The ~~ongoing~~ collapse of Bárðarbunga Caldera, Iceland

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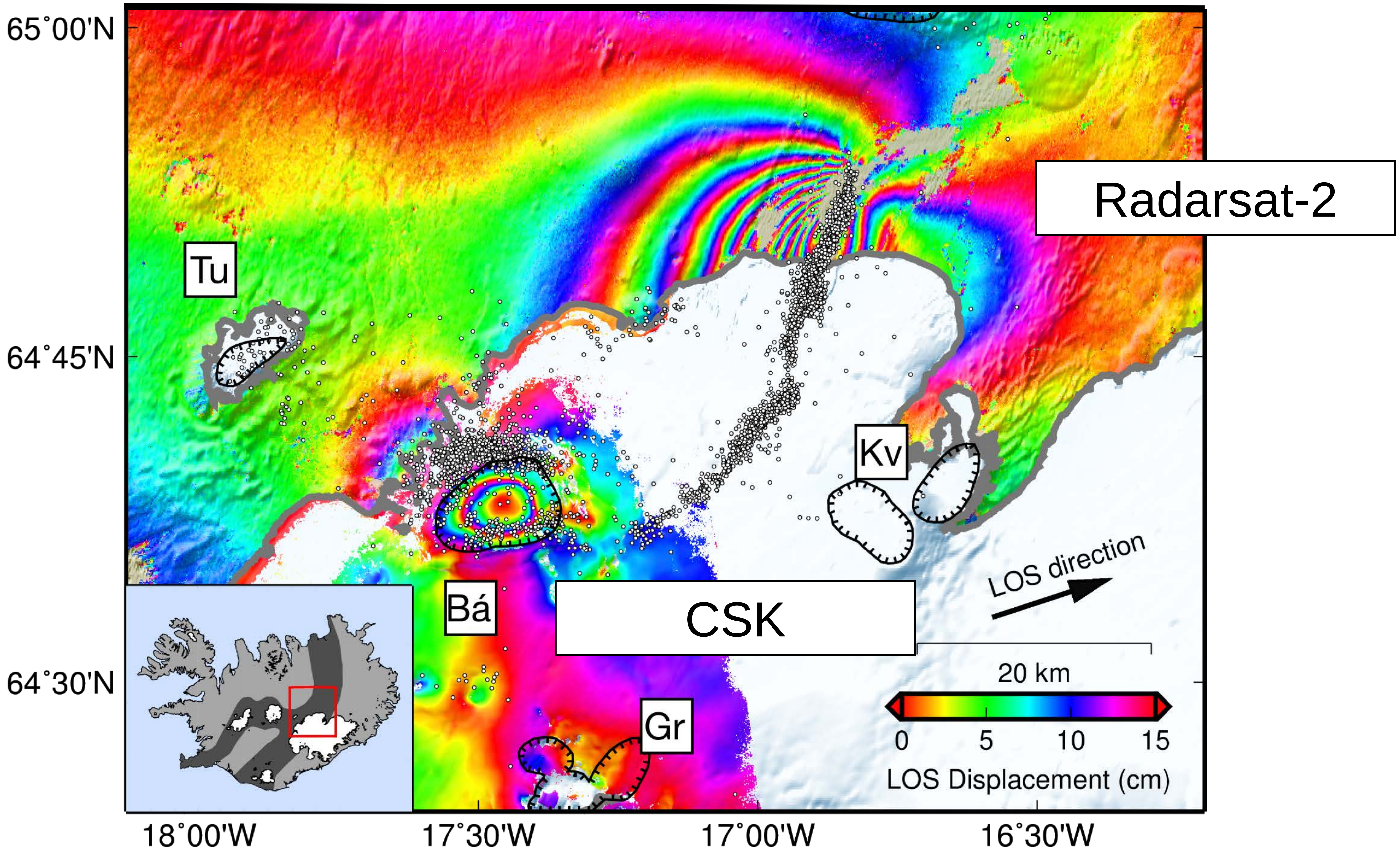
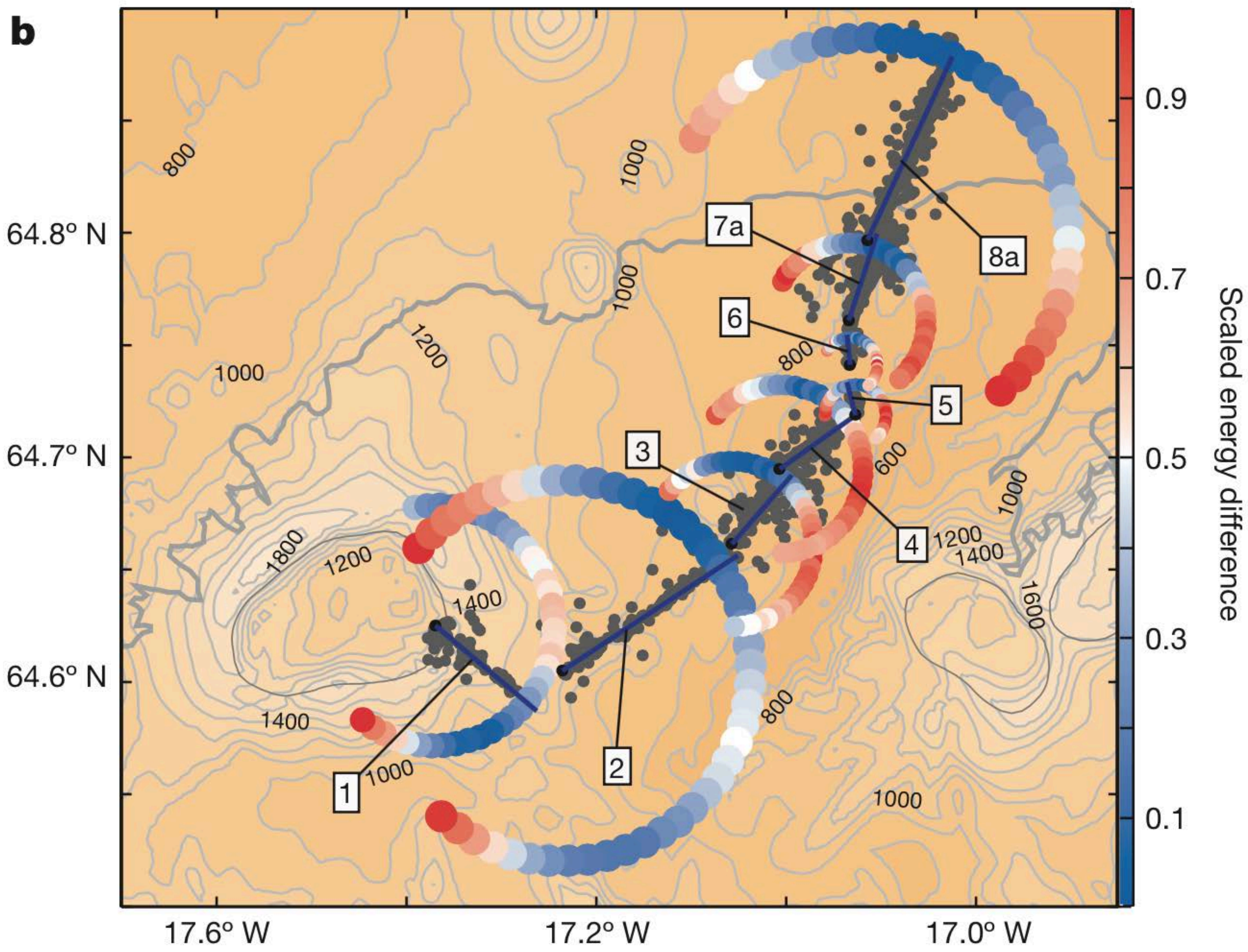
IMAGE: EXTREMEICELAND.IS

Eruption at Bárðarbunga volcano, Iceland

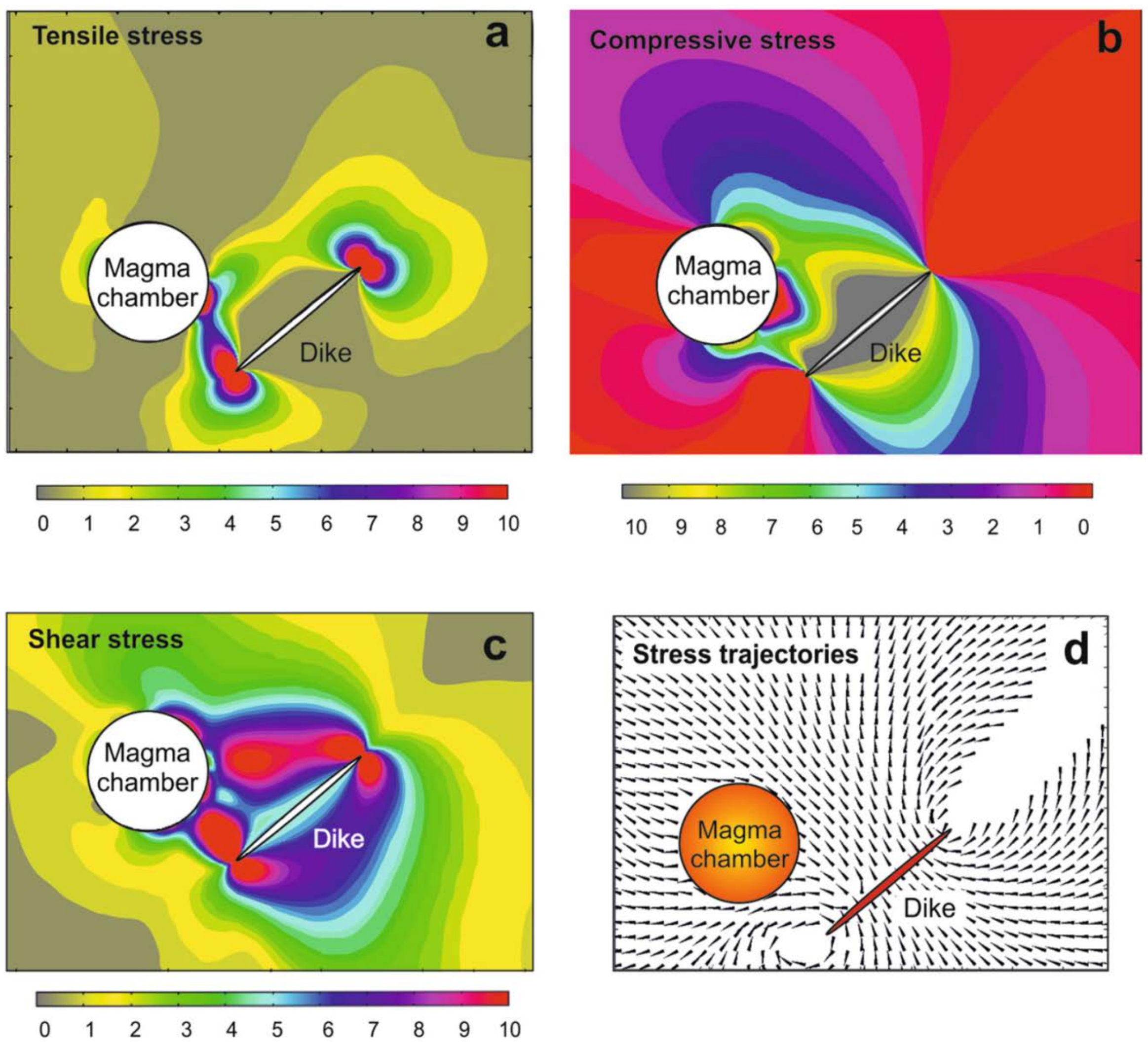
- On Aug. 16, 2014, a seismic swarm was detected underneath Bárðarbunga caldera
- Magma and associated seismicity propagated away from caldera, signifying the formation of a regional-scale dike with an eventual eruption at Holuhraun lava field



Dike propagation and induced stress



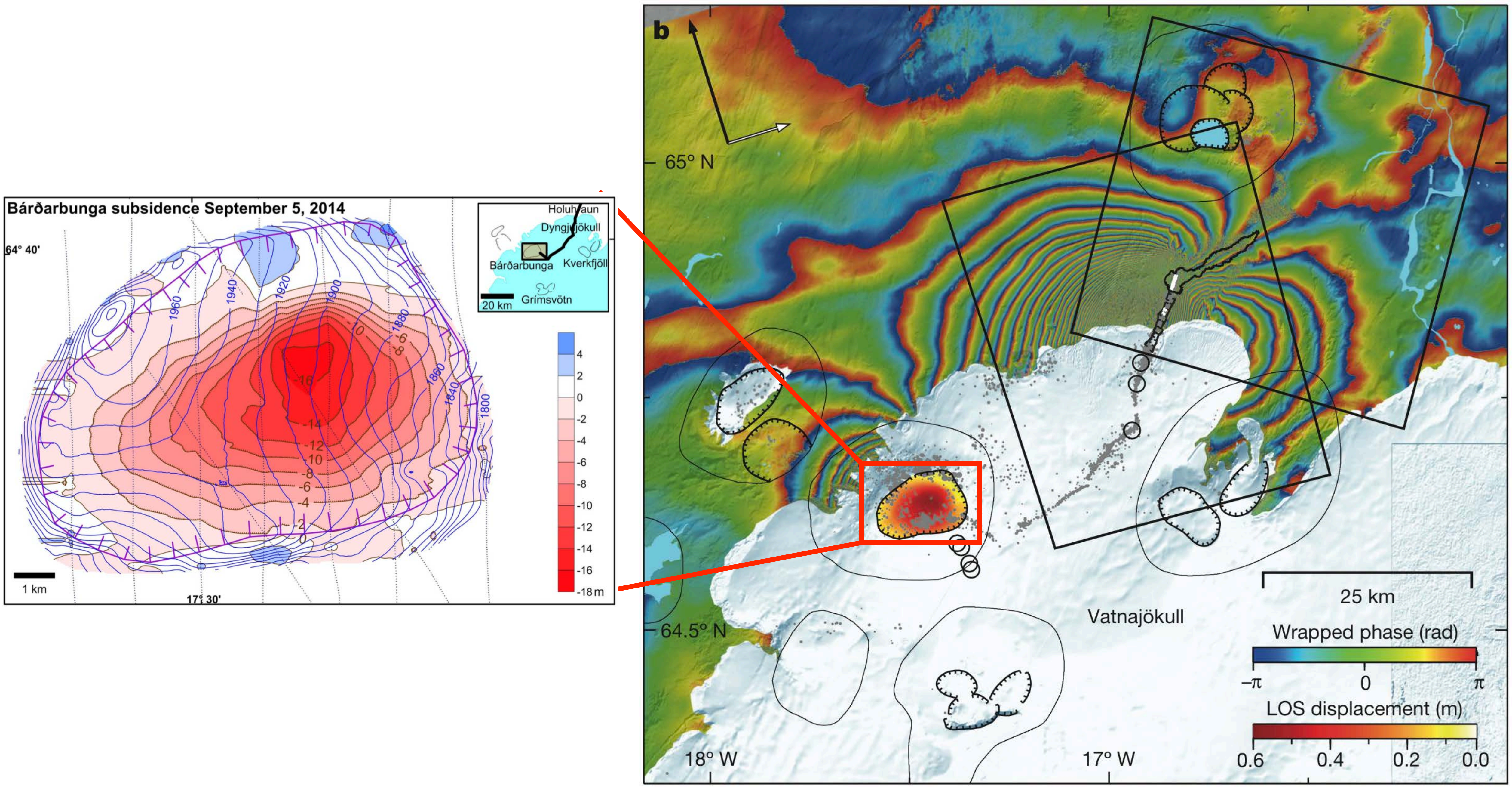
Sigmundsson, et al. 2014



Gudmundsson, et al. 2014

The collapsing caldera

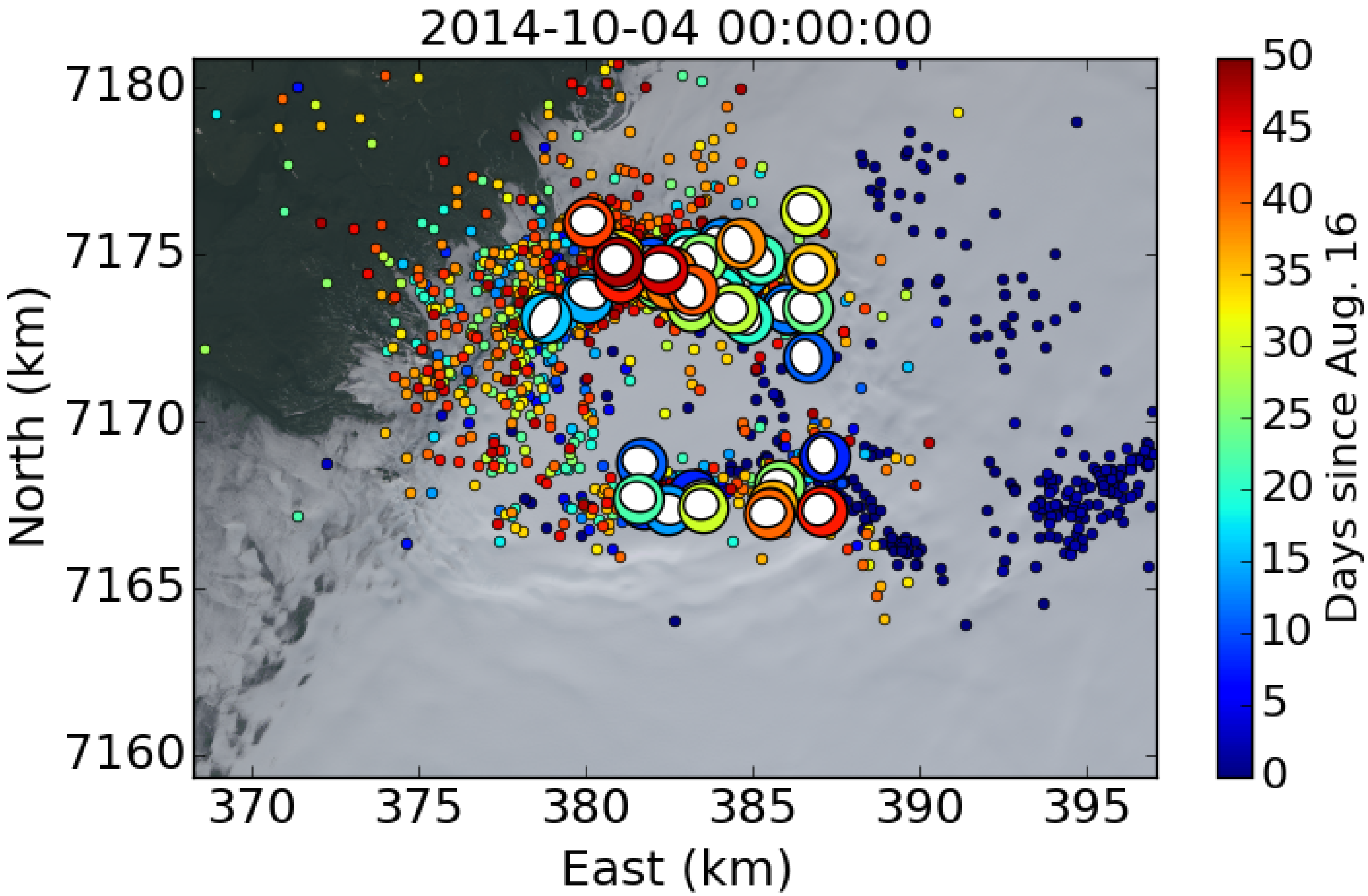
- Radar altimetry measurements in early September indicated that the surface of the ice over the caldera had subsided approximately 20 meters



Sigmundsson, et al. 2014

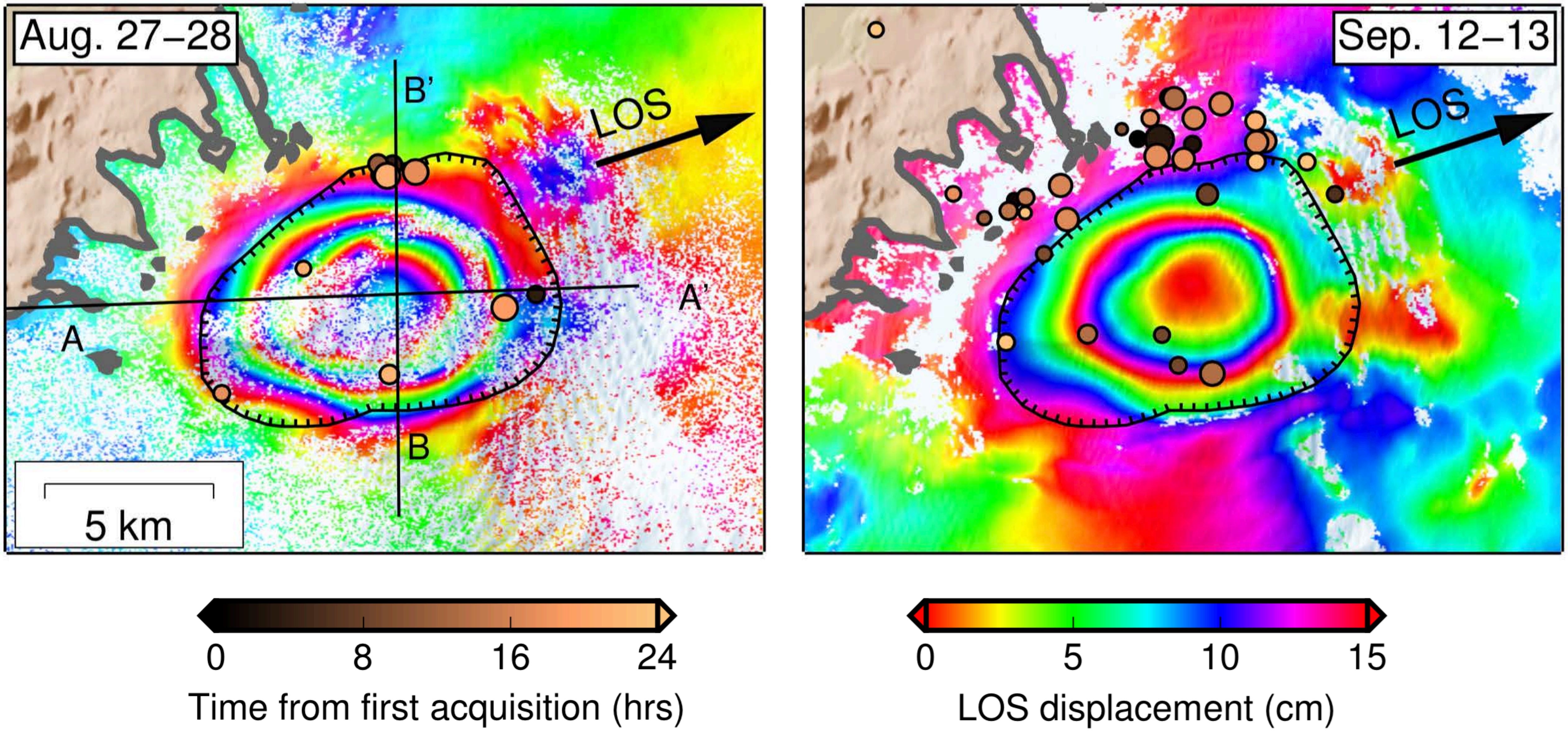
Anomalous seismicity along caldera rim

- Initiation of M > 5.0 events was associated with rapid subsidence of the ice surface overlying the caldera



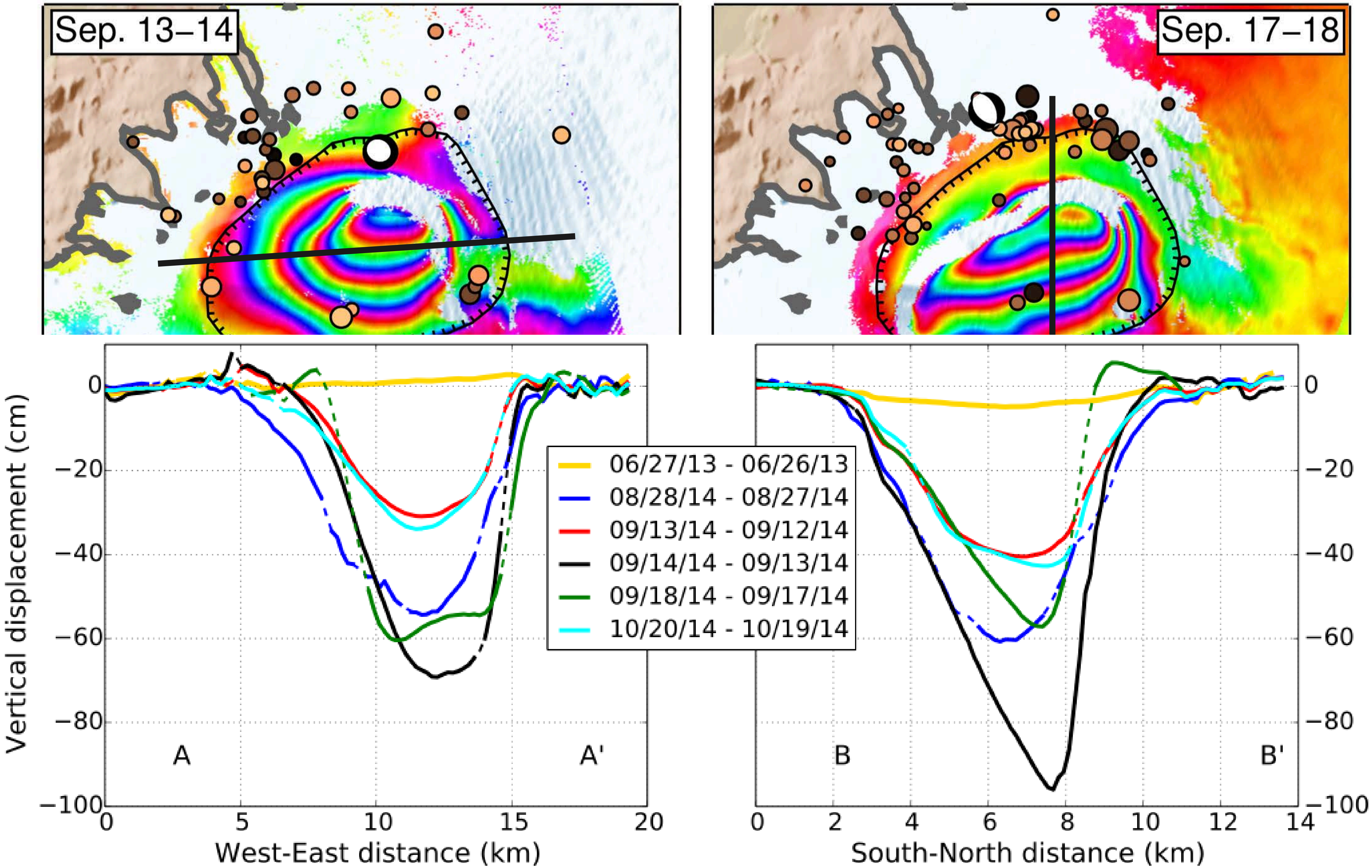
InSAR and the collapsing caldera

- 1-day COSMO-SkyMed interferograms provide high quality snapshots of the ice subsidence (30 - 60 cm of LOS displacement per day)
- Predominantly **aseismic** deformation



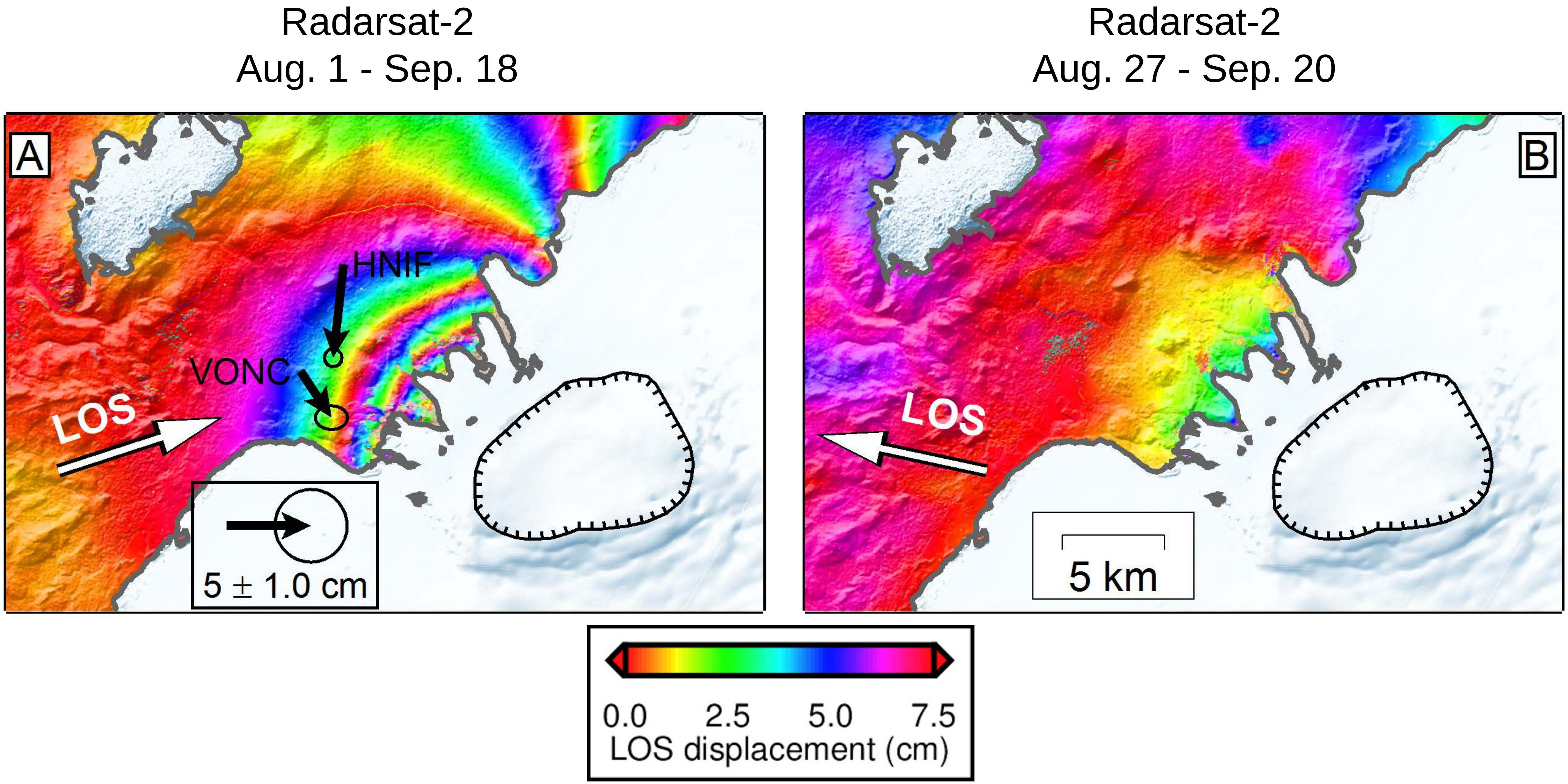
Geodetic signature of anomalous seismicity

- However, larger events on the caldera rim perturb the subsidence pattern

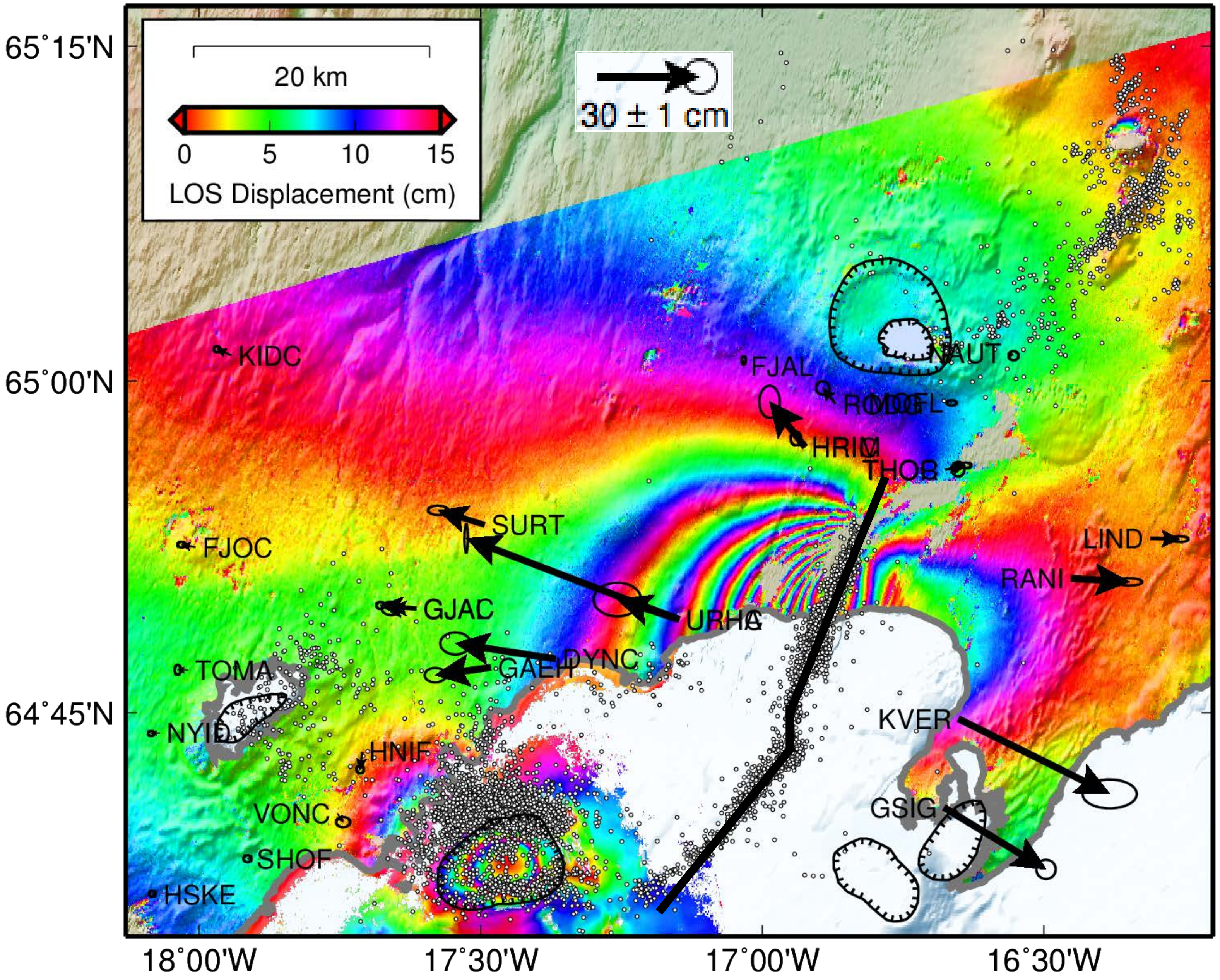


Data for modeling magma chamber (Part 1)

- Due to large uncertainties associated with the interaction between the subsiding ground and the overlying ice, we only use data on ice free regions adjacent to the caldera
- However, we need to remove any signal due to the dike emplacement



Modeling the dike emplacement

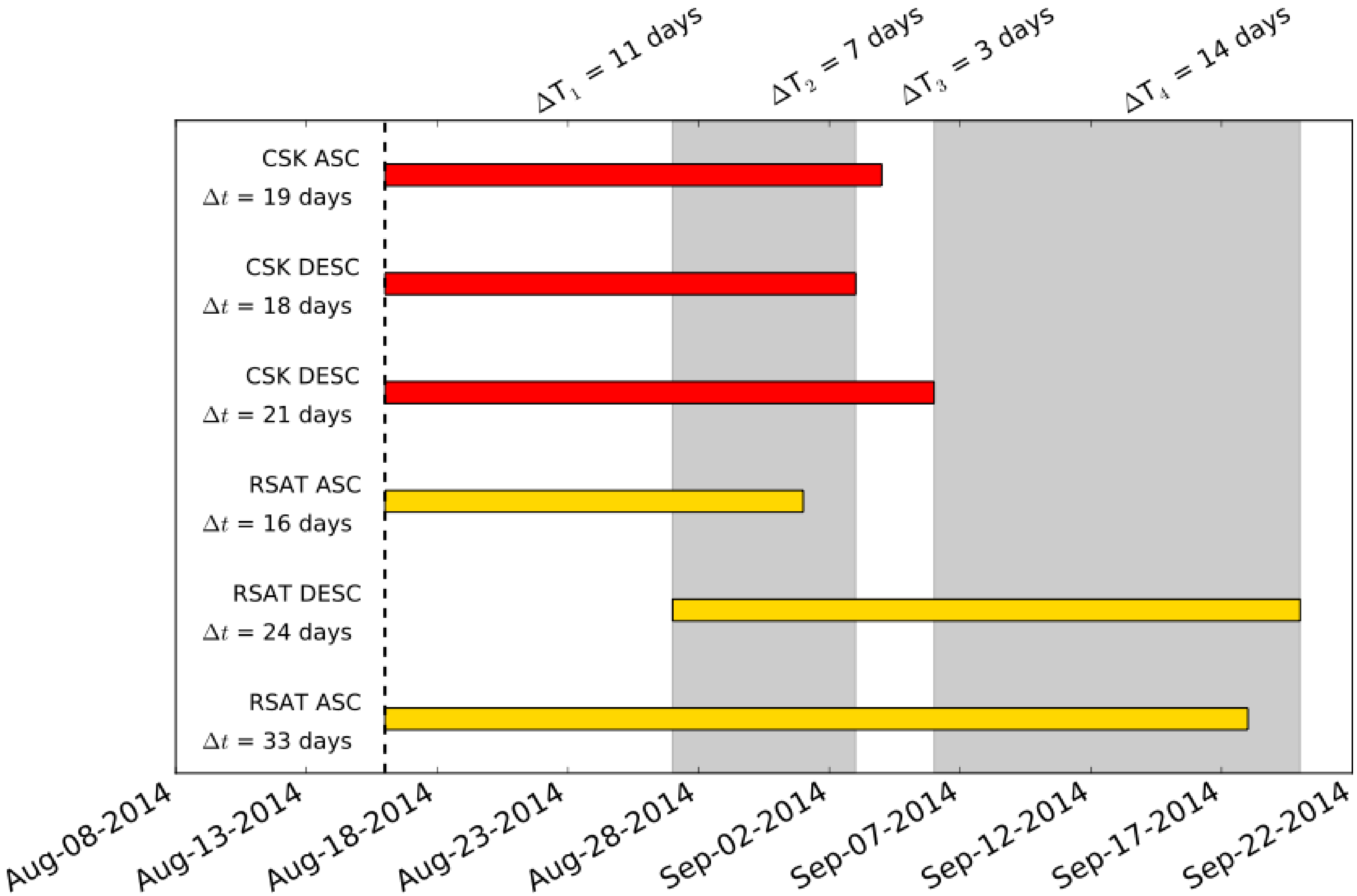


- Discretize a 3-segment vertical fault tracing the seismicity along the dike
- Maximum fault depth of 10 km
- Only allow for tensile (opening) dislocations
- InSAR + GPS observations
  - GPS observations from Sigmundsson, et al. 2014

InSAR coverage of rift zone

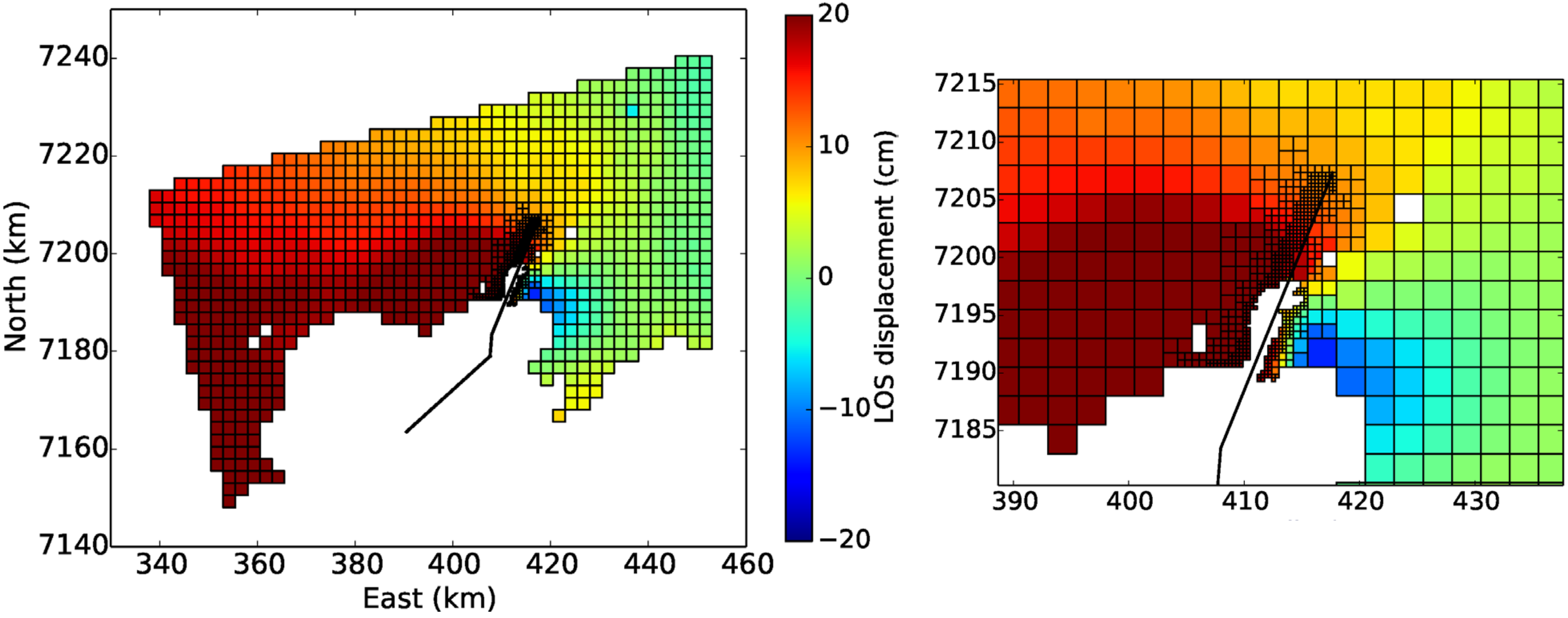
Inversions using temporal subdomains

- Divide overlapping InSAR observations into 4 temporal subdomains
- Include available GPS displacements within each subdomain
- Solve for distribution of opening for each subdomain

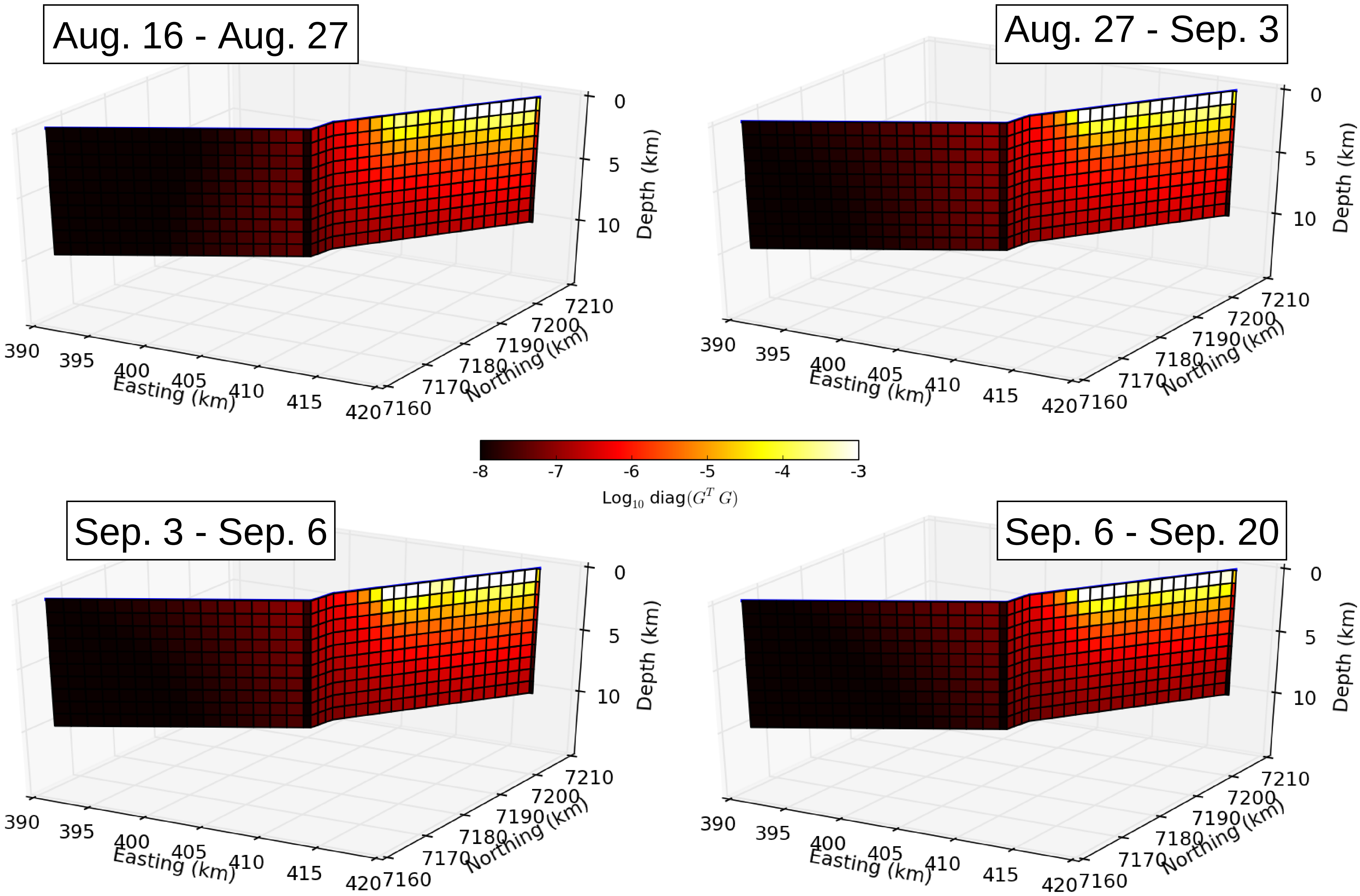


InSAR downsampling and covariance

- Use a resolution-based downsampling method (Lohman and Simons, 2005) for InSAR data
  - retain a higher density of observations where dike model has greater data resolution
- Exponential distance-weighted covariance function to form data covariance matrices



Time dependent model resolution



Inverse problem for the dike model

- Set up the inverse problem uses Bayes' Theorem:

$$p(\mathbf{m}|\mathbf{d},\mathbf{G}) \propto p(\mathbf{d}|\mathbf{m},\mathbf{G})\, p(\mathbf{m})$$

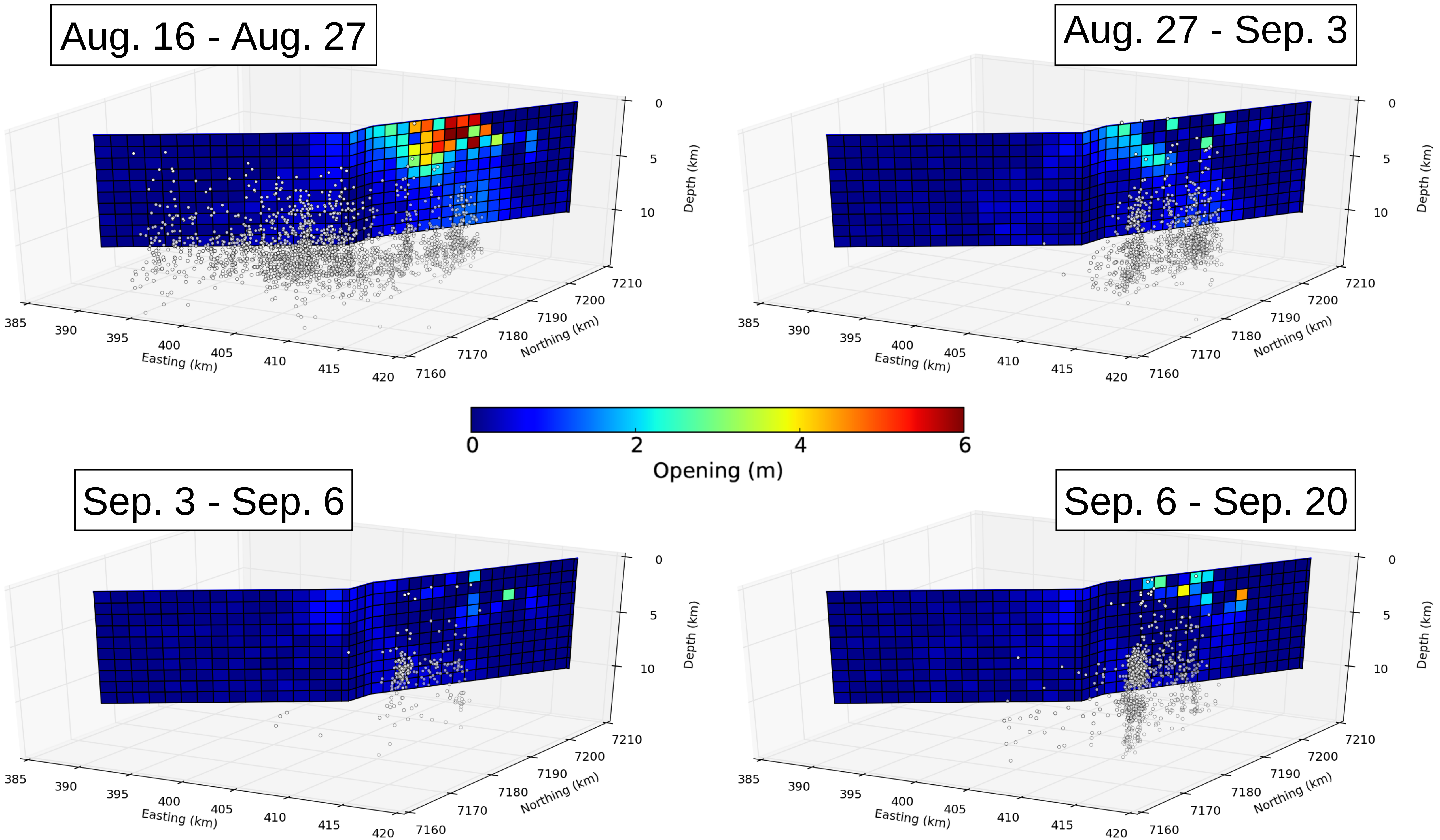
Posterior probability for model parameters **m**

Data likelihood of data **d** given design matrix **G** and parameteters **m**

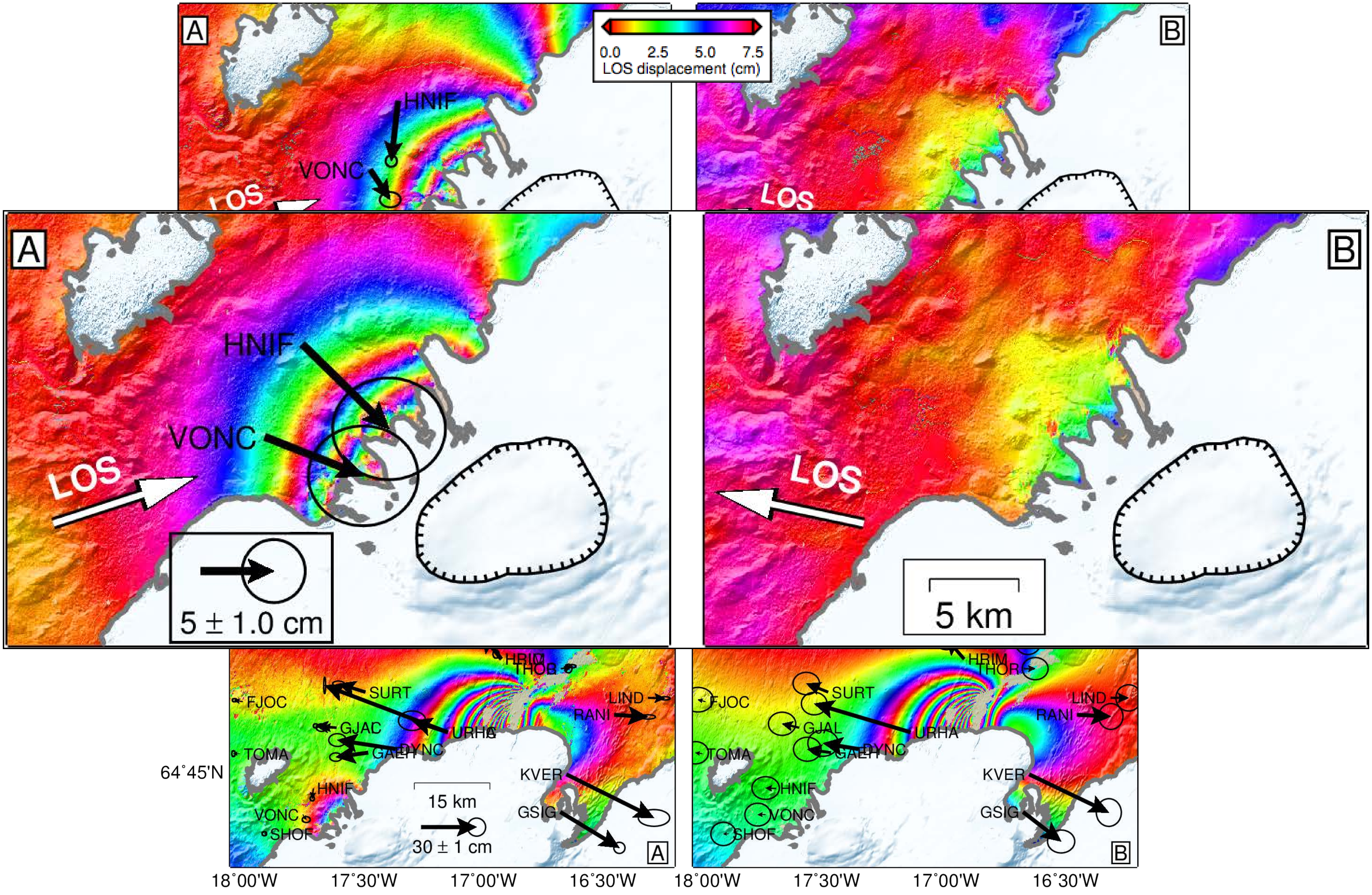
Prior probability for model parameters **m**

- Sample the posterior distribution using a Hamiltonian Markov Chain Monte Carlo (MCMC) sampling method
- Sample for spatial distribution of non-negative opening values along the fault
  - also sample for a 2D quadratic polynomial to account for long-wavelength errors
- No spatial smoothing of the opening values is imposed for the priors

Maximum a posteriori model for dike

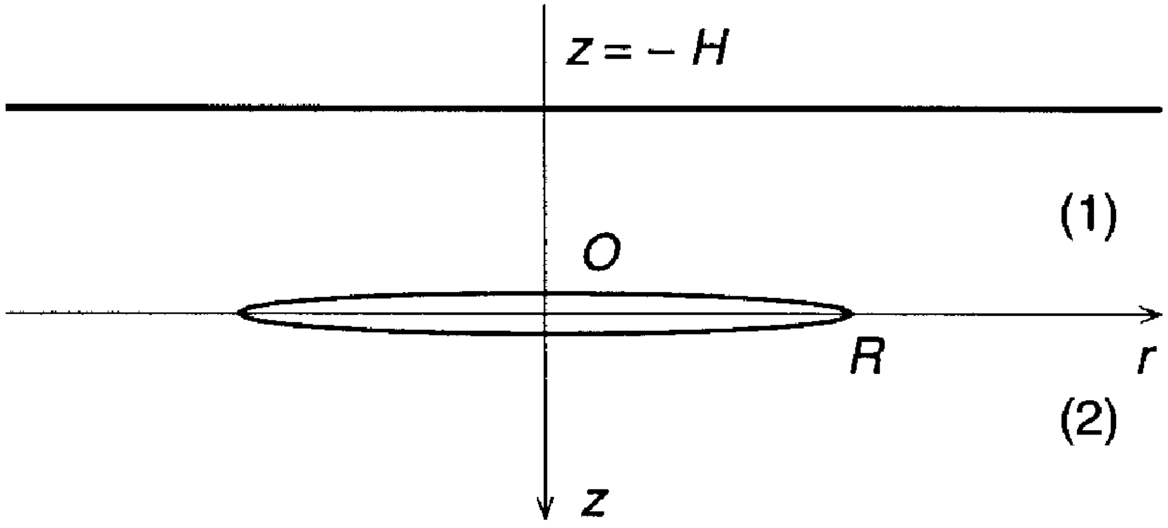


Data for modeling magma chamber (Part 2)



Model of magma chamber

- A model for a subsurface magma chamber must satisfy the following observations:
  - Meter-scale subsidence of the caldera
  - Centimeter-scale deformation on ice-free areas adjacent to caldera
  - Symmetric subsidence pattern on the caldera
- We model the subsidence with a collapsing horizontal circular crack (Fialko, et al. 2001)



Fialko, et al. 2001

MCMC for sill model parameters

- The model parameters are chamber <u>location</u>, <u>radius</u>, and <u>excess pressure</u>

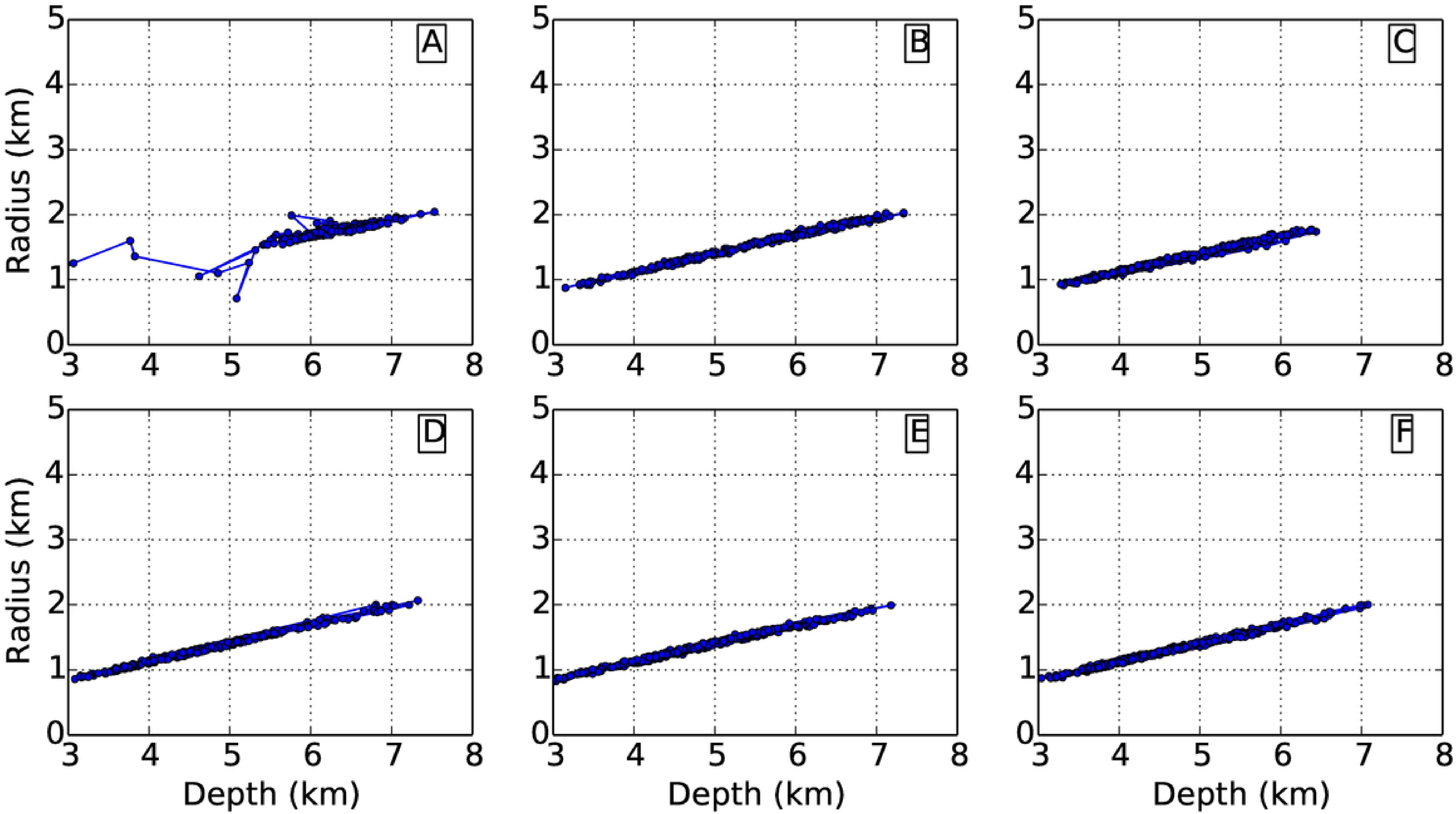
- Strong trade-off between radius, depth, and pressure
  - Main parameter is depth-to-radius ratio
  - Shallow, small chamber == Deep, large chamber

- Good constraints on horizontal location from InSAR (small prior variance)

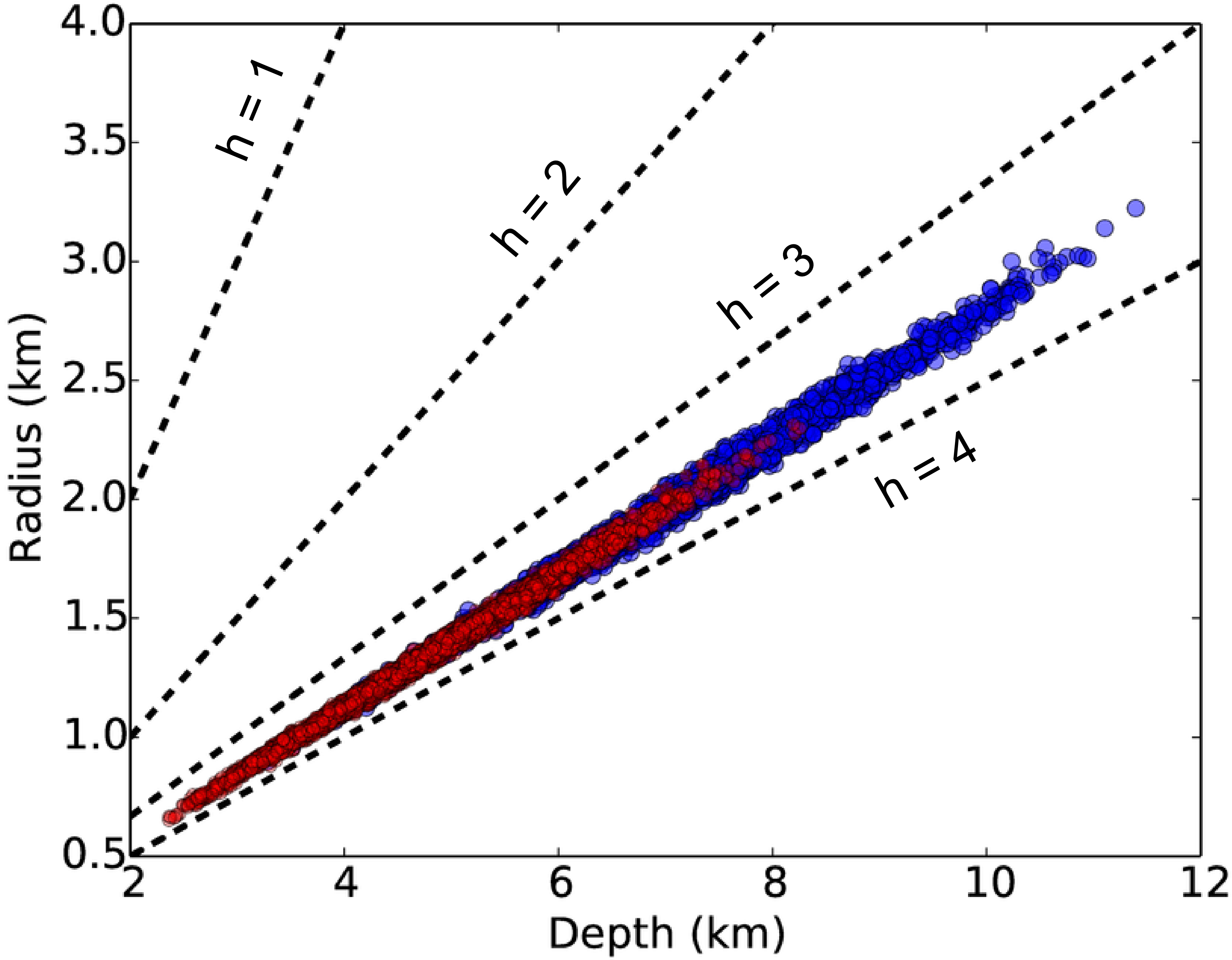
- Include Aug. 27-28 CSK interferogram but with large data uncertainties
  - provides some constraint on pressure change even with uncertain ice-rock interaction

Depth-radius convergence and trade-off

Every 5000 samples



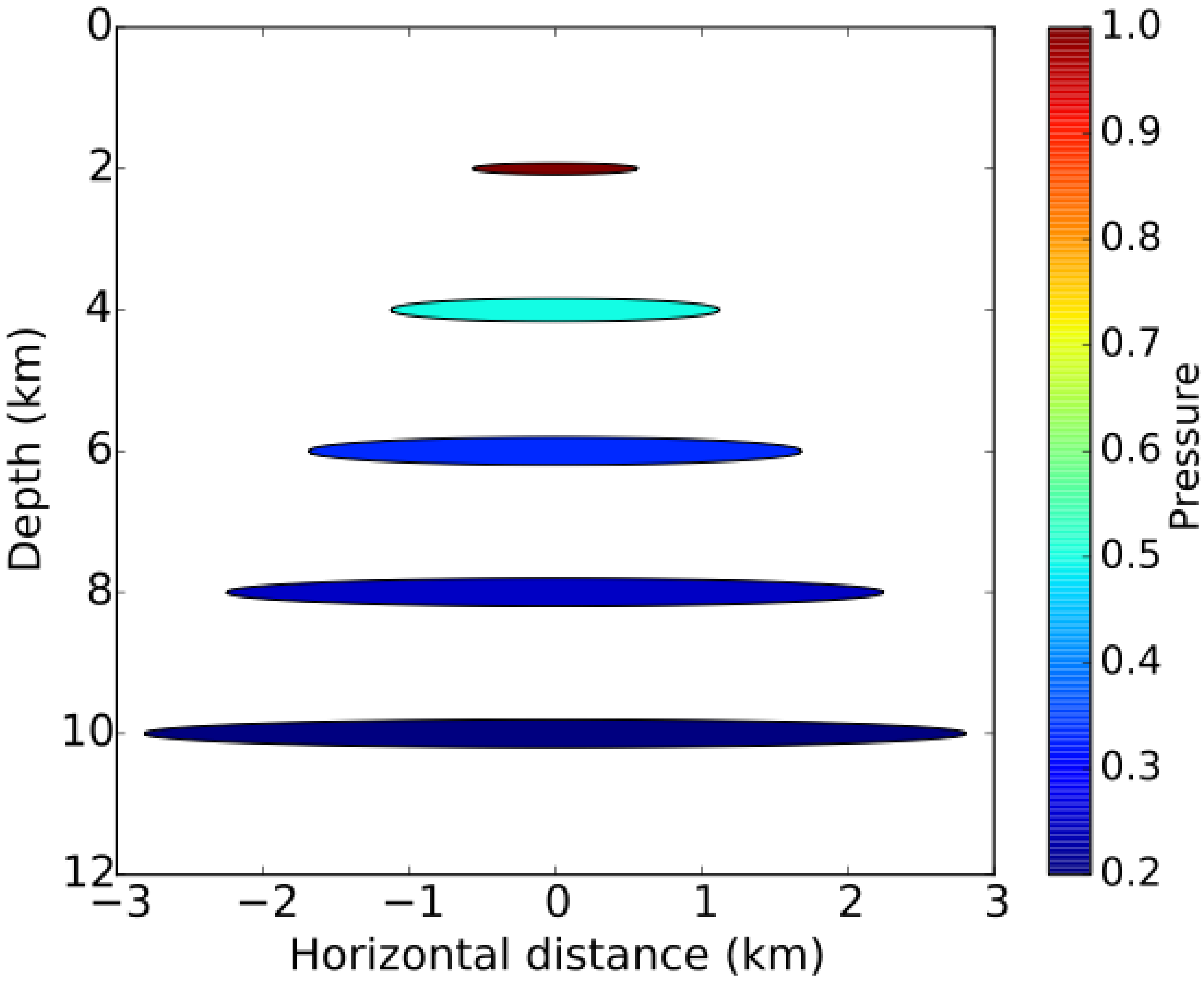
Depth-radius dependence on prior



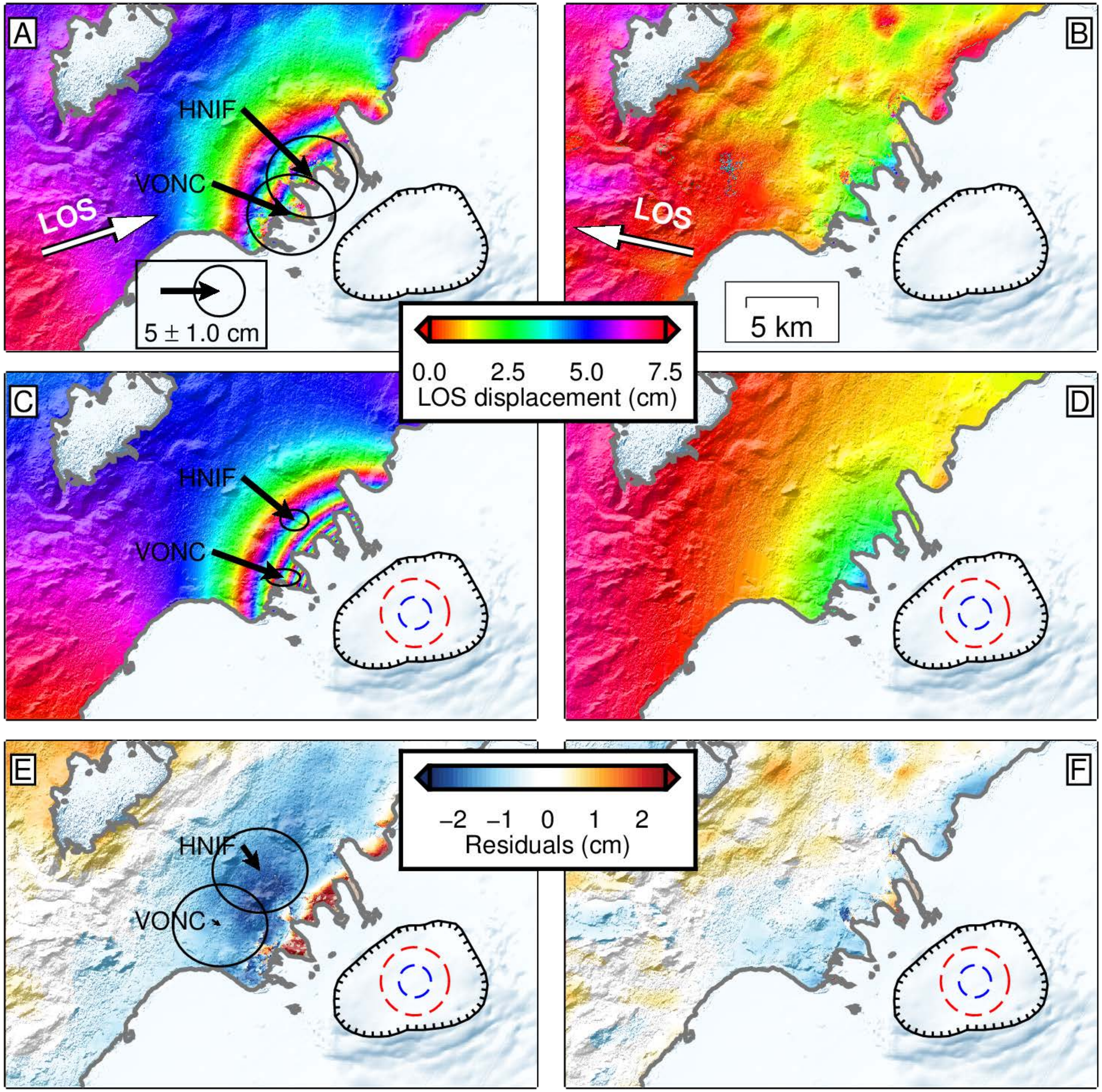
- h ≡ (depth / radius)
- **Blue** - mean prior depth is 6 m
- **Red** - mean prior depth is 3 m

“Family” of magma chambers

- Consistent depth-to-radius ratios for different depth/radius priors means we cannot constrain the depth
- Choice of depth requires independent observations (e.g., seismicity) or physical upper bound on pressure difference



Magma chamber model results



Model A (red)

- Depth: 8 km
- Radius: 2.3 km

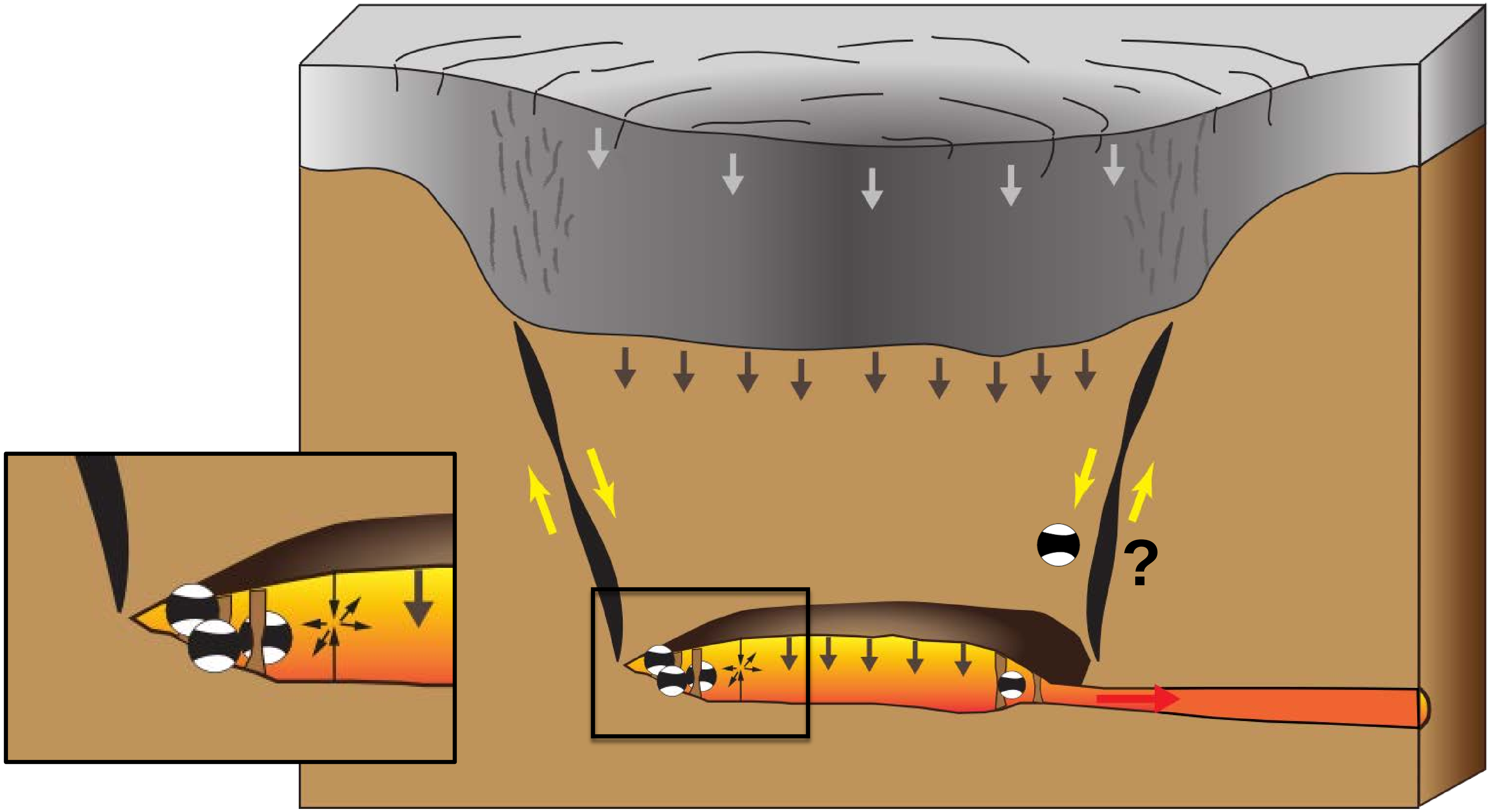
Model B (blue)

- Depth: 4 km
- Radius: 1.1 km

Mechanics of the caldera collapse

- The magma chamber can be modeled as a circular sill
- The radius of the chamber is likely smaller than the radius of the caldera rim

- M > 5 earthquakes along caldera rim with CLVD focal mechanisms may be caused by two different processes:
  - Closing cracks due to failure of internal chamber supports
  - Arc rupture along inward dipping ring faults

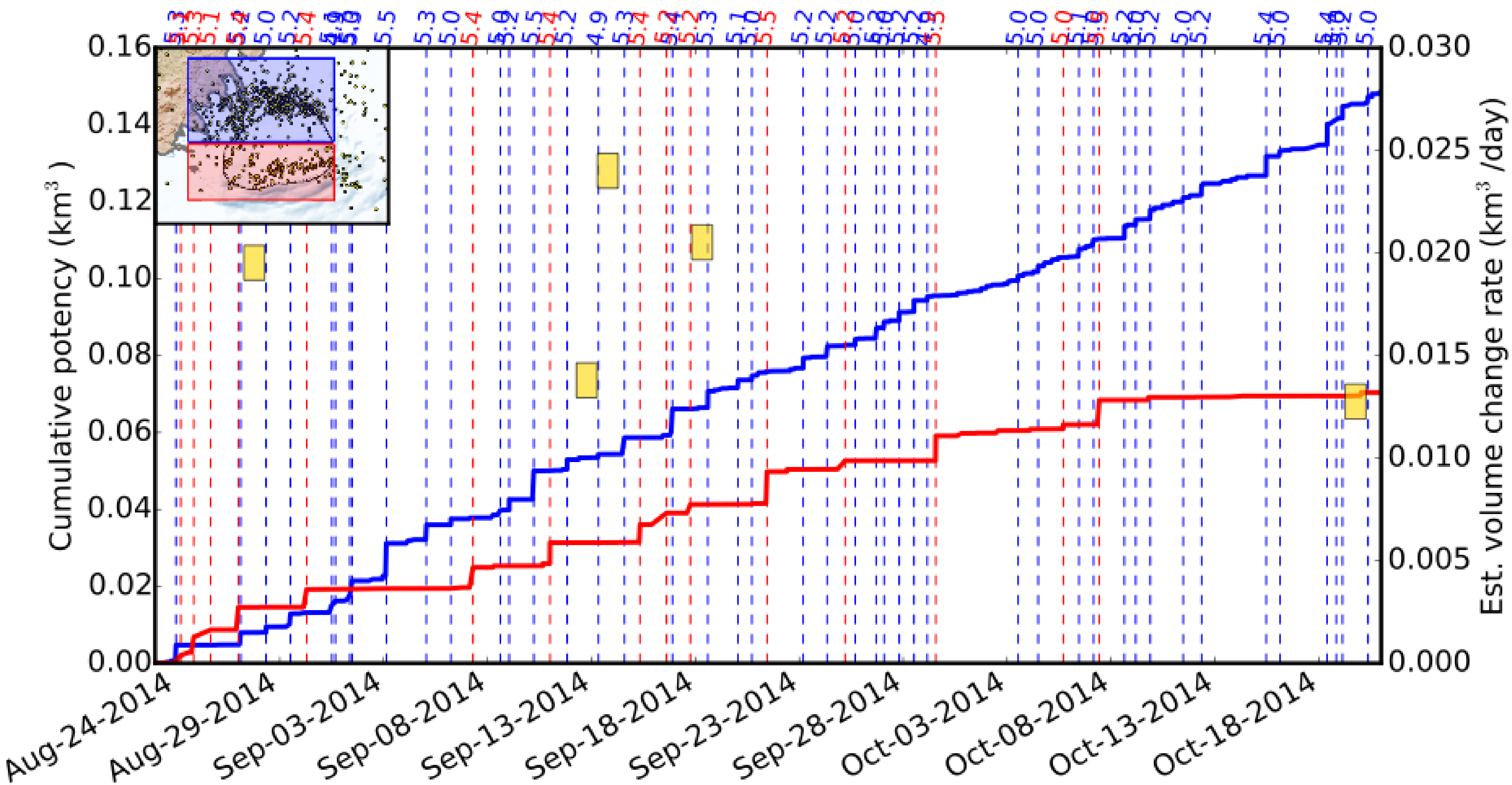


Summary

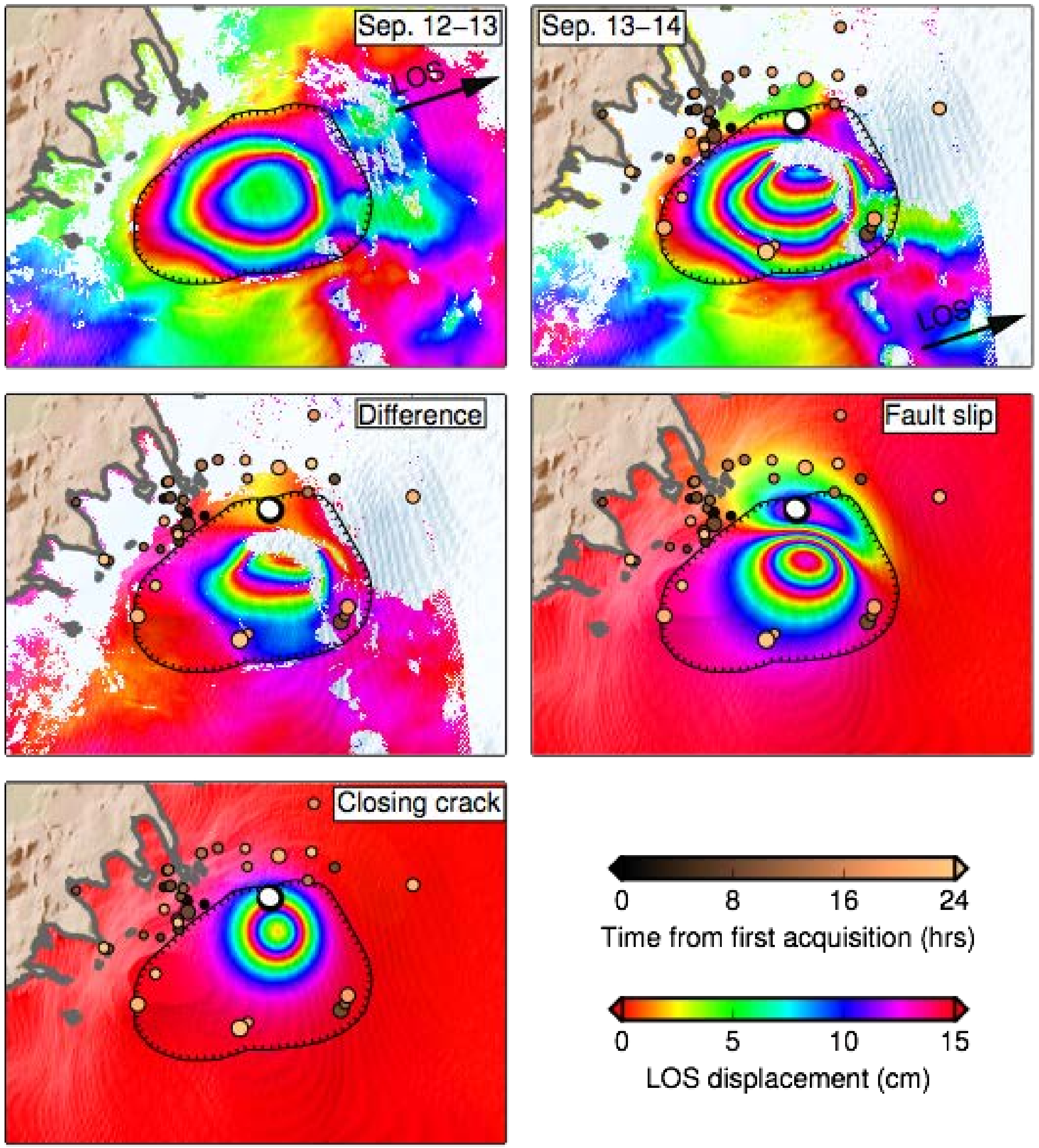
- The Bárdarbunga caldera collapse and Holuhraun eruption was well observed via a combination of InSAR, GPS, and seismic data
- The international constellation of radar satellites indicated rapid 50 cm/day subsidence of the ice-covered caldera and meter-scale crustal deformation in the active rift zone
- The large subsidence within the caldera rim (which has never been previously observed at Bárdarbunga) provides critical constraints on the collapse sequence
  - Most of the subsidence occurs aseismically
  - Circular horizontal sill can explain centimeter-scale deformation on ice-free regions and meter scale deformation over the caldera
  - CLVD events can possibly be explained by a “closing crack” mechanism (e.g., mine collapse) or rupture on curved ring faults

Thank you!

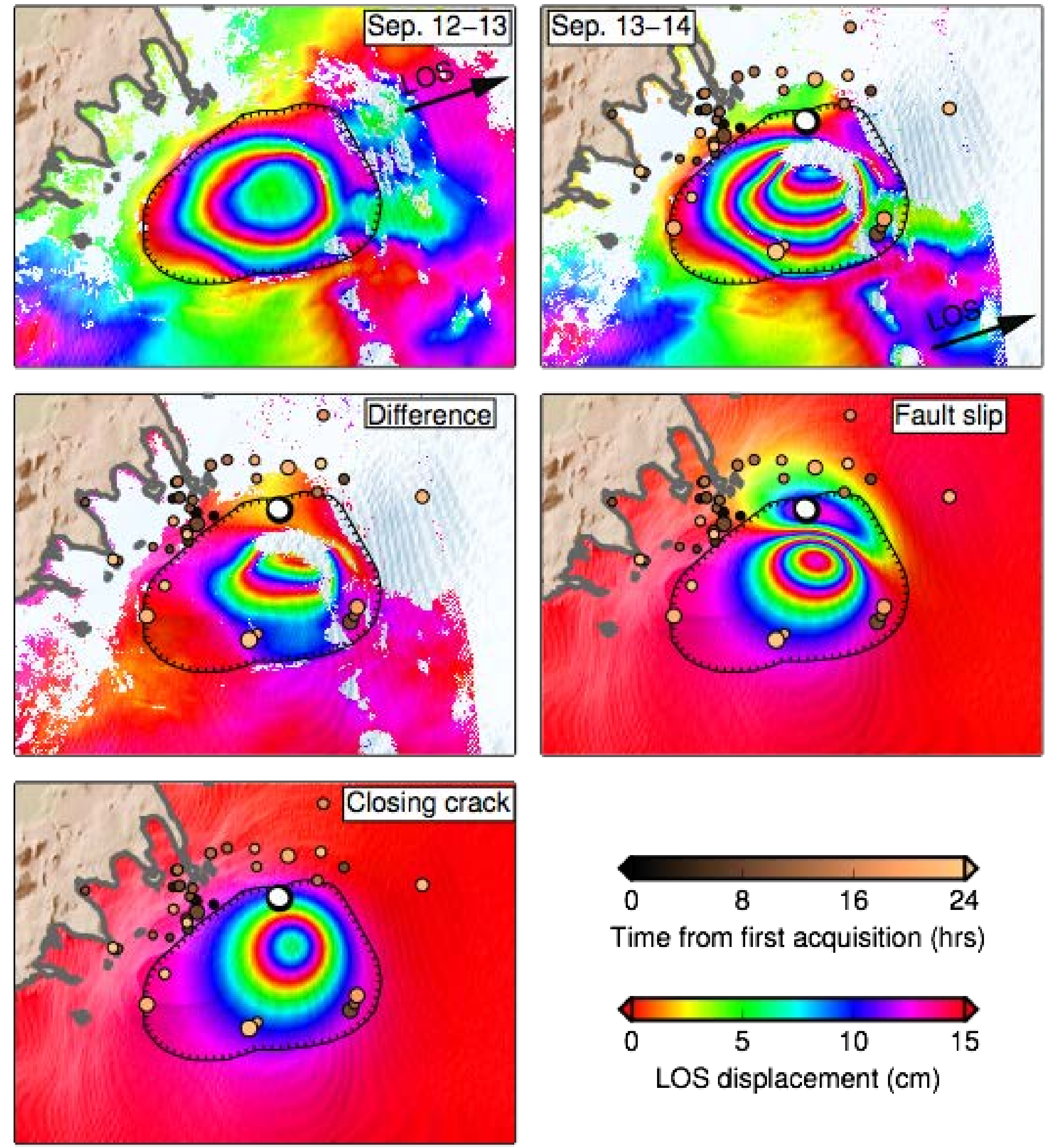
IMAGE: ARCTIC-IMAGES/CORBIS


Cumulative potency (km^3)
Est. volume change rate (km^3 /day)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.000
0.005
0.010
0.015
0.020
0.025
0.030
Aug-24-2014
Aug-29-2014
Sep-03-2014
Sep-08-2014
Sep-13-2014
Sep-18-2014
Sep-23-2014
Sep-28-2014
Oct-03-2014
Oct-08-2014
Oct-13-2014
Oct-18-2014

Isolating the earthquakes

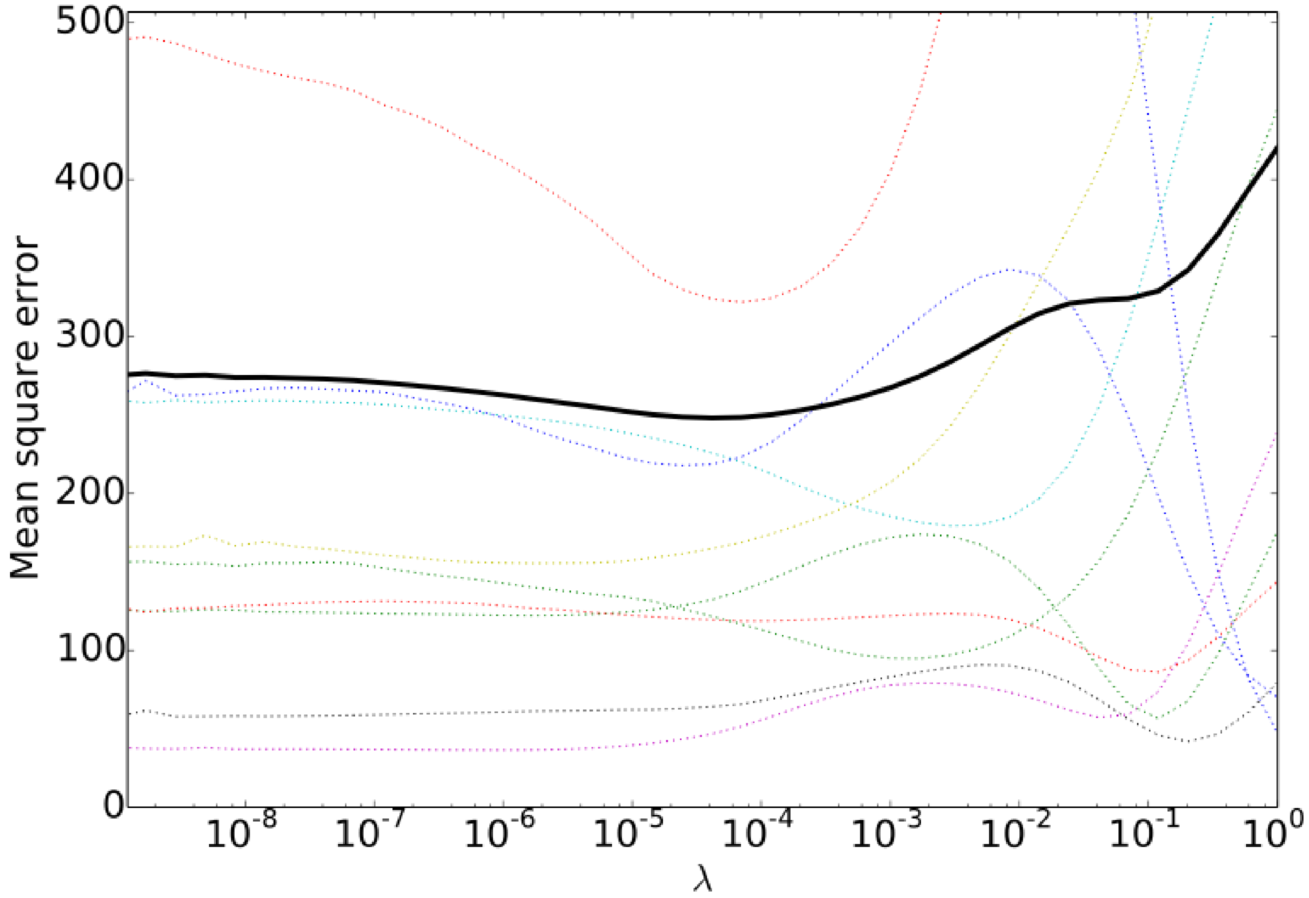


2 km deep penny shaped crack



2 km deep 30° dipping rectangular crack

Selection of the smoothing parameter



Dike emplacement and seismicity

Seismicity from Iceland Met. Office

GPS-only inversion