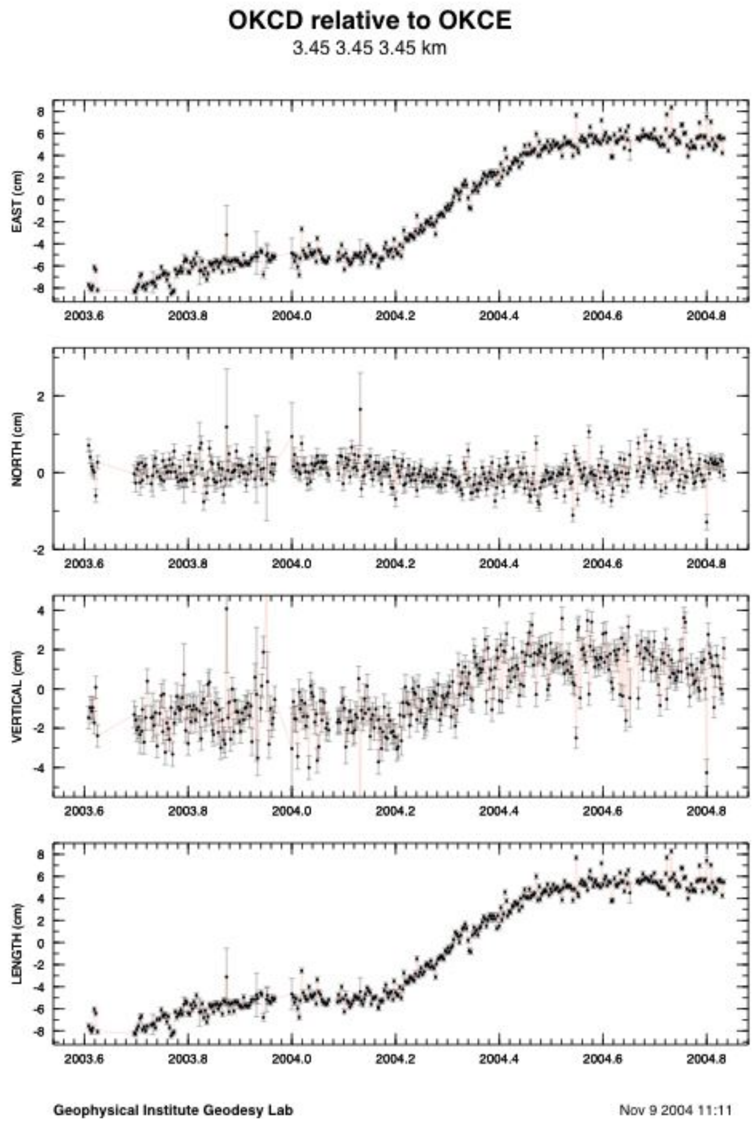
168 24
168 12
168 00
167 48
53 36
53 24
53 12
2002-2003
2cm
4cm
OKCE
OKCD
OKFG
FIXED
km
0
5
10

Intra-caldera Time Series



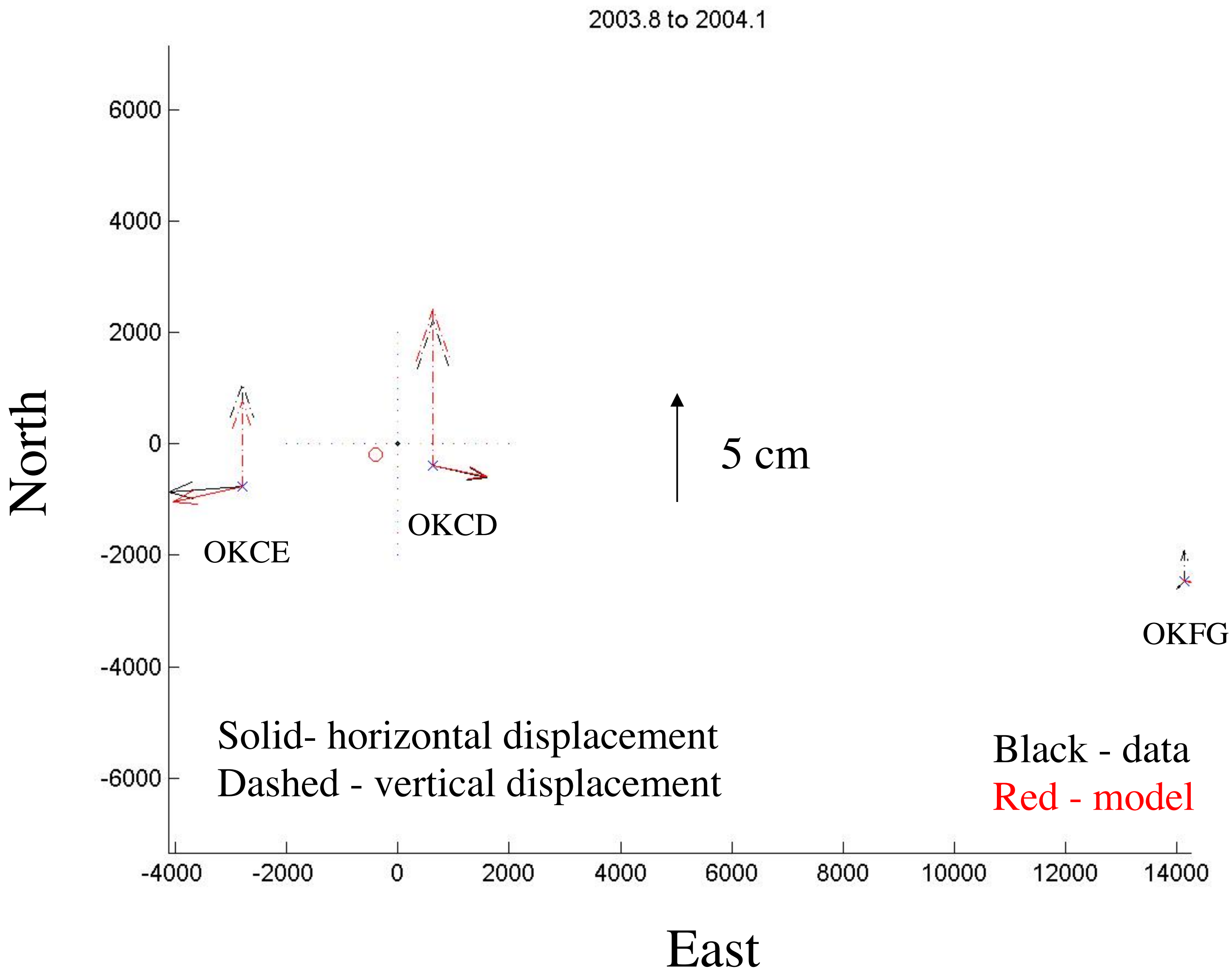


Rapid Inflation Event



- Inflation occurs almost continuously
- There was a very rapid inflation event Feb-July 2004
- Is source stronger during event? (more magma) Or simply shallower?

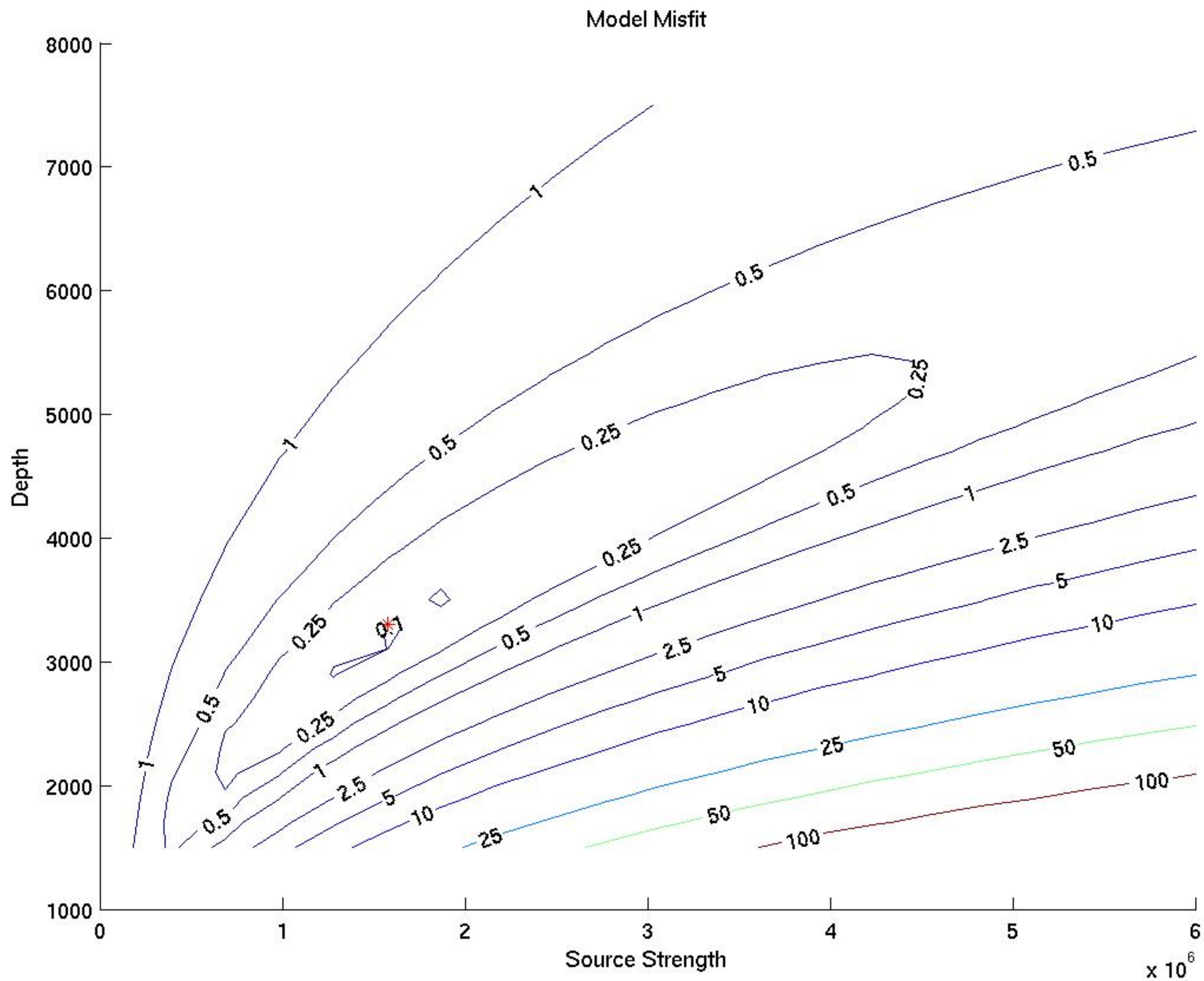
Before Event



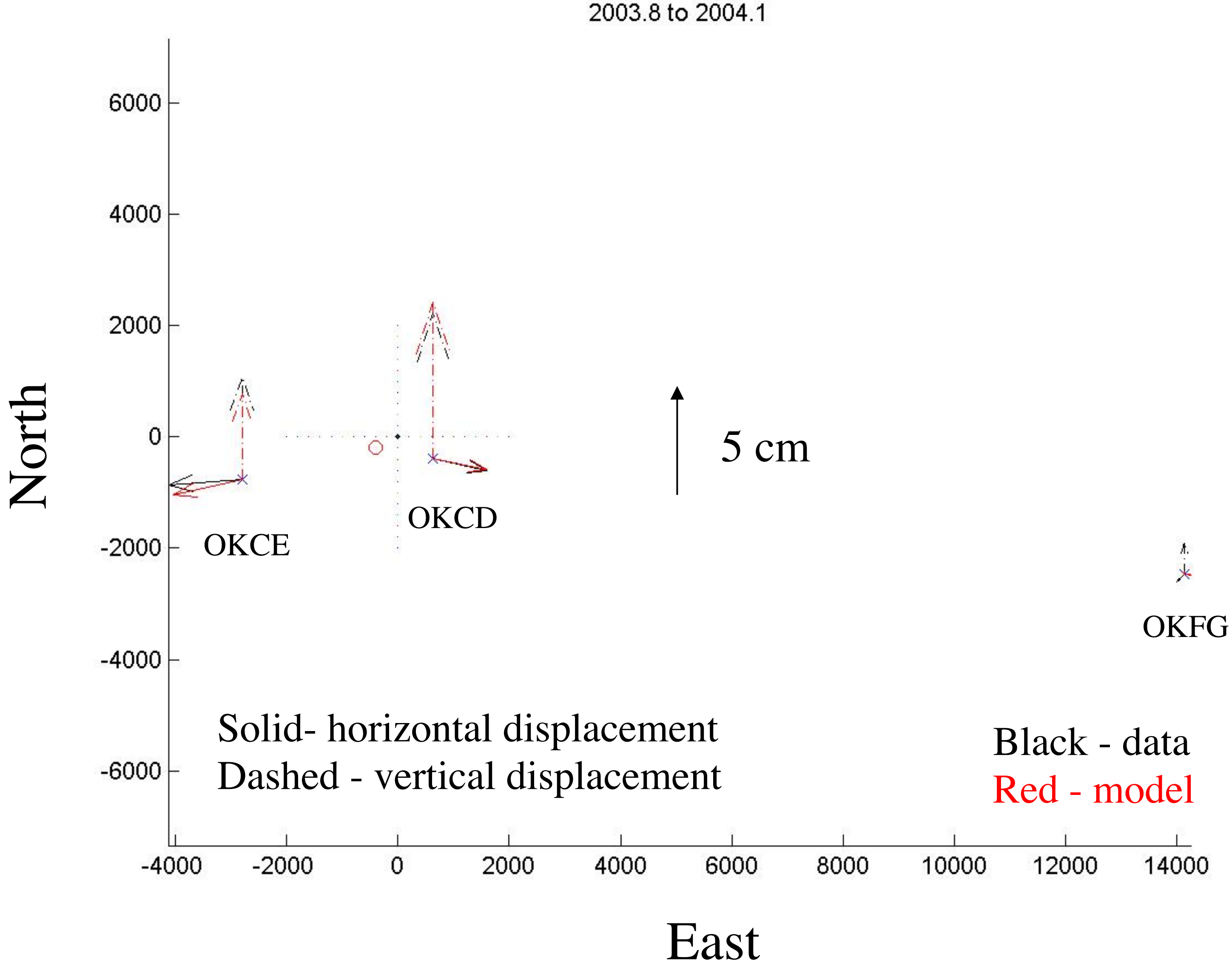
How Well Determined are Source Parameters?

- There is always a tradeoff between depth and source strength (p, or ΔV). Why?
  - Limitations in sampling
    - Stronger deep source produces same maximum uplift as a weaker shallow source
    - You distinguish the two by having enough data from different distances to distinguish spatial pattern
    - Often don't have enough data, or there are other complications
  - Problem with GPS: only a few displacements
  - Problem in InSAR: often no data directly above source

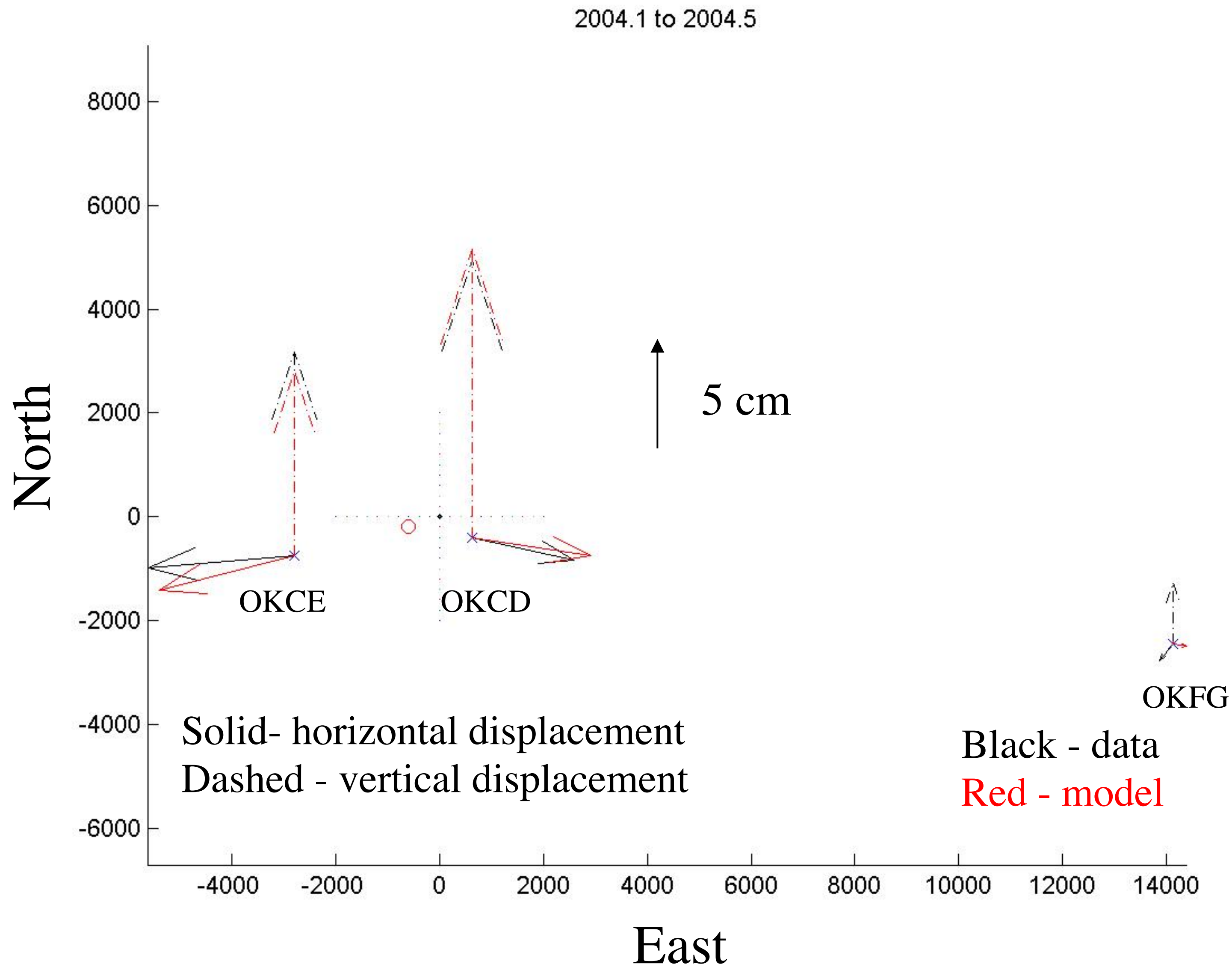
Depth-Source Strength Tradeoff



Before Event



Displacements During Event

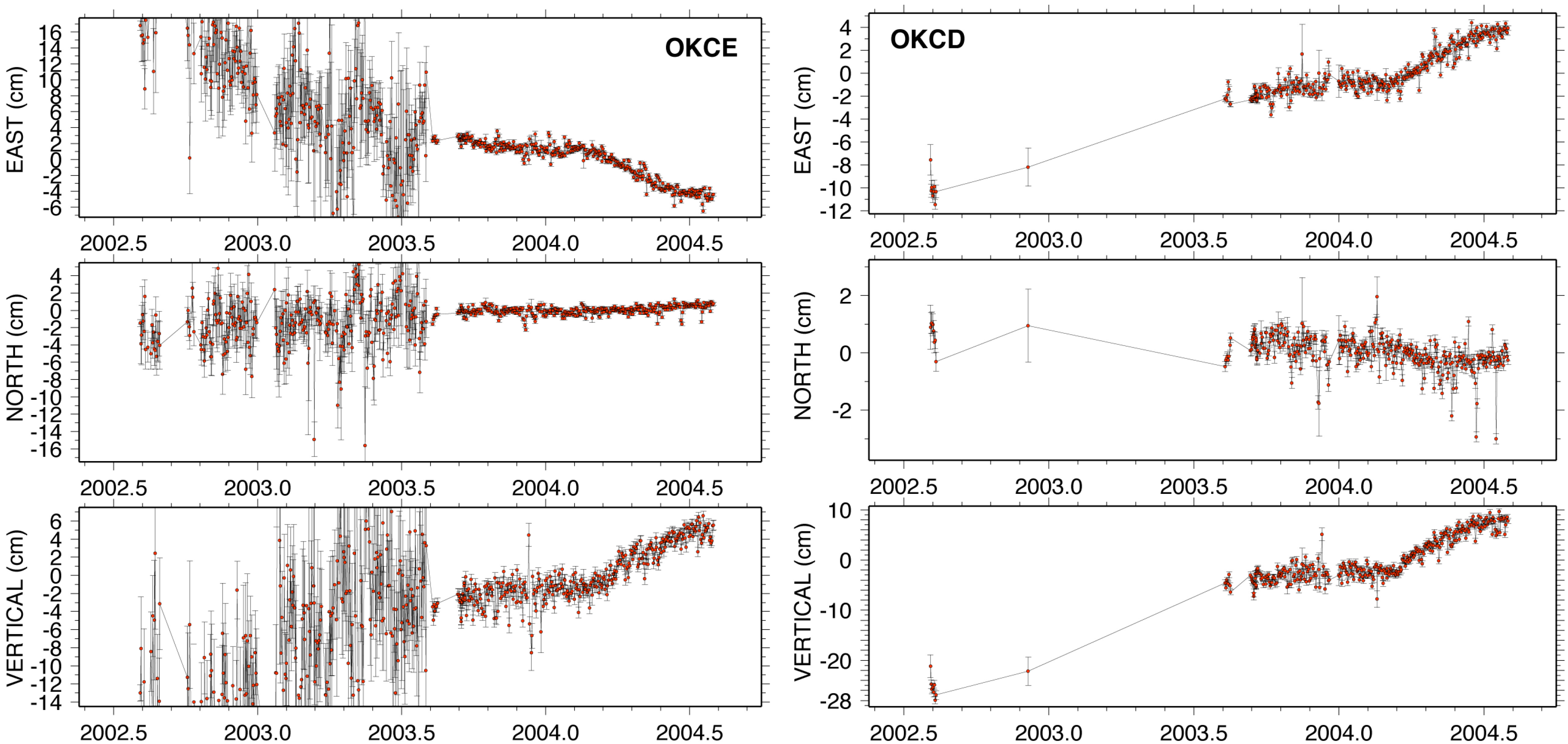


Comparison of Source Models

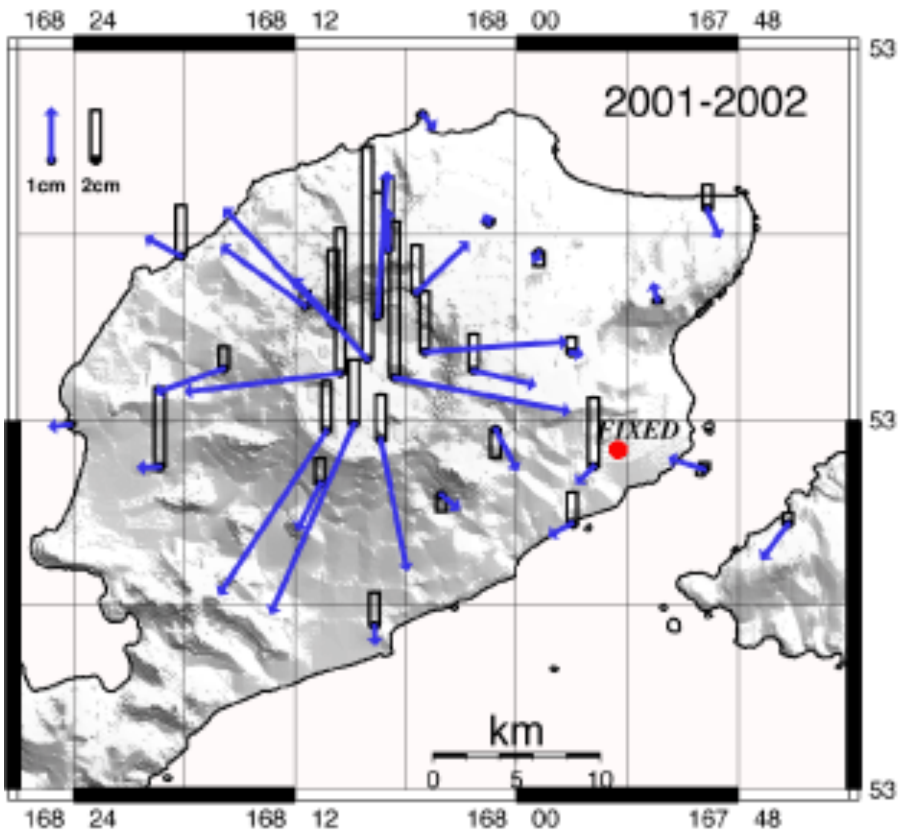
- Horizontal location of source is the same within 200 meters
- Best-fit depth is 3 km for both
- Source strength is 2.1 times higher during event.
  - If we require source strength to be the same during event, it would require source to be at ~2 km, and misfit would be ~3x higher.
  - Volume change ***rate*** before: $+7.3*10^6$ m^3/yr (0.4 yr)
  - Volume change ***rate*** during: $+19.6*10^6$ m^3/yr (0.4 yr)

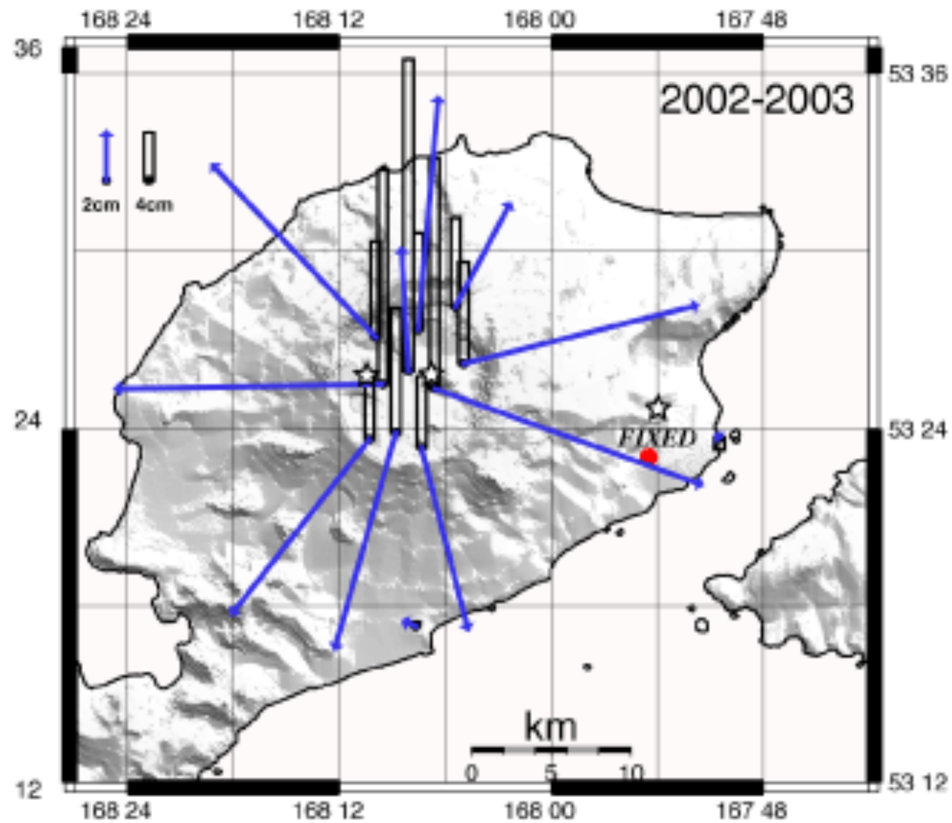
1990s rate (InSAR): $\sim+5*10^6$ m^3/yr; eruption: 70 m^3

Time Series (older data)

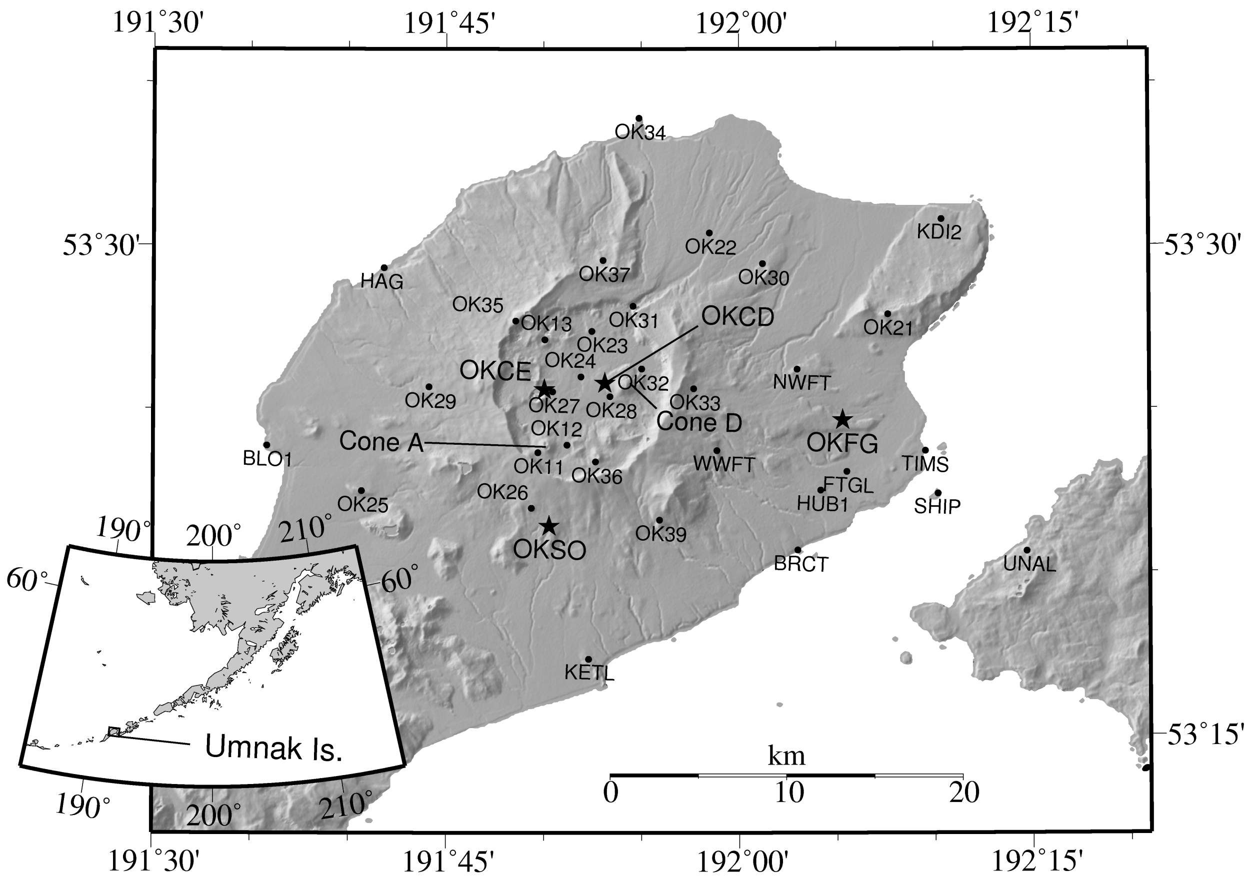


GPS Displacements

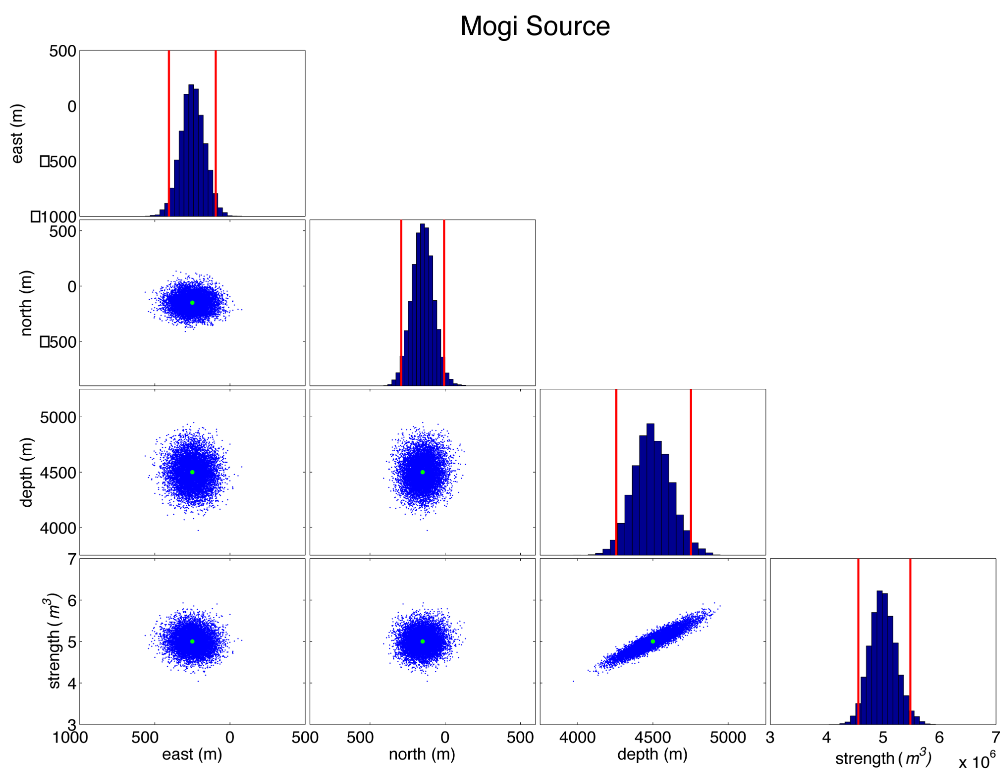




Okmok Recent Data + Eruption



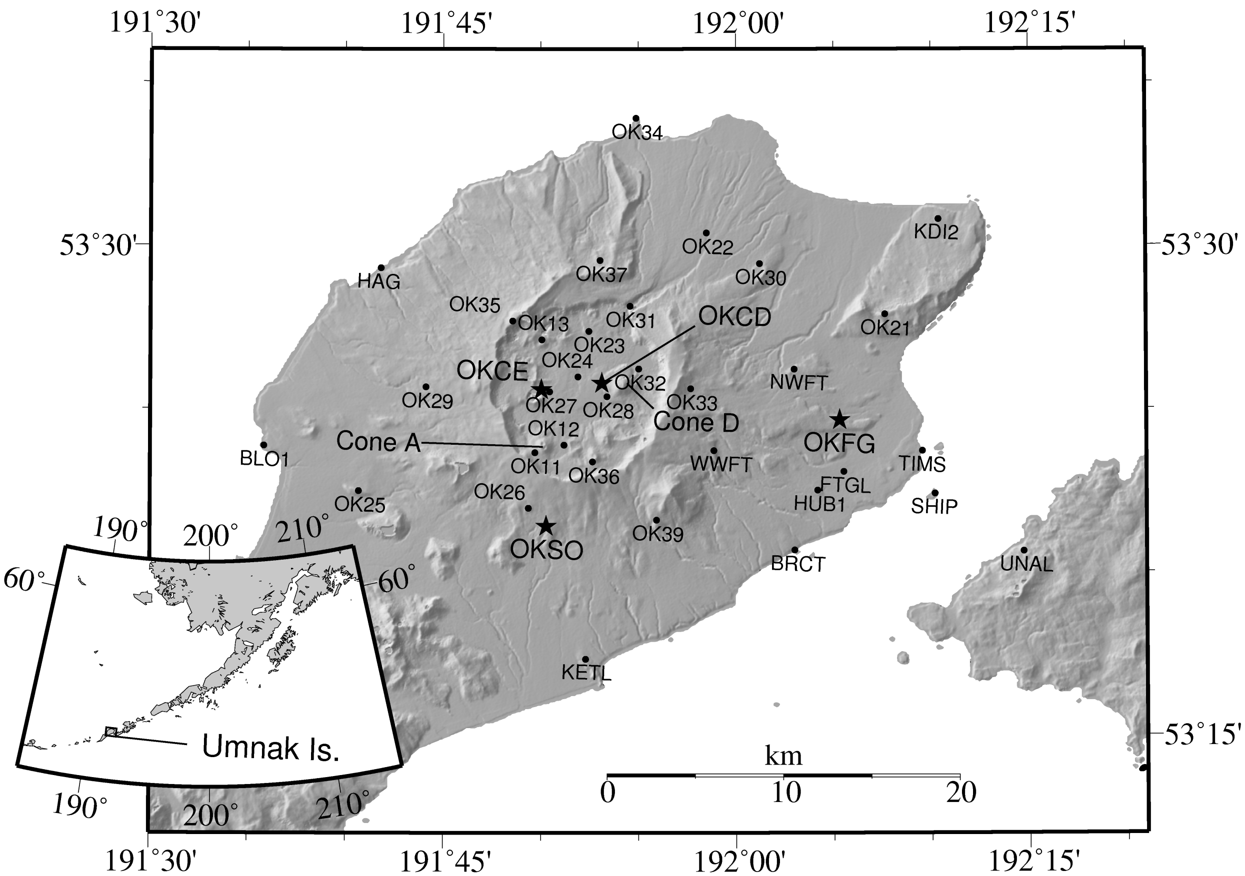
Theoretical Resolution of Network



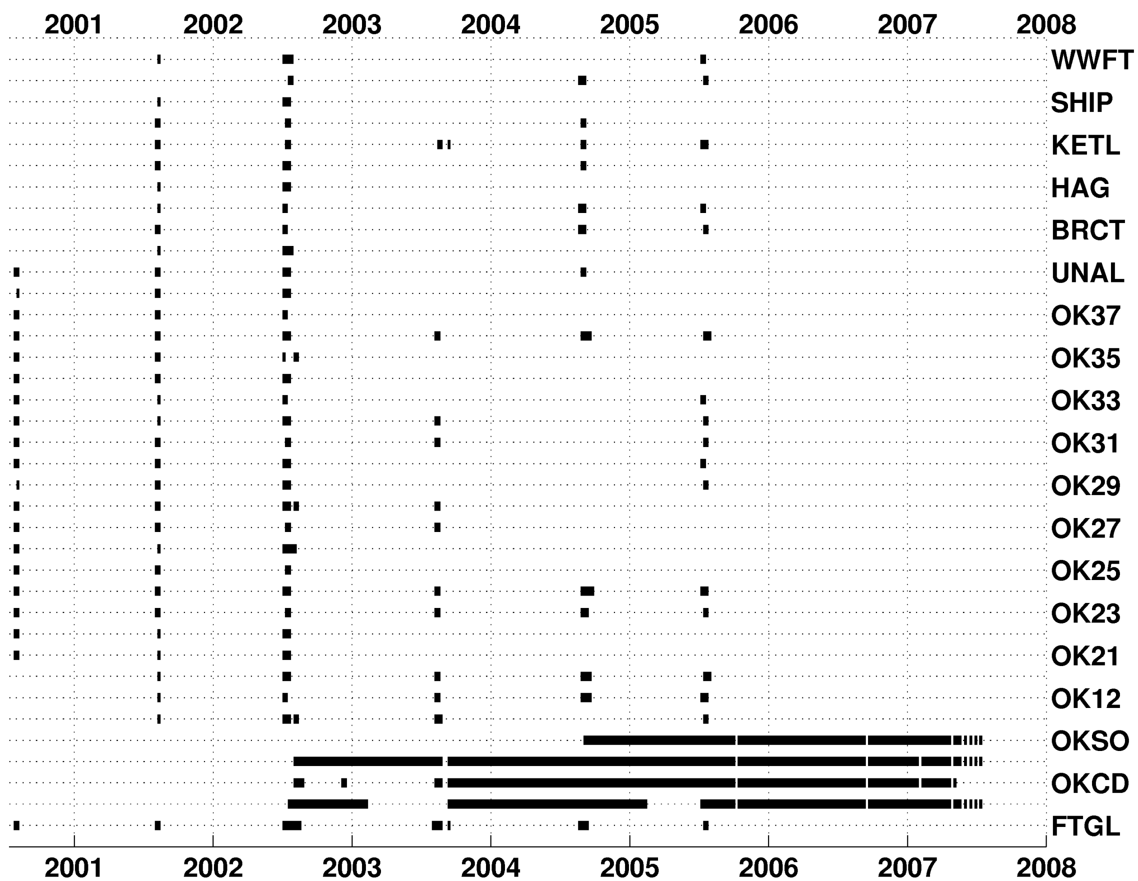
Fournier et al. [2009, JGR]

- Test ability of network to determine source location using synthetic data
- Depth-source strength tradeoff is still there even with dense GPS network
  – Can't get rid of it, only minimize it and live with it.

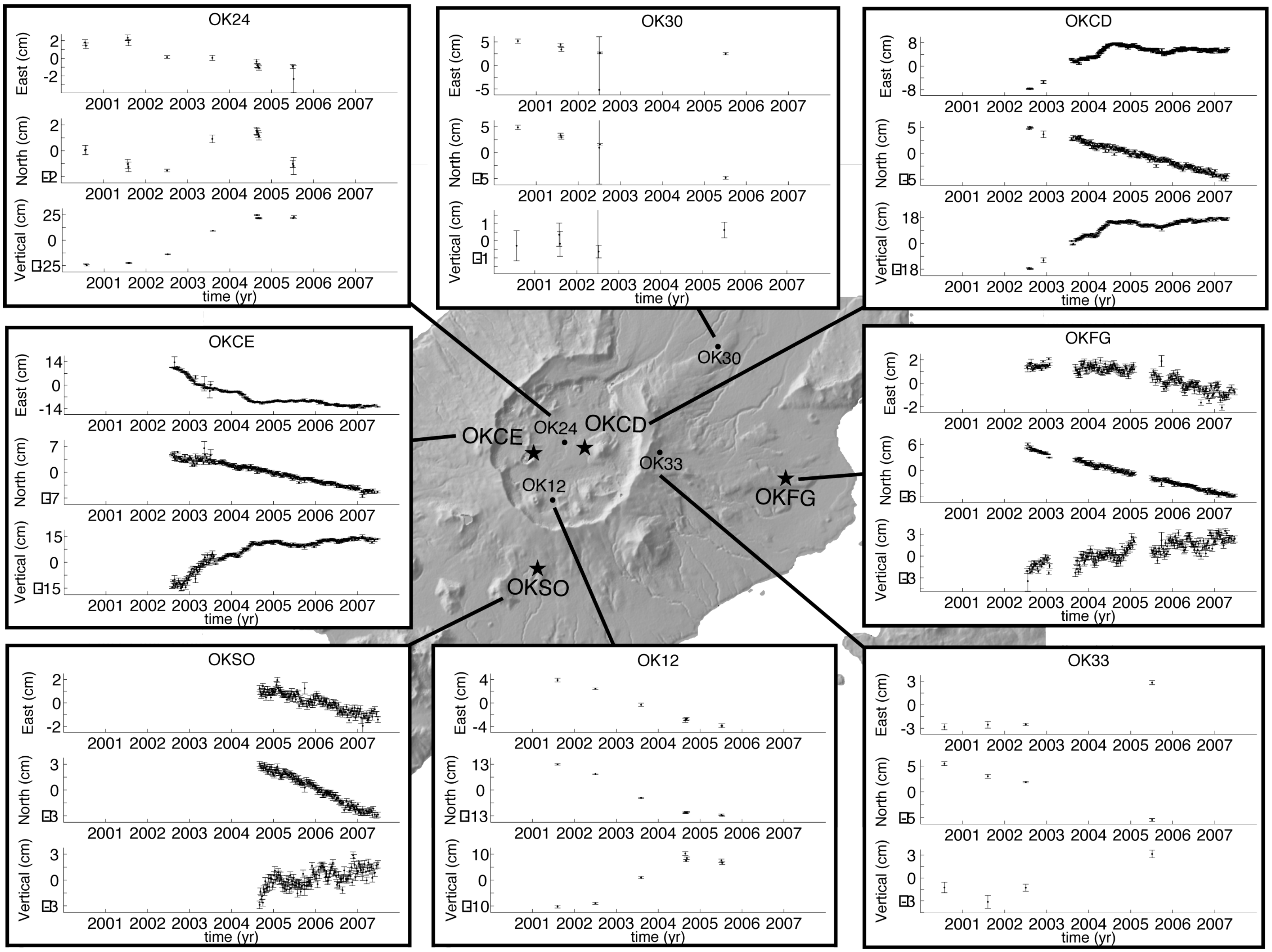
Okmok GPS Network



GPS Site Measurement History



Selected GPS Time Series

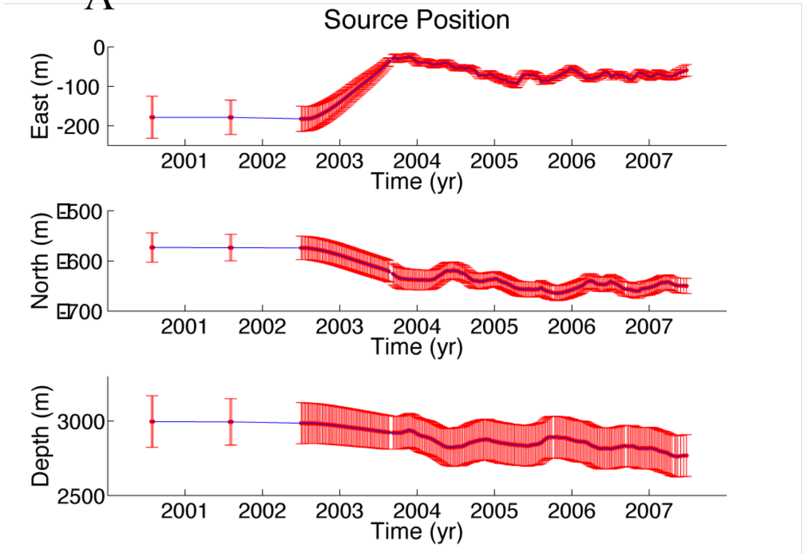


Modeling Strategy

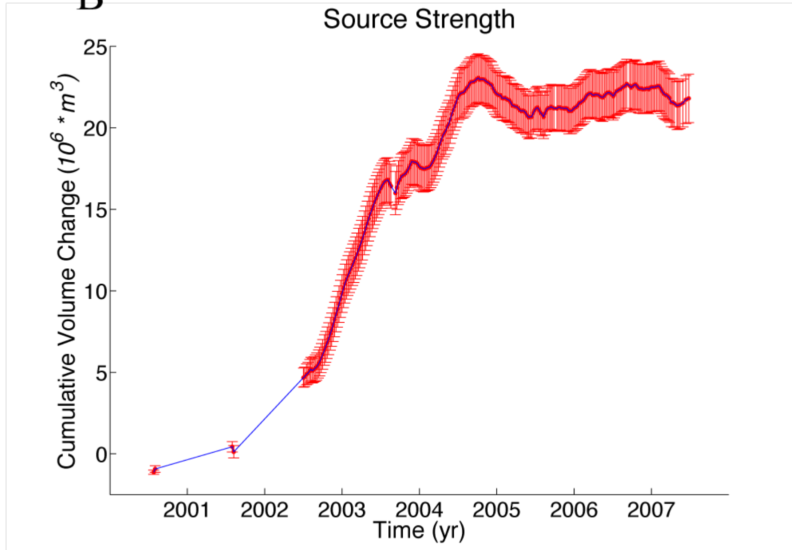
- Use a non-linear Kalman filter approach
  - Kalman filter is a sequential estimation scheme
  - Allows estimates to vary with time according to different stochastic noise models
  - This non-linear version is the "Unscented Kalman Filter", which attempts to estimate the probability distribution of the parameter values as a function of time.
- Model is Mogi source that is allowed to move with time, plus a steady tectonic velocity for all sites, plus daily reference frame noise.

Model Results

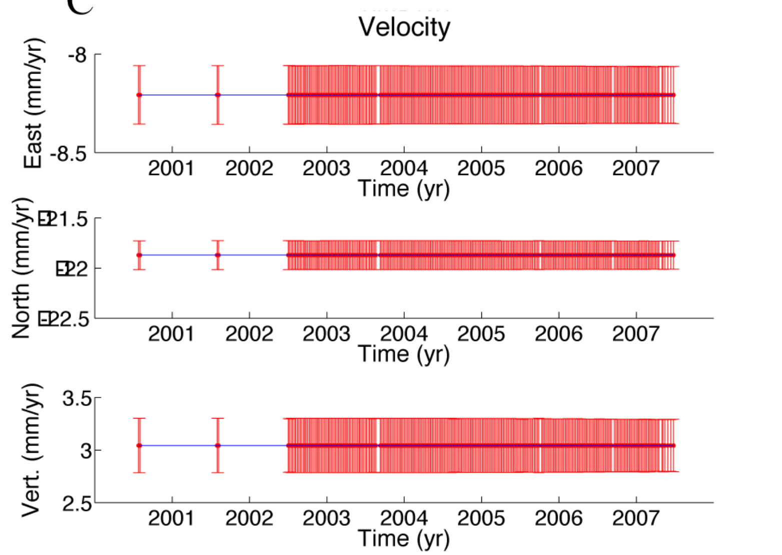
A



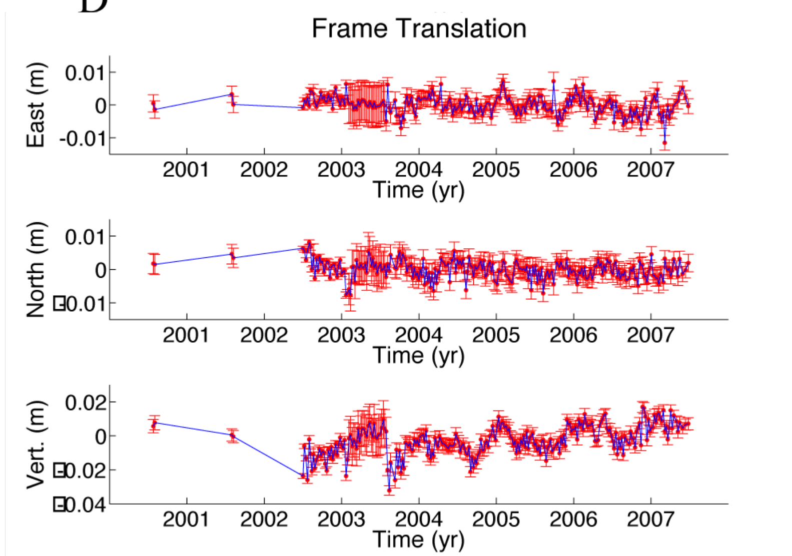
B



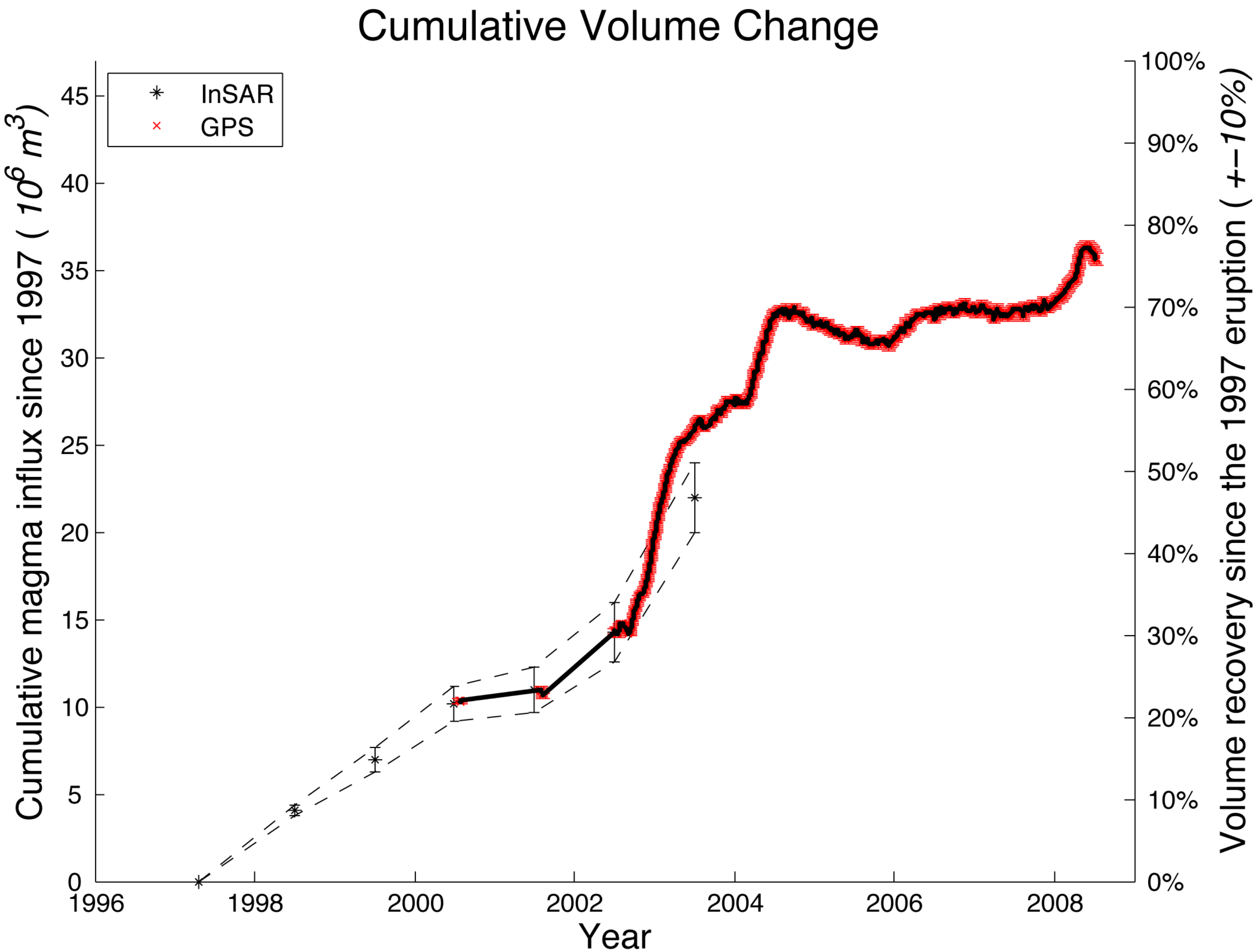
C



D

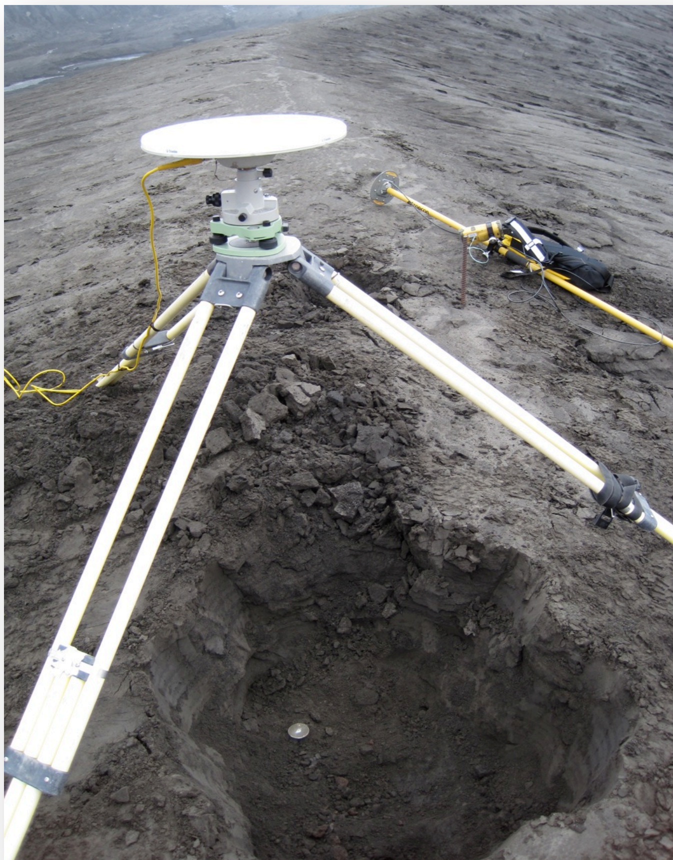


Volume Change Inferred from Model



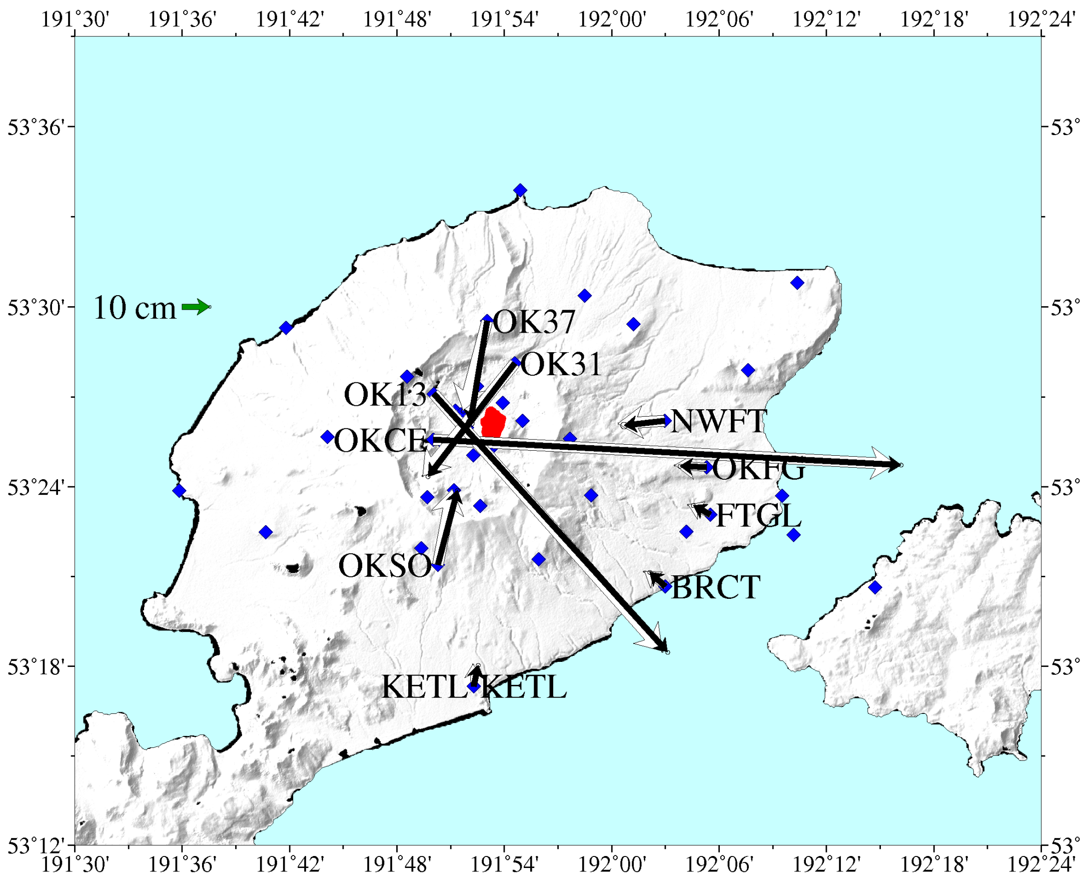
2008 Eruption

Inside the Caldera

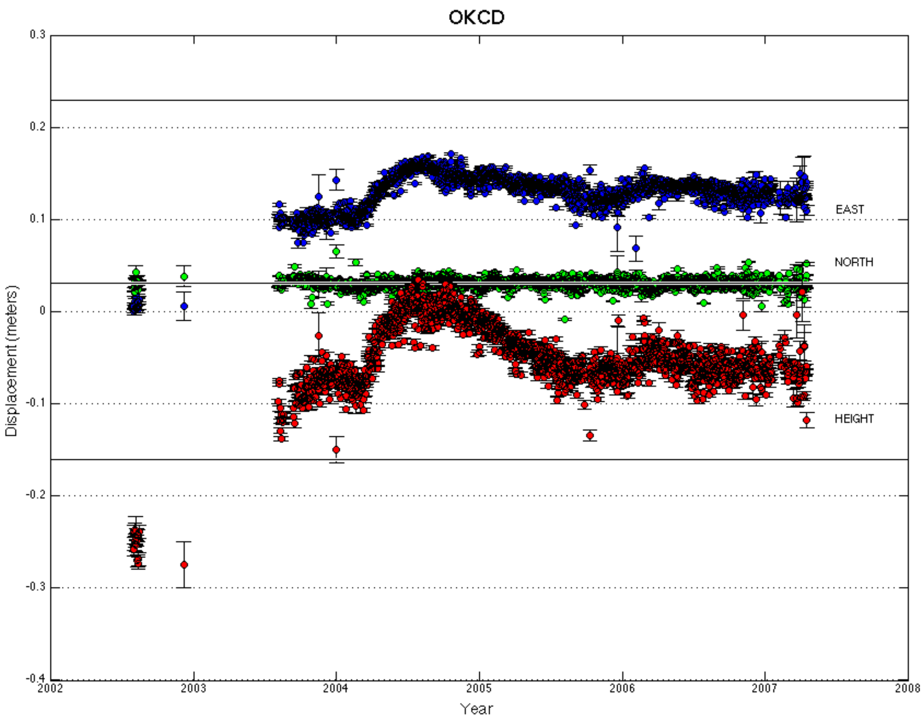


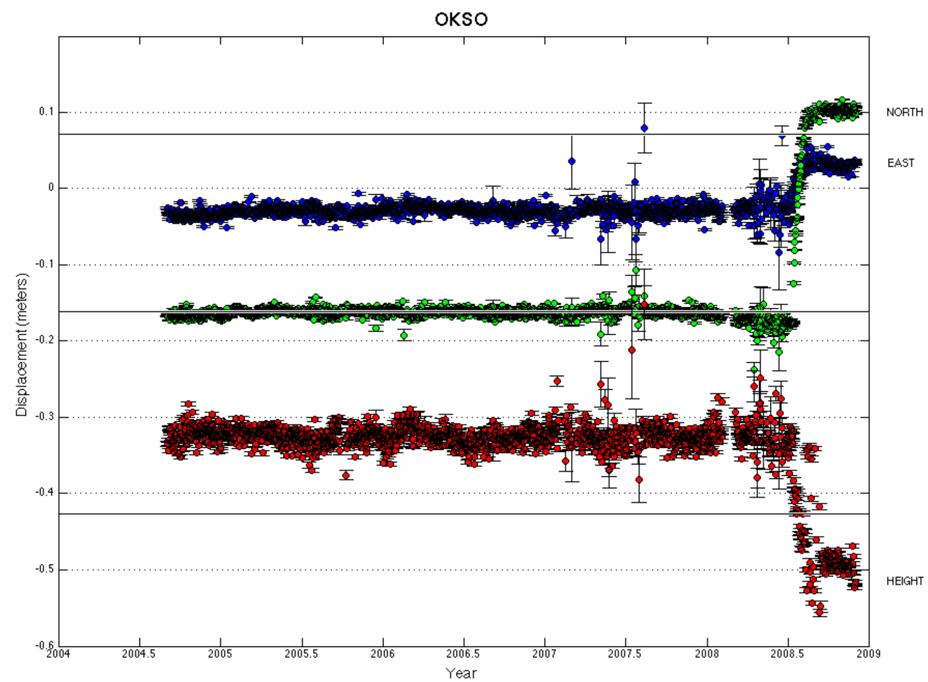
Site OK12 near base of Cone F: 40 cm airfall

Displacements >1 meter inside caldera



GPS Site Time Series

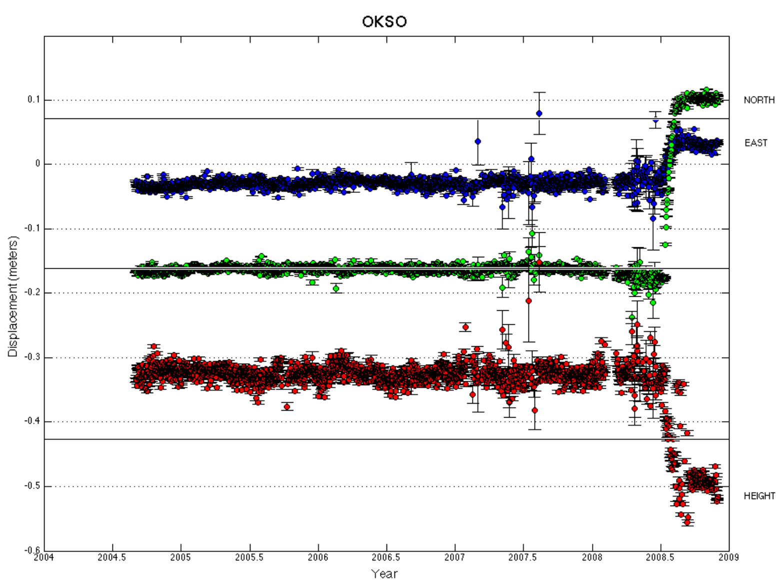


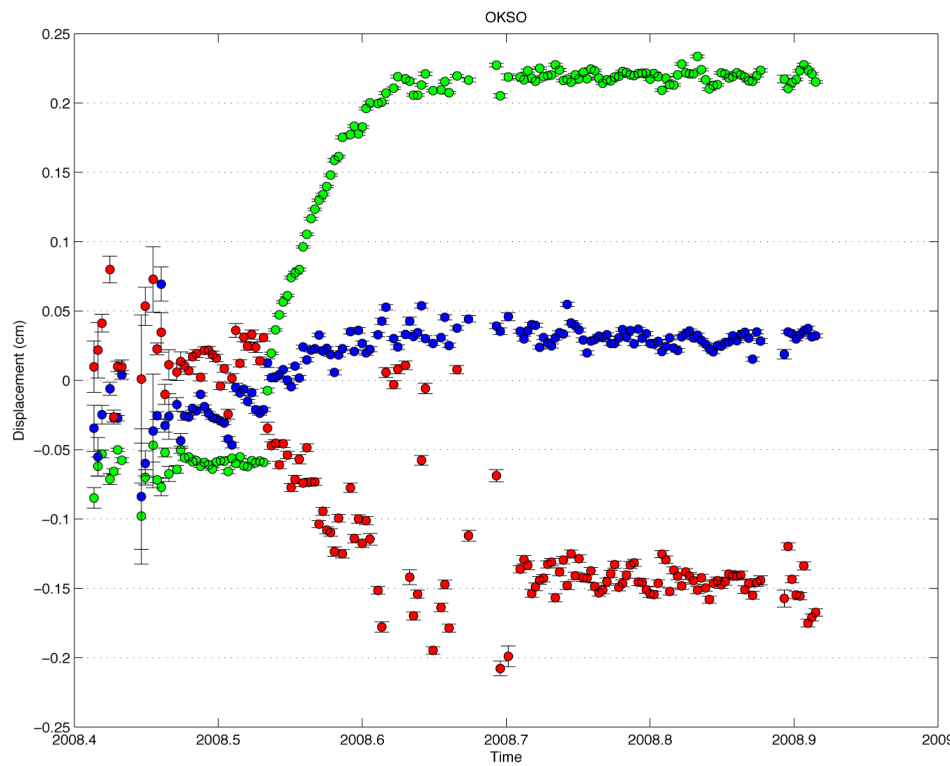


Average rate from 2005.0-2008.0 subtracted

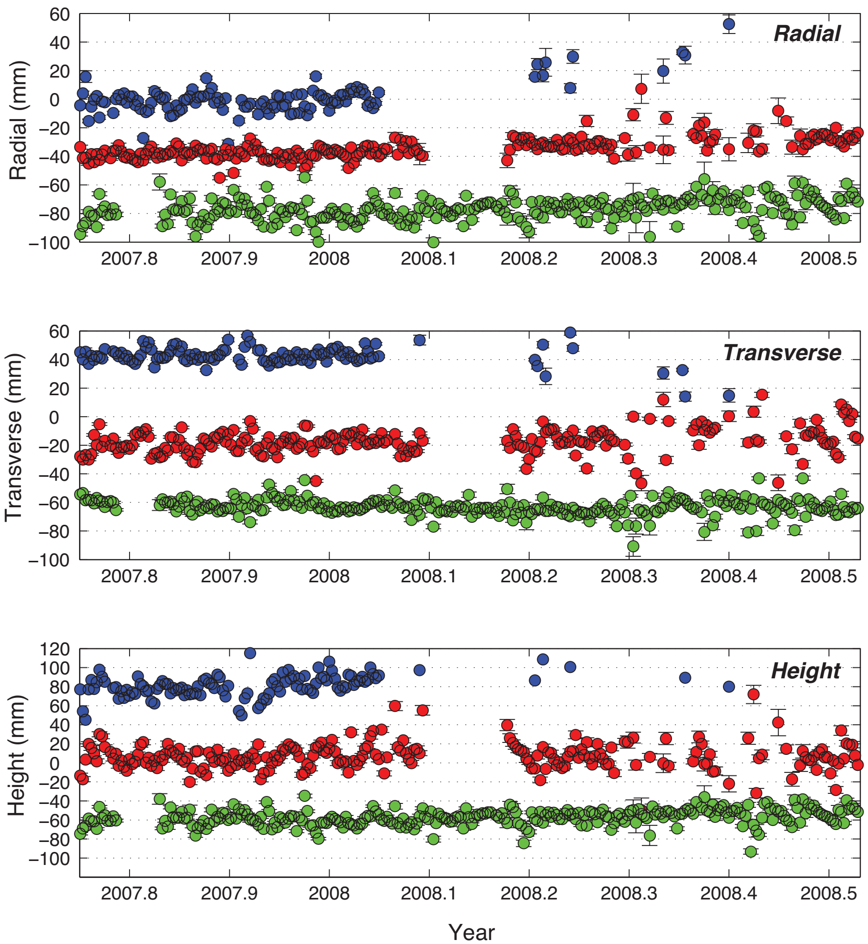
Eruption Time Period in Detail

Large scatter in vertical from signals delayed by heavy ash plume.



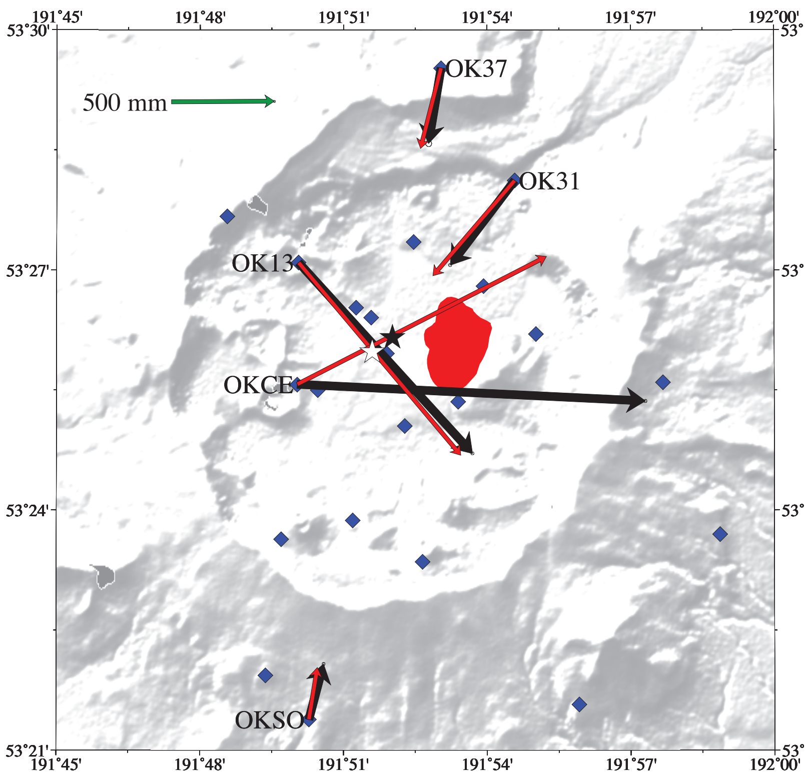


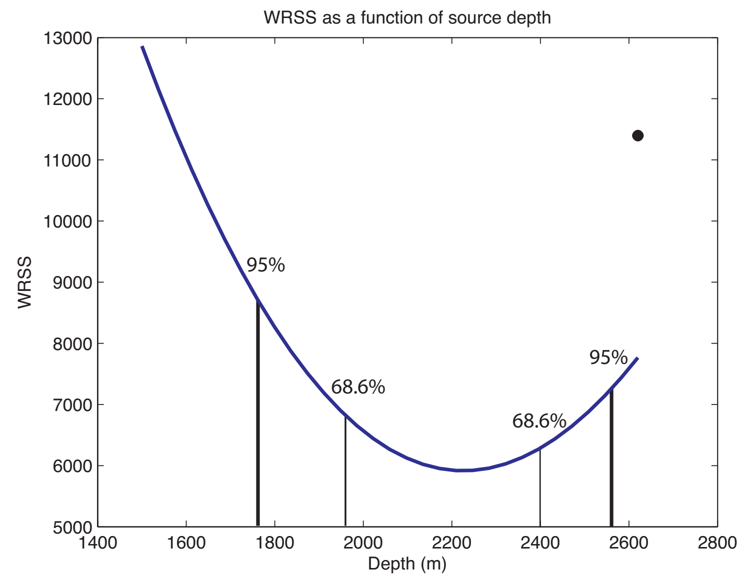
Final Pre-eruptive Inflation



- Radial, transverse and vertical components relative to the 25-2008 trend.
- Continuation of trend would give a flat line
- OKCE (blue) deviates by early 2008

Model, Residuals, Misfit





Deflation History During Eruption