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An Ongoing Episode of Magmatic Inflation at the Three Sisters Volcanic Center, Central Oregon Cascade Range

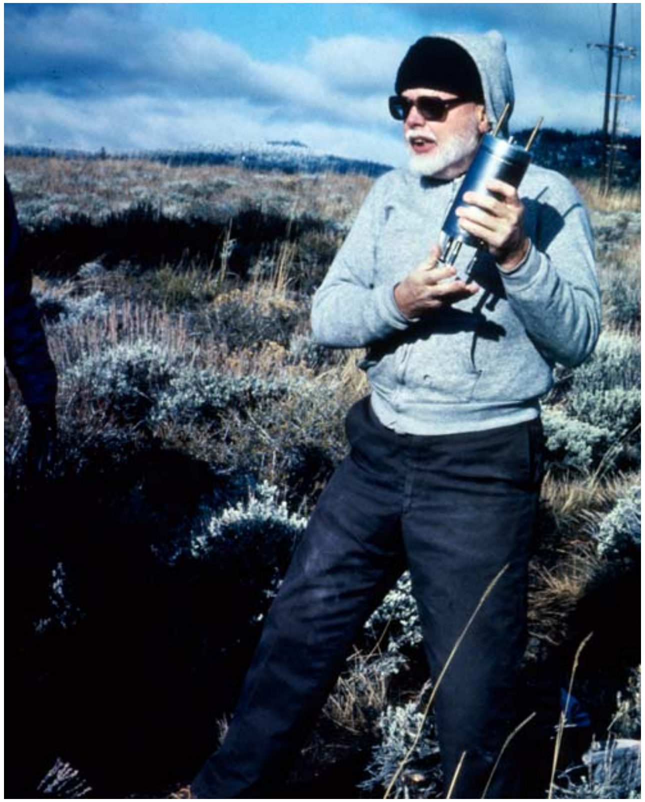
Inferences from Recent Geodetic and Seismic Observations

Dan Dzurisin, Mike Lisowski, Seth Moran, Chuck Wicks,
Mike Poland, and Elliot Endo

U.S. Department of the Interior
U.S. Geological Survey

IN MEMORIAM

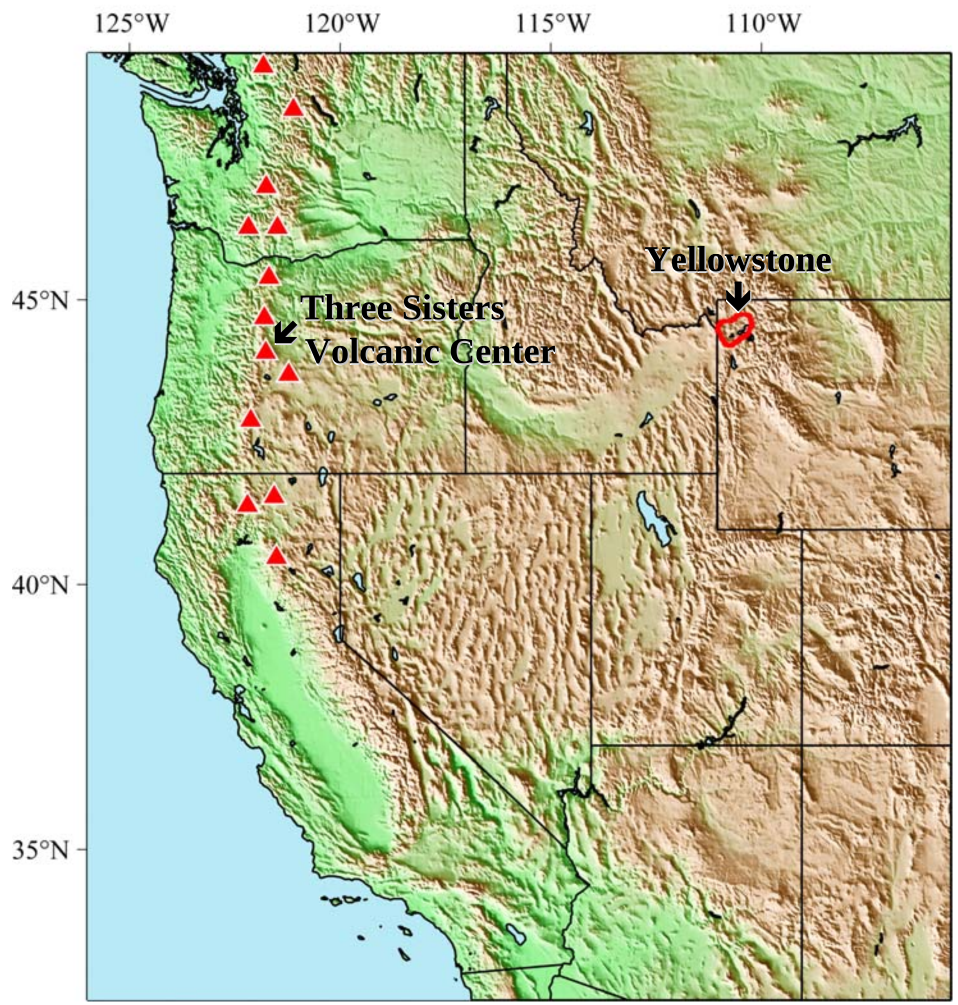
Robert P. Sharp
1912-2004



James A. Westphal
1930-2004

Three Sisters volcanic center

- Located in central Oregon Cascades, with highest vent density and lava production rate in the entire Cascade arc
- Tens of vents spread over 400-km^2 area have erupted in past 4000 years
- Five large Quaternary cones: North Sister, Middle Sister, South Sister (youngest), Broken top, and Mount Bachelor
- At South Sister, two eruptive sequences about 2200 and 2000 years ago produced rhyolite tephra, pyroclastic flows, lava flows, and lava domes
- Nearby, dominantly effusive eruptions of basaltic and andesitic lavas built large shield volcanoes such as Belknap Crater as recently as 1600 to 1200 years ago



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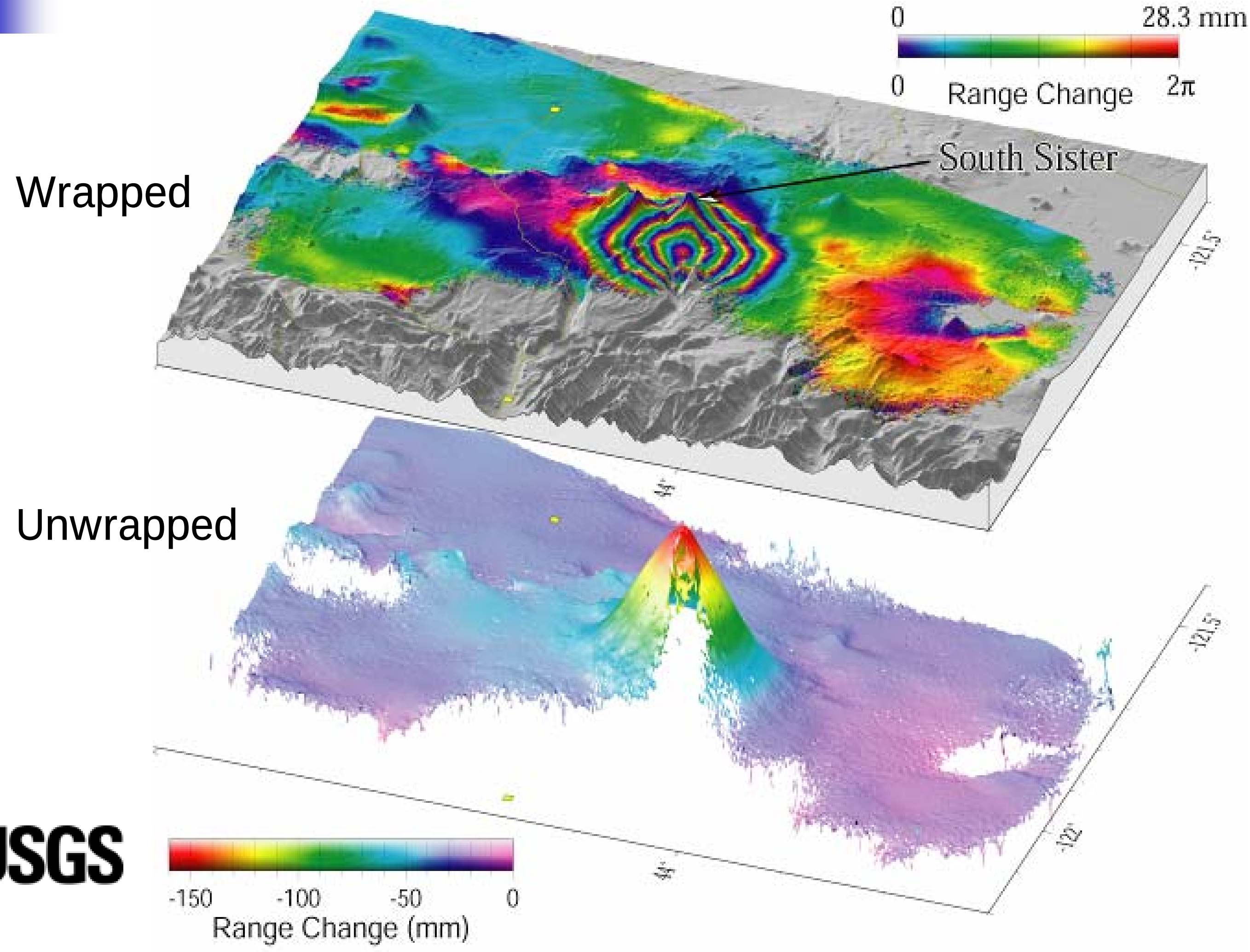
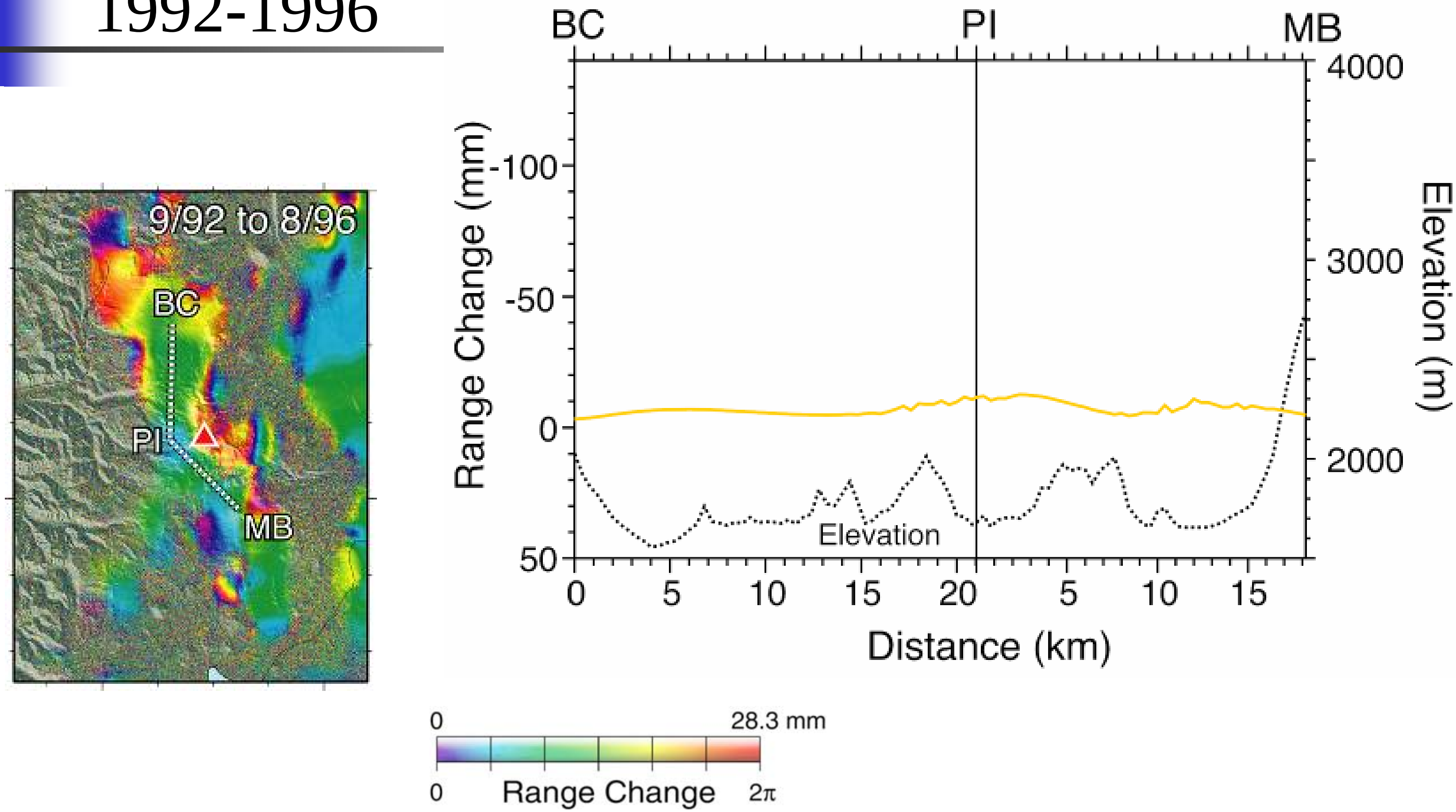
Radar interferometry reveals ~14 cm of uplift from 1997-1998 to 2001



1992-1996



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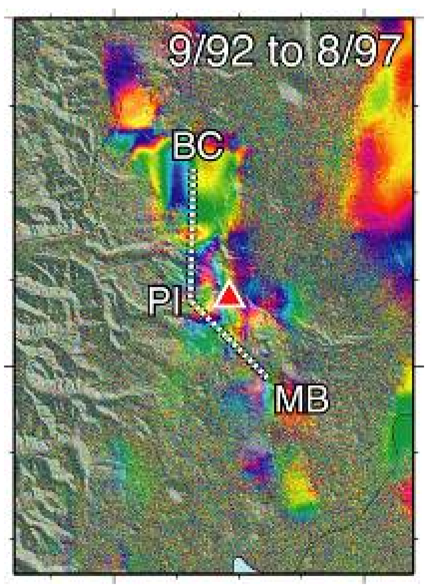
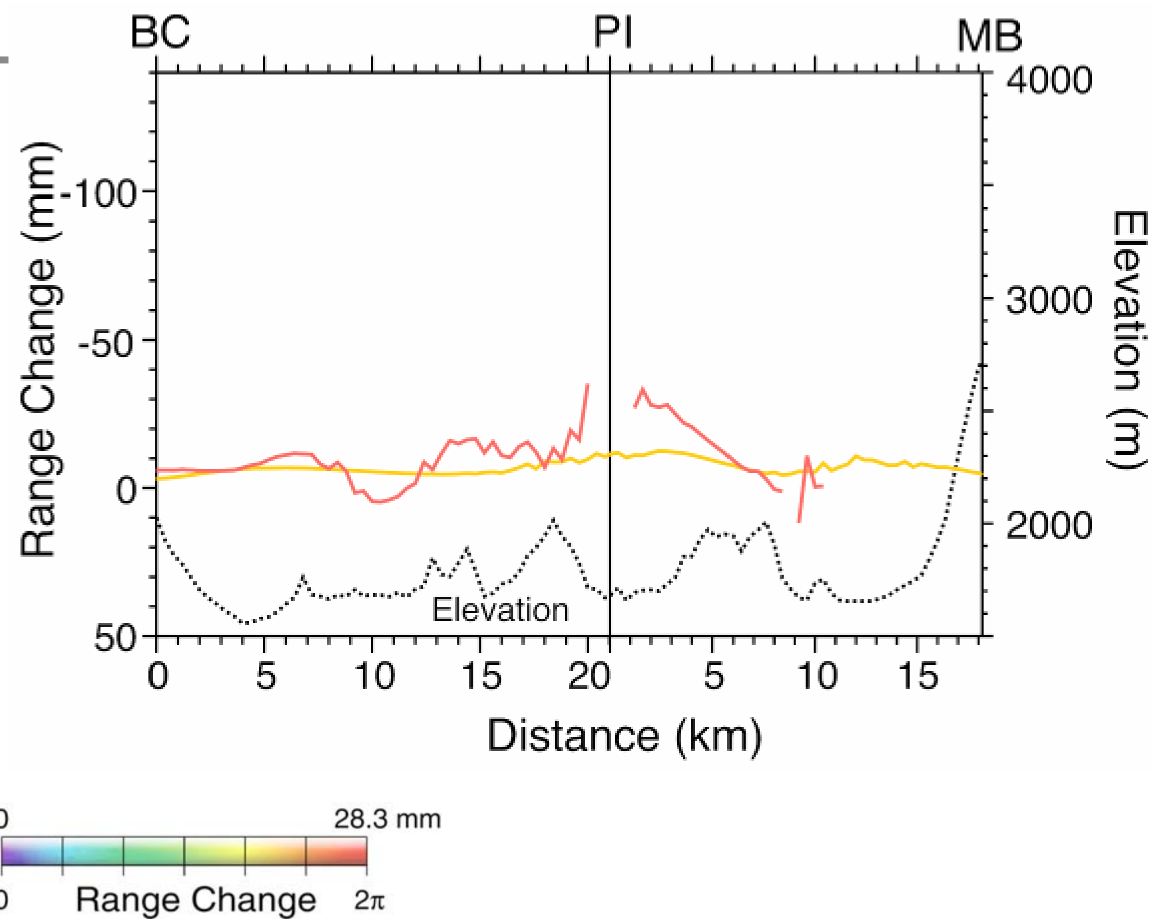
1992-1997





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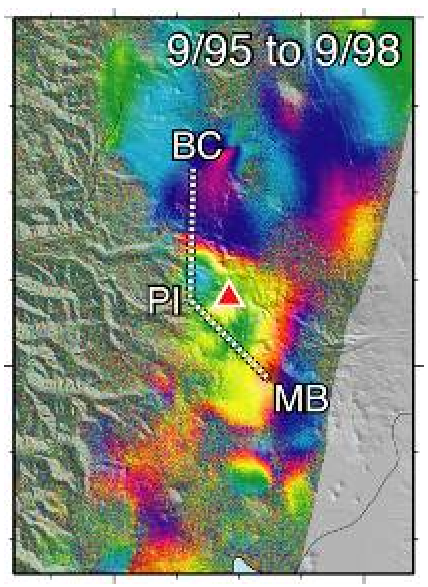
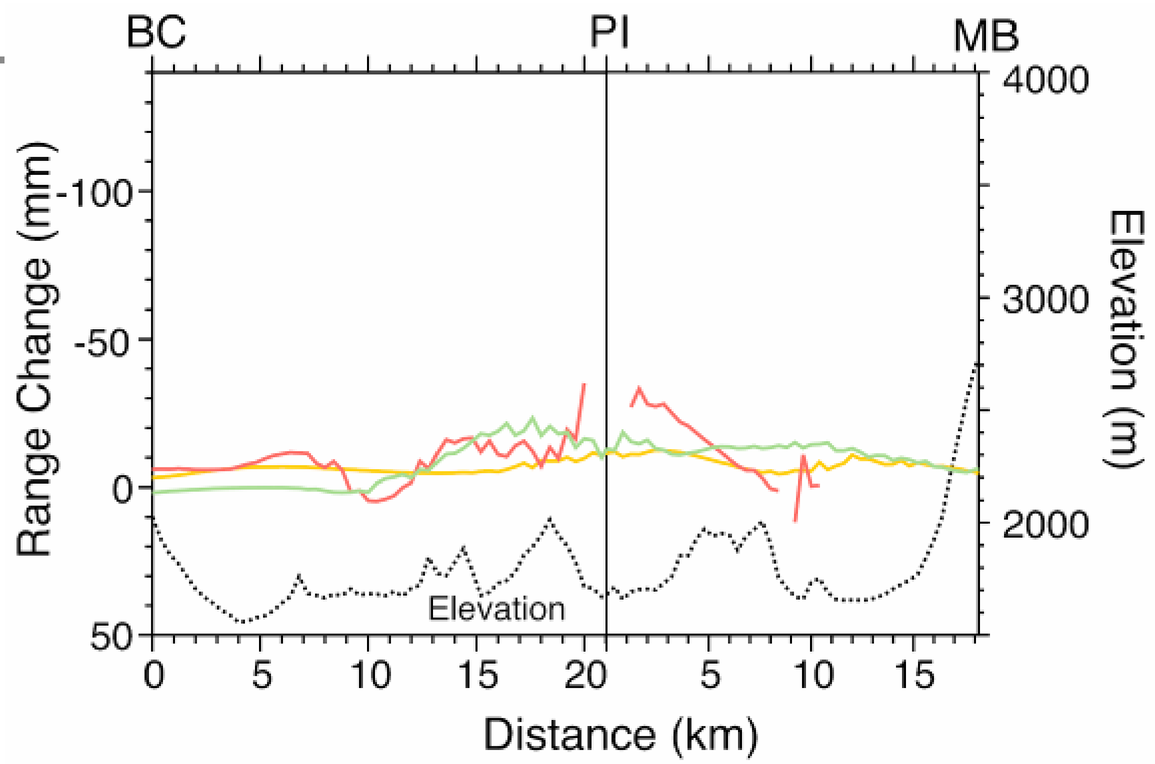
1995-1998





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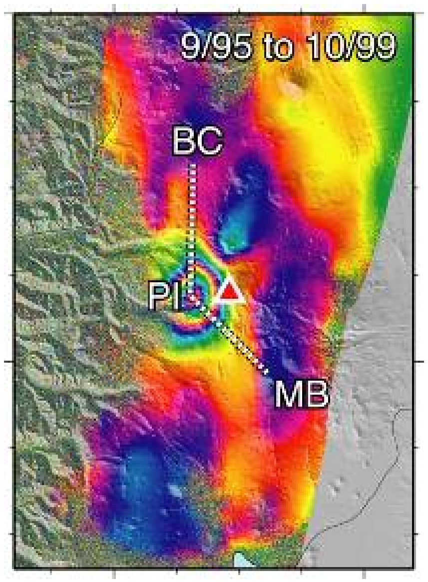

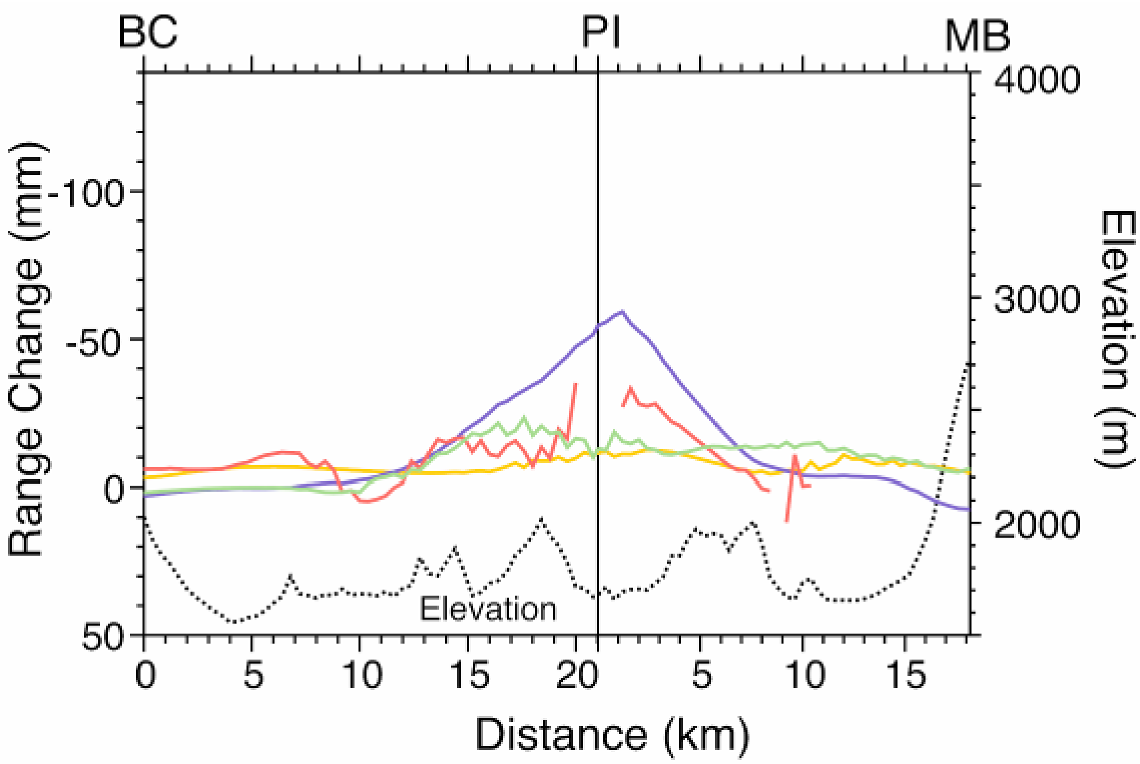

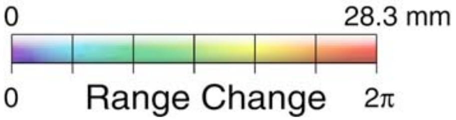

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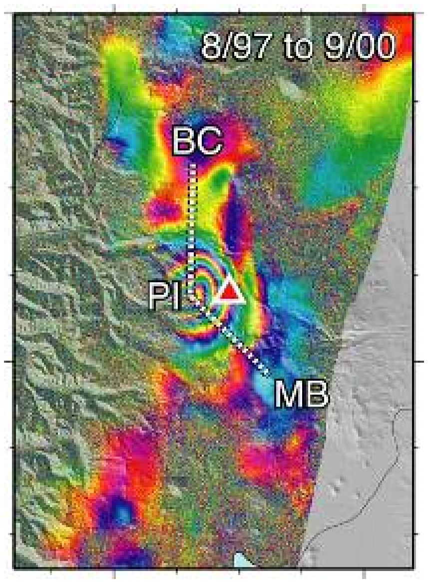
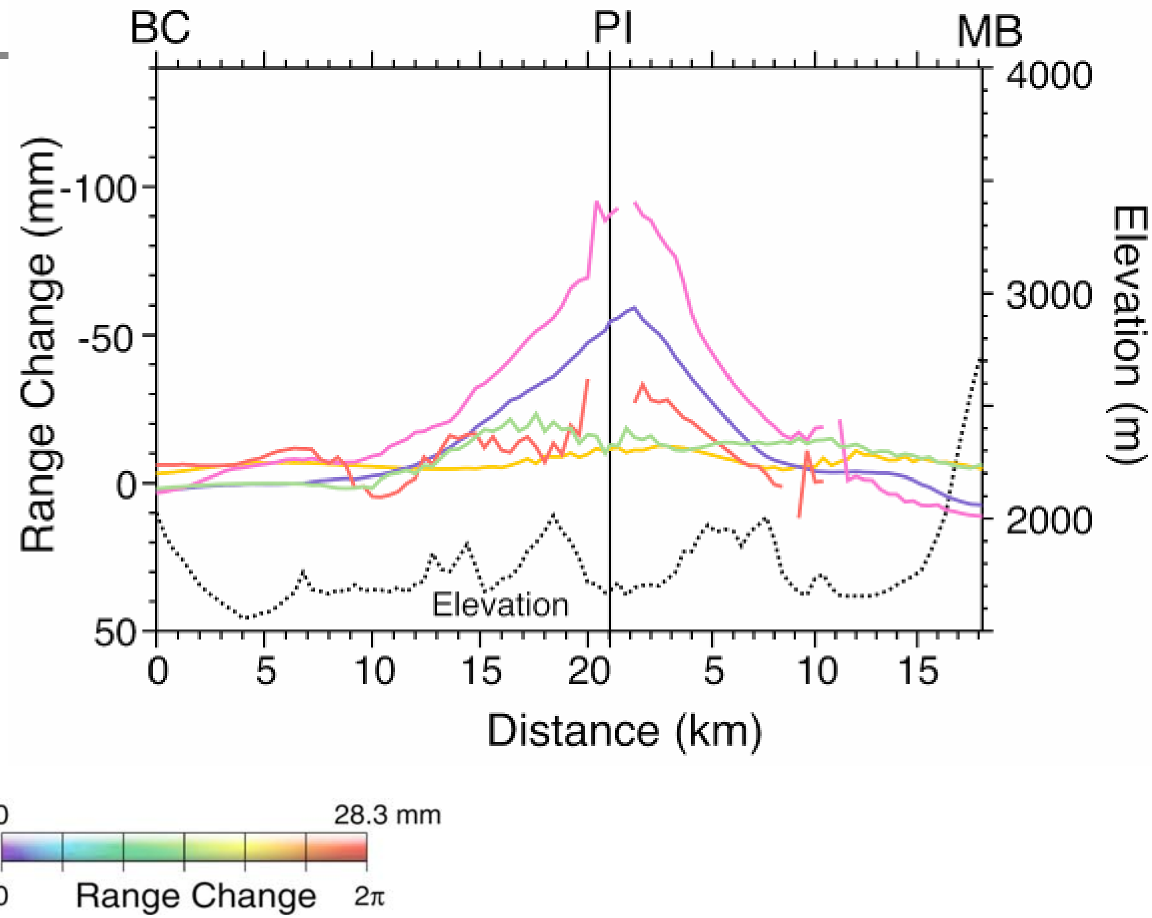
1997-2000





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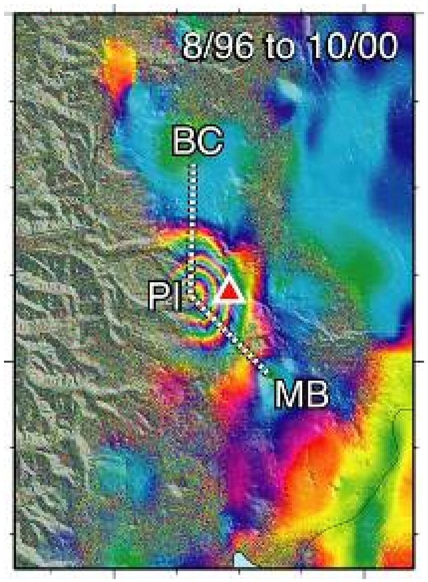

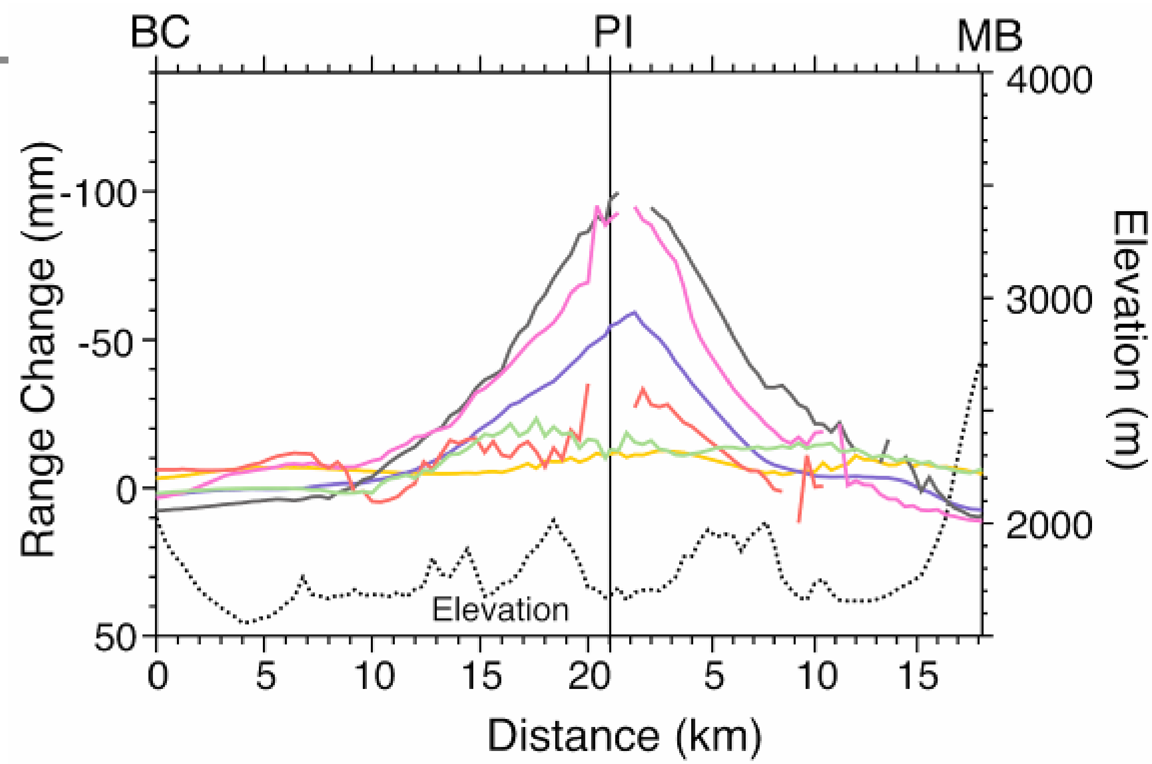

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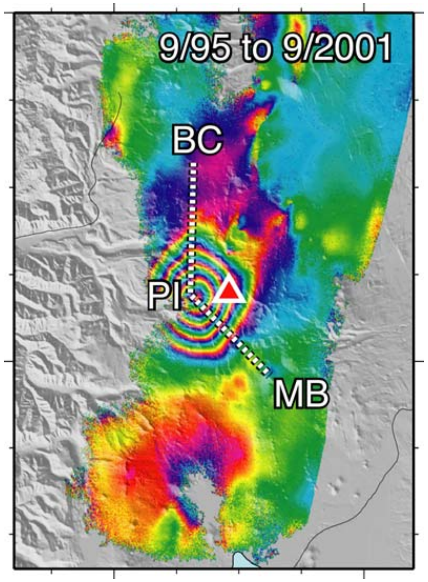

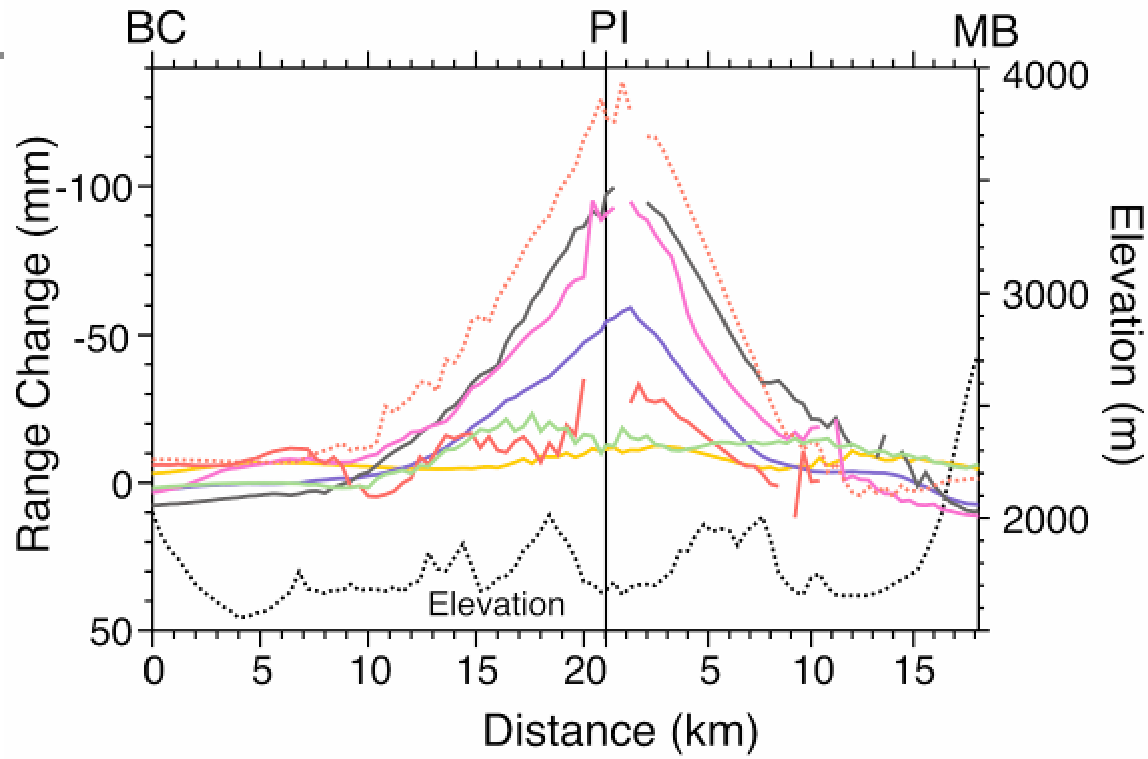

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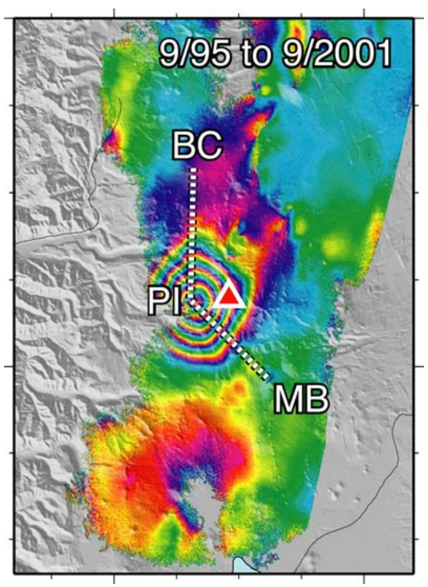
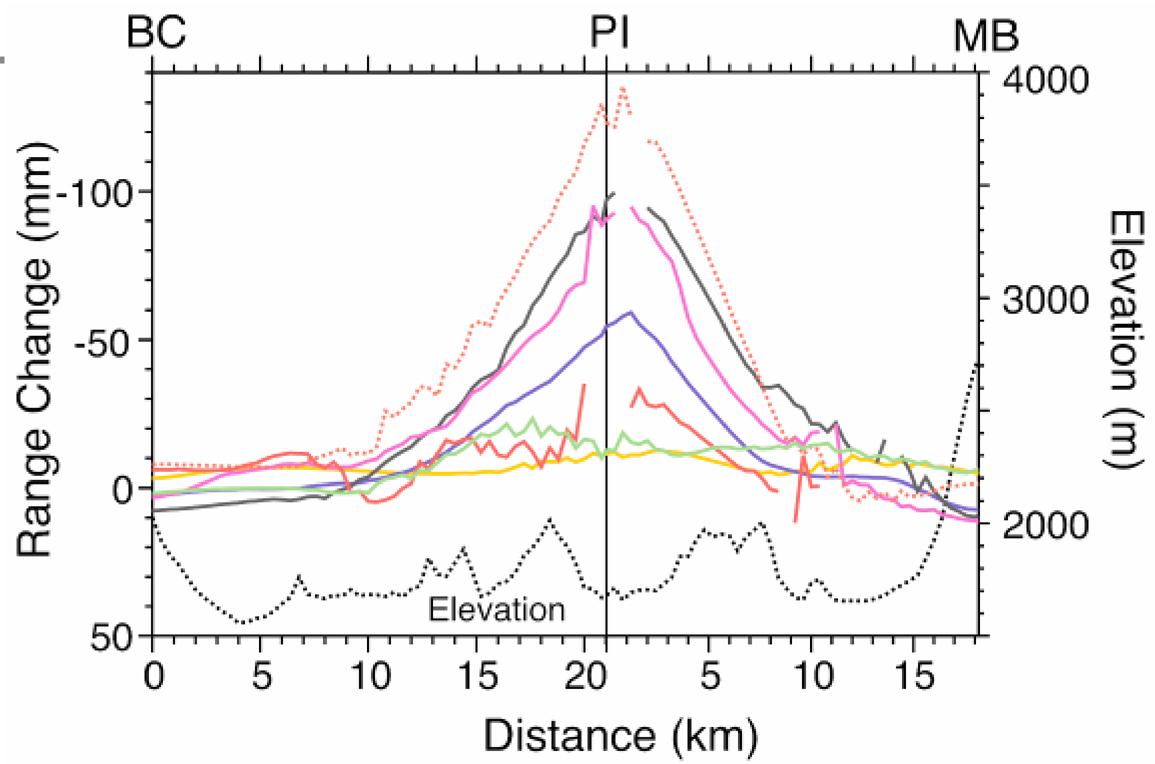


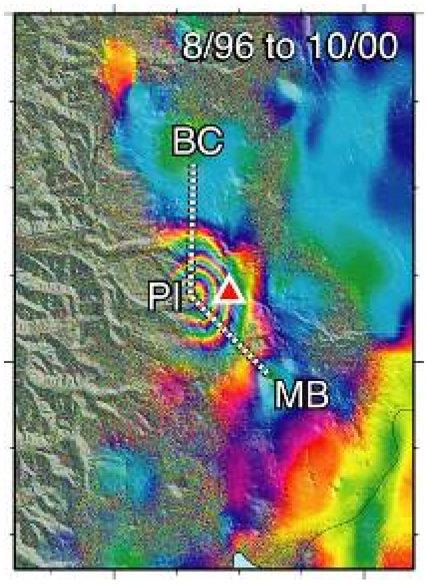
9/95 to 9/2001
BC
PI
MB

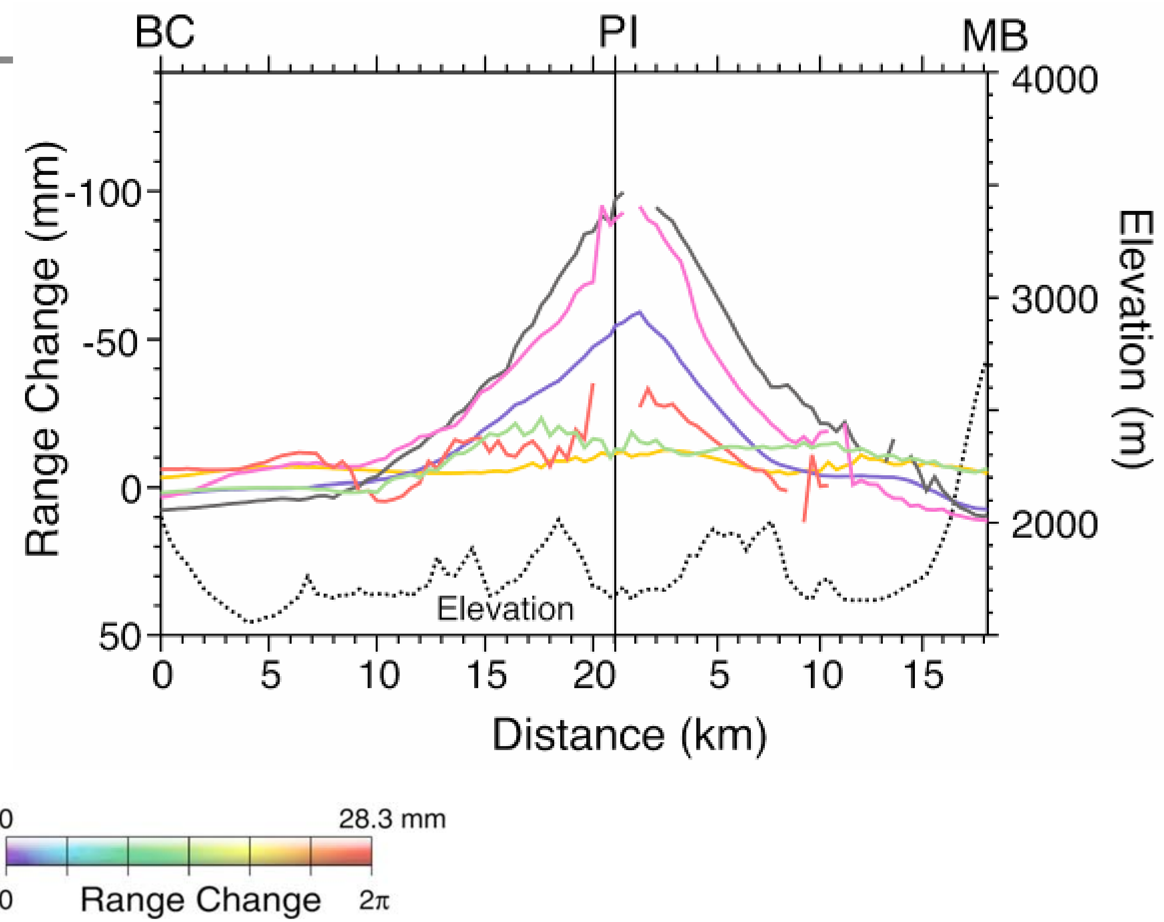


BC
PI
MB
Range Change (mm)
-100
-50
0
50
4000
3000
2000
Elevation (m)
Elevation
0
5
10
15
20
5
10
15
Distance (km)

0
28.3 mm
0
Range Change
2π

1996-2000





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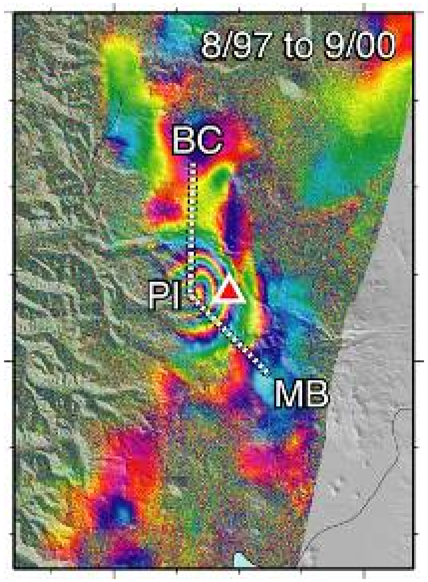
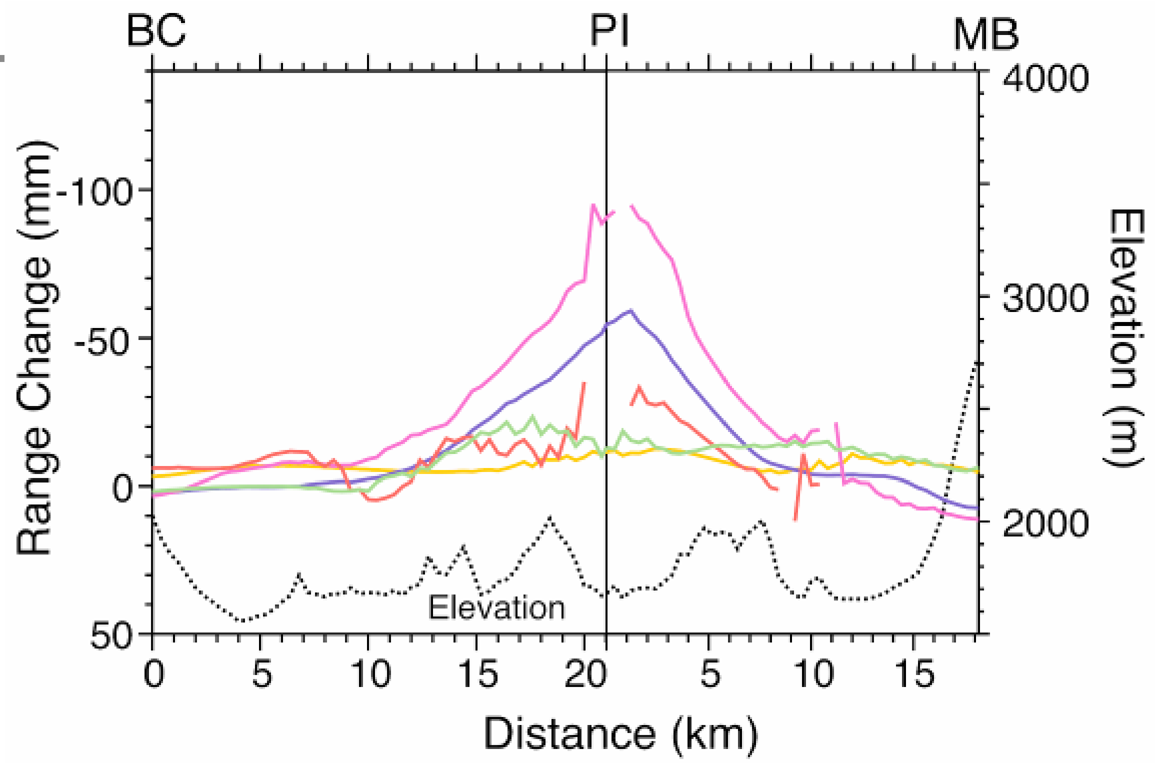
1997-2000


8/97 to 9/00
BC
PI
MB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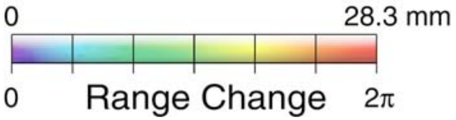
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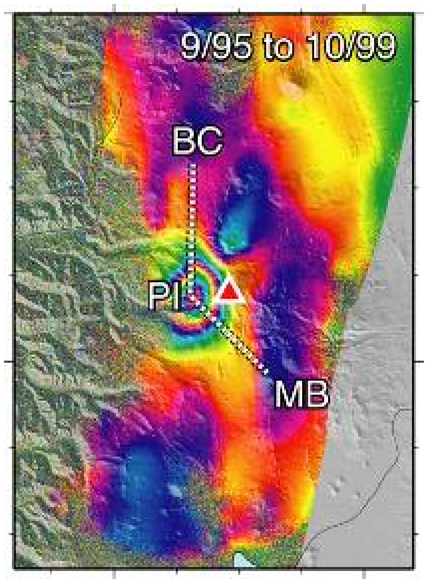
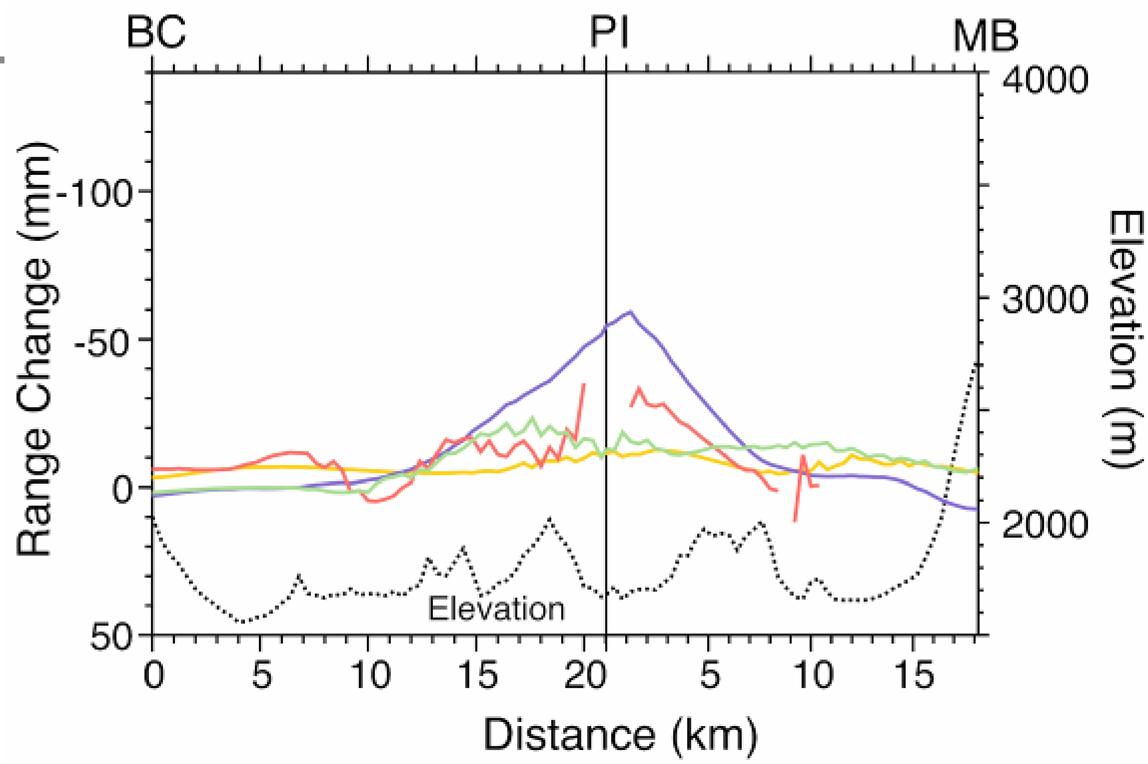
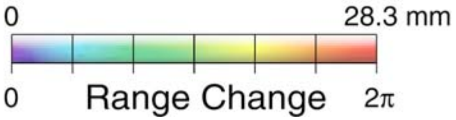
28.3 mm
0
Range Change
2π

1995-1999







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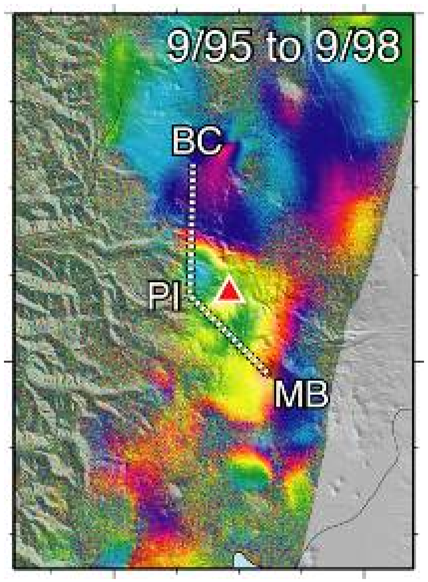
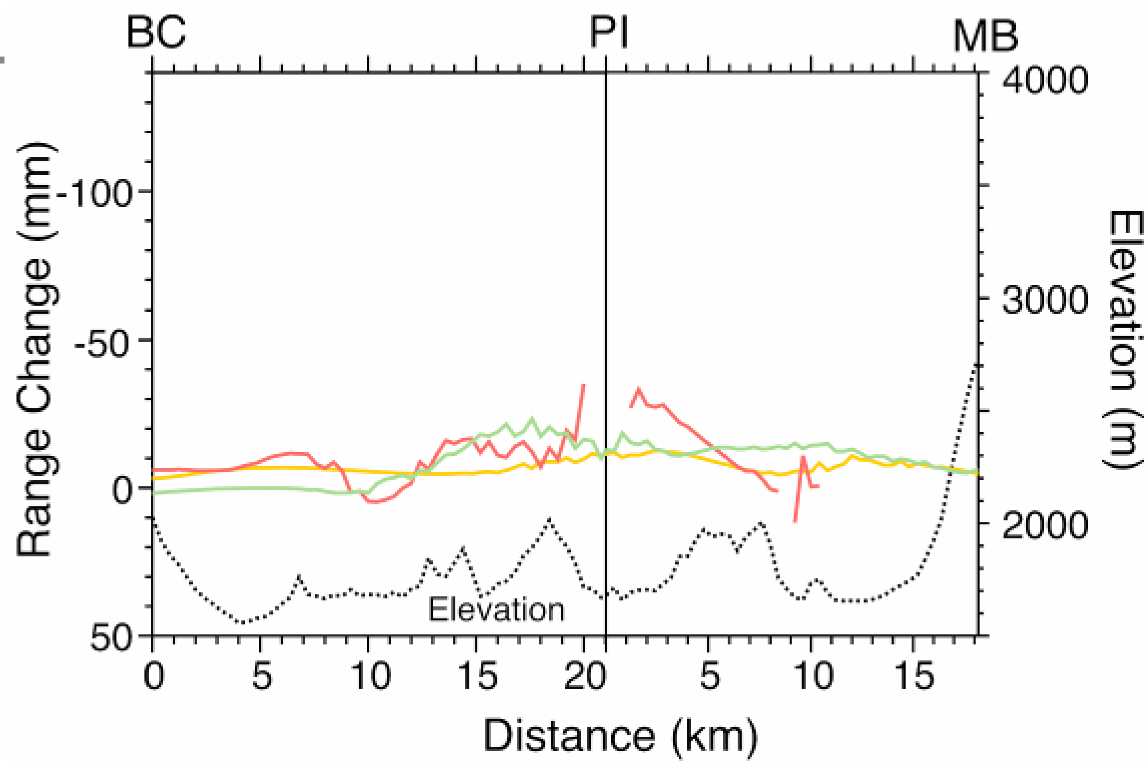
1995-1998


9/95 to 9/98
BC
PI
MB


BC
PI
MB
Range Change (mm)
-100
-50
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50
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2000
Elevation (m)
Elevation
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5
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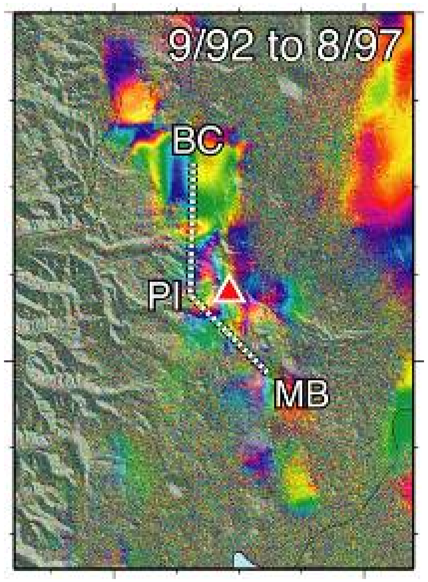
15
20
5
10
15
Distance (km)


0
28.3 mm
0
Range Change
2π

1992-1997


9/92 to 8/97
BC
PI
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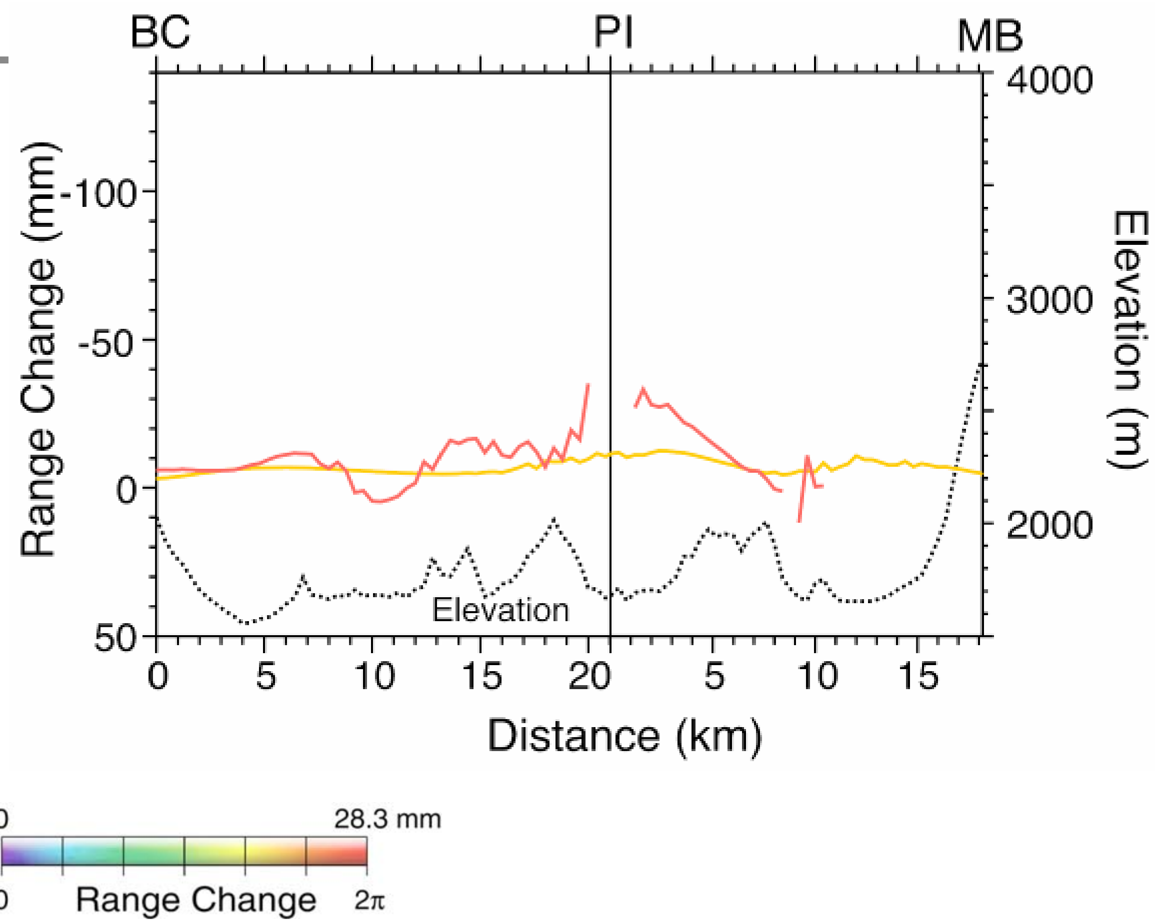
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Distance (km)
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28.3 mm
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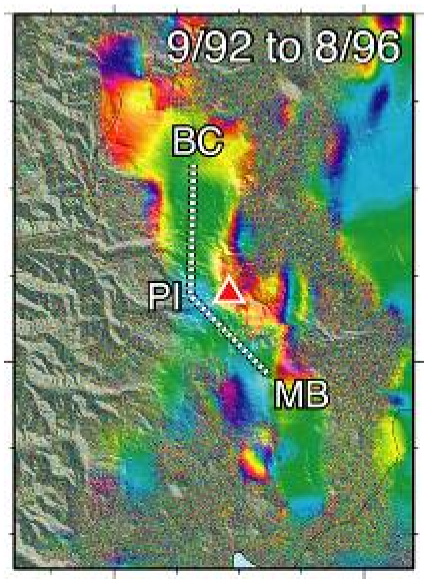
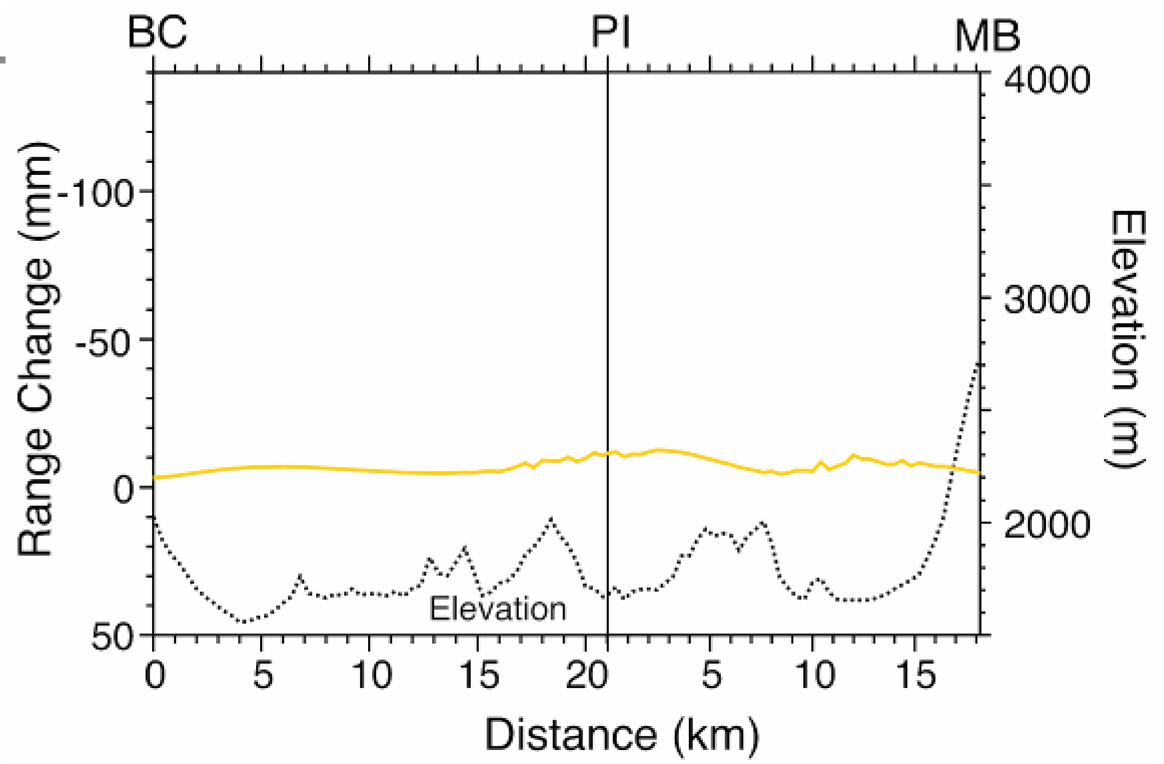
1992-1996





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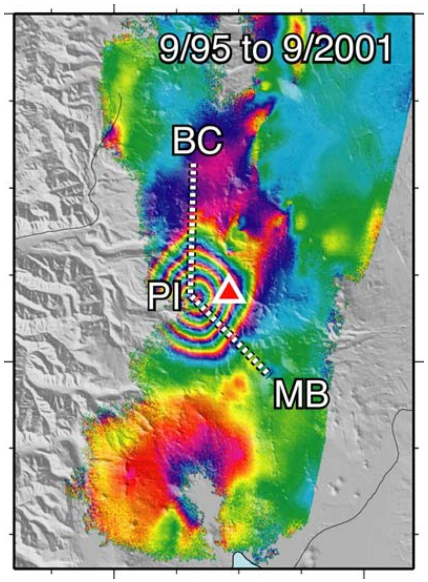
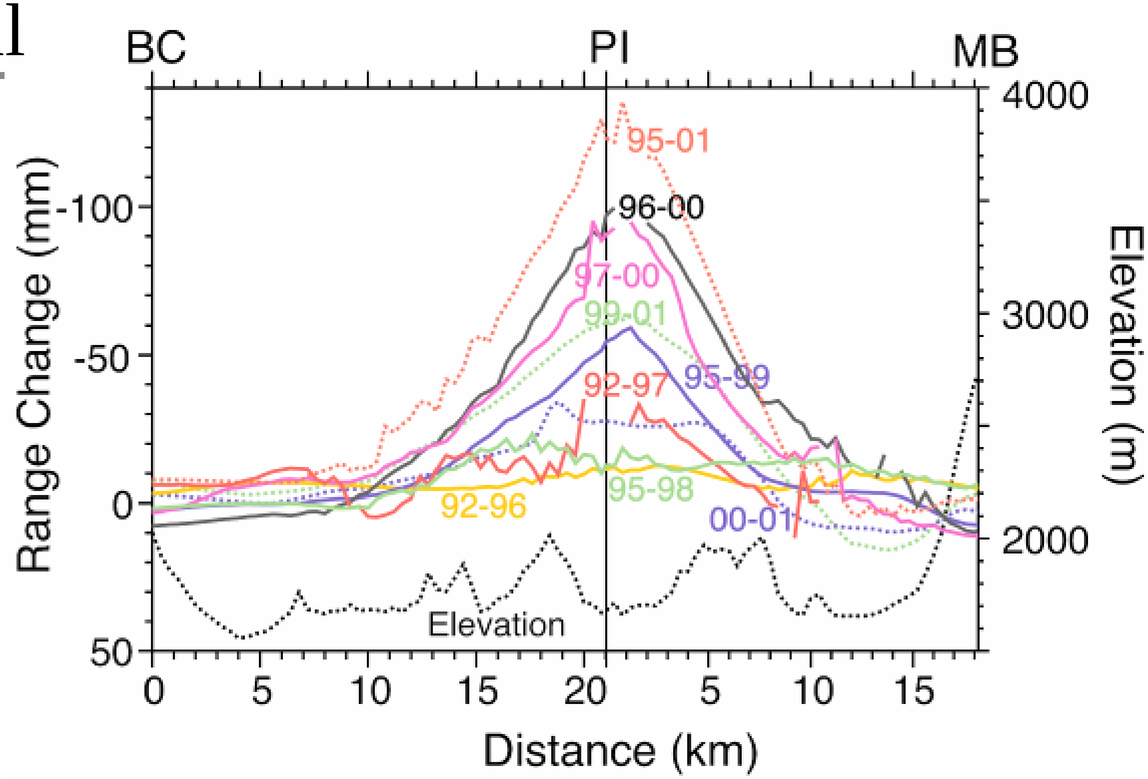
1995-2001 all





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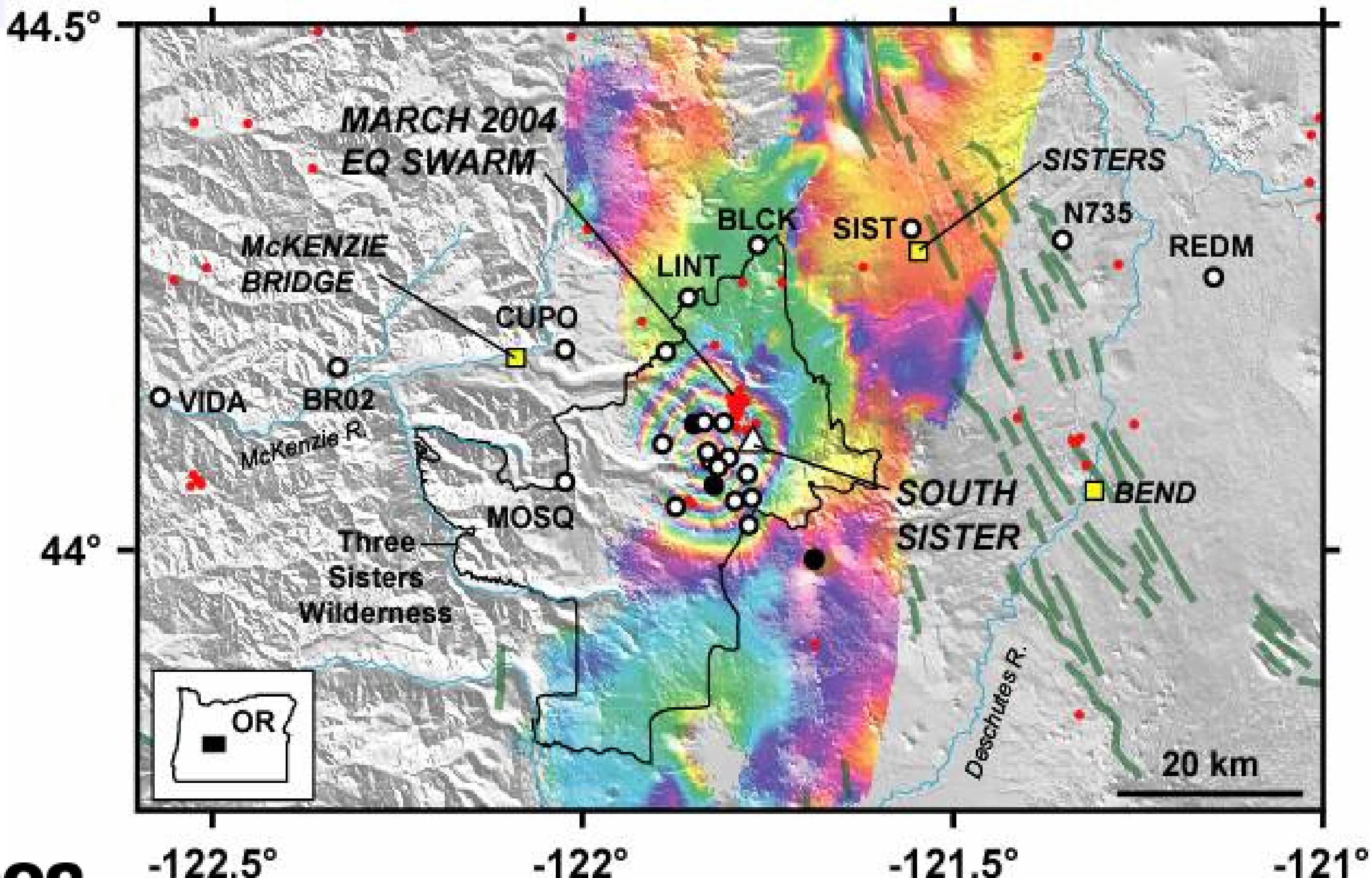
Historical seismicity and GPS network



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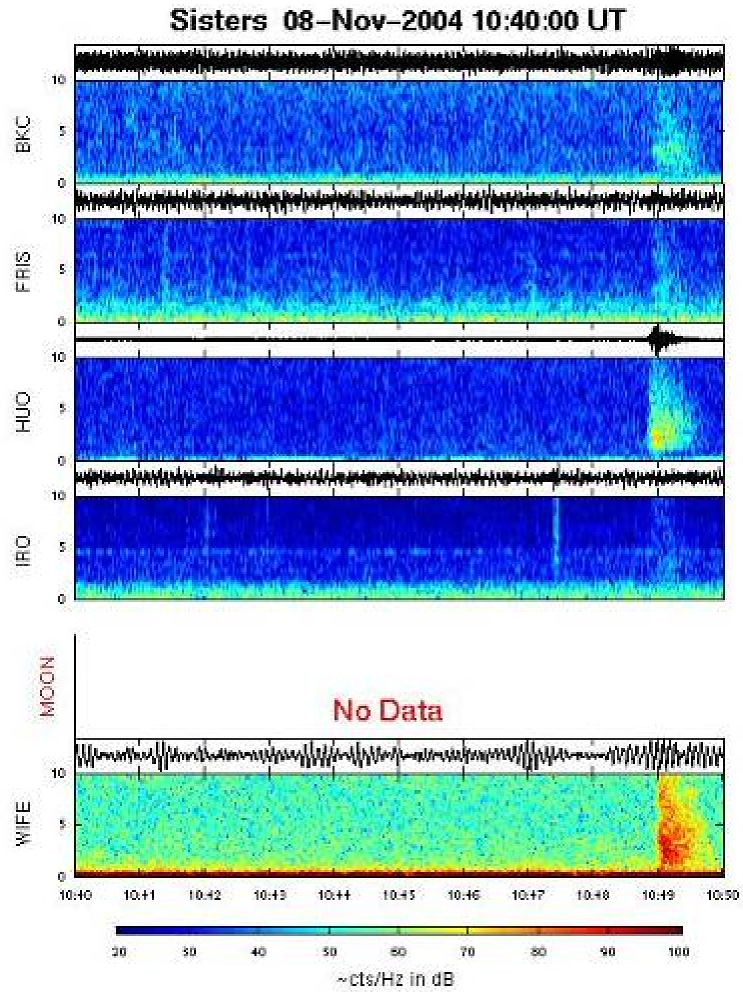
Recent low-frequency earthquake

- In addition to the March 2004 swarm, there have been several small low-frequency events beneath the deforming area or near Three Sisters
- The spectrogram shown here is for an event on November 8, 2004. Note the preponderance of energy at low frequencies
- The mechanism of such events is not completely understood, but they suggest the involvement of a fluid (magma or gas) or “gooey” rock (geophysical term)



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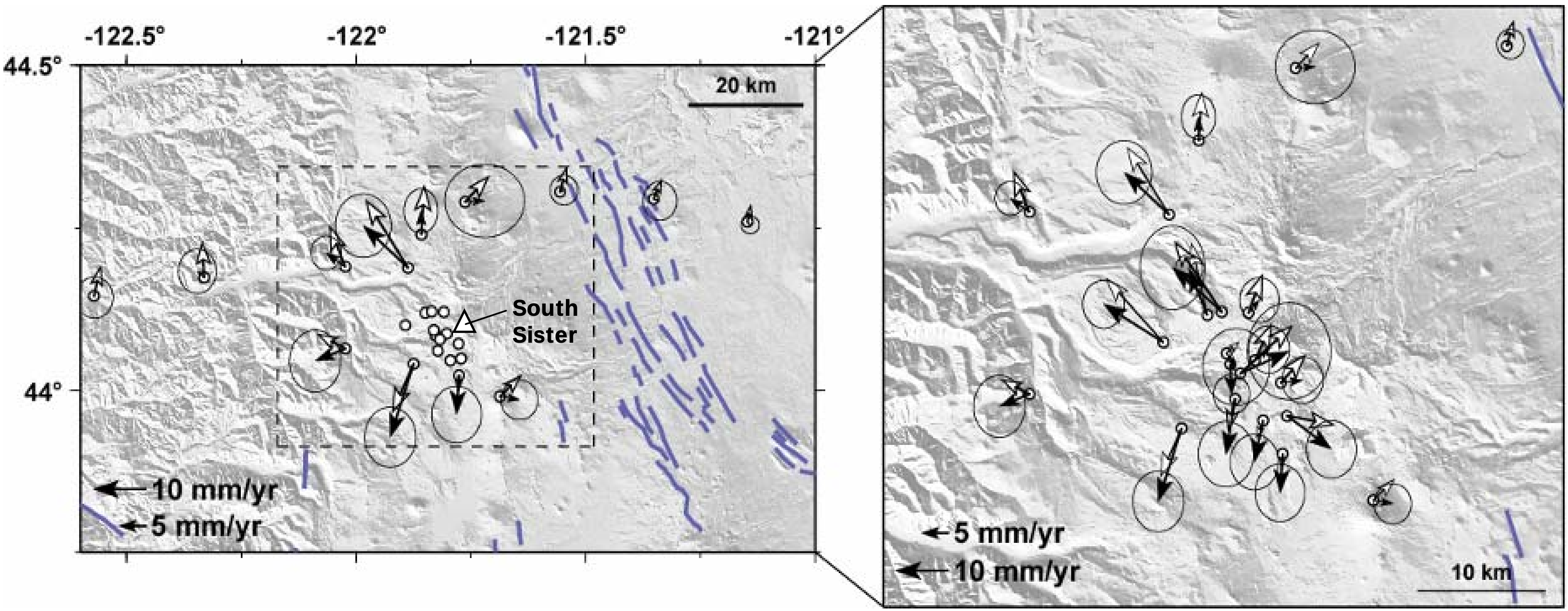
GPS station velocities, 2001-2003



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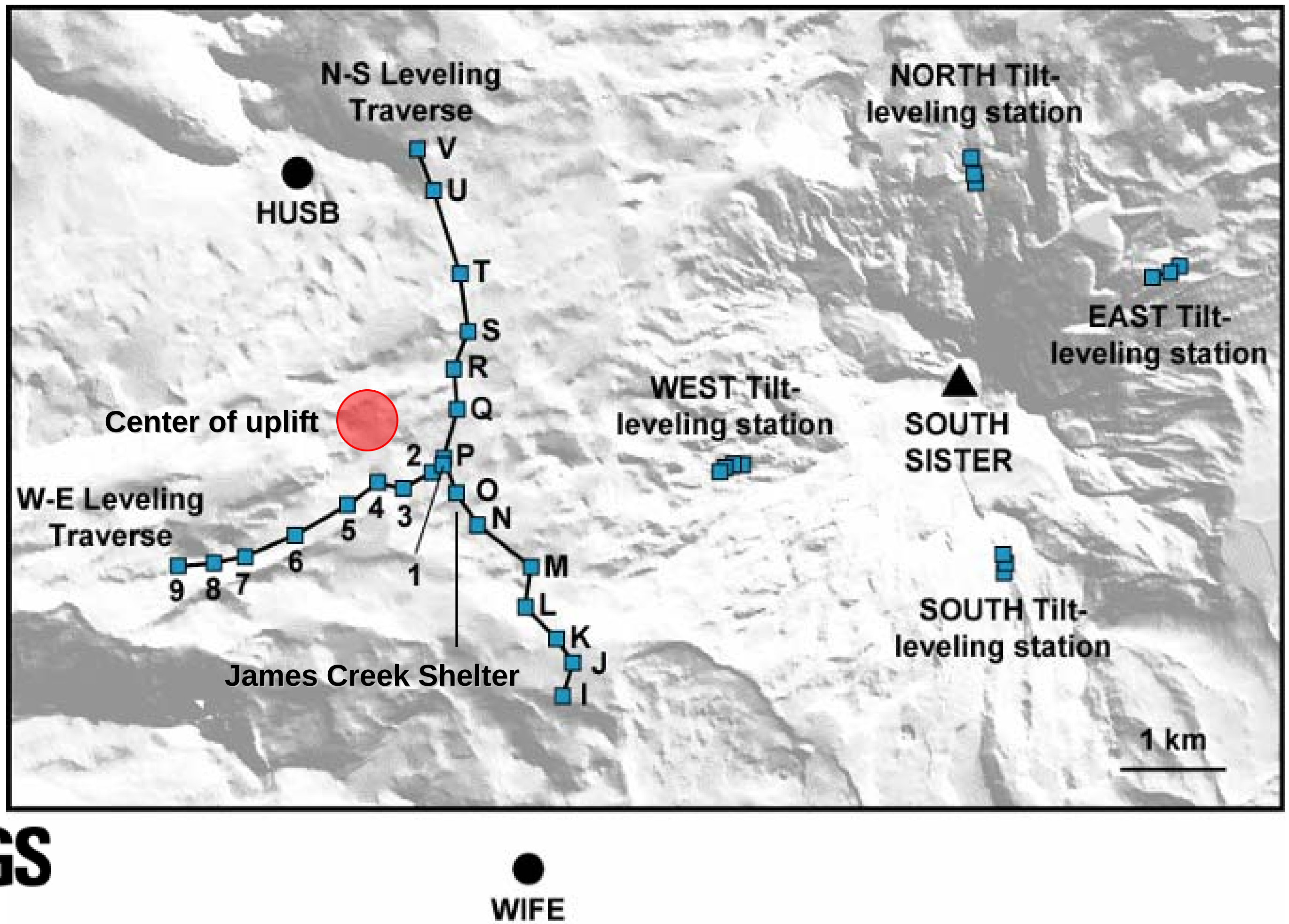
Leveling & tilt-leveling networks



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Tilt-leveling at South Sister, 1985-1986

- Four radial tilt-leveling lines, each 200-320 m long with 3 or 4 survey marks, established at South Sister in 1985 and remeasured in 1986 to establish baseline
- Lines next measured in 2001 in response to discovery of uplift by InSAR
- First-order, class II leveling standards and procedures
- Accuracy of tilt measurements about ± 2 microradians

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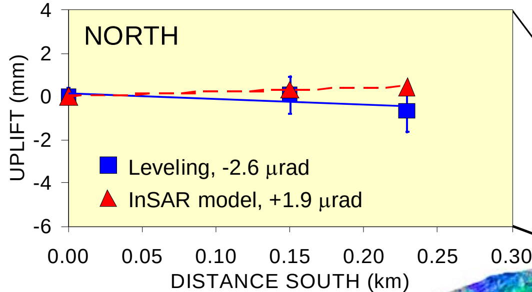
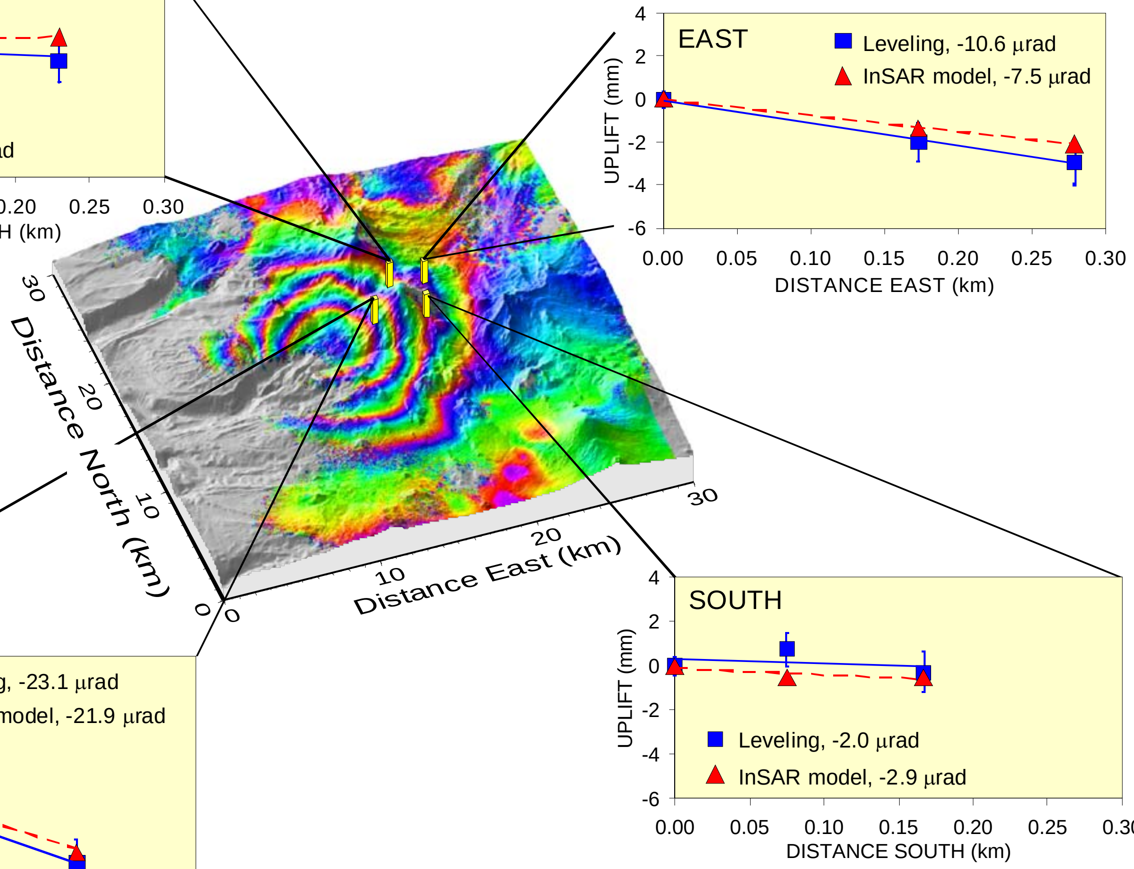
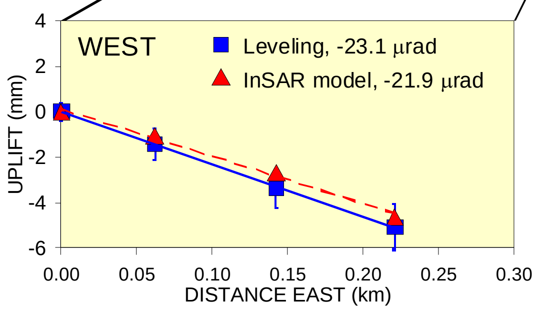
Tilt-leveling results (1985-2001) compared to InSAR model prediction (1996-2000 extrapolated to 2001)





Conclusion: Consistent with InSAR observations, i.e., uplift did not start before 1996 – probably in 1997-98



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Leveling near James Creek Shelter

- Two leveling lines that intersect near James Creek Shelter, less than 1 km from deformation center, established along trails in 2002
- Average pin spacing 385 m (50-800 m)
- N-S line is 7.4 km long, W-E line is 3.4 km long
- Digital level and first-order, class II standards and procedures

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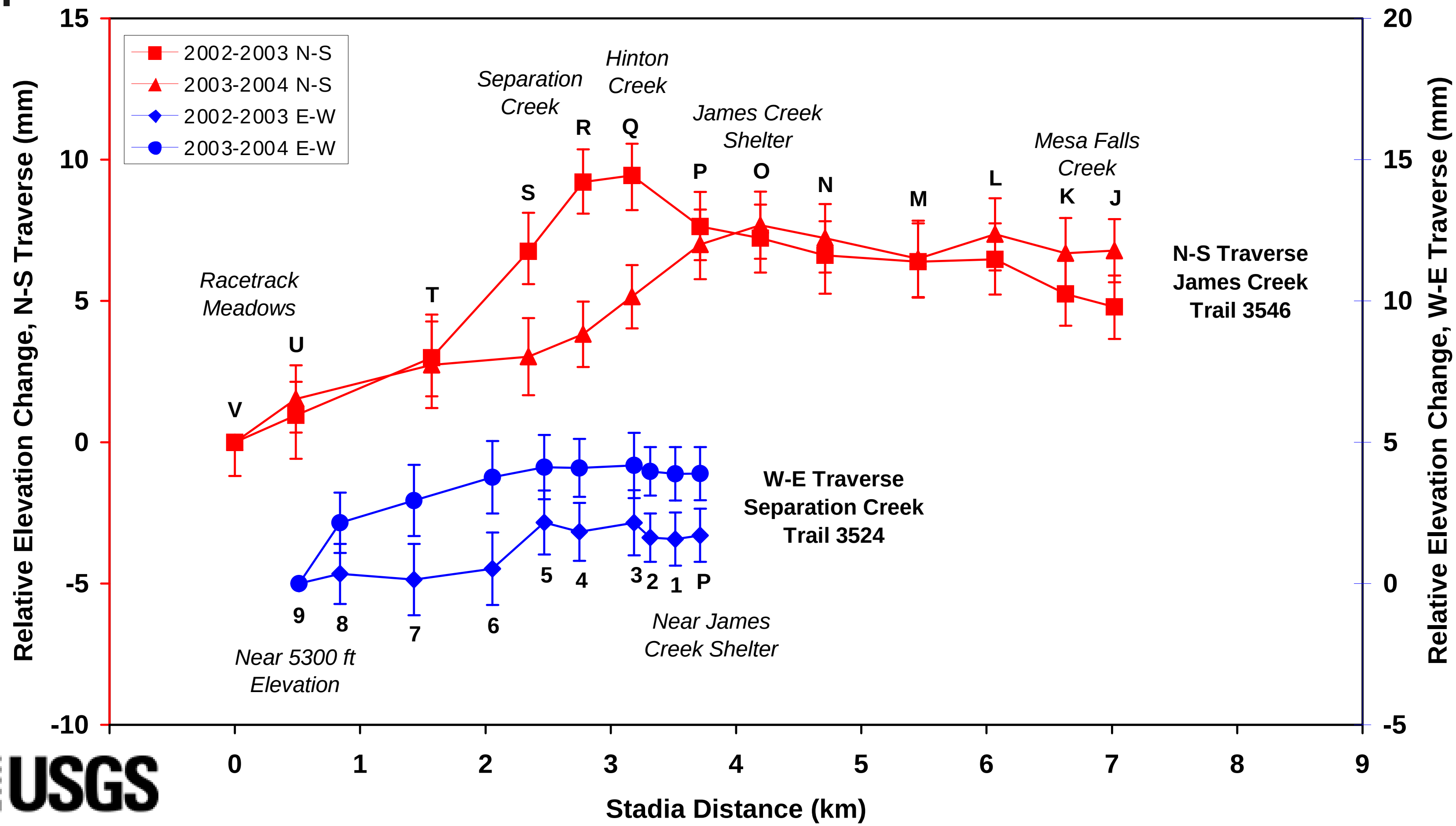
Leveling Results, 2002-2003 & 2003-2004



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Modeling approach I

- Three datasets were included: 1) campaign GPS from 2001, 2002, and 2003; 2) leveling data from 2002 and 2003; and 3) InSAR measurements that collectively span from 1992 to 2001
- InSAR data were decimated using the quad-tree method (Simons et al., 2002; Jónsson et al., 2002) to avoid overwhelming other datasets
- Assumptions:
  - Earth is an isotropic homogeneous half-space
  - Deformation source is simple: point source (Mogi, 1958), ellipsoidal source (Yang, 1988; Fialko and Simons, 2000; Fialko et al., 2001), or dislocation (dike or sill) source (Okada, 1985; Feigl and Dupré, 1999)
  - The location, geometry, and inflation rate of the source did not change from the time of the 1995-2001 interferogram through the time of the 2001-2003 GPS and leveling measurements.
  - The sub-sampled InSAR, GPS, and leveling data points are independent, so we can use standard F-tests of statistical significance to estimate 95% confidence intervals.

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Modeling approach II

- Constrained Monte Carlo approach used to select a large number of different starting models (~1000 per modeling run), which were fed into a non-linear least-squares procedure and inverted iteratively until convergence
- Weighting scheme as developed by Simons et al. (2002) and Fialko (2004):
  - Two datasets: 1) GPS and leveling (M = 84), 2) sub-sampled InSAR (N = 672)
  - Weighting for GPS and leveling data points: $w_i = \dfrac{1}{\sigma_i \sum_{j=1}^{M} \dfrac{1}{\sigma_j}}$
  - Weighting for sub-sampled InSAR data points: $w_i = \dfrac{\sqrt{n_i}}{\sum_{j=1}^{N} \sqrt{n_j}}$
  - Weighting vector with a sum of unity applied to each dataset: $\sum_{i=1}^{M,N} w_i = 1$

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Modeling approach III

- Minimize the quantity: $\sum_{i=1}^{M}[\alpha w_i(o_i - c_i)]^2 + \sum_{i=1}^{N}[w_i(o_i - c_i)]^2$
- To determine the relative weighting factor α, invert the data beginning with α = 7 and decrease the value until the fit to the InSAR part of the data is within the 95% level of the model that best-fit the InSAR data alone
- Final value of α that fits this criterion is 1.2
- Calculated values of deformation for the GPS data differ by less than 1 mm/year compared to those calculated for α = 1.0
- Final model that best-fits the combined datasets is within the 95% level of the best-fit model for each dataset modeled alone

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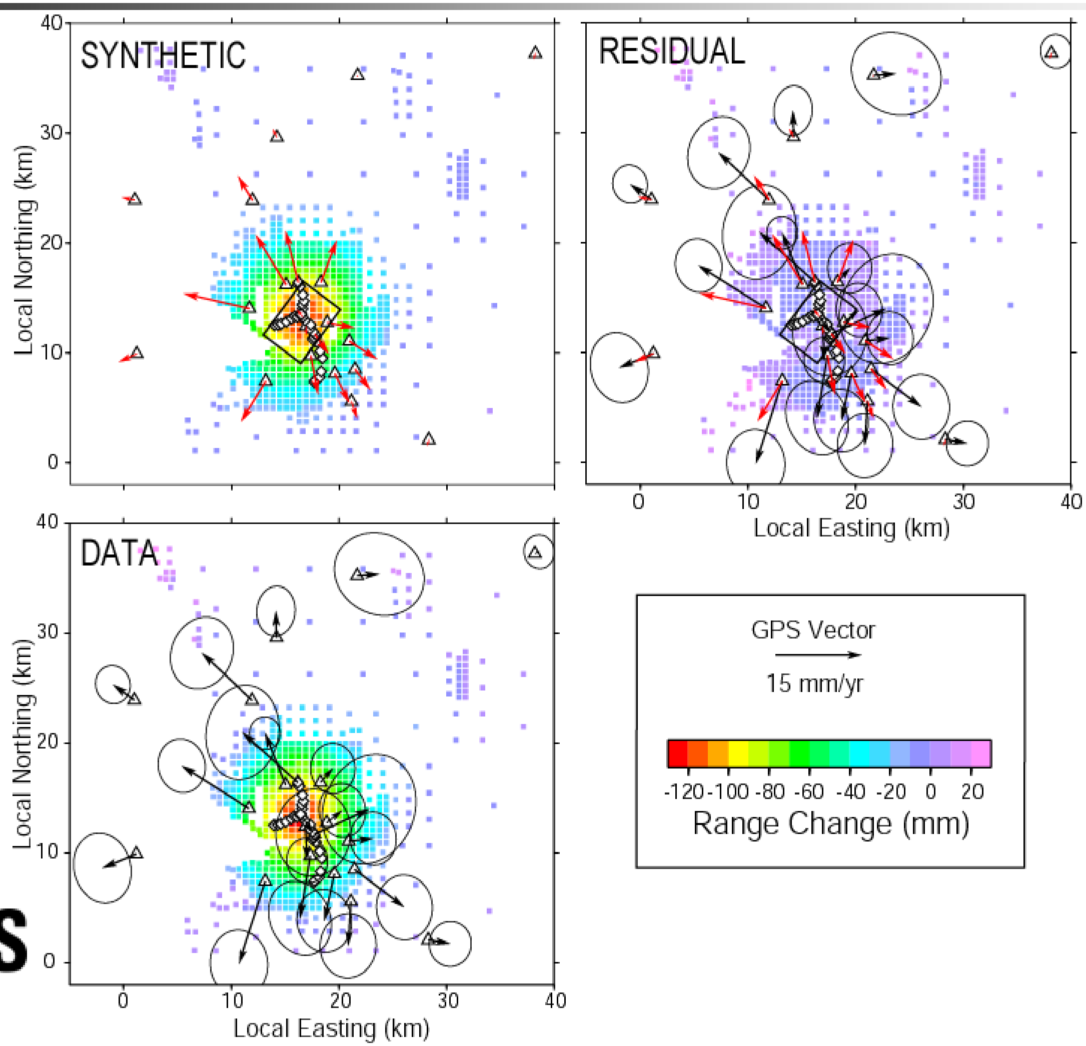
Best-fit dislocation (sill) model



Strike: 37 deg

Dip: -19.4 deg

Depth: 7.2 km

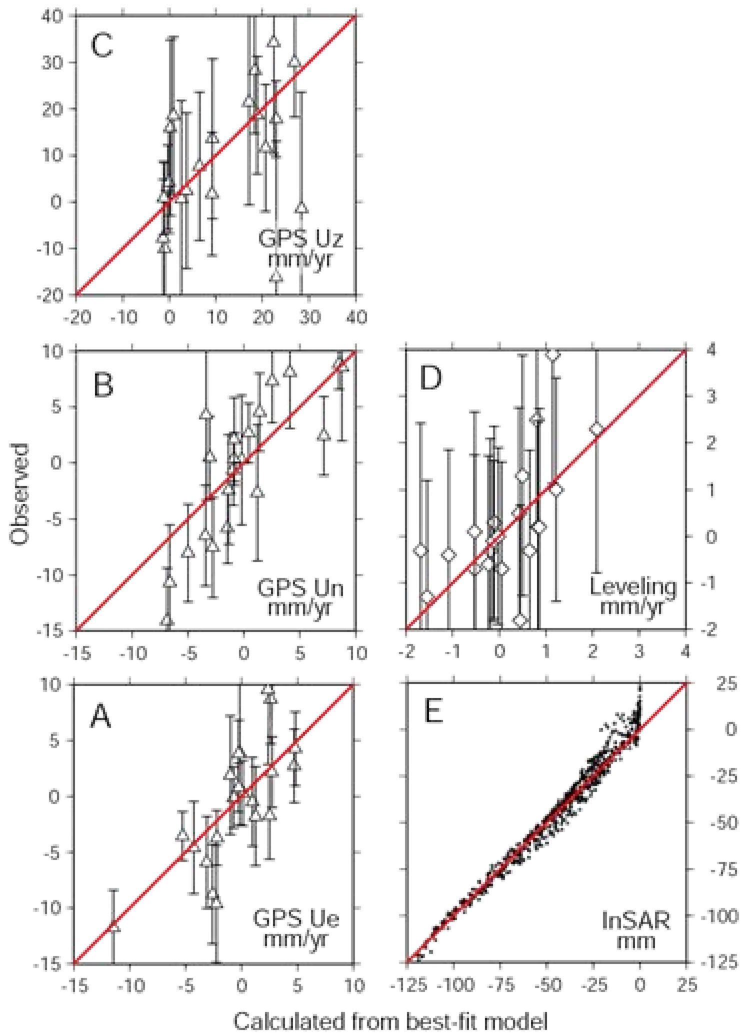
(4-9 km at 95%)

Opening: 185 mm

Length: 6.2 km

Width: 4.6 km

Data and best-fit model comparison



- Diagonal lines represent perfect fit of model to data
- Error bars represent 95% confidence range
- A-C: GPS North, East, Up velocities, respectively
- D: vertical velocities from 2002-2003 leveling data
- E: sub-sampled InSAR data (1992-2001) from quad-tree analysis

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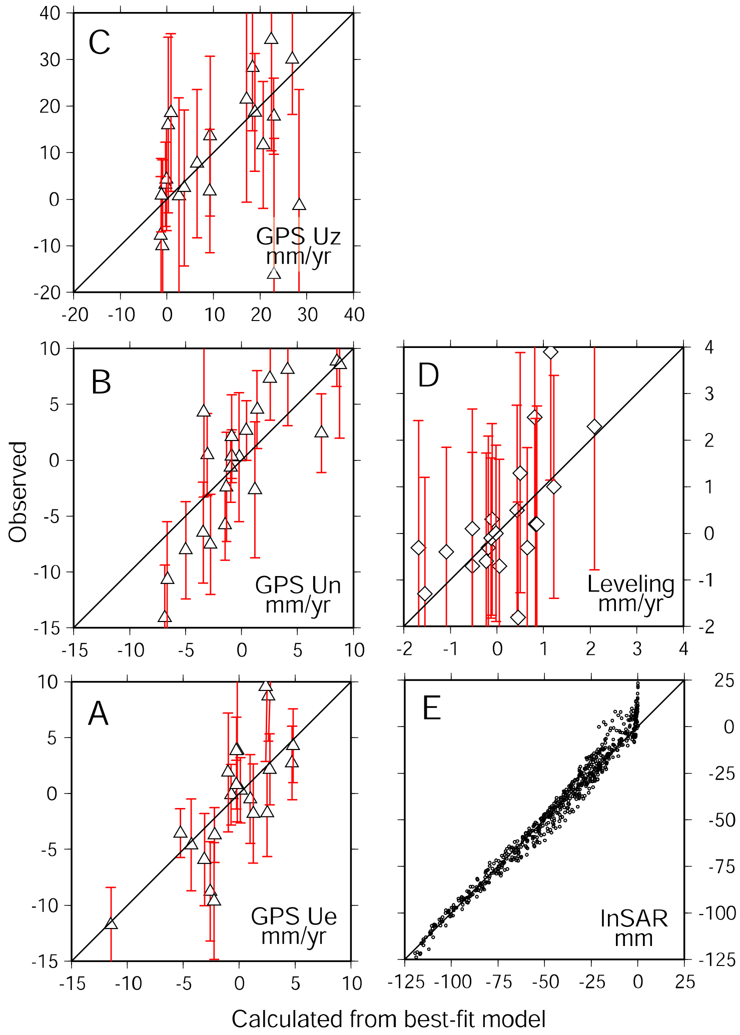

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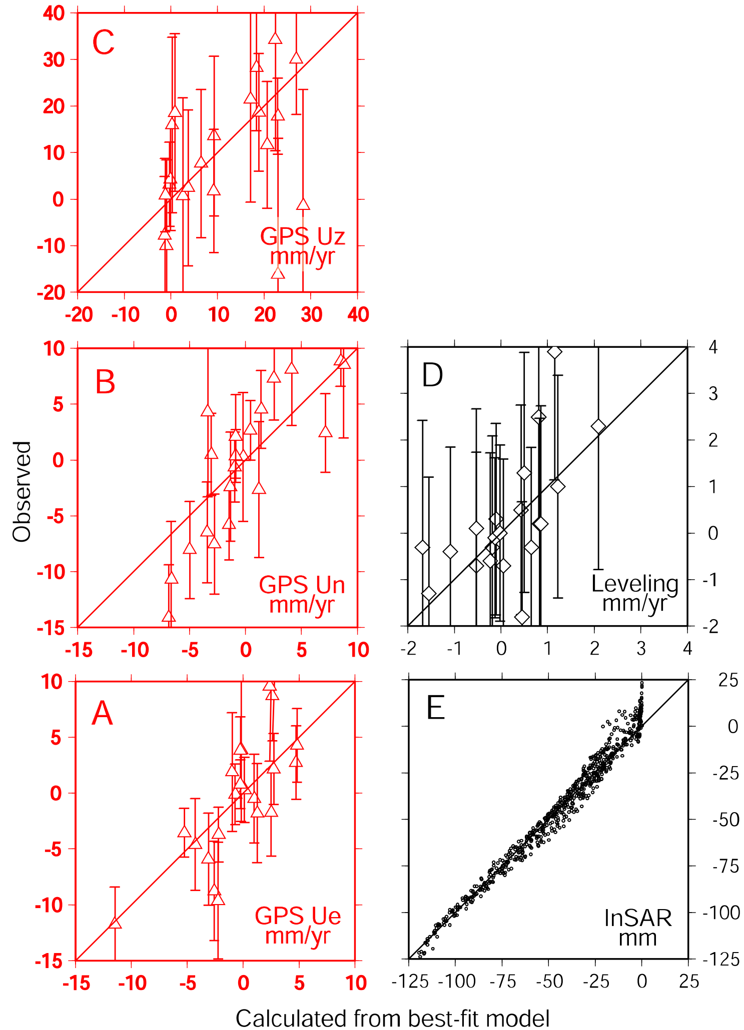

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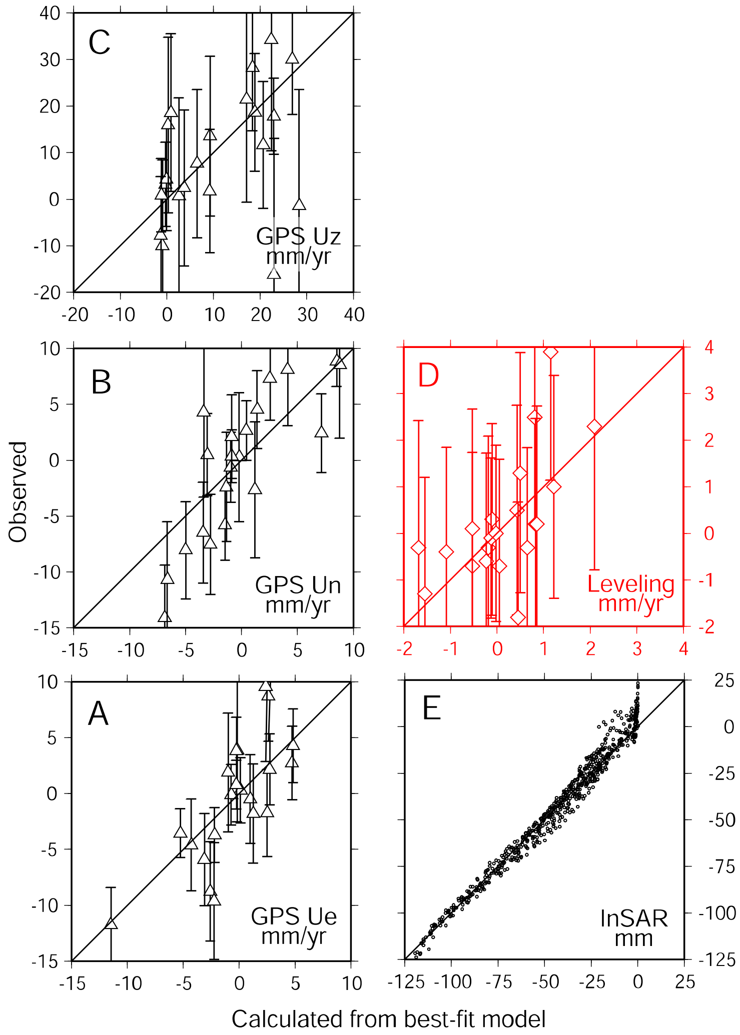

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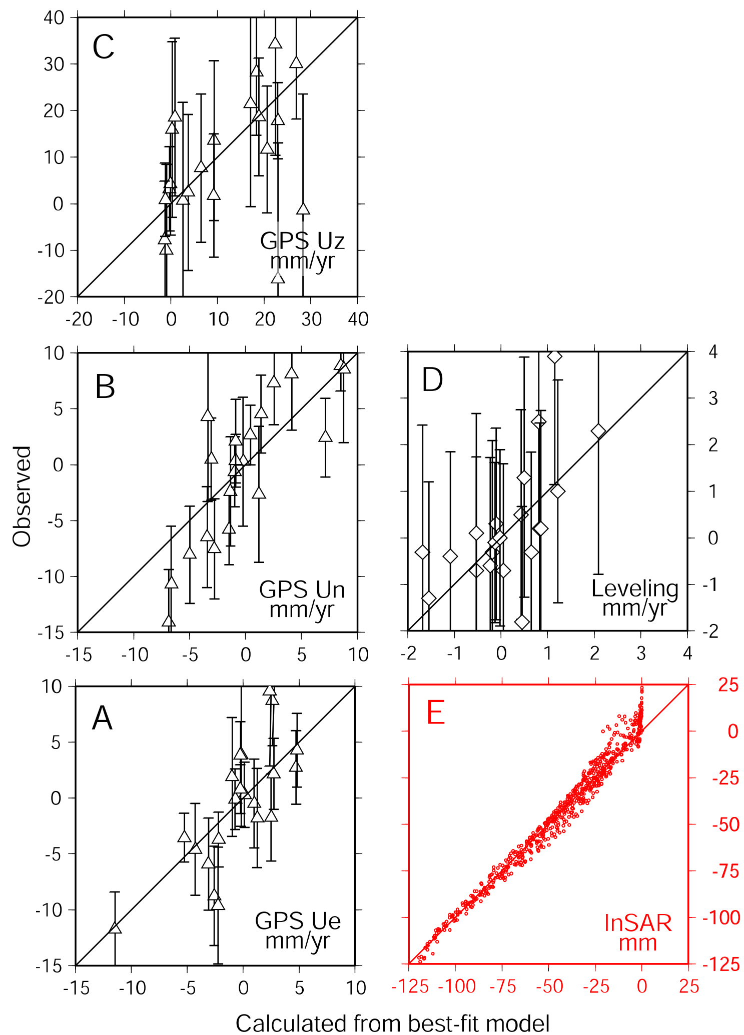

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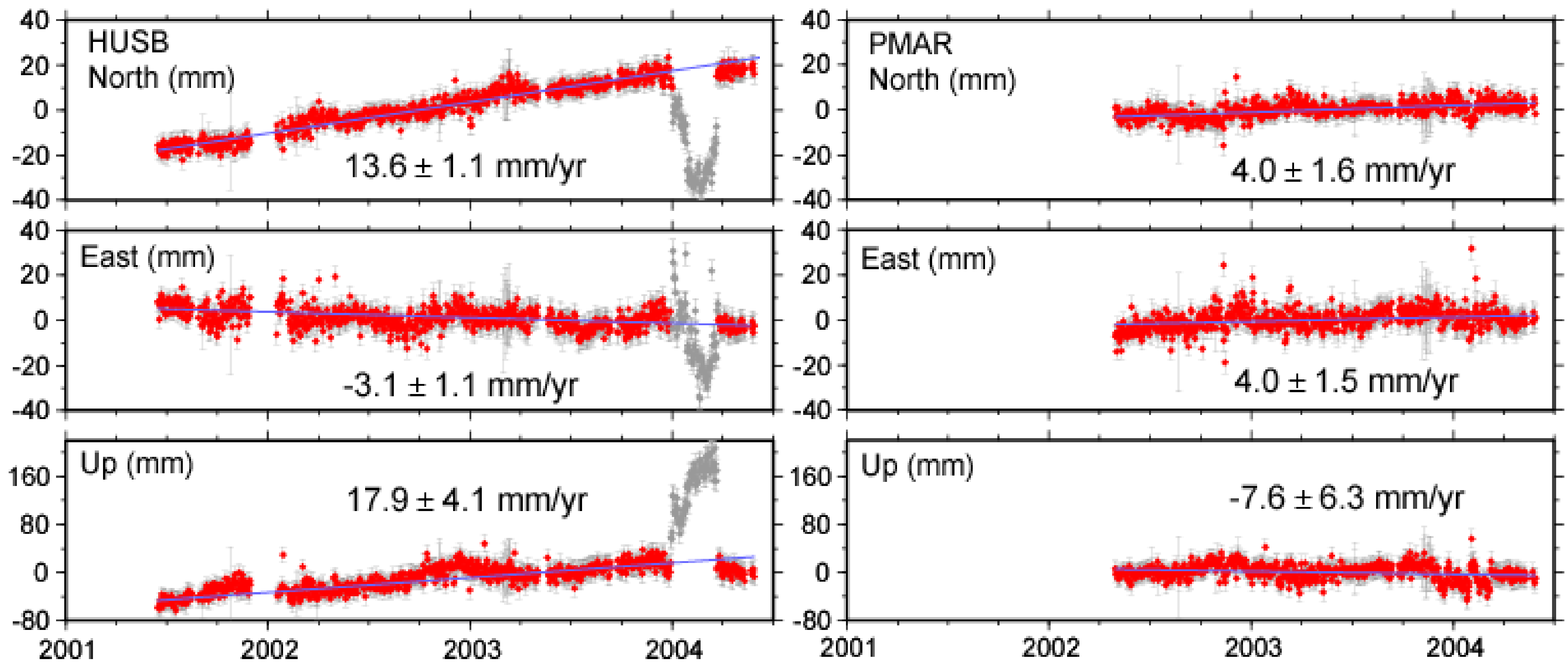
Conclusions

- Most likely cause of uplift is intrusion of basalt at 6.5 ± 2.5 km depth, probably at brittle-ductile transition
- A shallowly dipping sill or dike source provides a better fit to the geodetic data than a point source or an ellipsoidal source at the 95% confidence level
- The intrusion rate has been roughly constant since 1997 or 1998
- March 2004 earthquake swarm suggests accumulated strain is now great enough, or strain rate was locally high enough for a short time, to cause brittle failure
- Similar events may be relatively common, though heretofore unobserved, in the central Oregon Cascade Range; most do not culminate in eruptions.

Photo by C. Wicks, September 2003

HUSB and PMAR time series



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