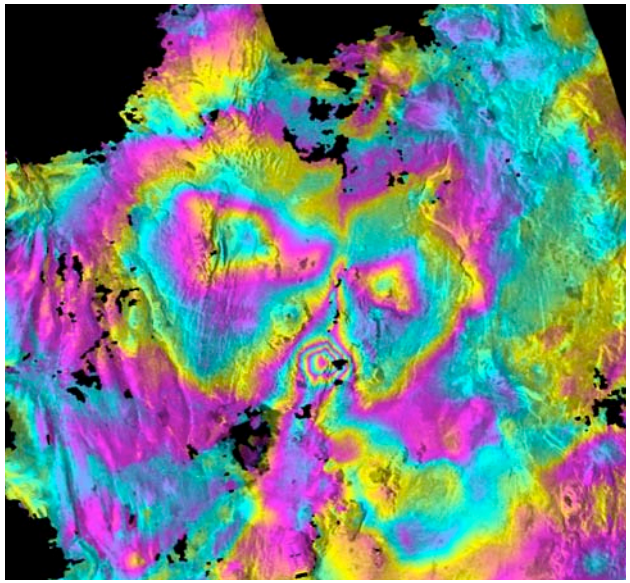
Modeling the post-rifting deformation on the Krafla volcanic system

Christopher DiCaprio, Mark Simons

Caltech

Outline

- Geophysical Goals
  - Modeling the post-rifting deformation on the Krafla fissure system
- Previous Work
  - Viscoelastic models and GPS data
  - Elastic models and InSAR data
- InSAR Constraints
- Modeling Workflow
  - What tools we use and how they are applied
- Intuition Building via FEM Modeling
- Challenges and Next Steps
  - What technical issues need to be addressed



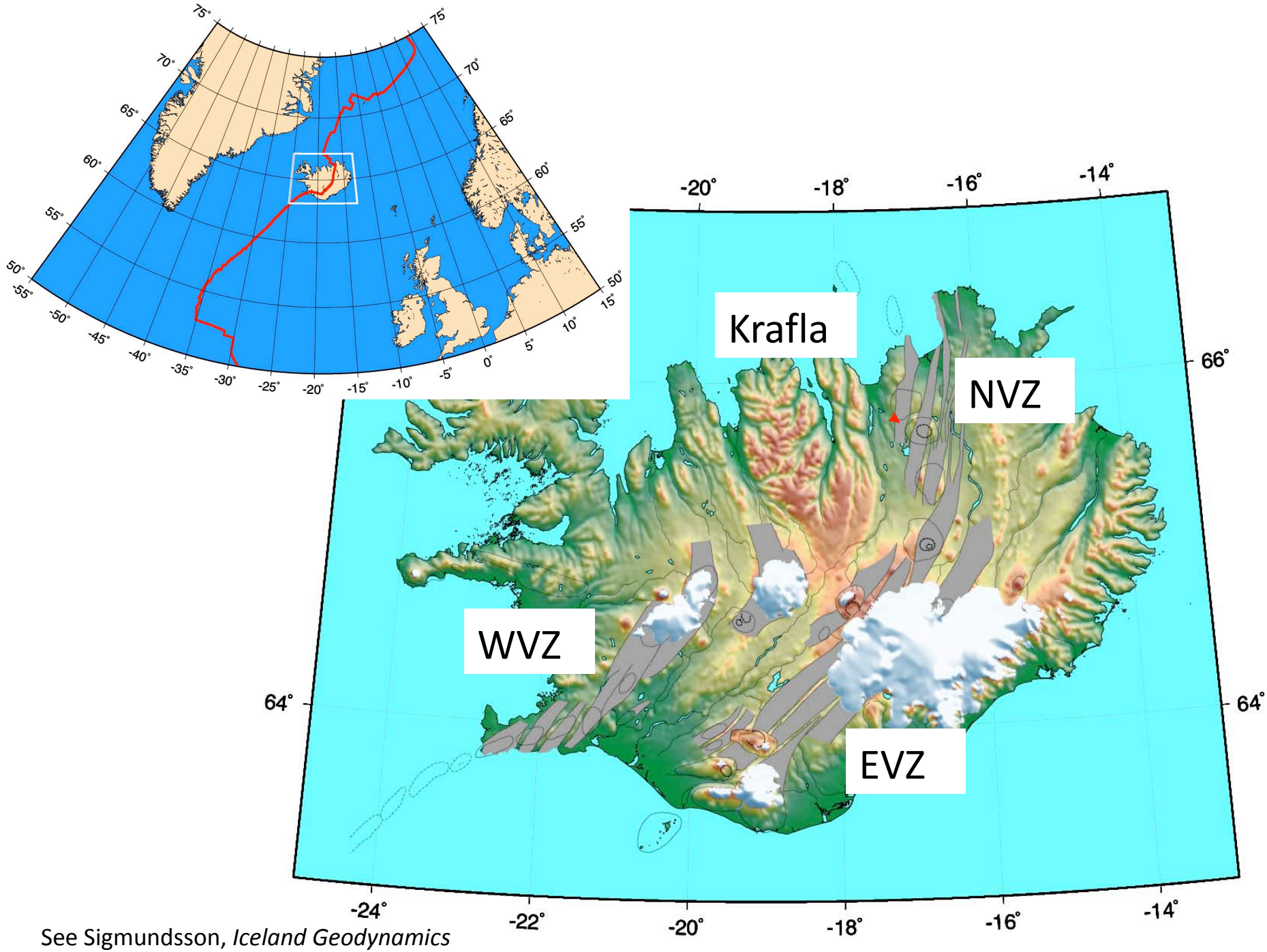
Today's Goals:

–Demonstrate use of PyLith and modeling workflow

–Describe modeling challenges and needed tools

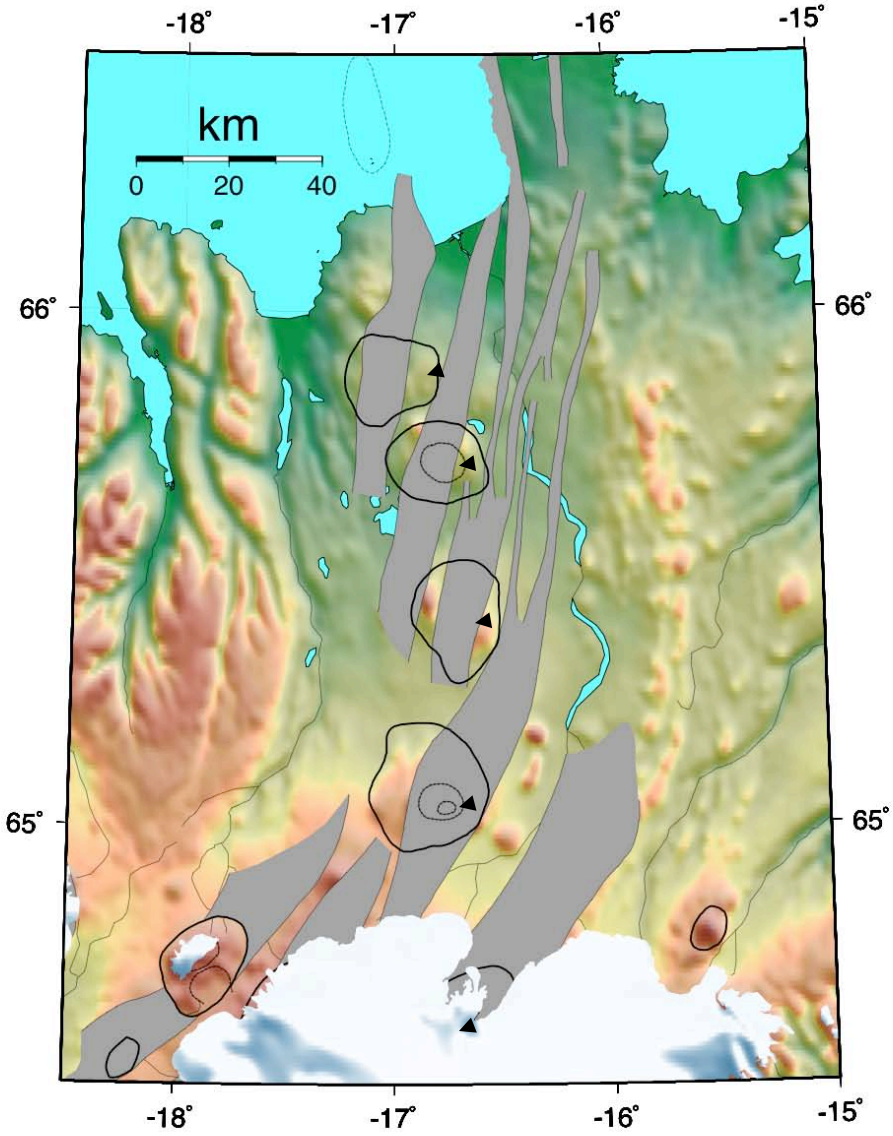
Geophysical Goals

- What are we trying to do?
  - Constrain rheology of northern Icelandic lithosphere by observing response to a rifting event
- How are we approaching the problem?
  - Analysis of the large InSAR data set
  - Structural models using geophysical and geological constraints
  - Two and three dimensional FEM models of viscoelastic deformation using PyLith



See Sigmundsson, *Iceland Geodynamics*

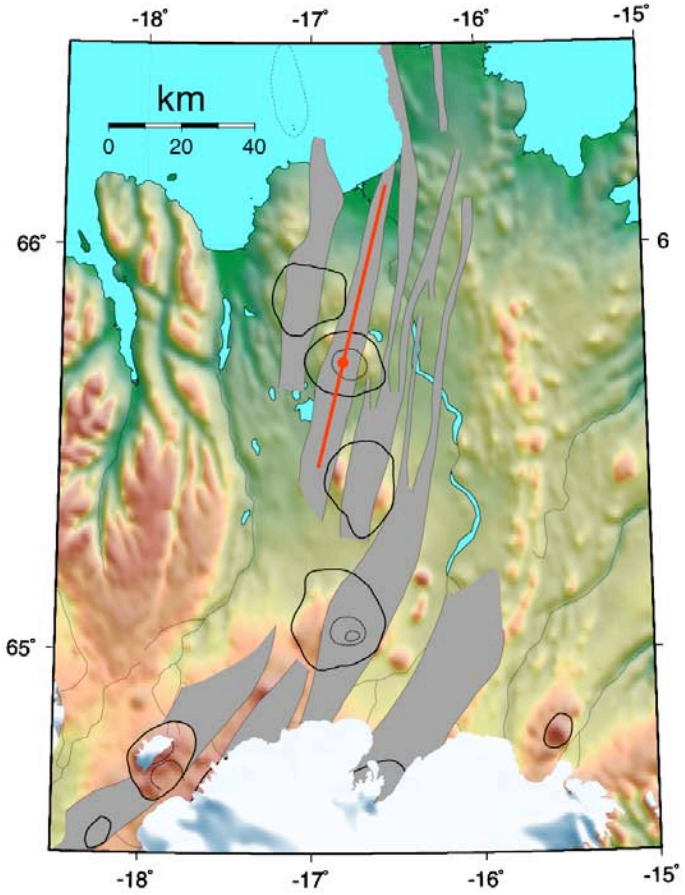
Northern Volcanic Zone

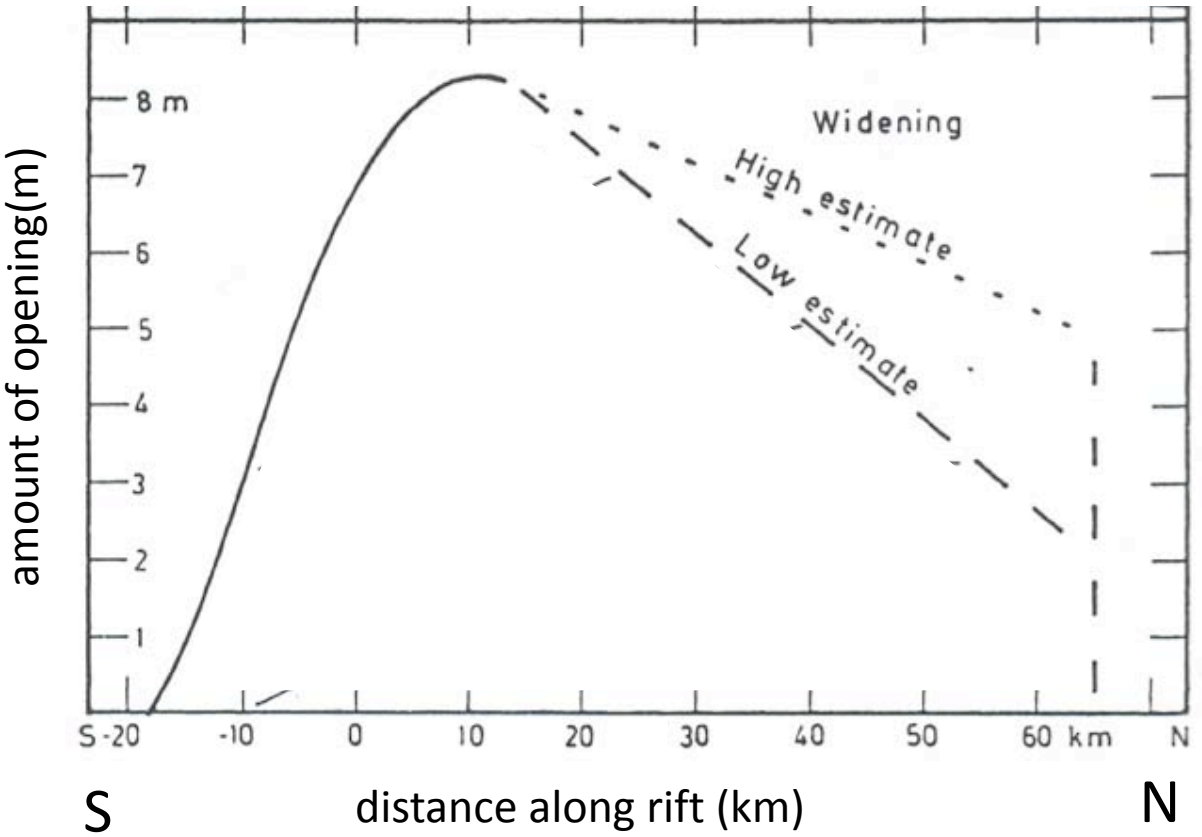


volcanic systems	historic rifting
Theistareykir	1618 A.D.
Krafla	1724, 1975 A.D.
Fremri-Namur	
Askja	1874 A.D.
Kverkfjoll	

- 100 - 150 year rifting episode interval
- Each event 50 - 100 km extent

Krafla Fires 1975 - 1984

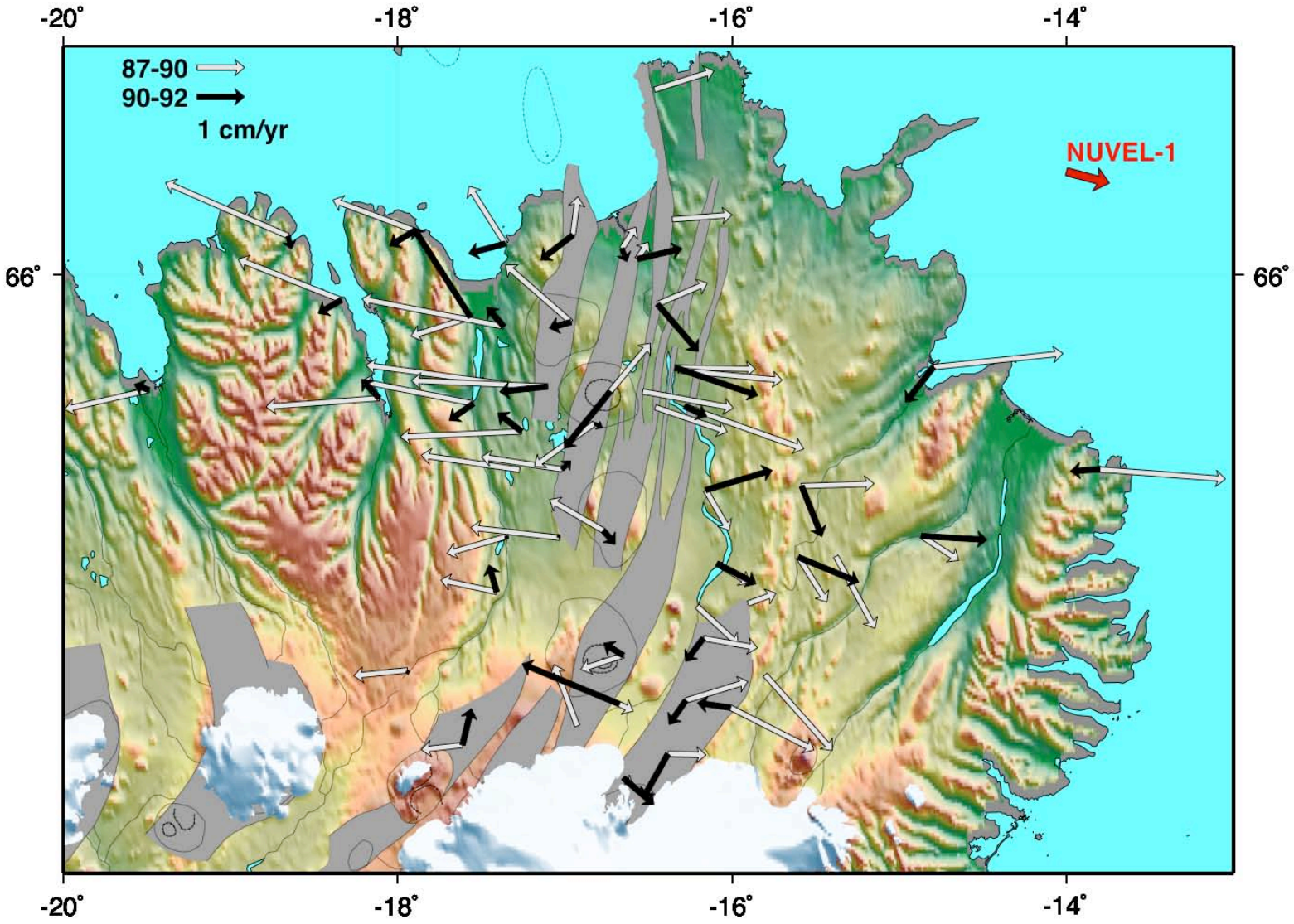




Series of individual rifting episodes last hours to days

Tryggvason, 1984, *B. Vol.*

GPS Record of Post-Rifting Deformation



Previous Visco(elastic) Modeling

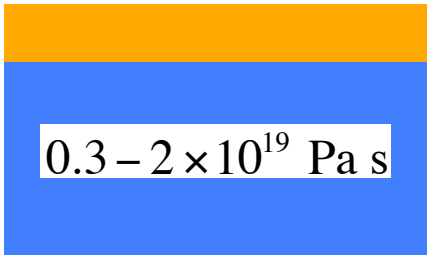
elastic

viscous

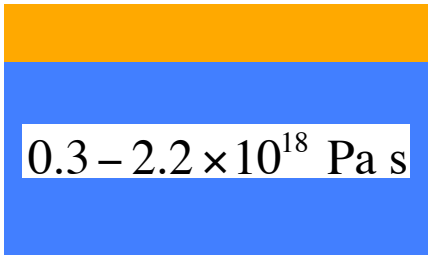
Maxwell viscoelastic

standard linear solid

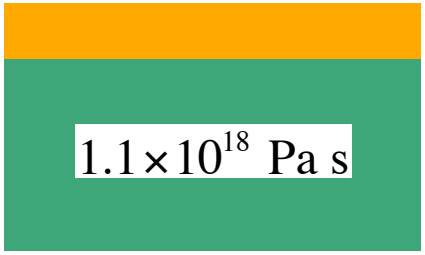
Foulger et al 1992



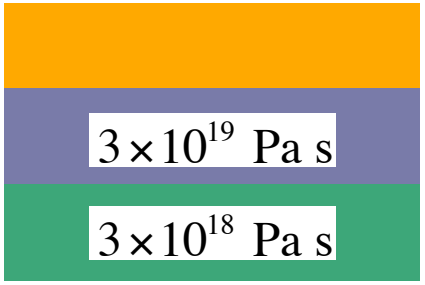
Heki et al 1993



Hofton and Foulger, 1996



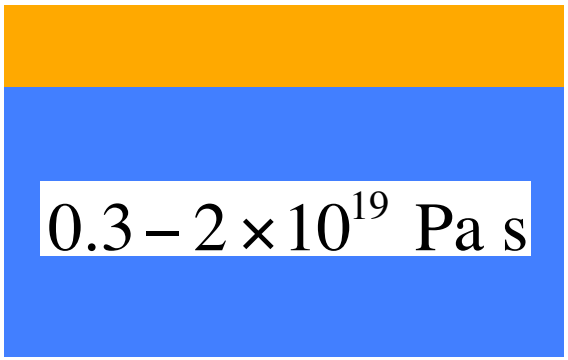
Pollitz and Sacks, 1996

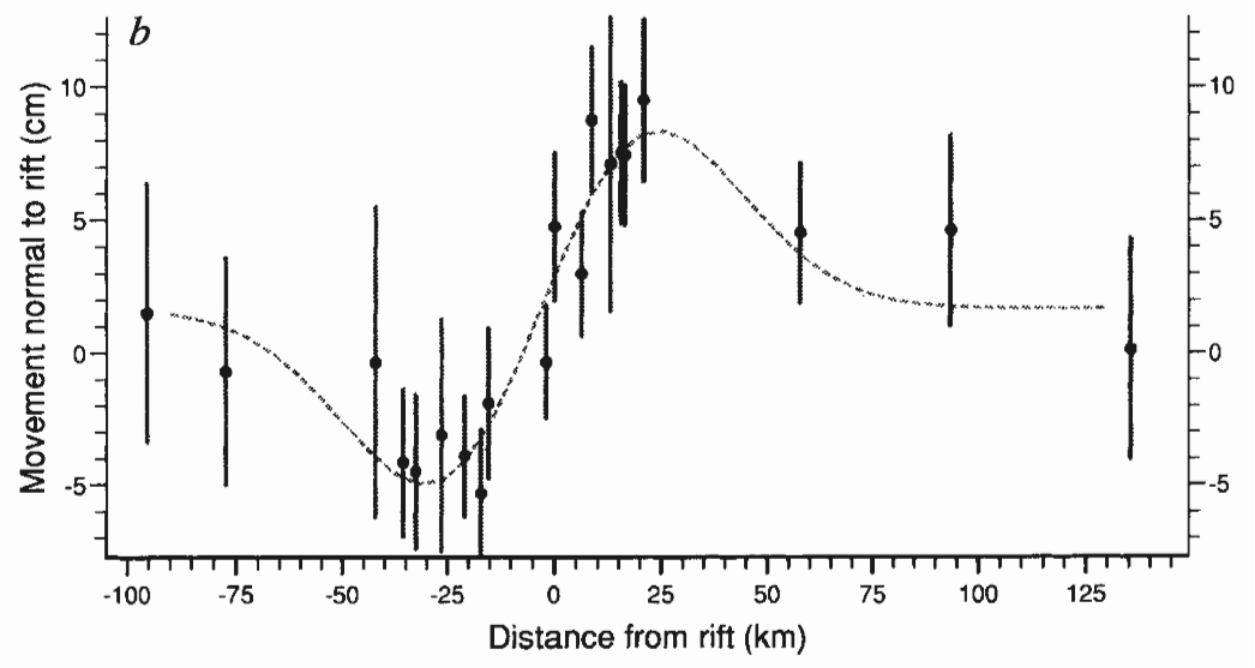


Foulger et al. 1992

- Material varies only with depth (Elastic layer over viscous channel)
- Only considered rift normal displacement data from 1987 and 1990 GPS campaign
  - ➢ Solve for amount of opening and diffusivity (Elsasser model)

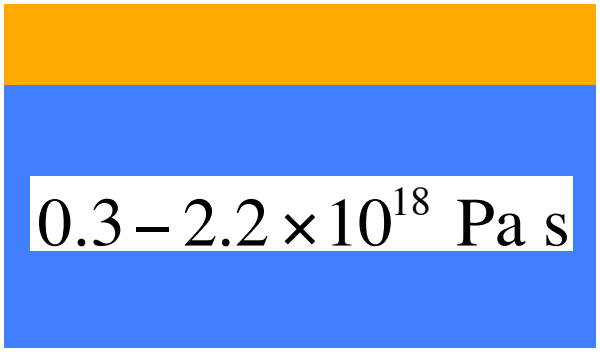
2 meters of opening

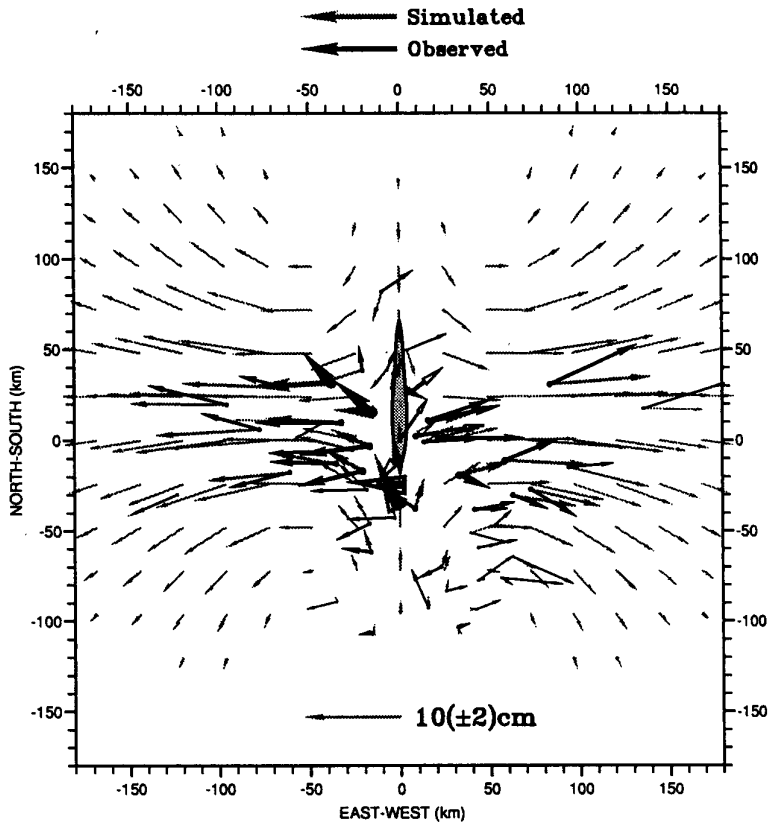




Heki et al. 1993

- Material varies only with depth (elastic layer over viscous channel)
- Model horizontal displacement data from 1987 and 1990 GPS campaign
- Elastic layer over viscous channel
  - ➢ Find three diffusion coefficients



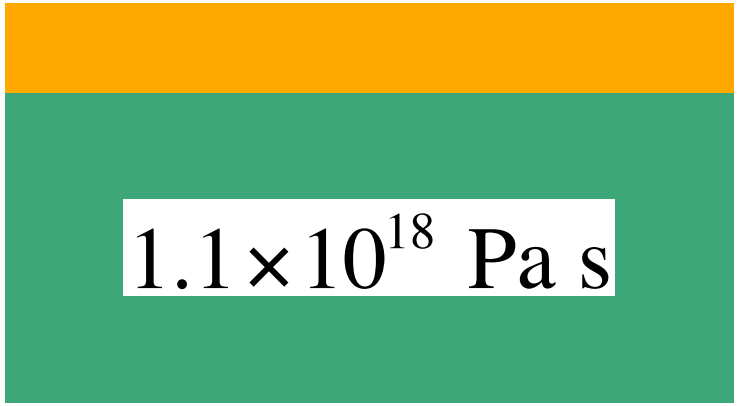


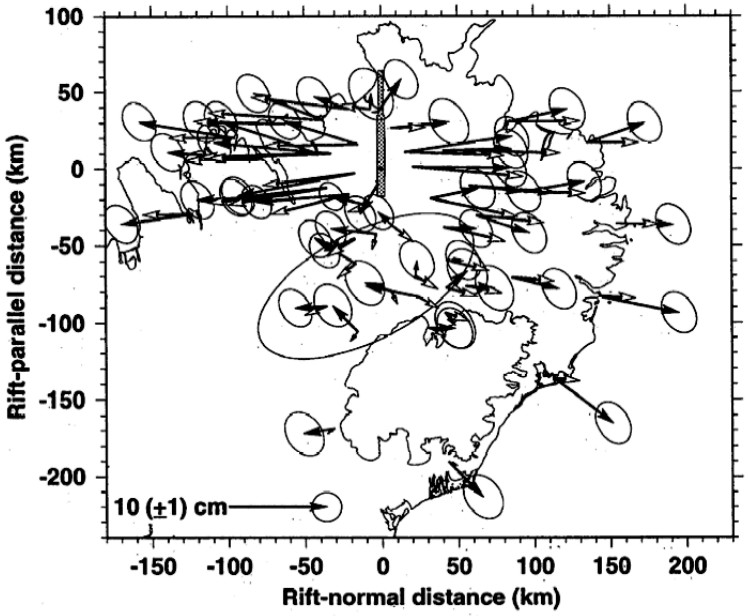
Hofton and Foulger 1996

- Material varies only with depth
  - Elastic layer over Maxwell viscoelastic ½ space
- Model three dimensional displacement data from 1987 and 1992 GPS campaign

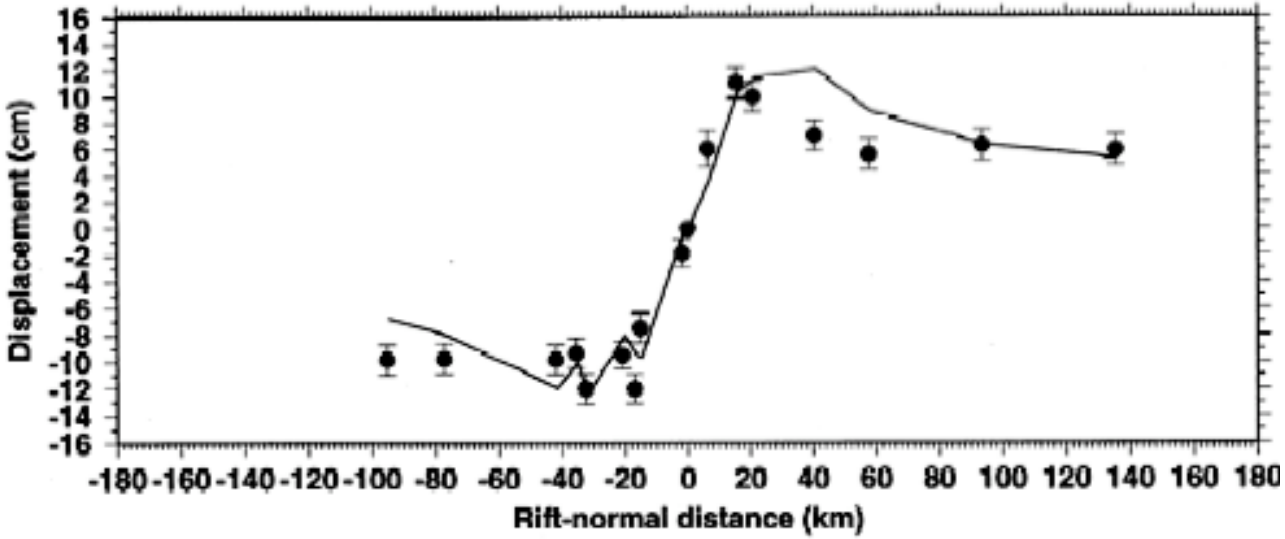
➢ Find viscosity of ½ space

➢ Refine estimates of dike height, dip, and elastic layer thickness

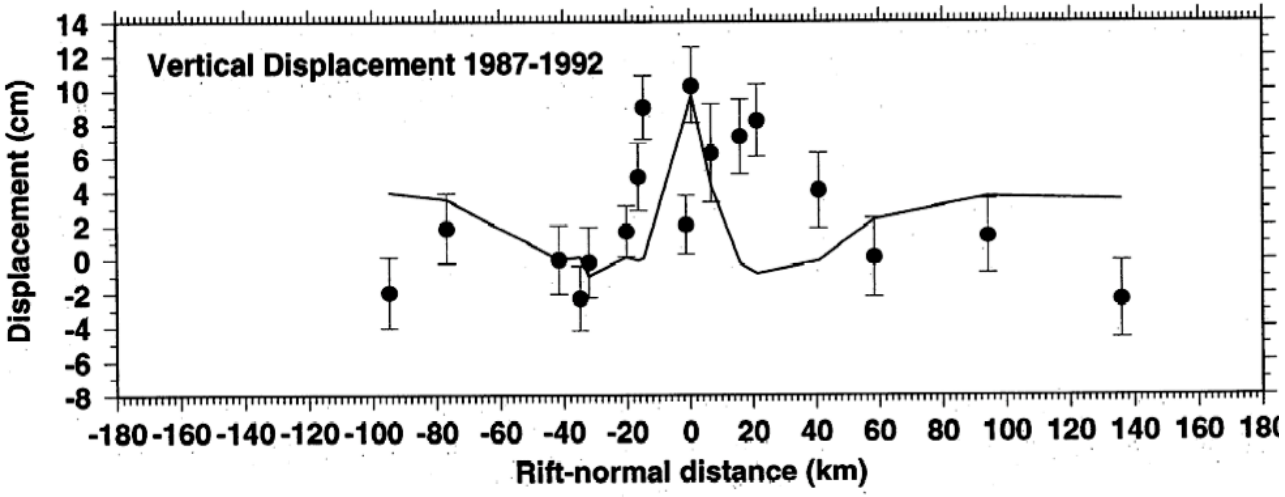




Hofton and Foulger 1996



Horizontal displacements fit for 1987-1992



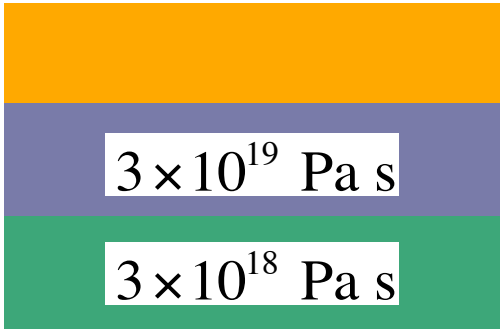
Verticals are more difficult to fit but also much noisier

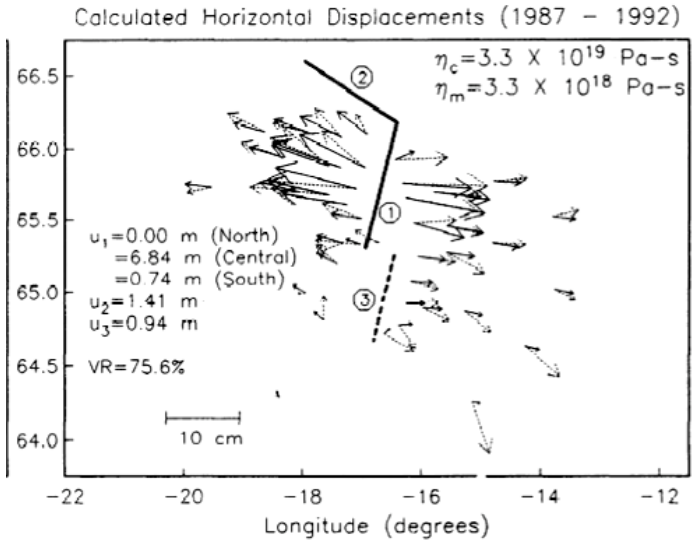
Pollitz and Sacks 1996

- Material varies only with depth
  - Elastic over SLS over Maxwell viscoelastic
- Model three dimensional displacement data from 1987, 1990, 1992 GPS campaign

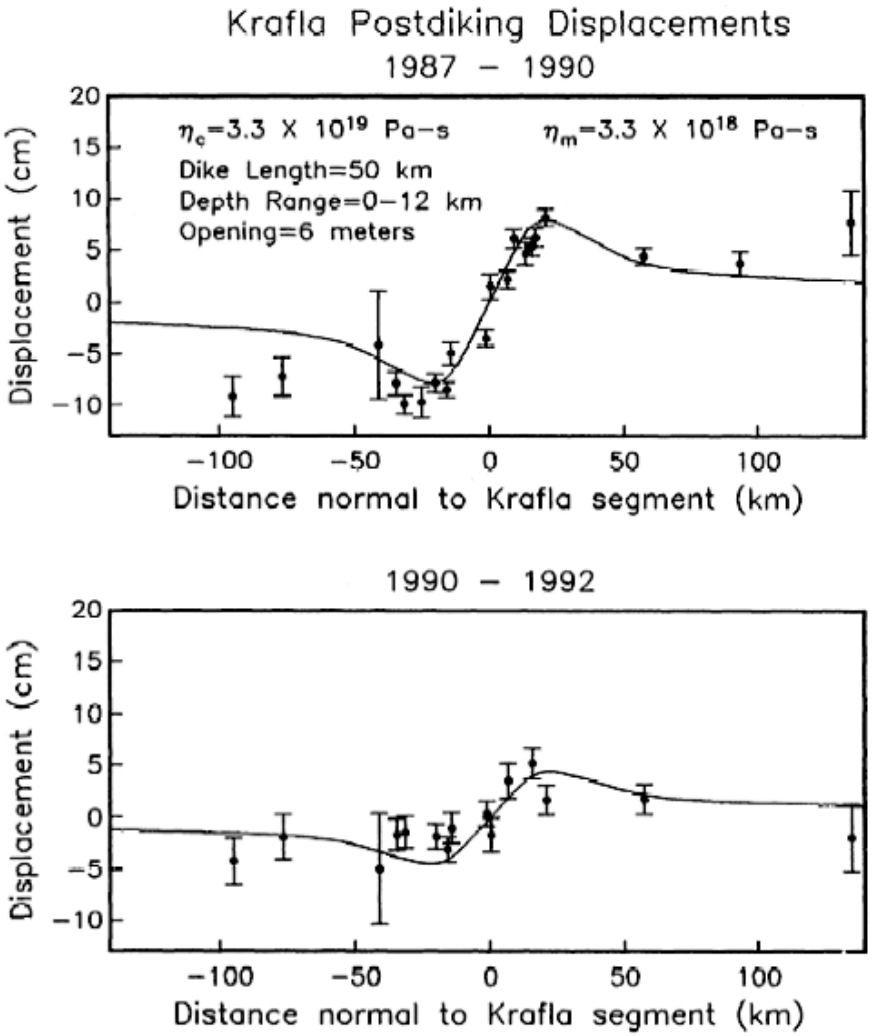
➢ Invert for amount of opening

➢ Find viscosity of VE layers





Pollitz and Sacks 1996



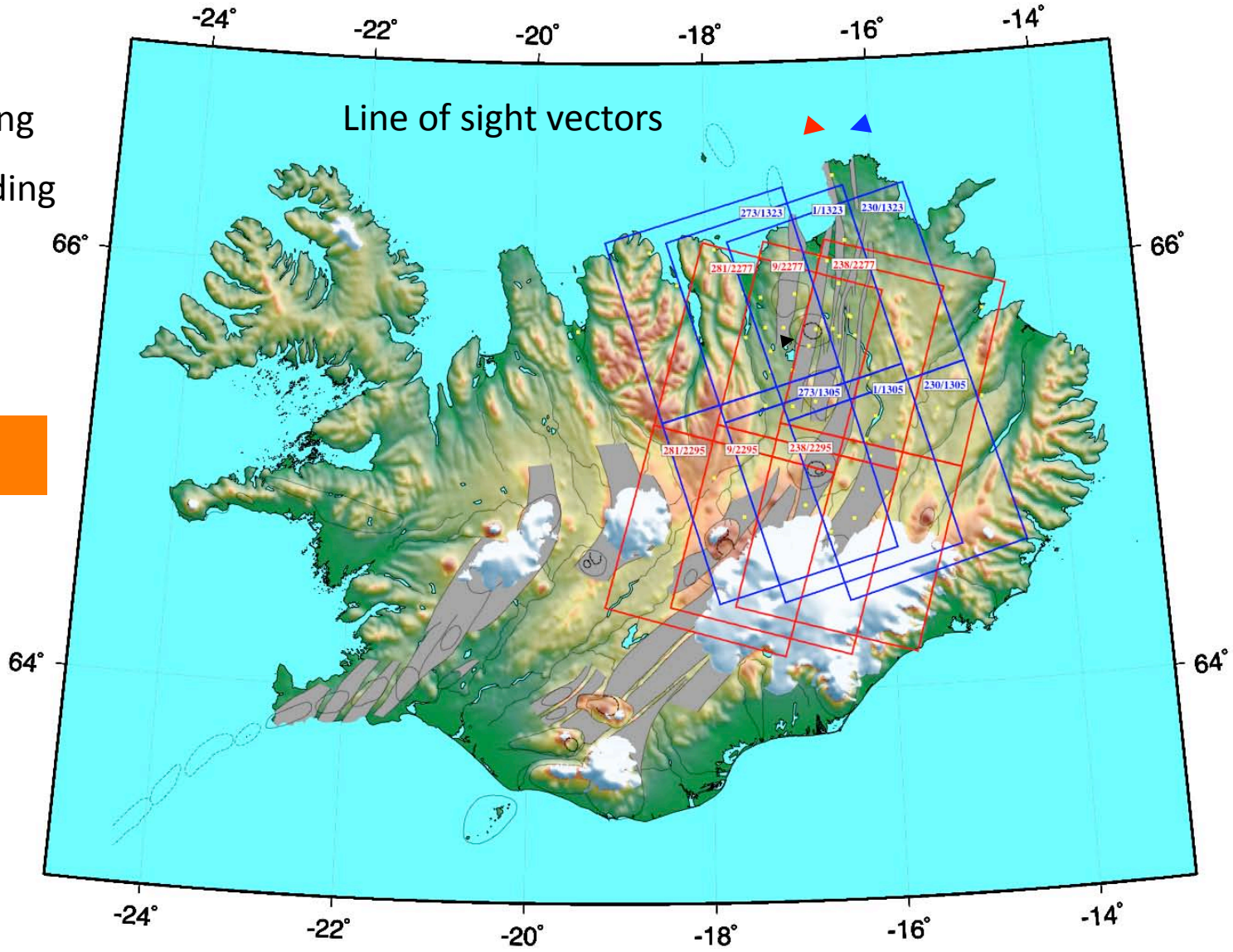
Horizontal displacements fit near rift 1987-1990 and 1990-1992

InSAR Coverage

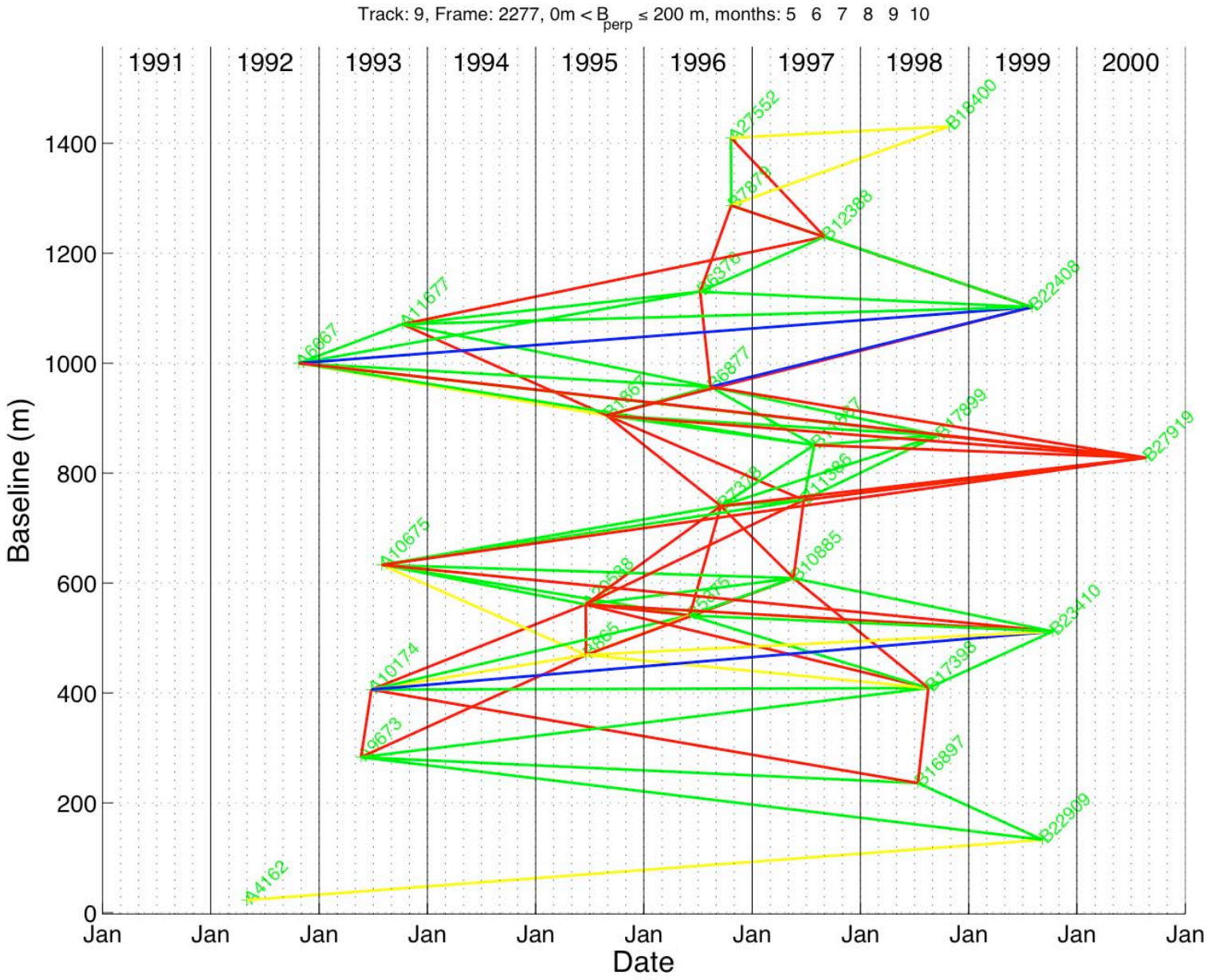
ascending

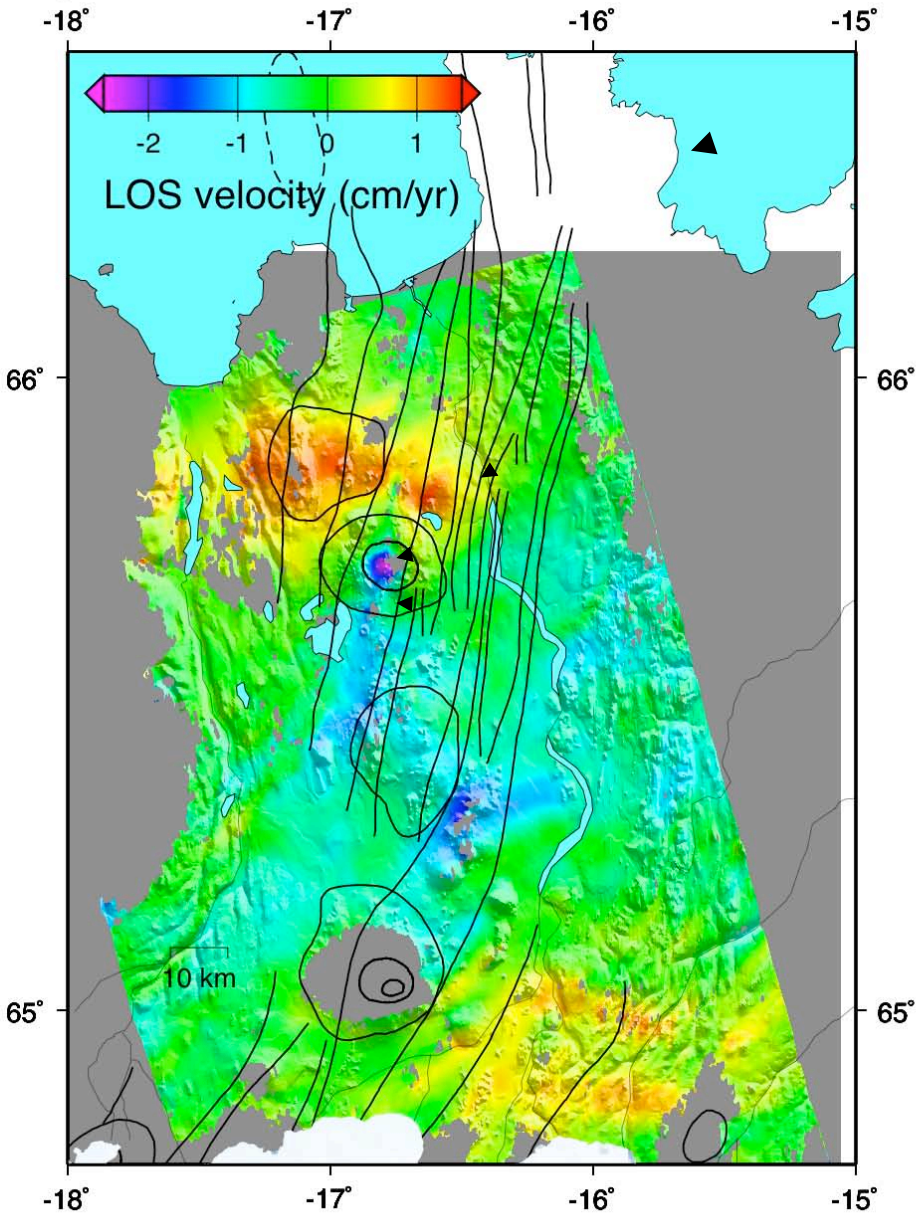
descending

Krafla



Interferometric Pairs





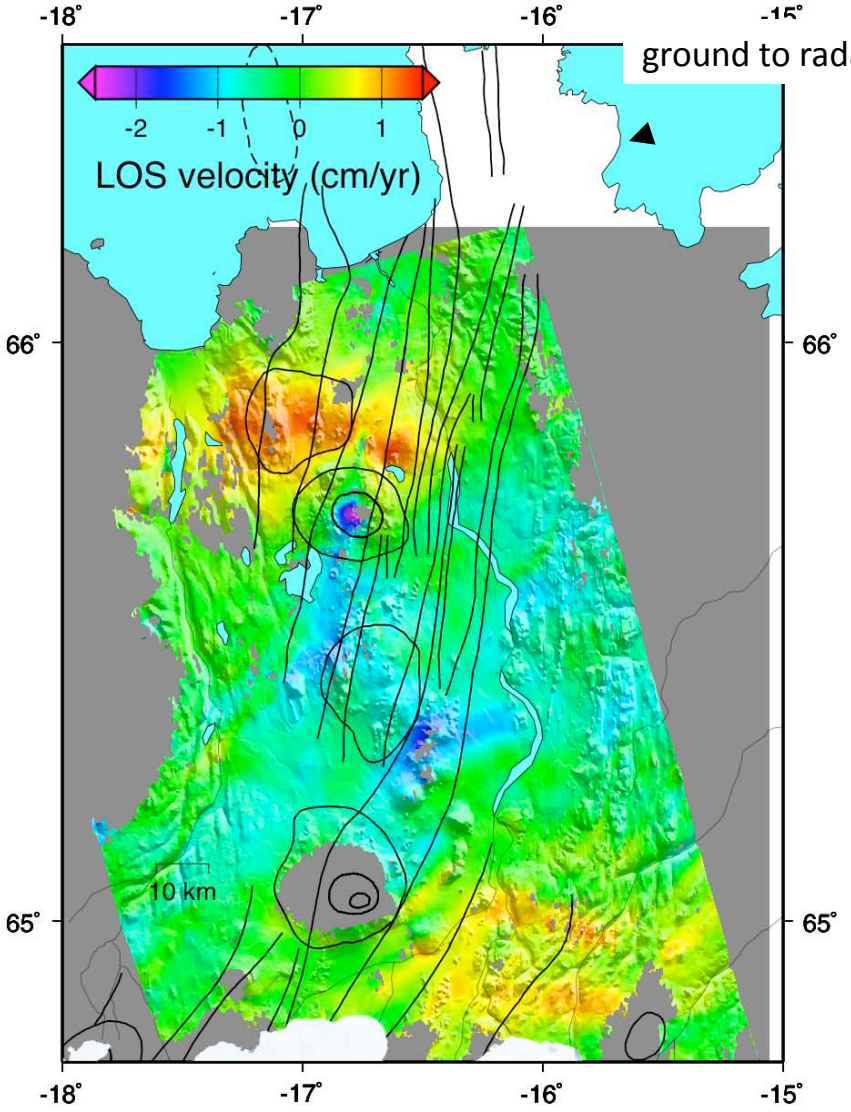
Broad post-rifting signal (viscoelastic relaxation)

deflating Krafla magma chamber

contraction, cooling?

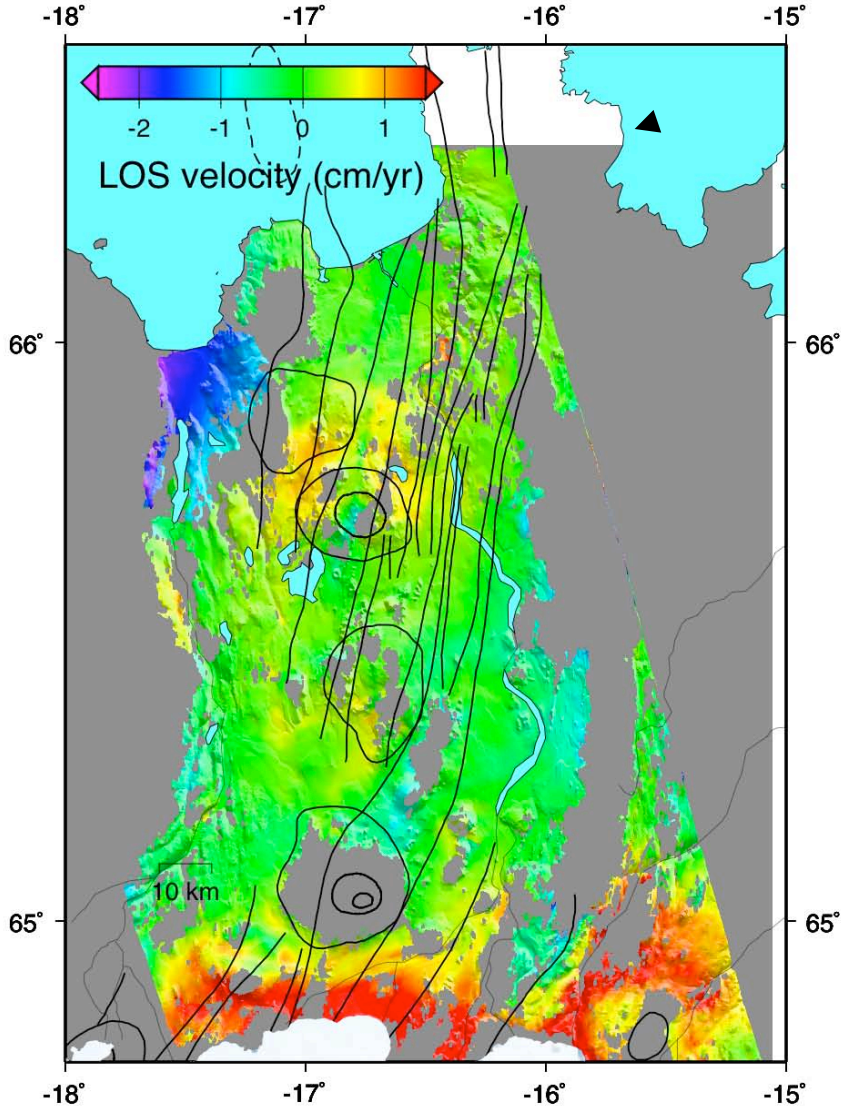
95/06/19 - 92/09/18

95/06/19 - 92/09/18



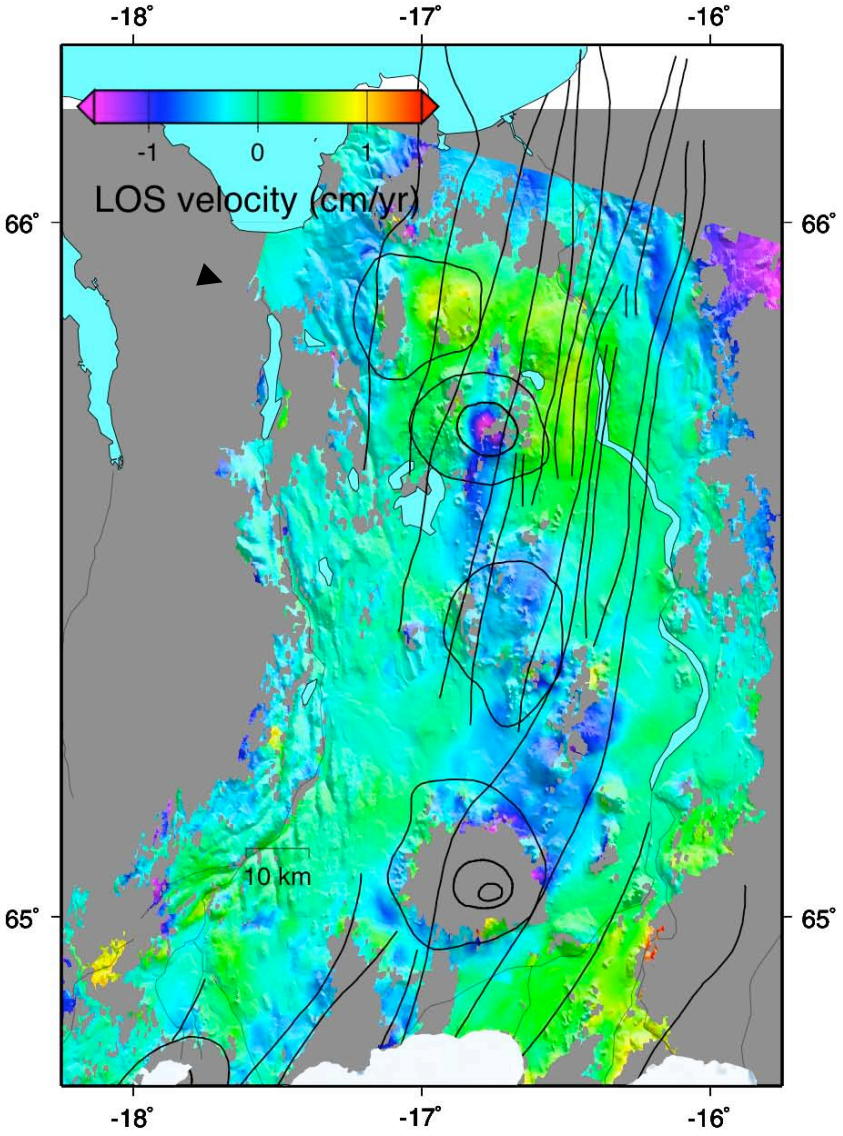
ascending orbit - T1

99/10/11 - 96/10/21



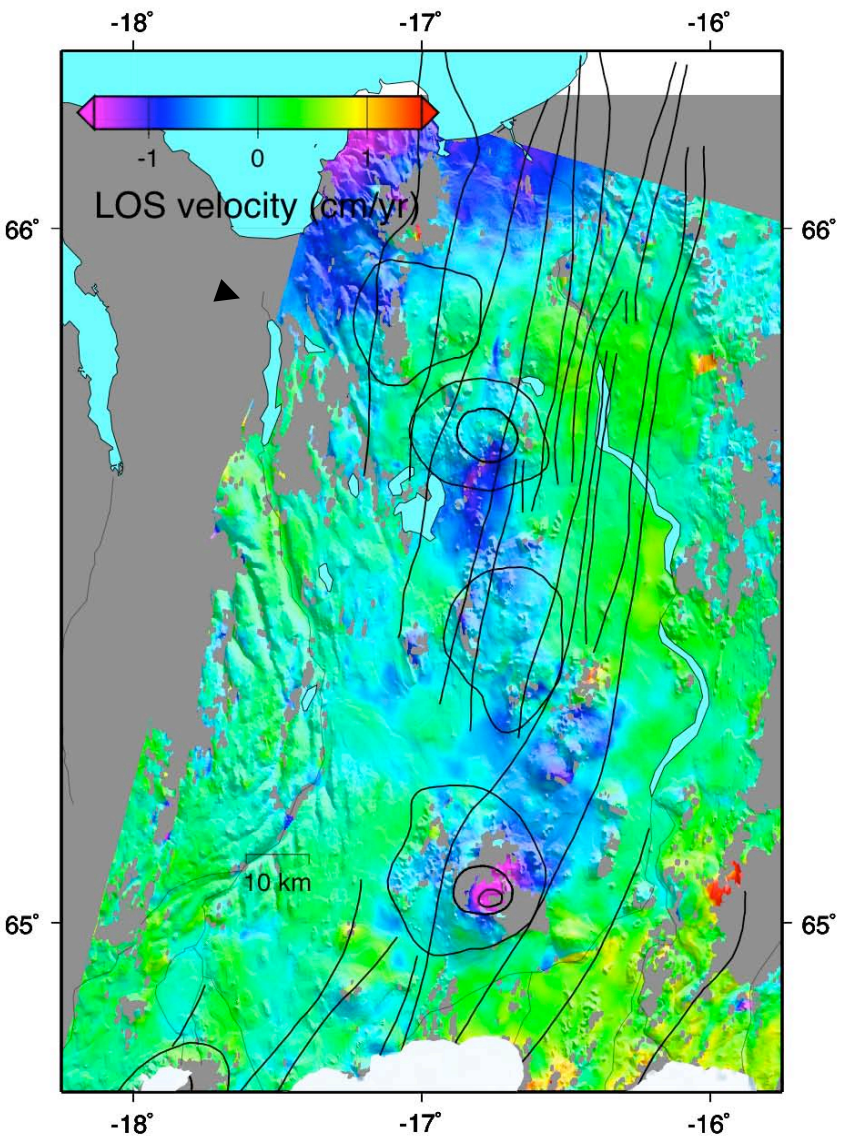
Rate of deformation slowing down

96/06/04 - 93/07/31



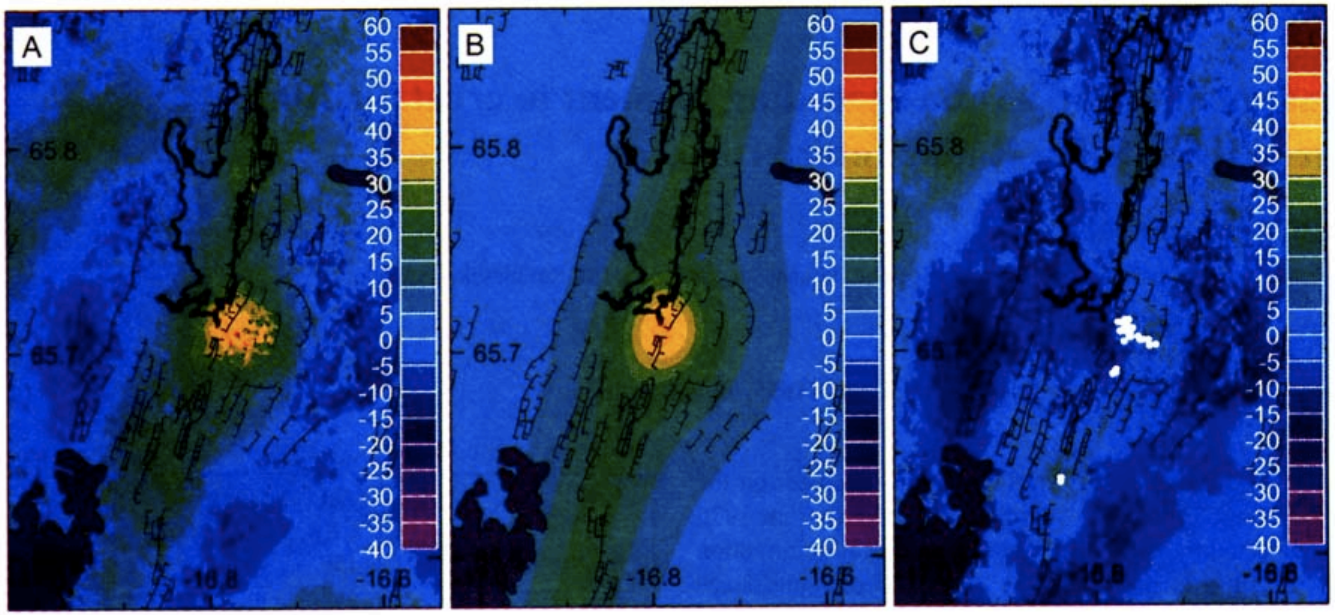
descending orbit - T9

06/06/027- 03/09/16



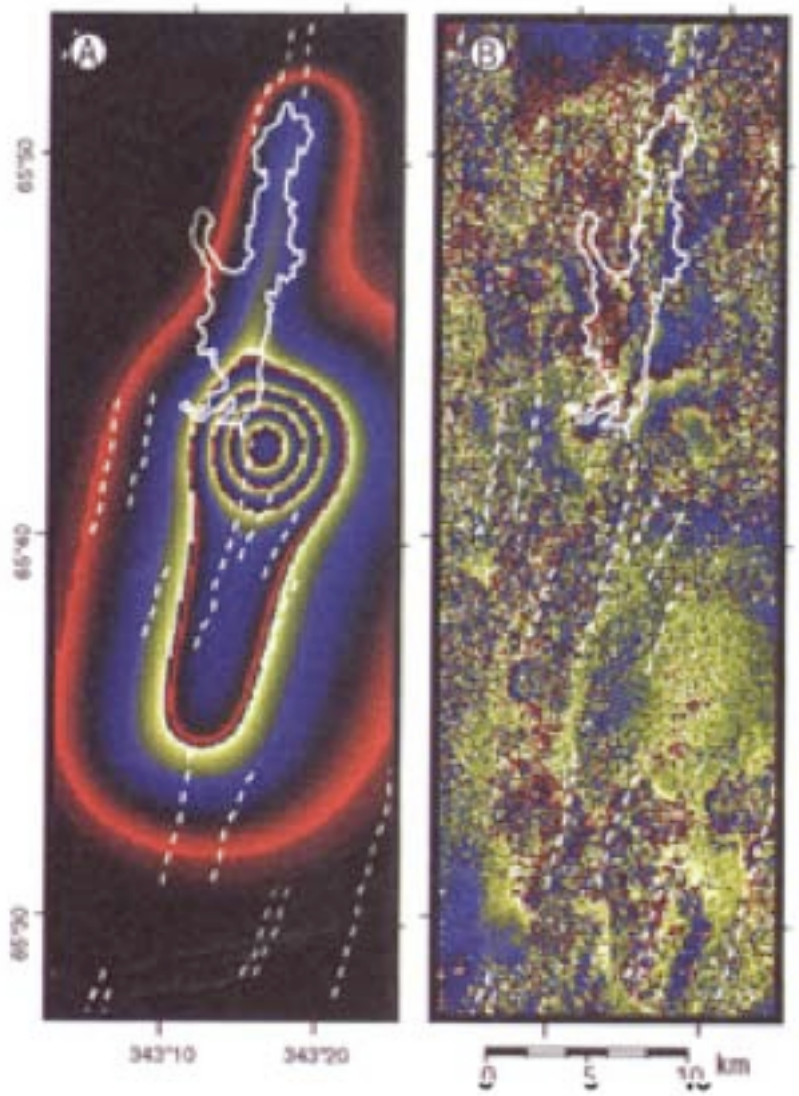
Small signal 20 years after rifting

Sigmundsson et al. 1997



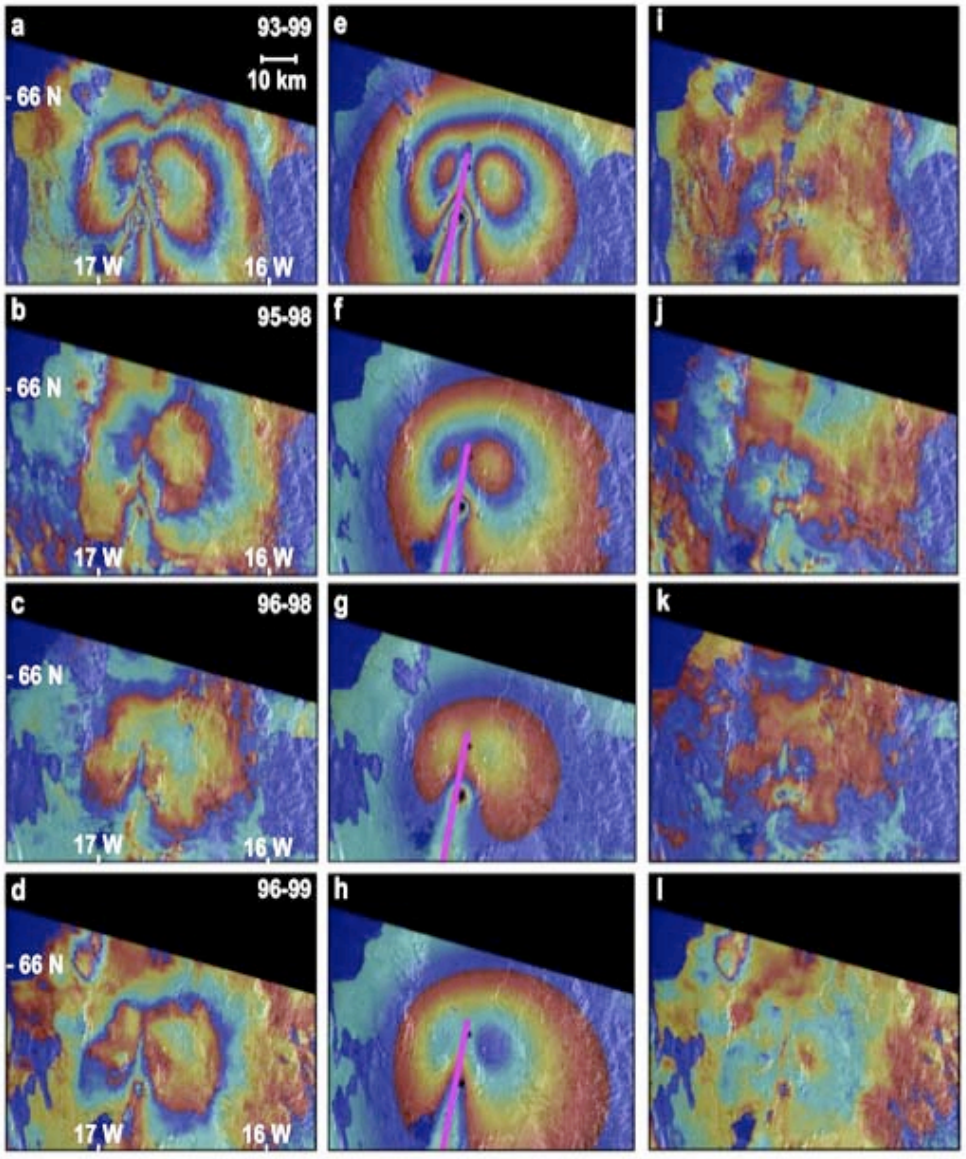
- Model local deformation near Krafla volcano using 3 interferograms from track 9
- Mogi source – draining or cooling of shallow magma chamber
- Line source – cooling or post-rifting ductile flow

Henriot et al. 2001



- Model local deformation near Krafla volcano using 14 interferograms
- 3 shallow elastic sources of deformation
  - 2 sills
  - 1 magma chamber

de Zeeuw-van Dalfsen et al. 2004



- Model wider region of deformation using 4 interferograms from track 9
- Deep inflating Mogi source (21 km) invoked to explain broad deformation

FEM Modeling with PyLith

- Big Picture:
  - Three dimensional rheologic structure
  - The workflow allows us to build complex models that use geologic and geophysical data sets
  - Bigger computers and parallel processing allow us to test more and bigger models
    - What groups of rheological structures agree with the data?
- This Talk – intuition building:
  - How do various rheological structures affect the surface deformation?
  - Two-dimensional
  - Linear Maxwell viscoelasticity
  - No gravity
  - All rifting occurs in single event

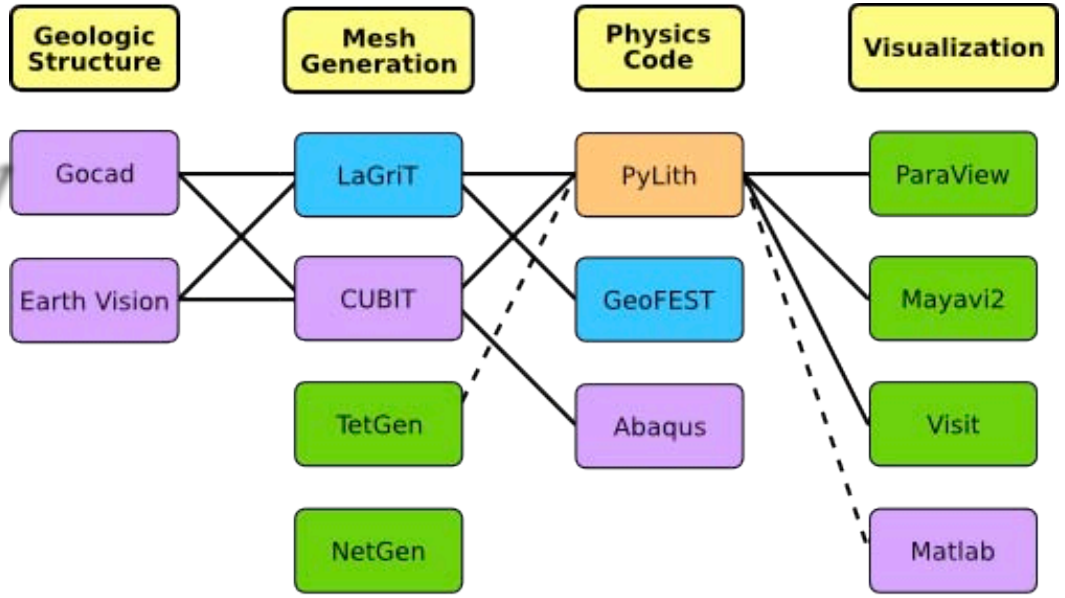
Workflow

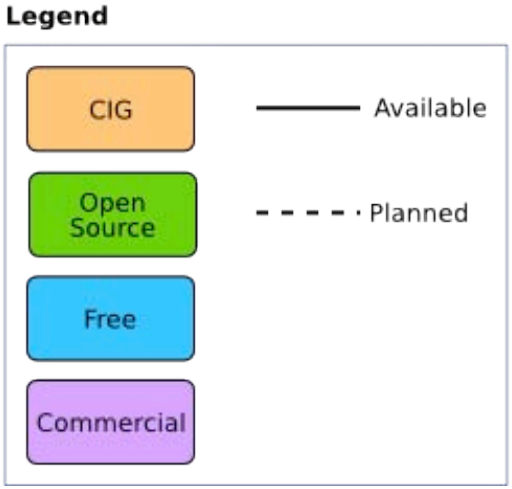
Tools written by
Eric Hetland

ASCII files

GMT grids

images

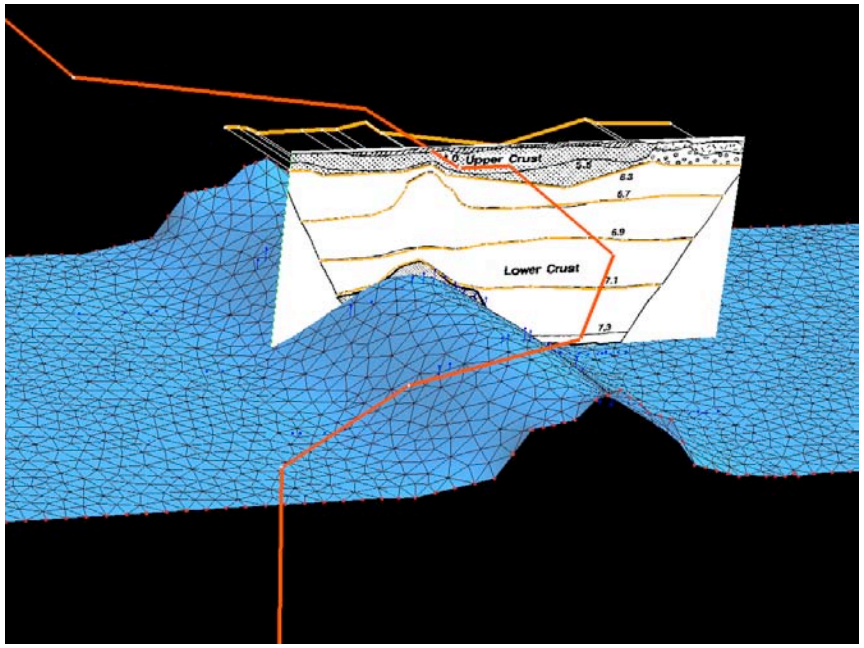


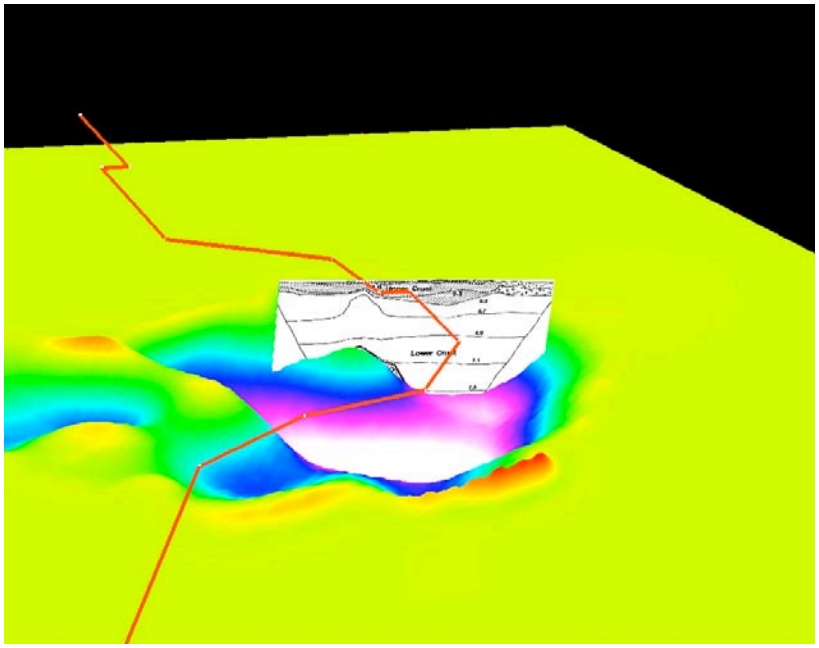


VTK Python
Matplotlib

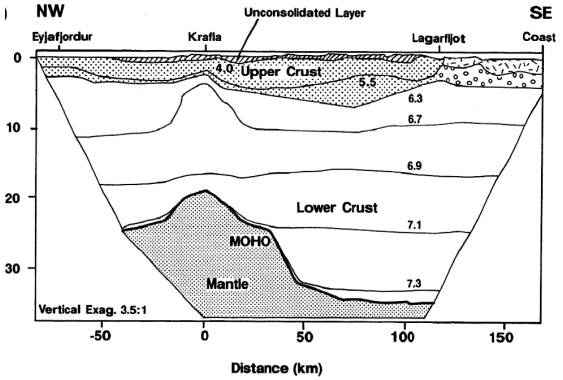
Workflow Diagram
from Brad Aagaard
geodynamics.org

GOCAD

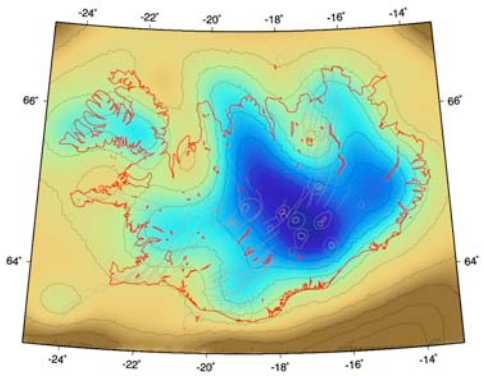




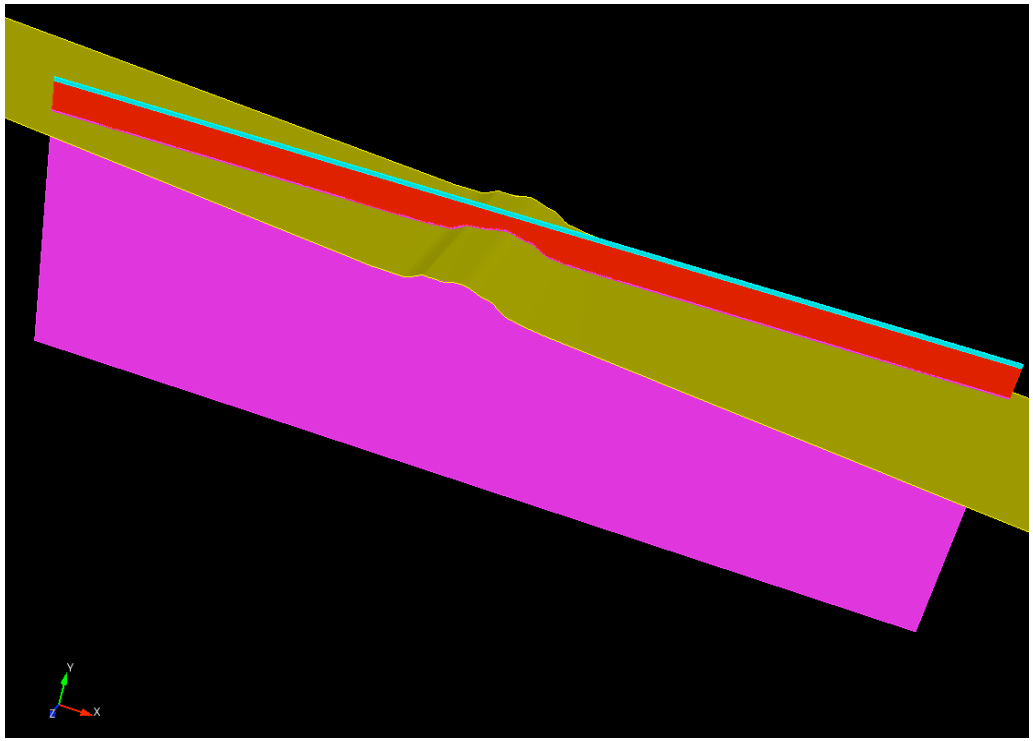
- Faroe-Iceland Ridge Experiment [Staples et al 1997]



- ICECRTb [Allen et al 2002]

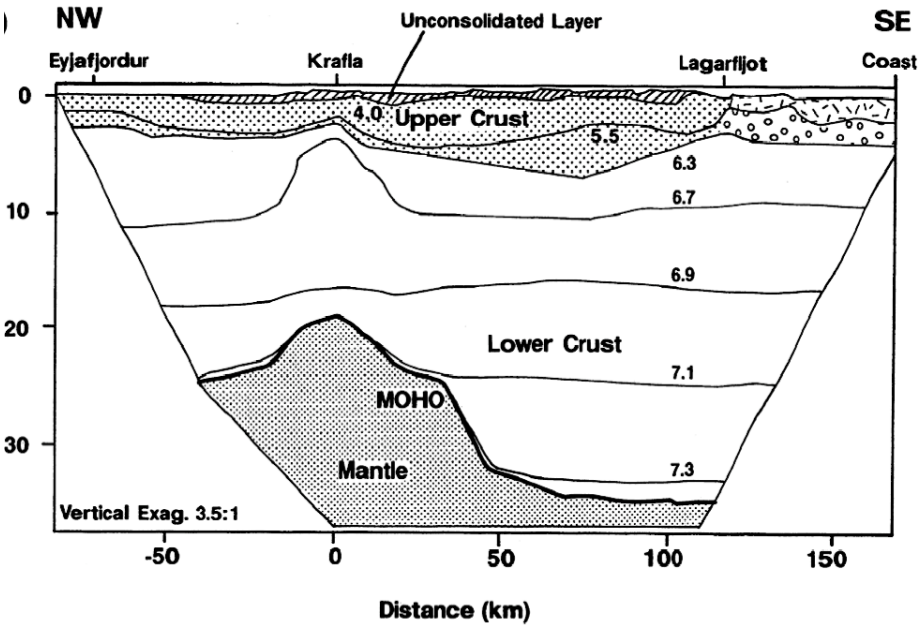


Cubit

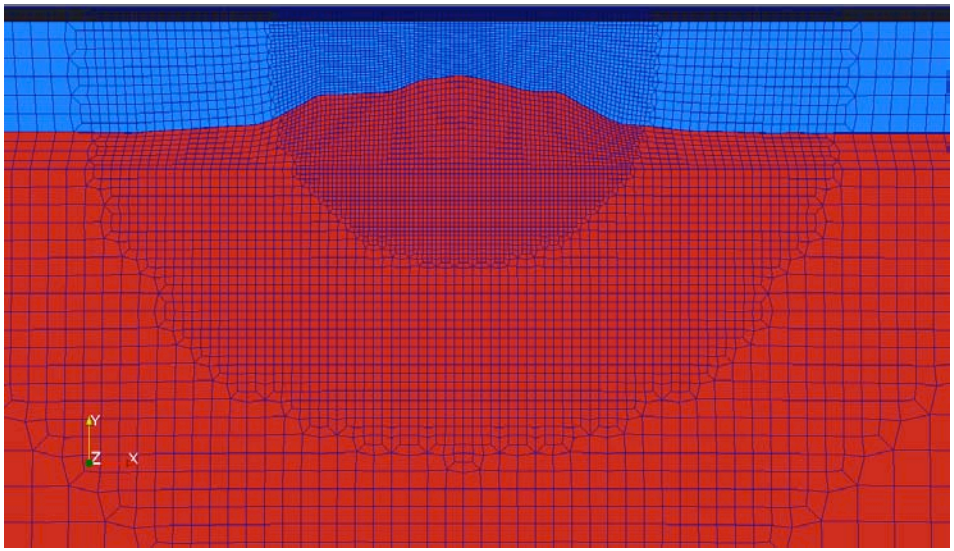


- Gocad surfaces are used to webcut volume to establish fault and material boundaries
  - TSurfs from Gocad are meshed and a new surface in the ACIS geometry engine is created from the mesh

Construct material boundaries using geophysical data



- Elastic upper crust – 5km thick
- Maxwell viscoelastic lower crust
- Maxwell viscoelastic mantle
- Moho from the Faroe-Iceland Ridge Experiment (Staples 1997)



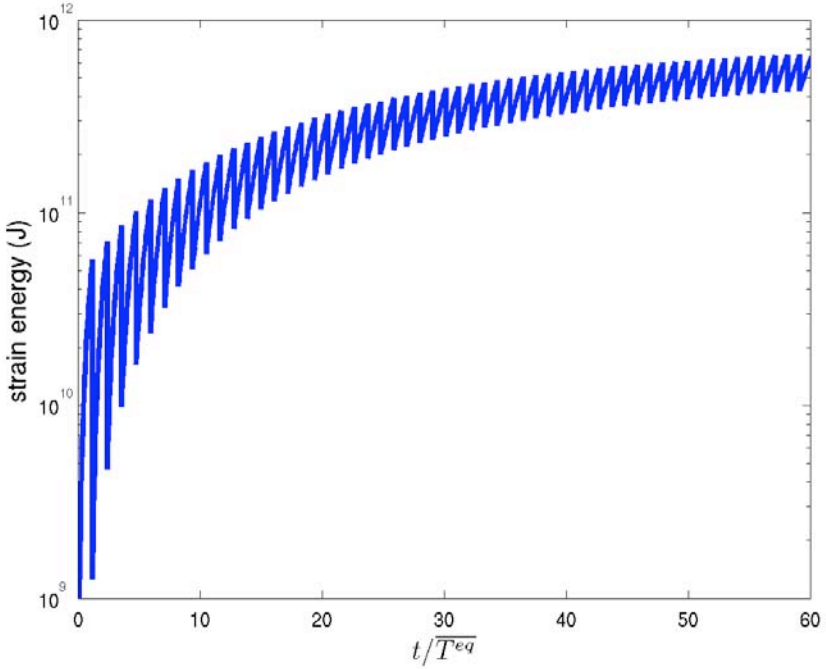
Variable Time Stepping

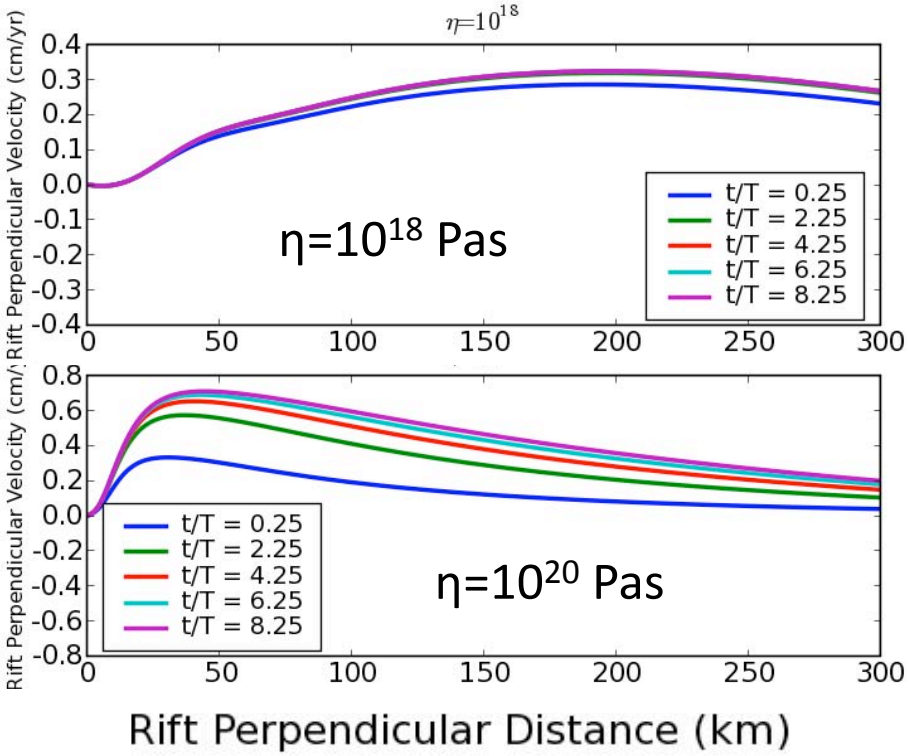
- Simple solution: specify all time step sizes
  - Not adaptive
- PyLith: time stepping handled at Python level
- Created new component `ImplicitManualdt`
  - Modification of `Implicit` component
  - Reads from file to get time stepping information
  - Method `stableTimeStep()` returns new time step size when called

```
[pylithapp.timedependent]
formulation = pylith.problems.ImplicitManualdt

[pylithapp.timedependent.formulation]
filename_dt = dt_var
units_dt = 1.0*year
```

Spin-Up



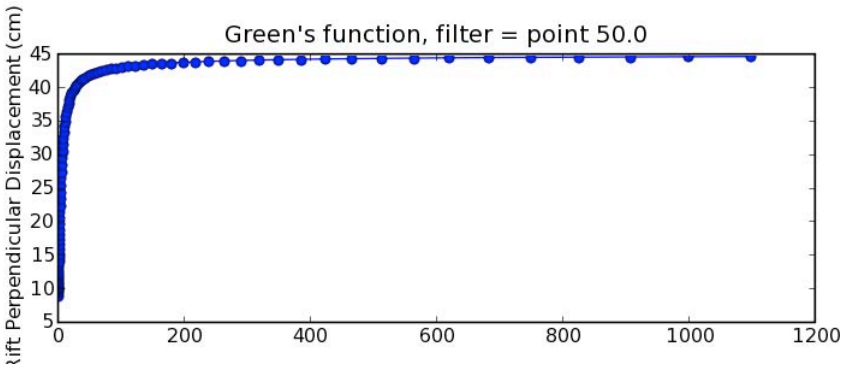


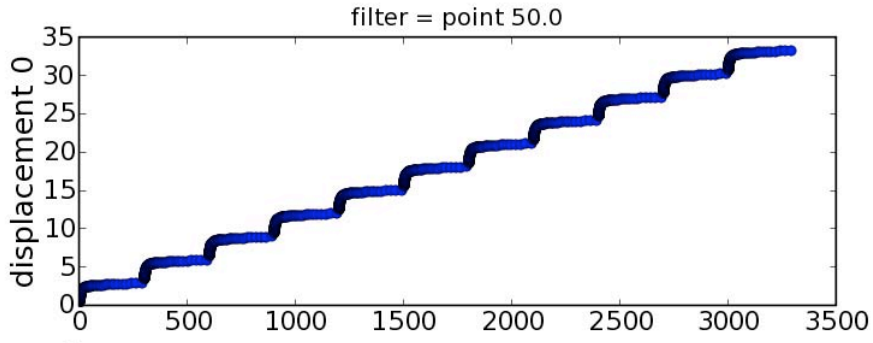
- Inelastic materials have memory of past rifting events
- Stresses in model must reach steady state
- Number of events needed to reach steady state scales inversely with the Savage parameter (Hetland and Hager 2006)

$$\tau_0 = T/2\tau_M$$

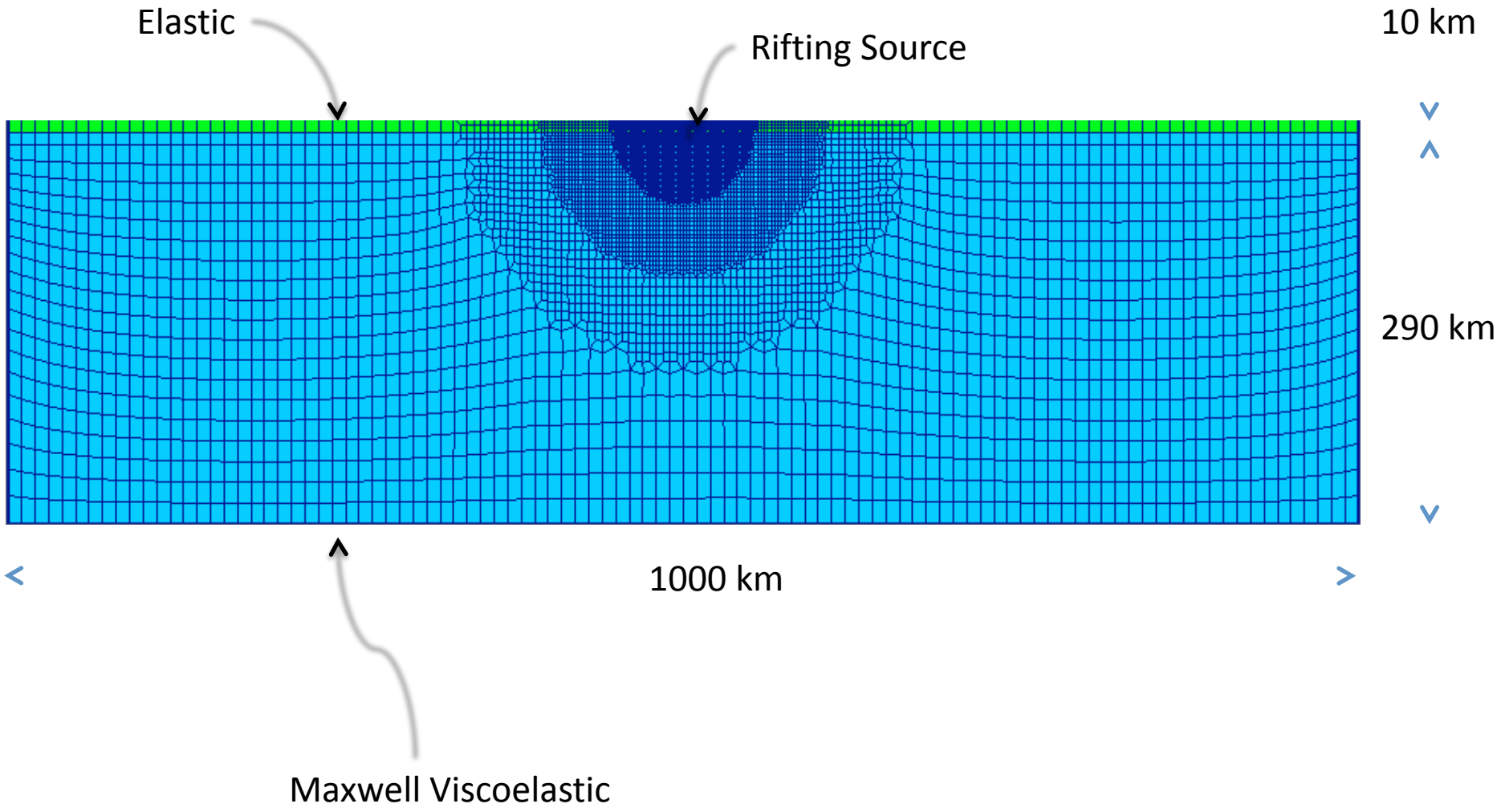
Repeated Rifting Events

- Cannot specify repeated slip on faults
- Linear rheology allows us to use Green's function approach
  - Calculate response to single event using FEM
  - Sum sequence with appropriate time lags
- Saves computation time





2D Models – Intuition Building

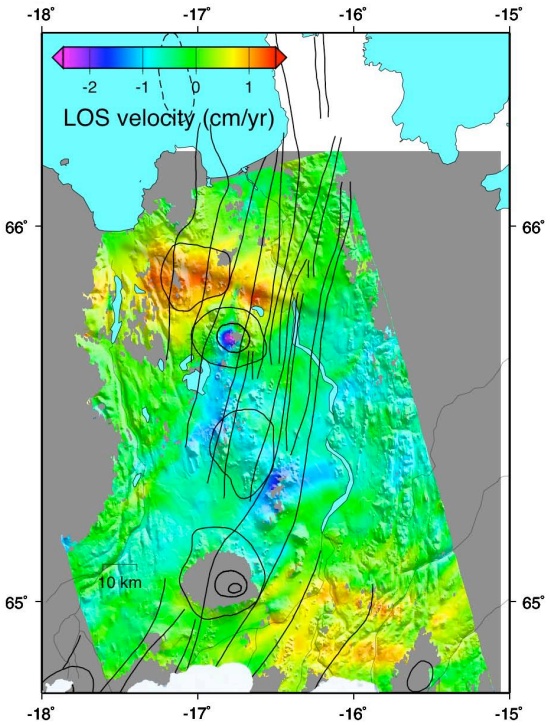


1D analysis:

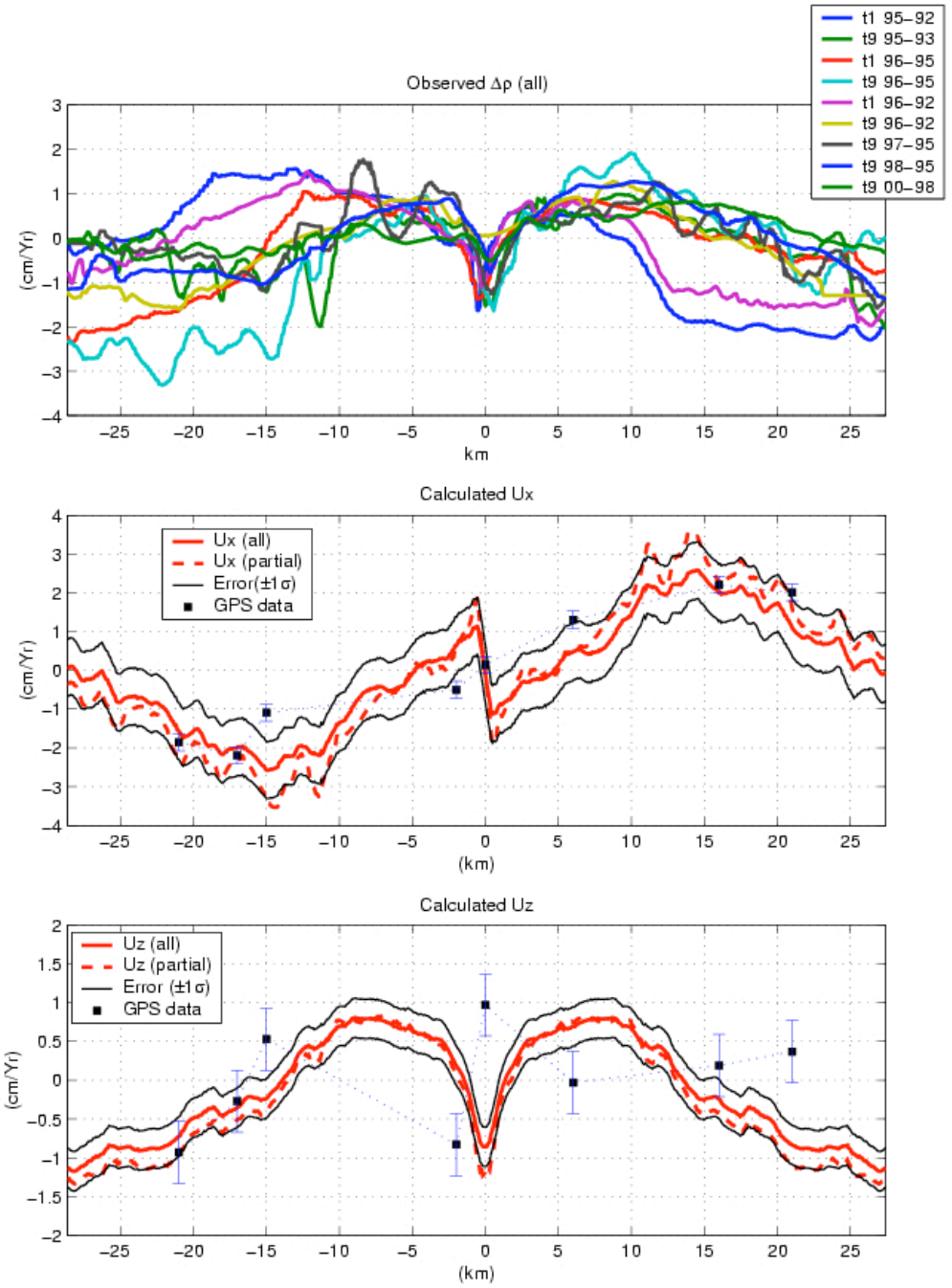
•Profile from center of rift segment

•Assume symmetric deformation

•Assume negligible sensitivity to along axis displacements
→only vertical & X-rift components



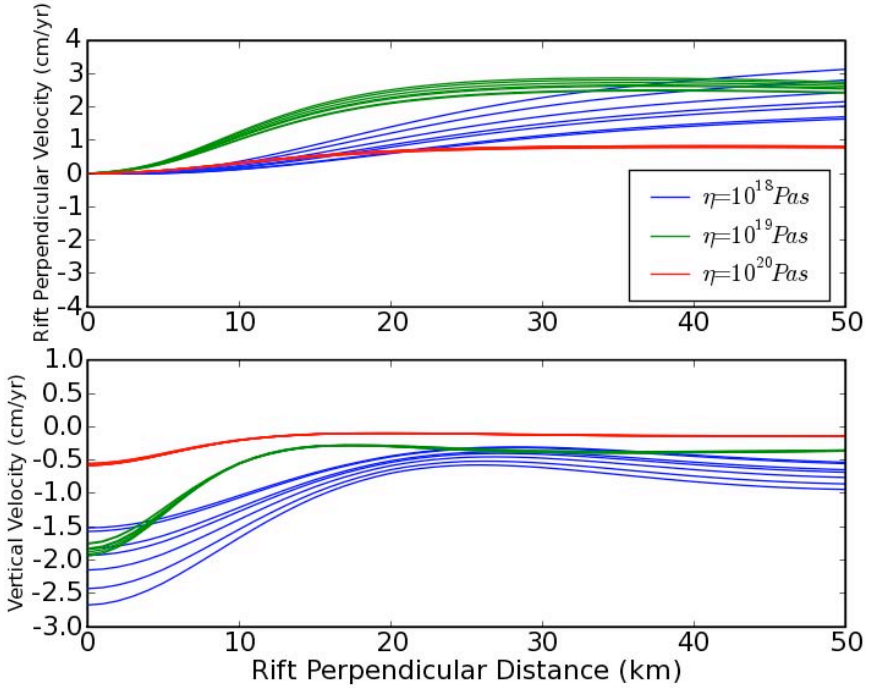
Simons et al, AGU Fall 2001



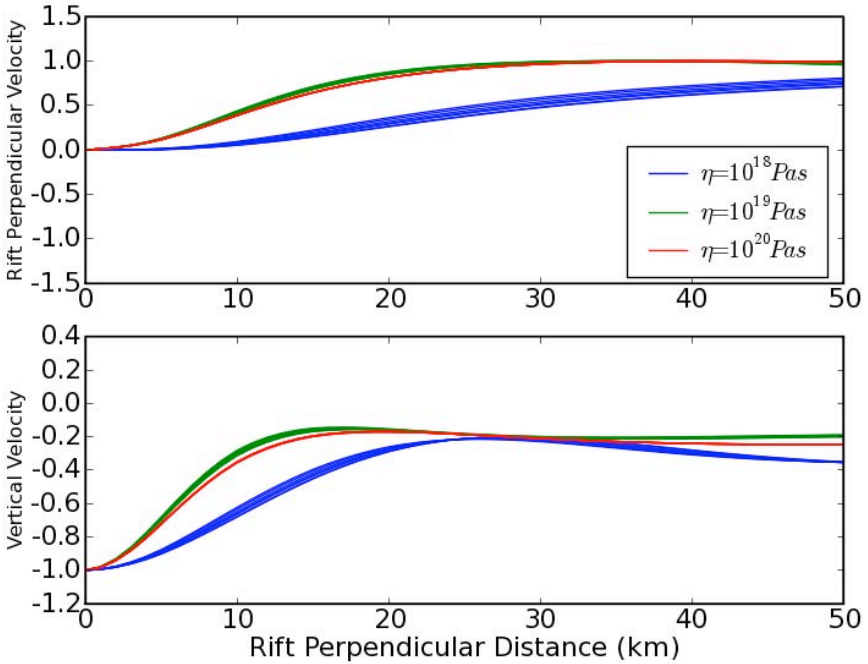
Homogeneous Viscosity

velocity snapshots for each year: 13 – 20 years after rifting

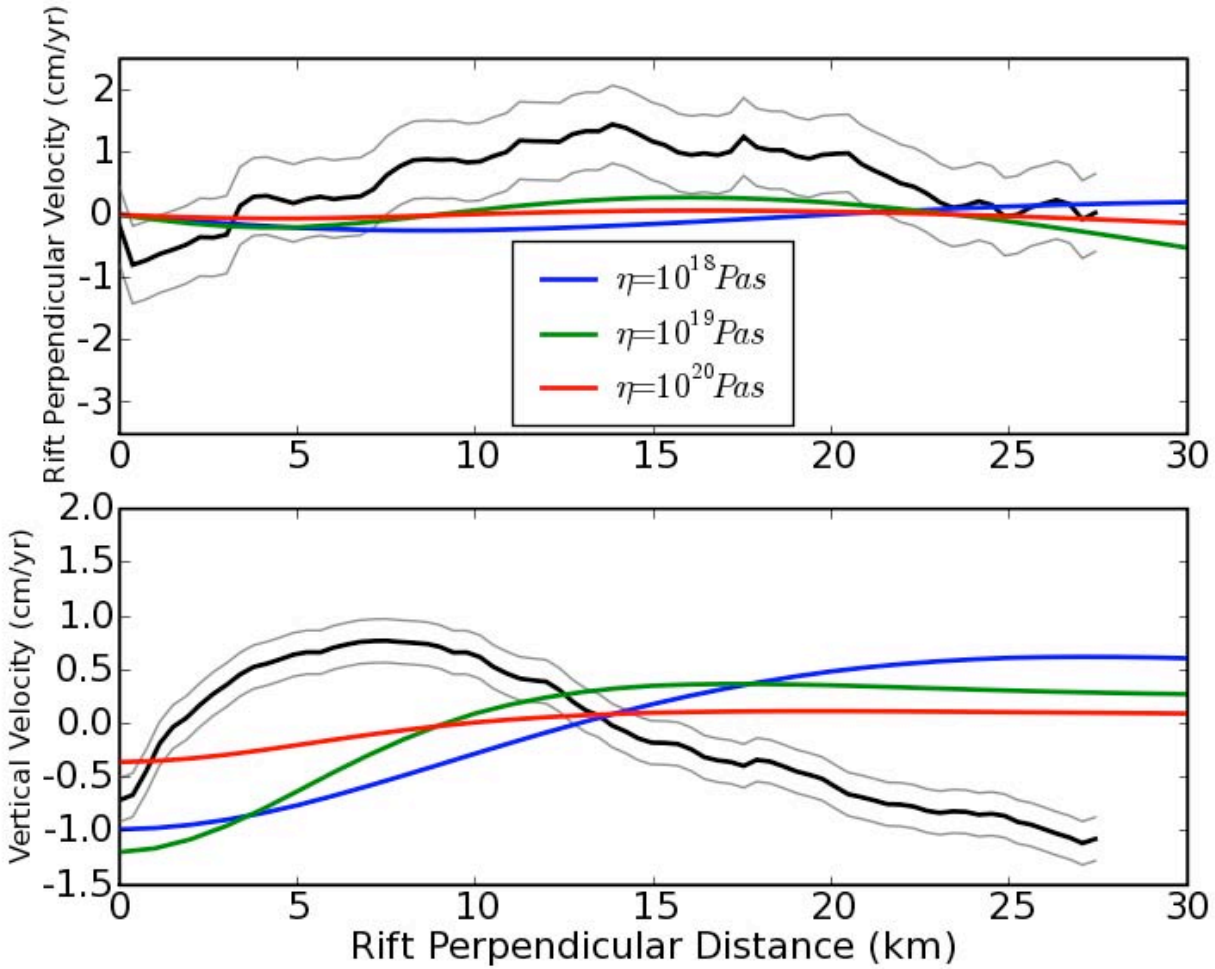
Absolute Velocities



Normalized Velocities

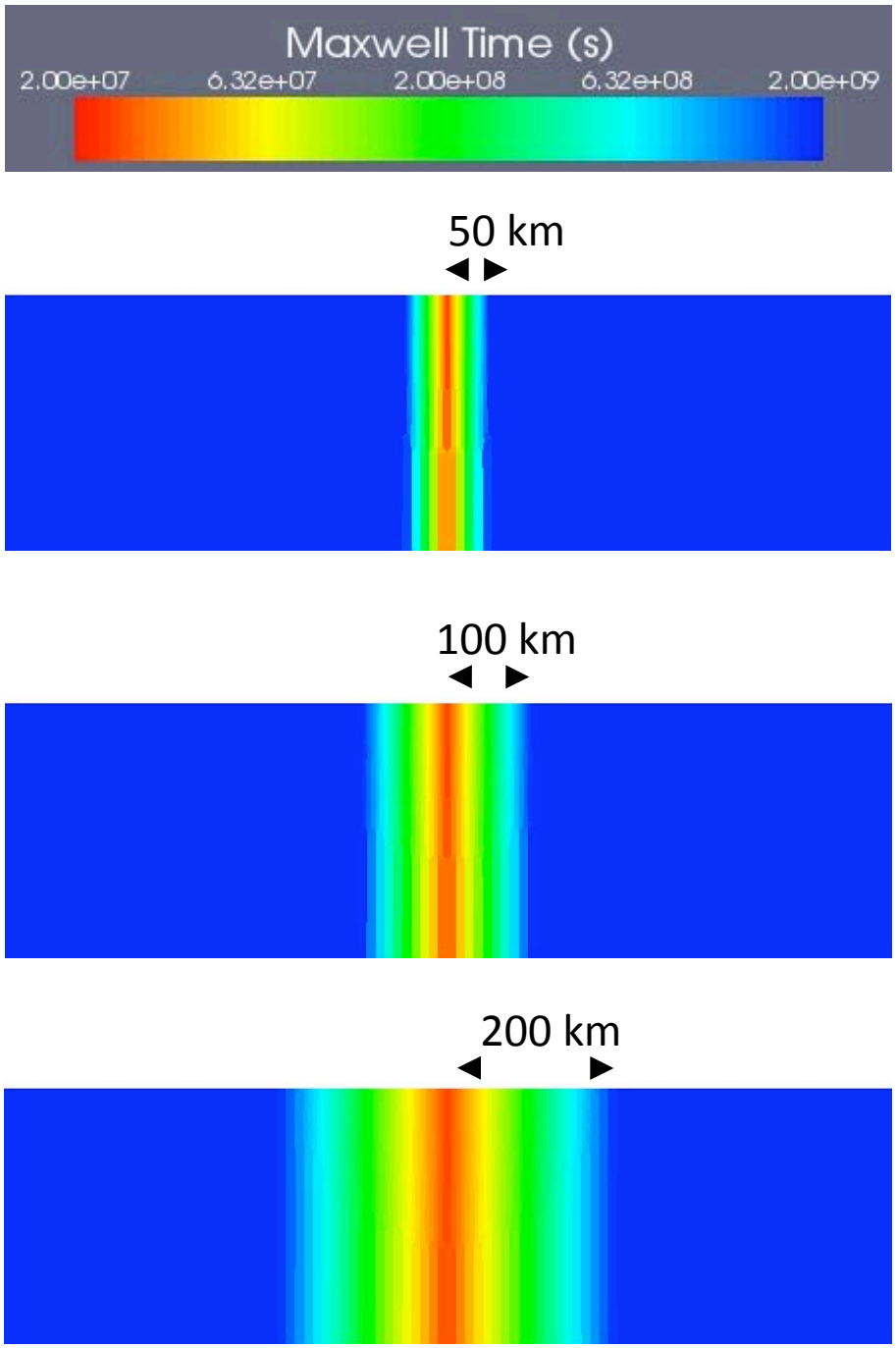


Compare to average InSAR velocities



Data and model de-ramped

No model with a Homogeneous viscosity structure can match the data (includes Hofton and Foulger 1996)

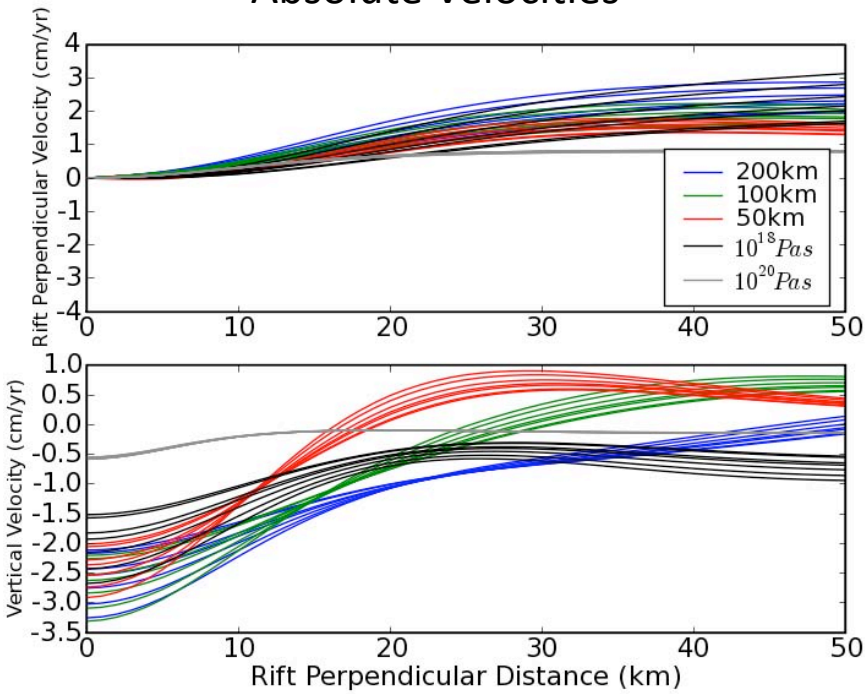


What are the effects of horizontal gradients in viscosity?

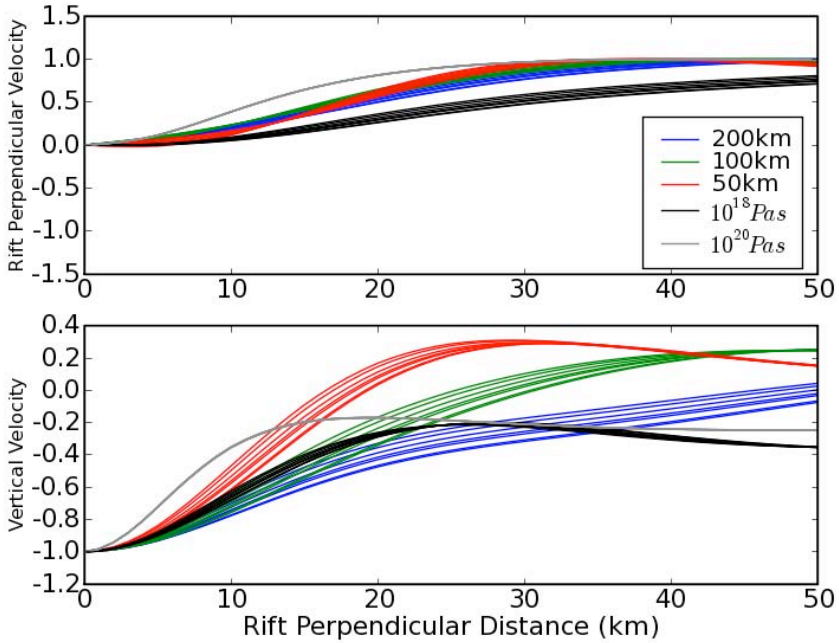
Horizontal Viscosity Gradients

velocity snapshots for each year: 13 – 20 years after rifting

Absolute Velocities



Normalized Velocities



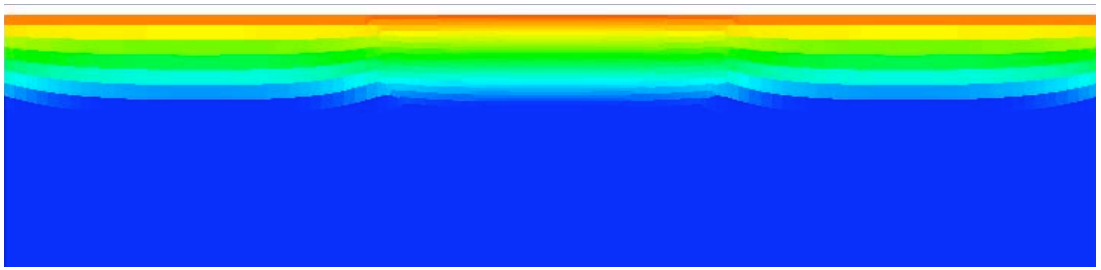
Horizontal deformation:

- Models are difficult to distinguish

Vertical deformation:

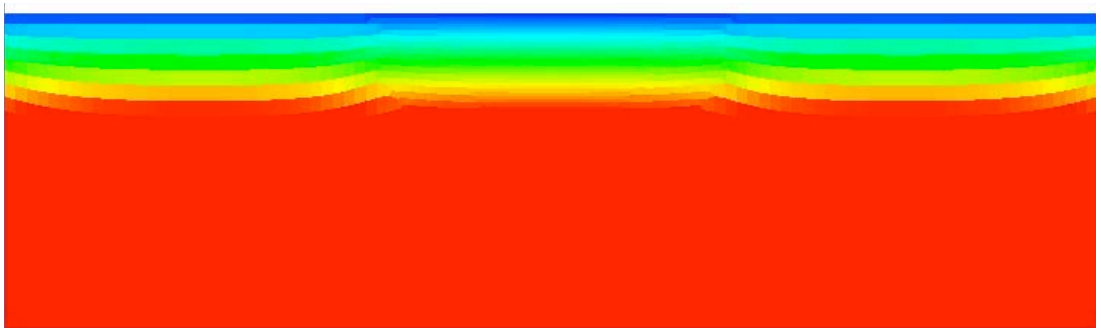
- Wider viscosity gradients result in wider deformation fields (not surprising)

What is the effect of strong lower crust over weak mantle vs. weak lower crust over strong mantle?



100 km

Weak lower crust
Strong mantle

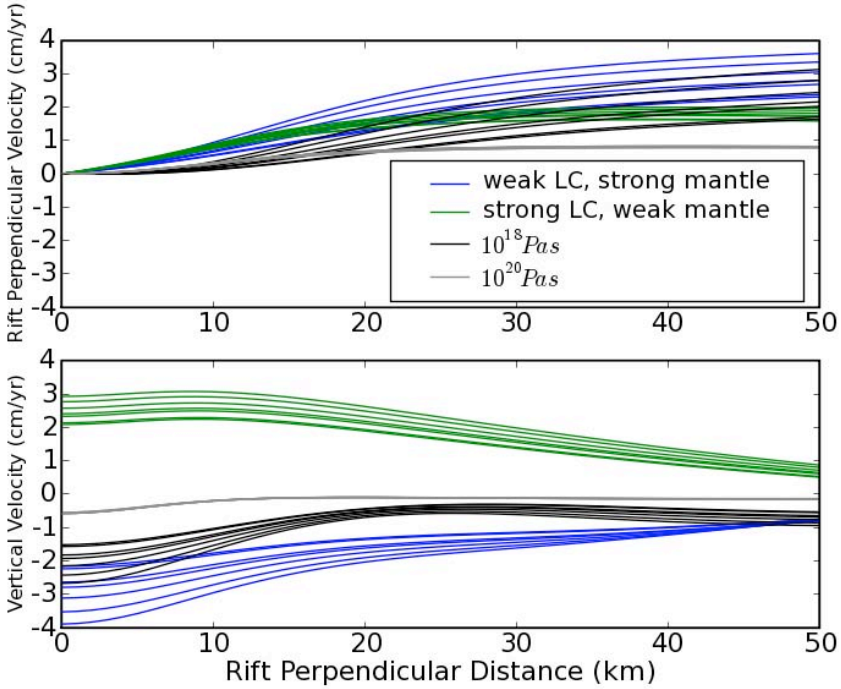


Strong lower curst
Weak mantle

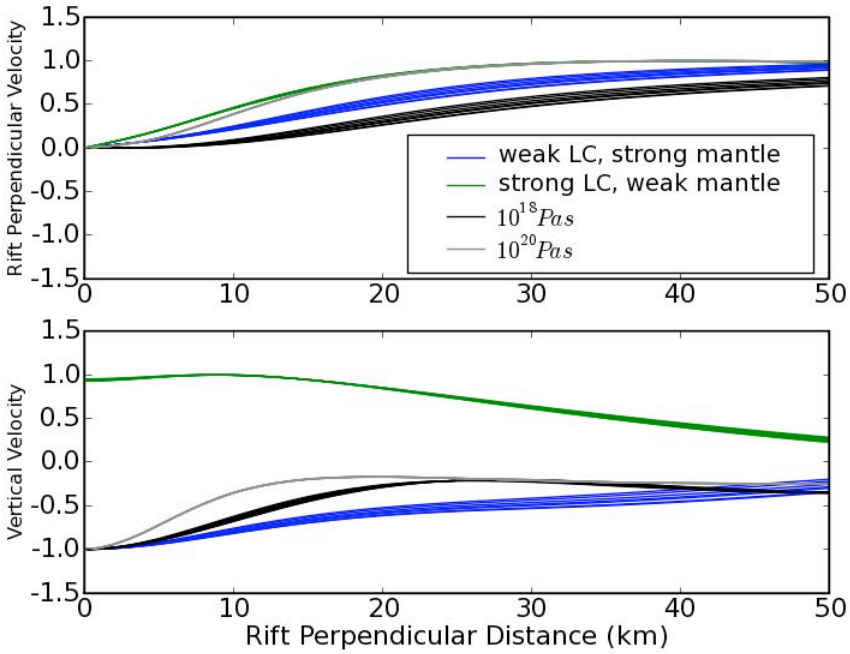
Vertical Viscosity Gradients

velocity snapshots for each year: 13 – 20 years after rifting

Absolute Velocities



Normalized Velocities



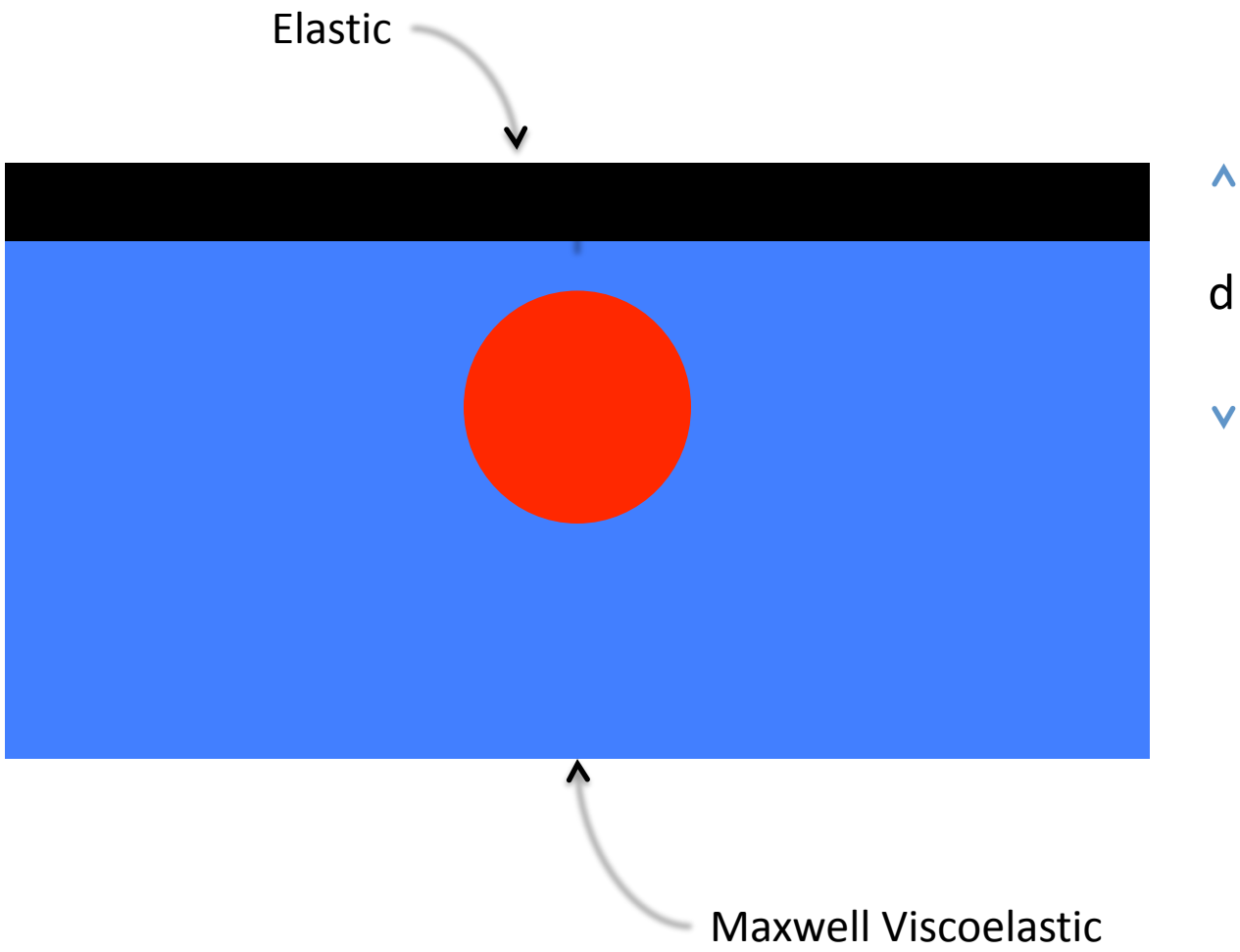
Horizontal deformation:

- Models are difficult to distinguish

Vertical deformation:

- Models easily distinguished by shape of deformation field

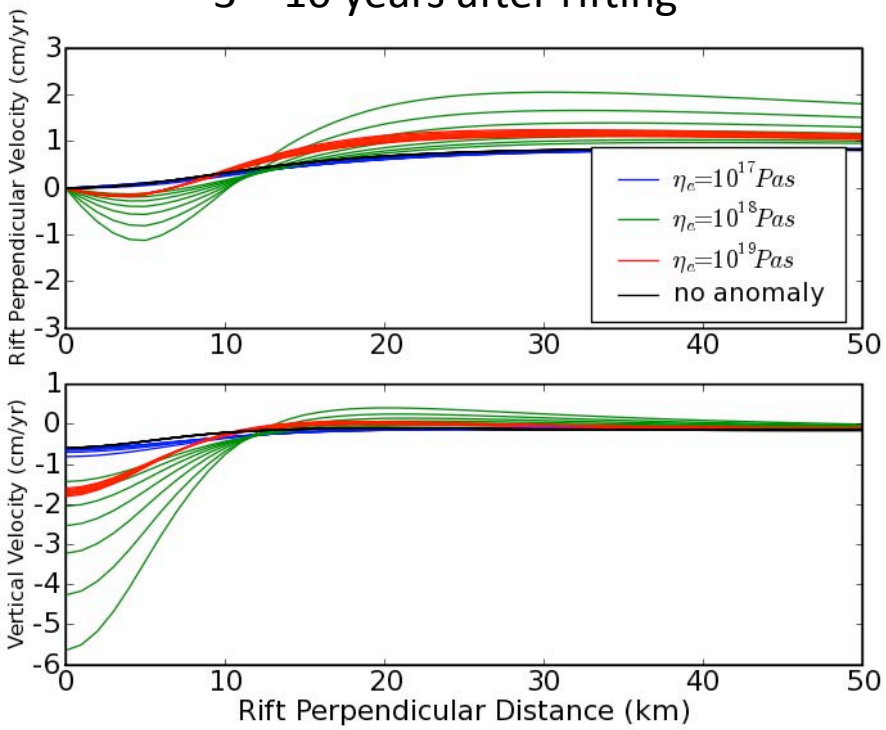
Impact of a localized viscosity anomaly beneath a rift



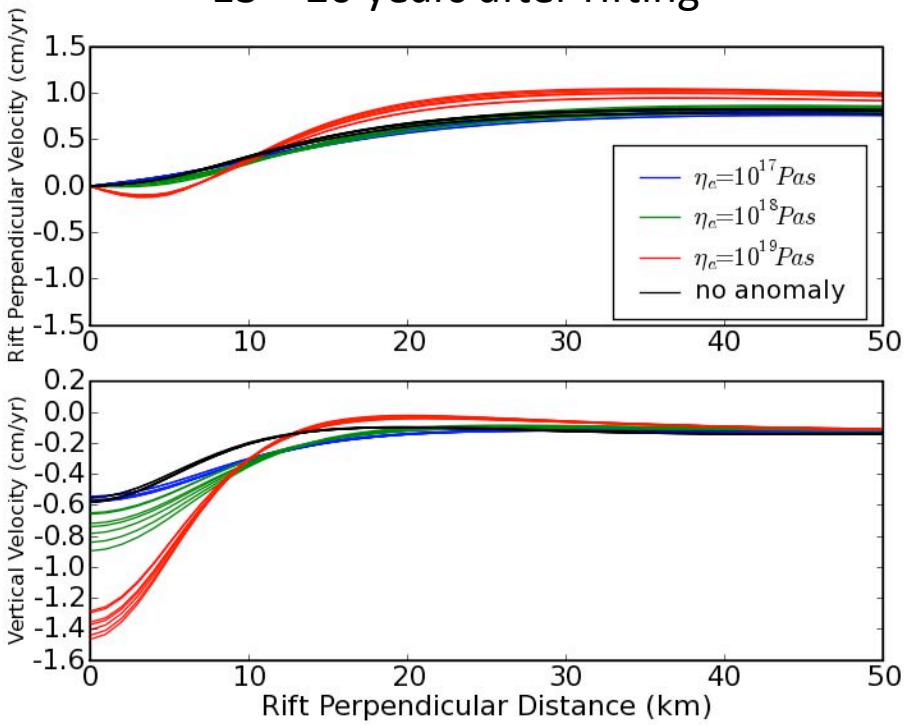
Changing Viscosity of Anomaly

velocity snapshots for each year

3 – 10 years after rifting



13 – 20 years after rifting



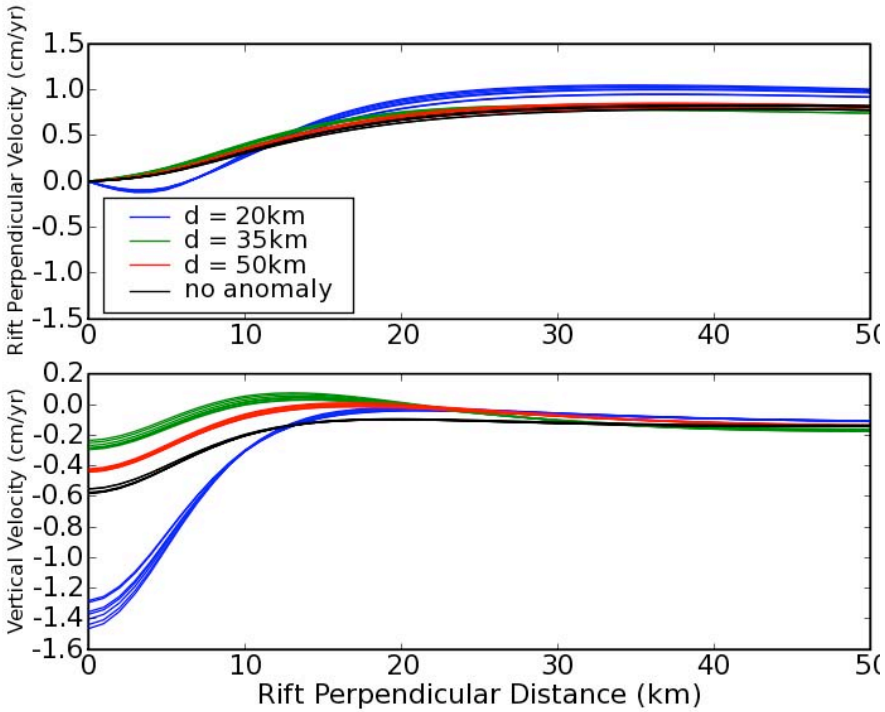
$\eta_{bulk} = 10^{20}$ Pa s, $R = 10$ km, $d = 20$ km

Ability to detect anomaly depends on viscosity contrast and time period of observation

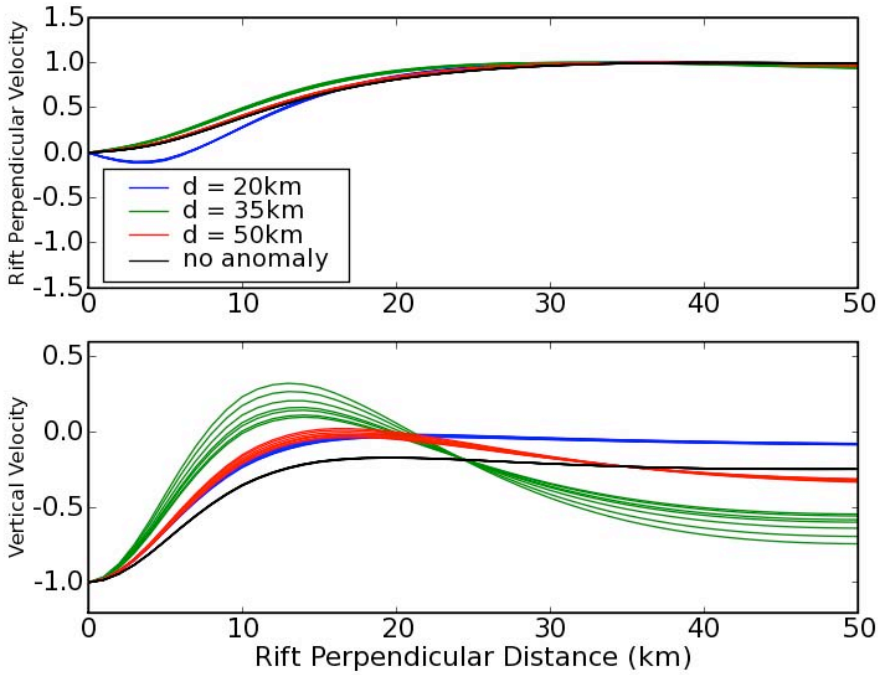
Changing Depth of Anomaly

velocity snapshots for each year: 13 – 20 years after rifting

Absolute Velocities

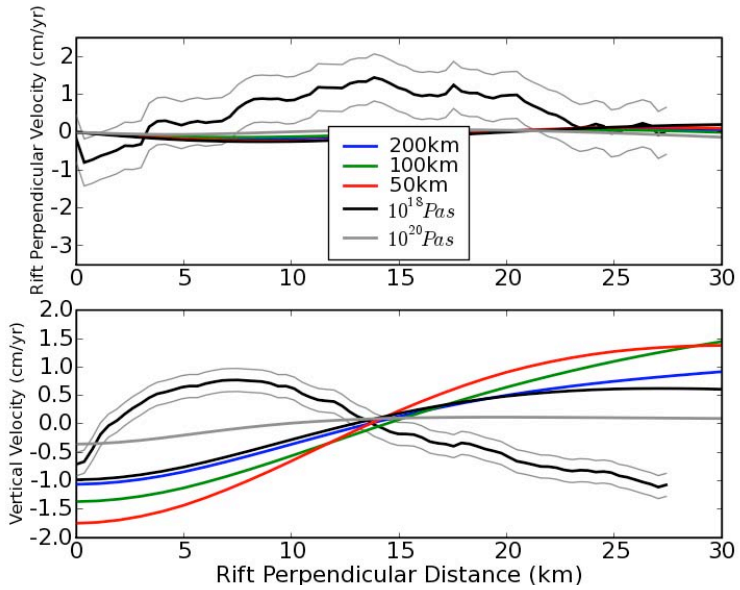


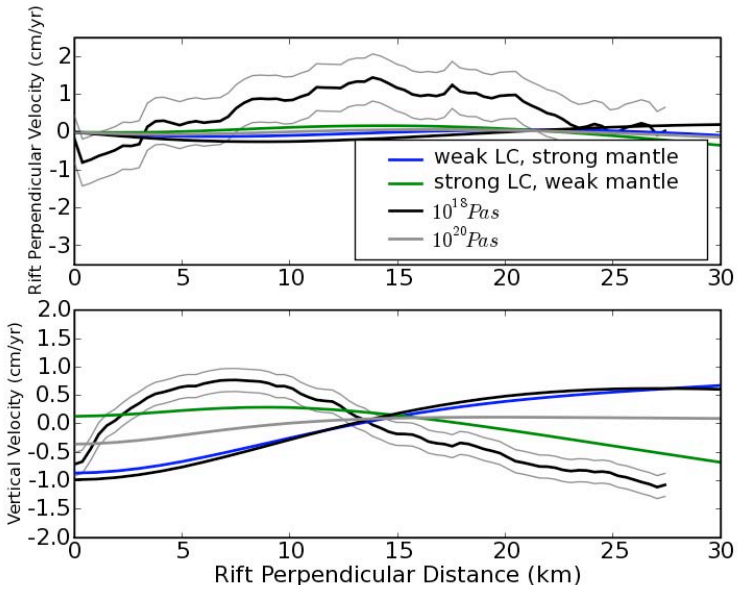
Normalized Velocities

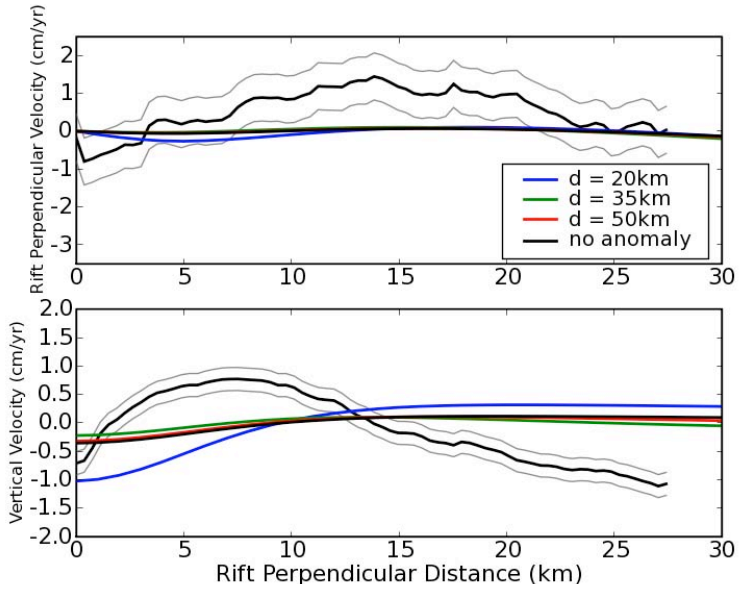


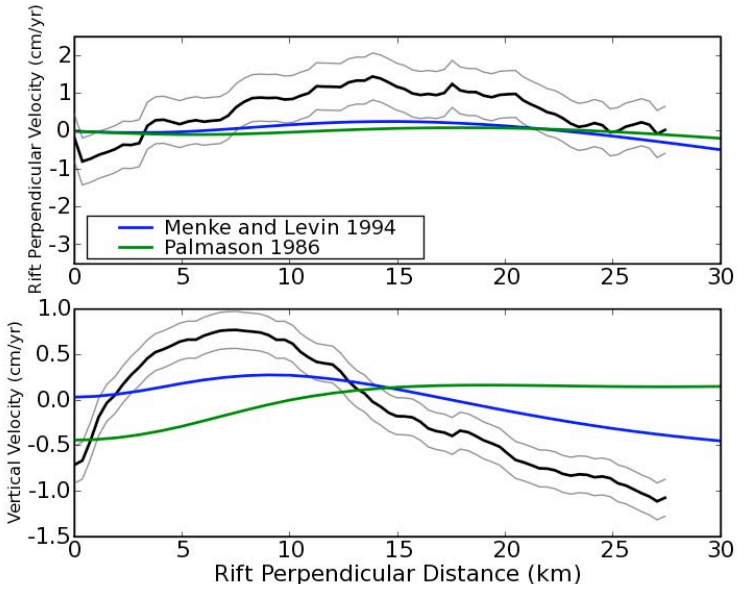
$\eta_{anomaly} = 10^{20}$ Pa s, $\eta_{bulk} = 10^{20}$ Pa s, $R = 10$ km

- Sensitivity to anomaly depth not monotonic









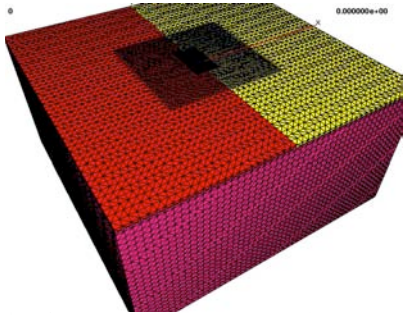
- No single test model fits InSAR data
- We will require large, localized contrasts in rheology

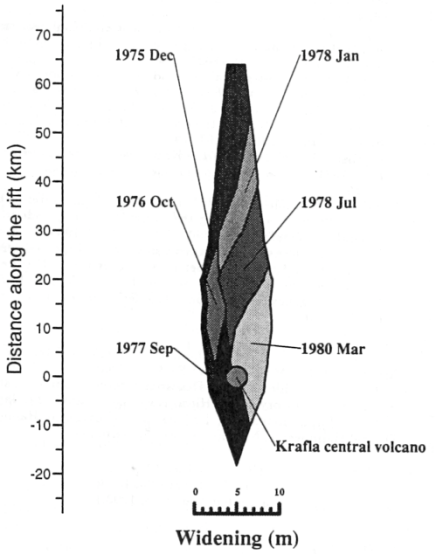
Preliminary conclusions

- Vertical displacements are important for distinguishing among post-rifting models
  - InSAR has high sensitivity to verticals (ERS look angle is 23° from vertical)
- It is not possible to match the post-rifting deformation as measured by InSAR using an elastic layer over an viscoelastic half space model
- Vertical gradients in viscosity have a large impact on shape of deformation field.
- Localized anomalies will likely be required
- Existing workflow greatly facilitates exploration of different models

Next Steps

- Continue intuition building exercise
  - Localized anomalies
- Three-dimensional models
- Spatially and temporally diffuse diking
- May want to invert for diking parameters
  - Opening may not be uniform with depth
- Other rheologies
  - Non-Maxwell
  - Non-linear
- InSAR Processing
  - Reprocess without re-estimating baseline to keep long-wavelength deformation
  - Time series analysis



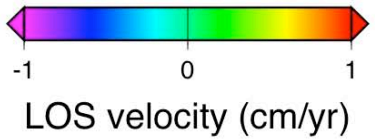


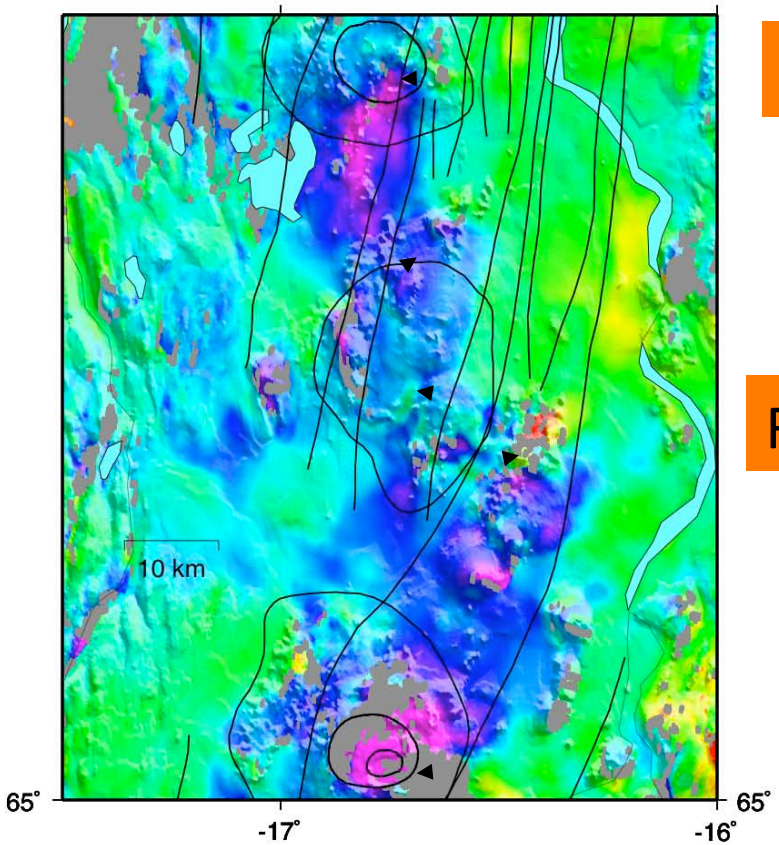
Challenges

- Non-uniqueness
  - Elastic source(s)
  - Non-Maxwell rheologies
- Non-linear rheologies remove the ability to use the Green's function approach to multiple events
  - More computational cost
  - Need multiple earthquakes on a single fault
  - Large deformations
- Repeated EQ ✓1.2
- Non linear rheologies 1.4
- Gravity ✓1.2
- Adaptive time stepping 1.3
- Higher order shape functions 1.5

- Inelastic models must be spun-up to steady state over several rifting cycles
- How do we accommodate the stress created at the crack tip during repeated rifting events?
- St. Venant's Principle may allow us to use “easiest” mechanism
  - The localized effects caused by any load acting on the body will dissipate or smooth out within regions that are sufficiently away from the location of the load.

Accommodation of rift-tip stress ?





Krafla

Fremri-Namur

Askja