Surface deformation during a magmatic intrusion : the example of the Dabba'hu rift crisis of 2005-2007 (Afar, Ethiopia)

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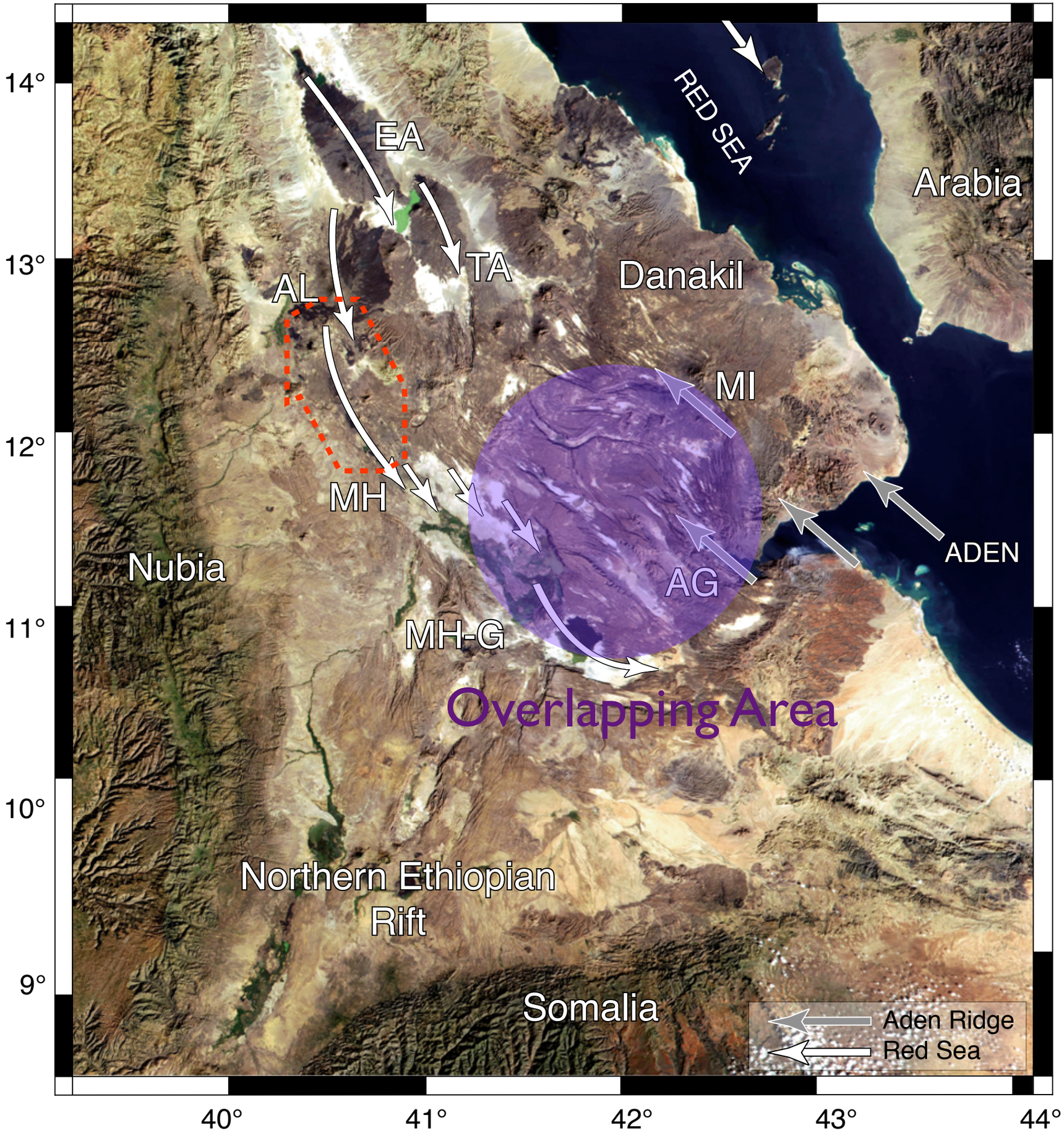


Tectonic setting

A system of overlapping rifts, forming two groups:

- Red Sea - Erta Ale - Alayta - Manda Hararo - Goba'ad
- Aden - Ghoubbet - Asal - Manda Inakir

Extension rate across Afar:
~ 1.5 cm/year (*Vigny et al.*, 2006)

Extension rate across Dabba'hu rift:
~ 1.0 cm/year

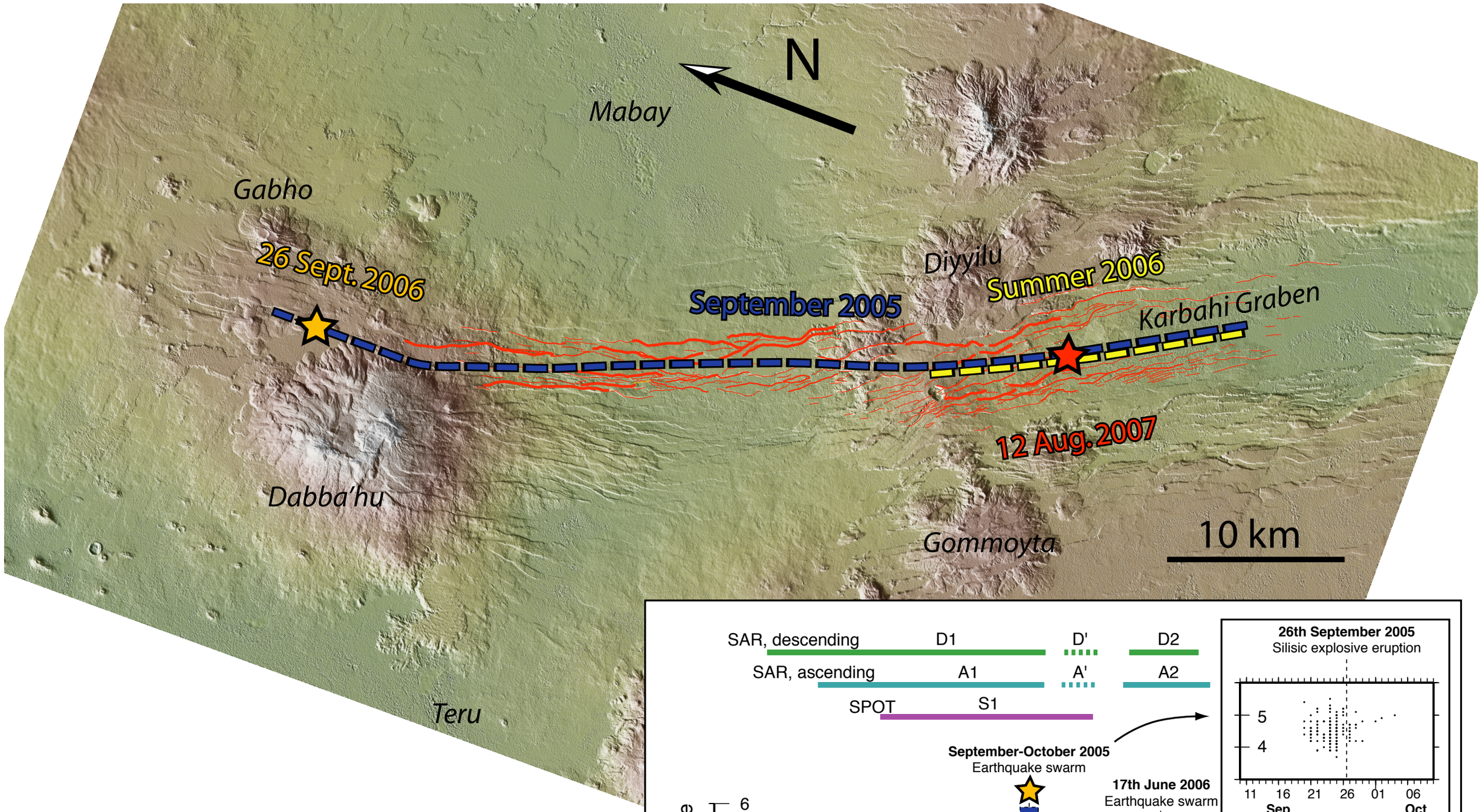
Amount of extension during the crisis (co + post):
~ 5-10 m

➪ One similar event every 500-1000 years?

Arrows modified from *Manighetti et al.* (1998) and *Pinzuti* (2006)

Landsat mosaic from *Pinzuti* (2006)

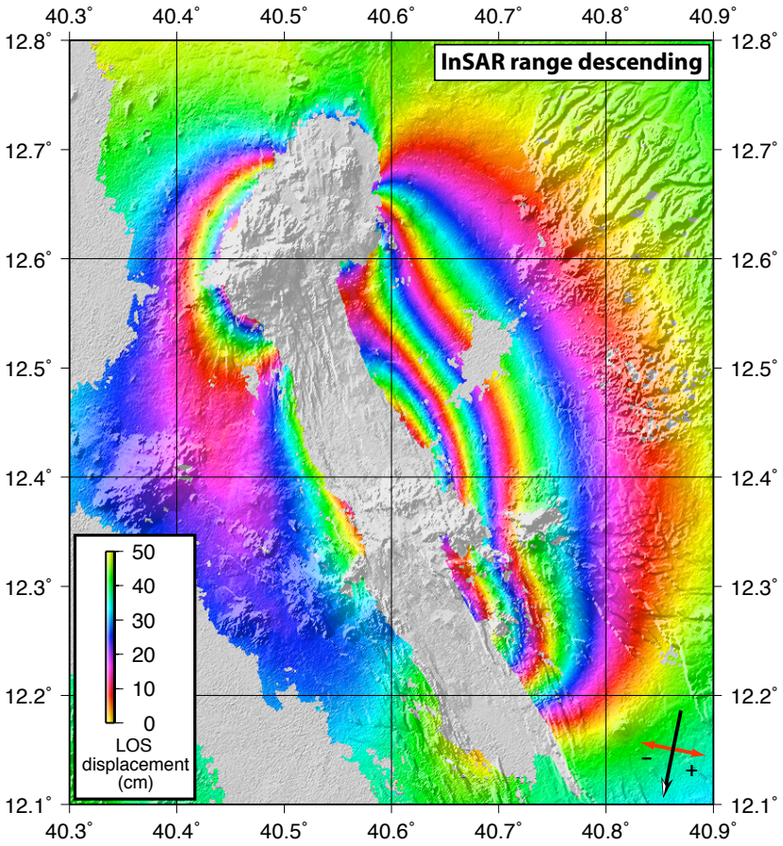
Location of the main intrusive and eruptive events within the Dabba'hu rift

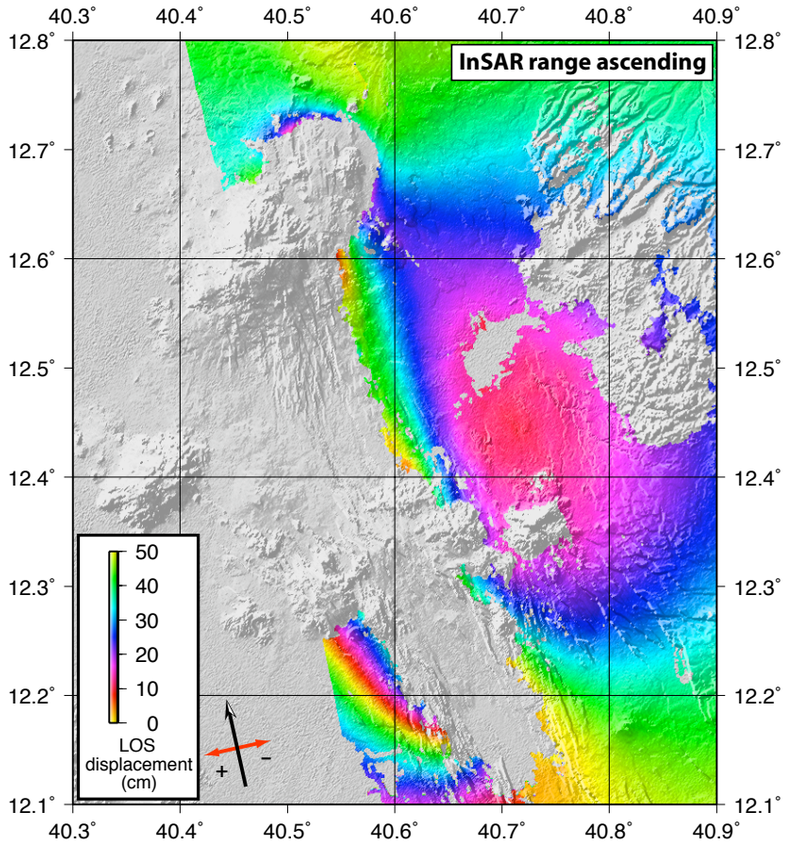


In red: faults mapped using InSAR images D' and A' (late november 2005 to early February 2006)

20 m DEM, generated with SPOT images

InSAR data





- Very accurate measurement (precision: ~ 1 cm)
- Mostly sensitive to the vertical component of surface displacement
- Acending and descending tracks can be combined to separate vertical and horizontal components, if we make a kinematic hypothesis (e.g. displacement is rift perpendicular)
- Unwrapping is only possible in the far field: we cannot reach the rift floor

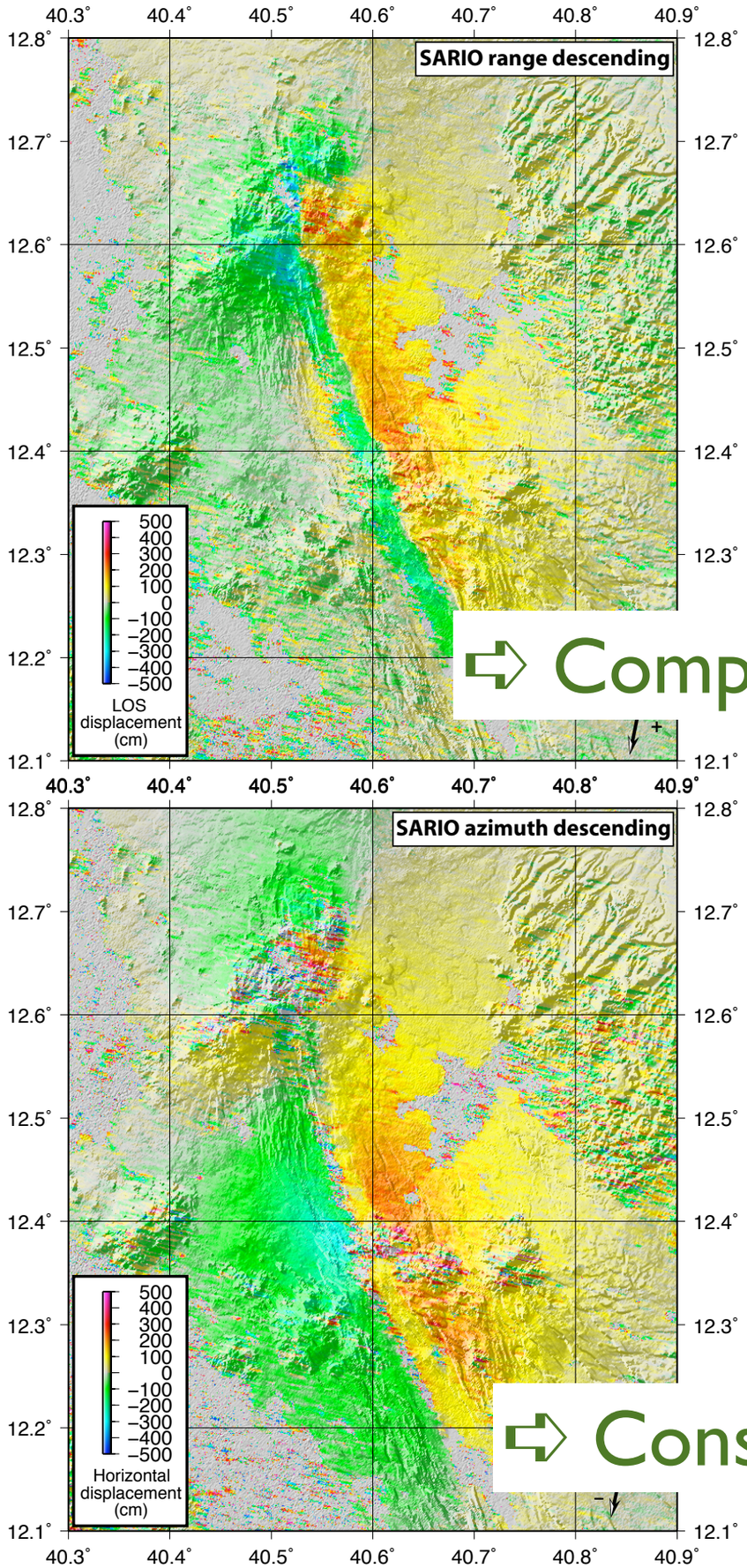
➪ Provides a very good constraint on opening at depth

SARIO data

Descending track

Ascending track

Range offsets



Azimuth offsets

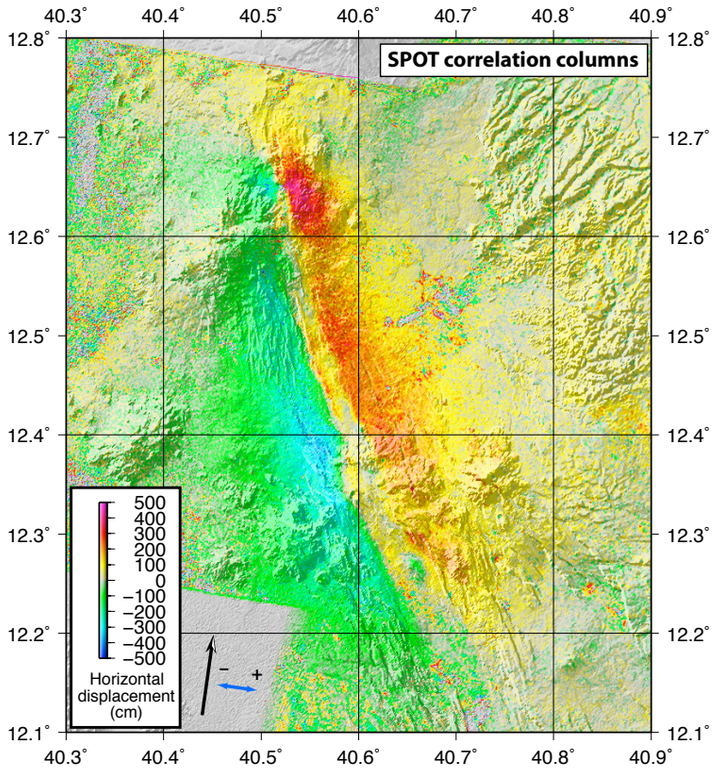
- Accuracy ~ 50 cm
- Same geometry as InSAR

⇨ Complementary of InSAR in the near-field

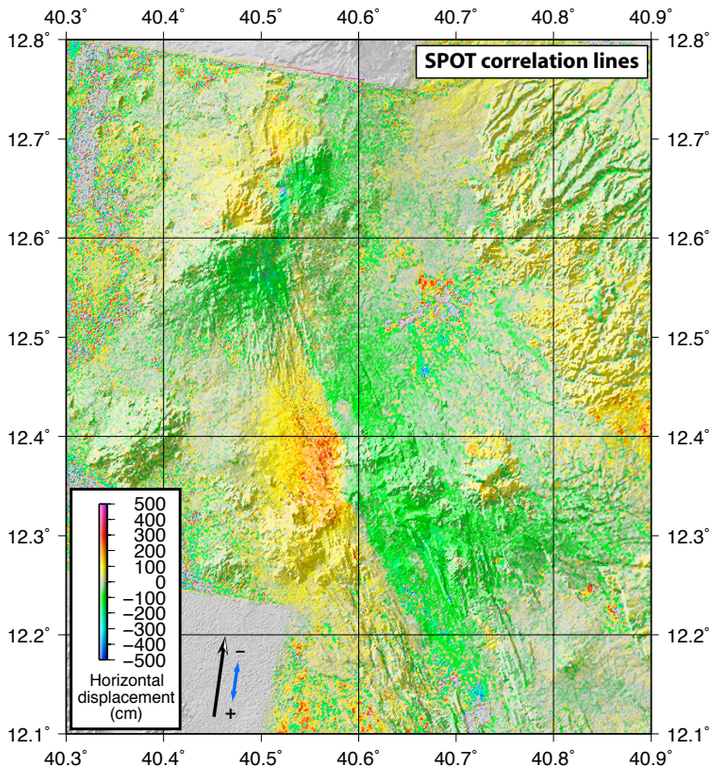
- Accuracy ~ 30 cm
- Measures horizontal displacements

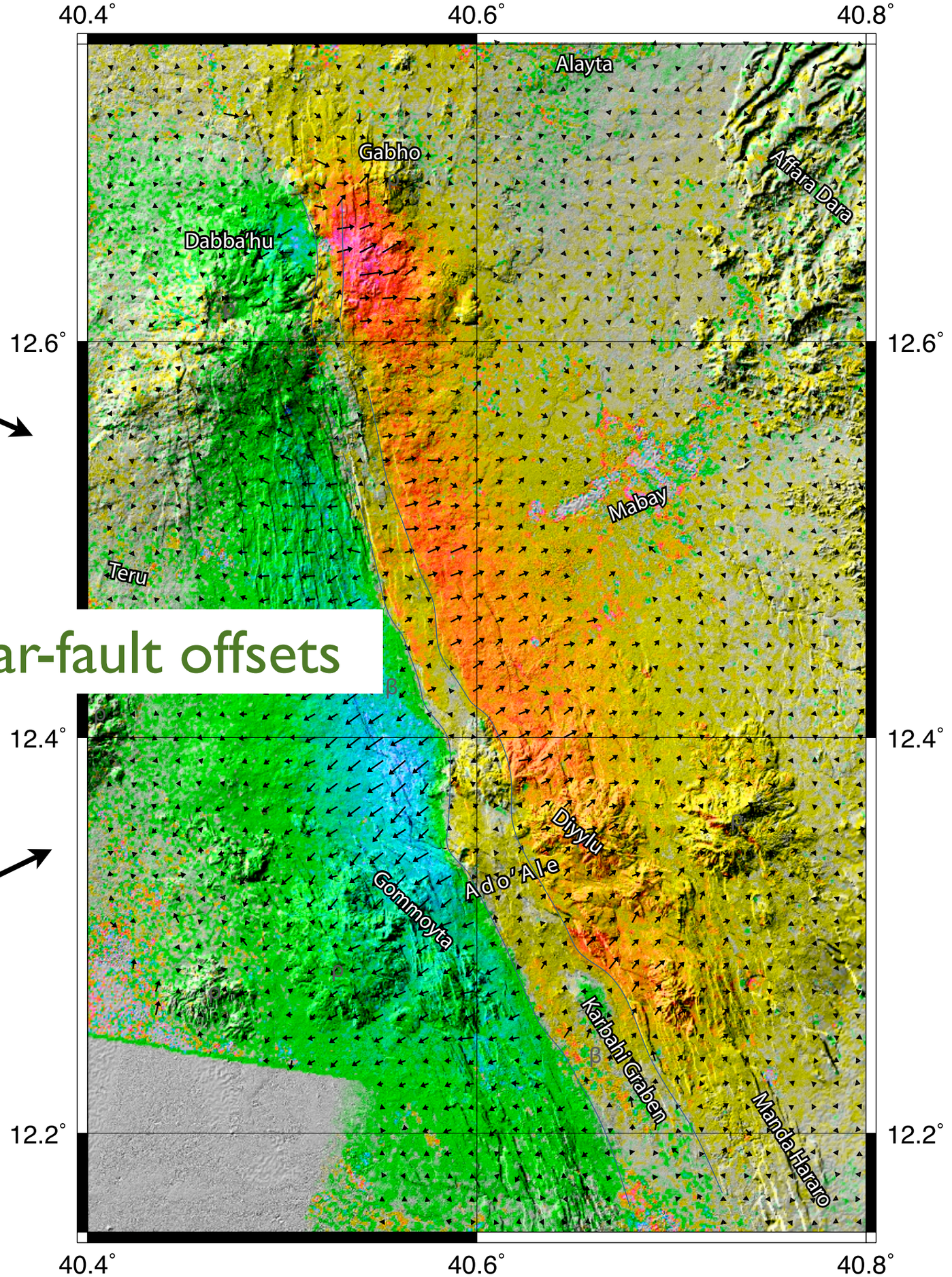
⇨ Constrains horizontal displacements

SPOT correlation data

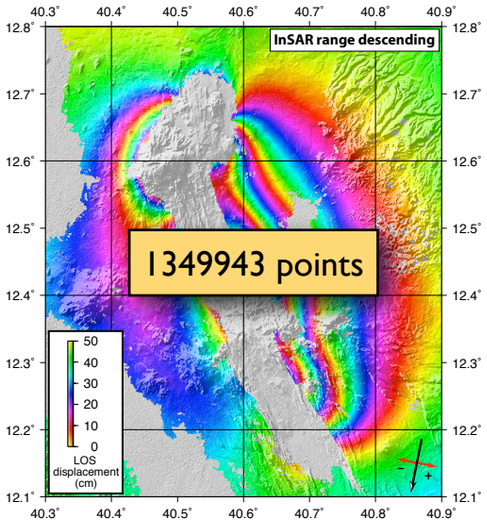


➪ Constrains near-fault offsets

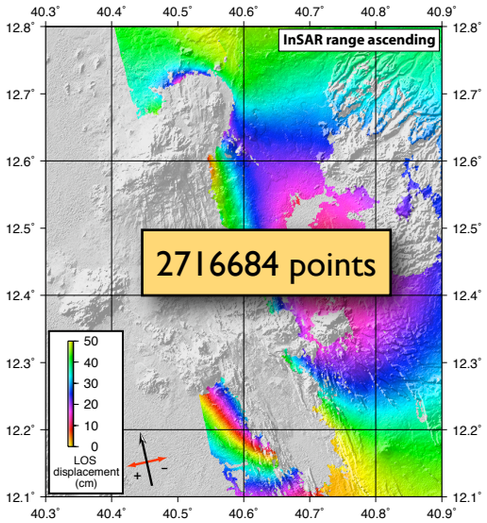




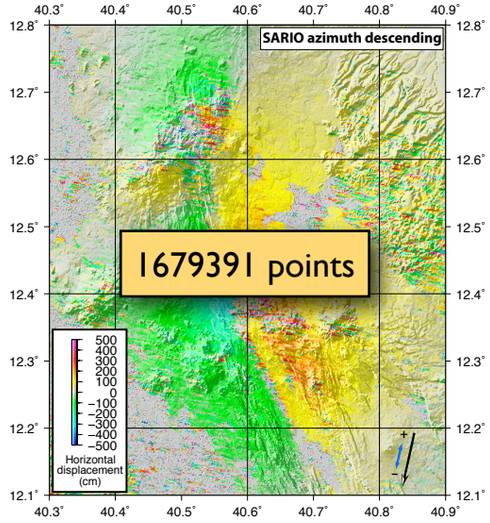
Data set overview



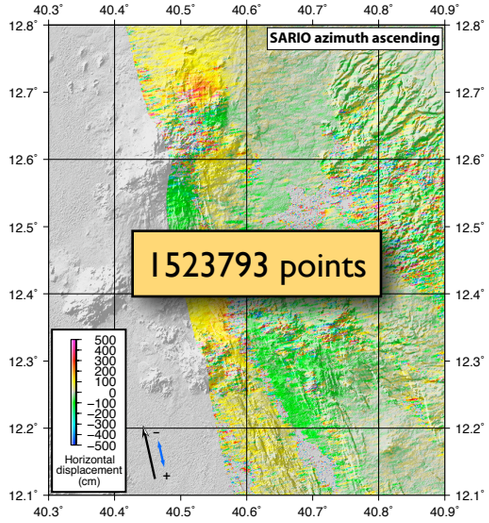
σ~0.3cm



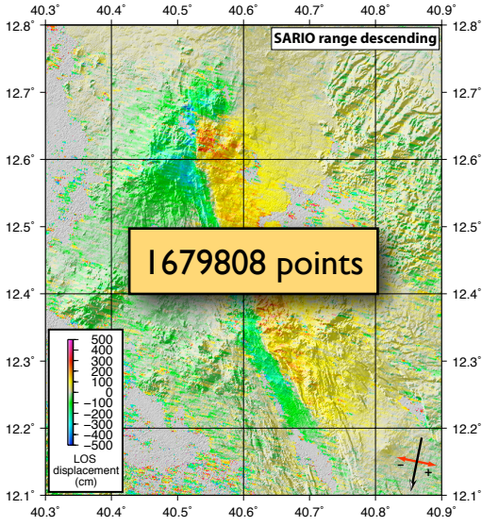
σ~0.3cm



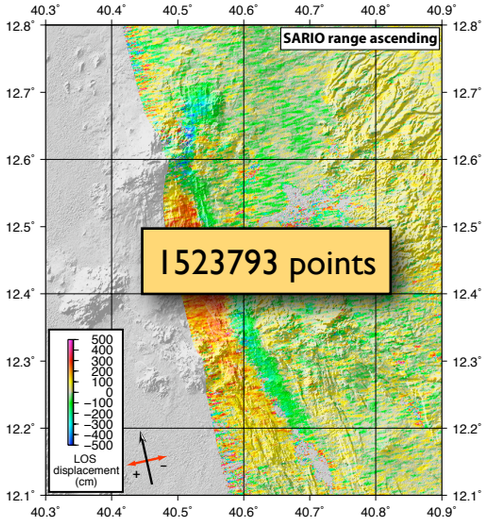
σ~30cm



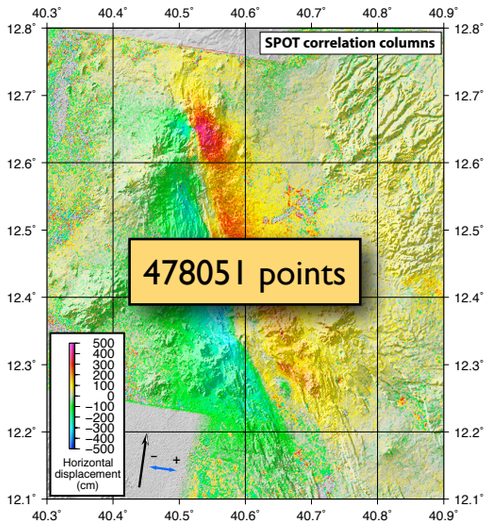
σ~30cm



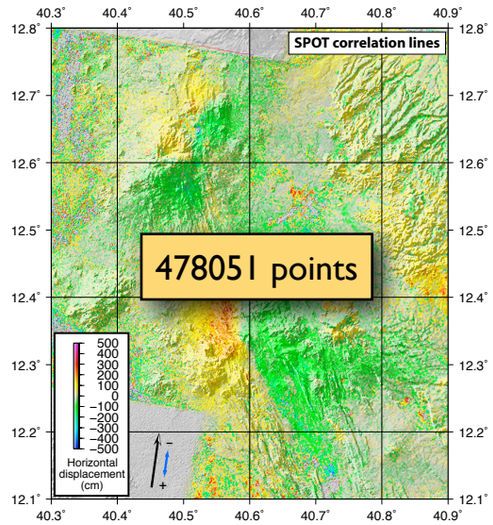
σ~50cm



σ~50cm



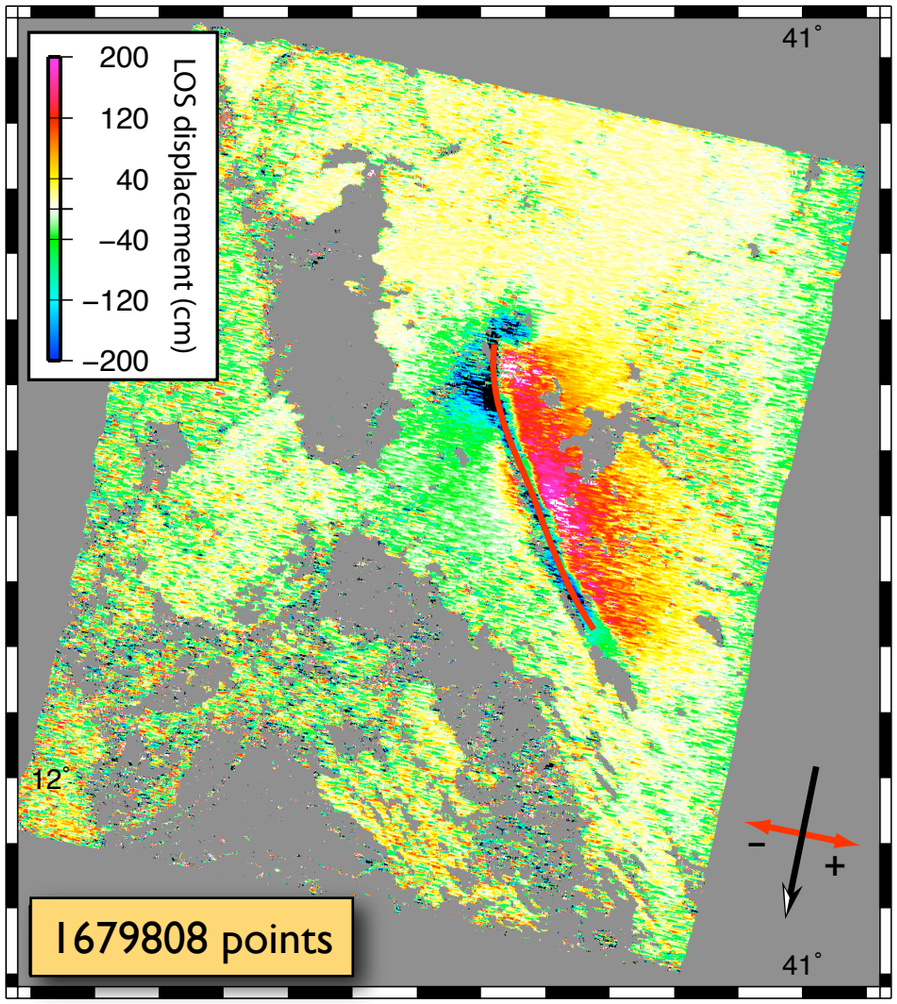
σ~10cm HF
σ~100cm LF



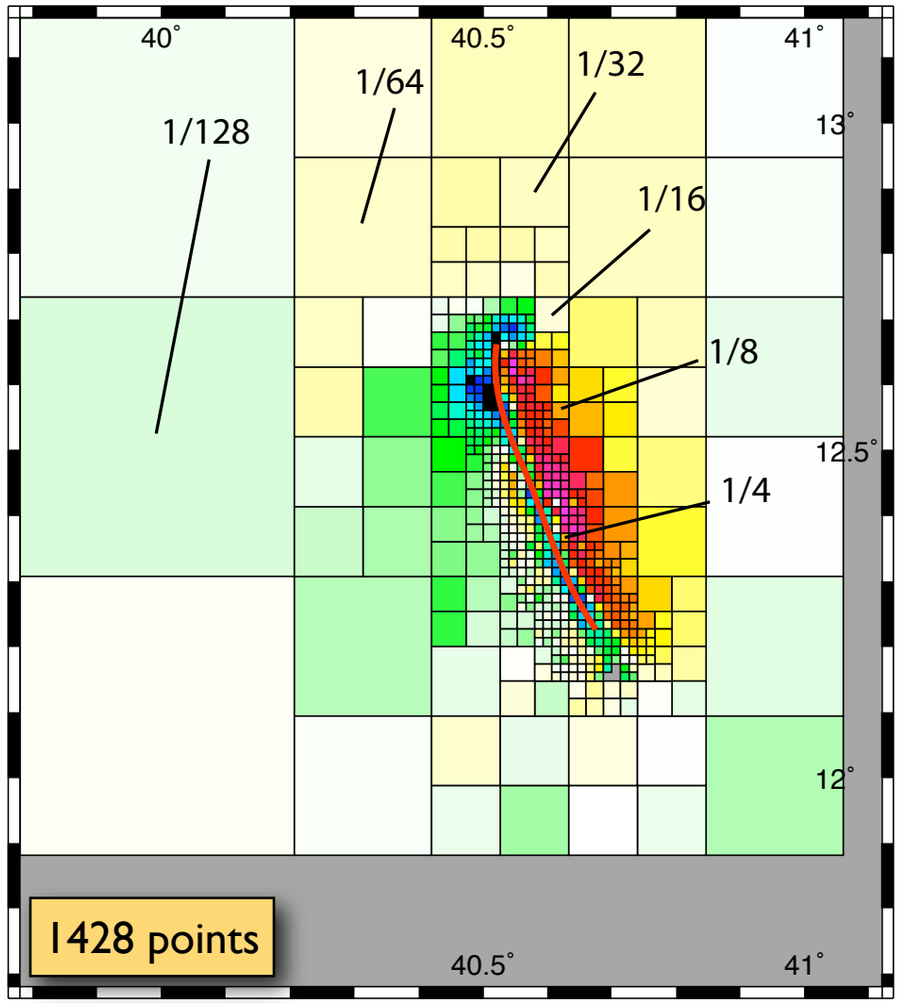
σ~10cm HF
σ~100cm LF

➪ Over 10 million points!

Data resampling



quadtree resampling



- Measured displacements are averaged over a few pixels
- The size of the averaging area is a function of the distance to the assumed dike
- Sampling density increases when approaching the rift zone
- The relative sampling density between the various data sets is always constant

➪ Less than 10000 points

Stategy for inversion

Initial assumption

Observed surface displacements can be explained by the opening, closure or slip on dislocations.

elasticity ➡ Okada (1985)

→ opening of a vertical dislocation = dike

→ slip on a dipping dislocation = fault

→ closure of a horizontal dislocation = sill

1. Constrain the geometry of the dike and sills

non-linear ➡ Tarantola & Valette (1982)

→ crude discretisation of the dike

→ far-field data only

2. Constrain the geometry of the faults

non-linear ➡ Tarantola & Valette (1982)

→ crude discretisation of the dike and faults

→ near and far-field data

3. Invert for opening/slip with the resulting geometry

linear ➡ least-square inversion

→ fine discretisation of the faults

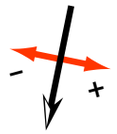
→ near and far-field data

⇨ Final model

Inversion #1

Geometry:

- 3 dike segments
- 2 sills



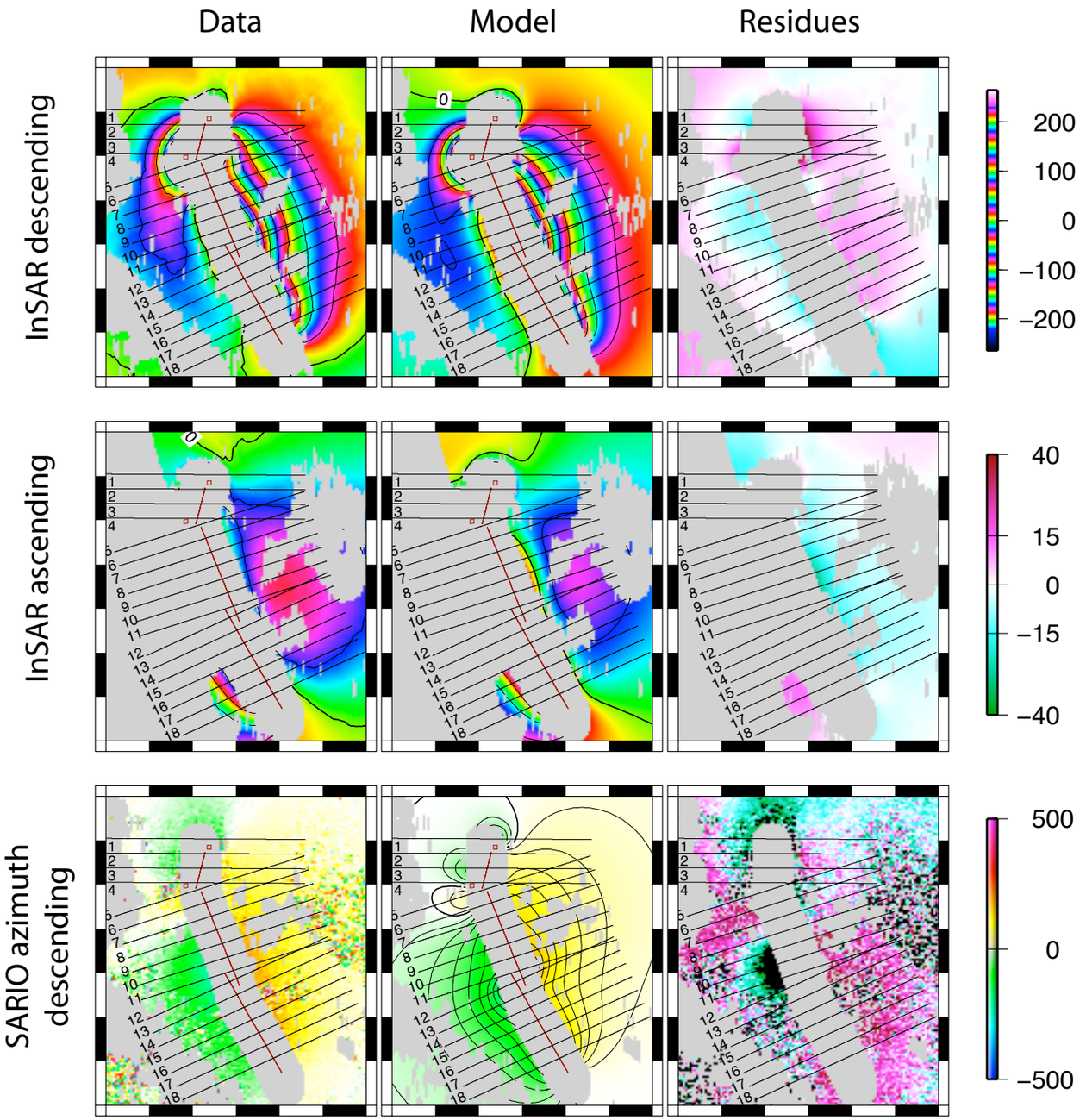
Inverted parameters (for the dikes):

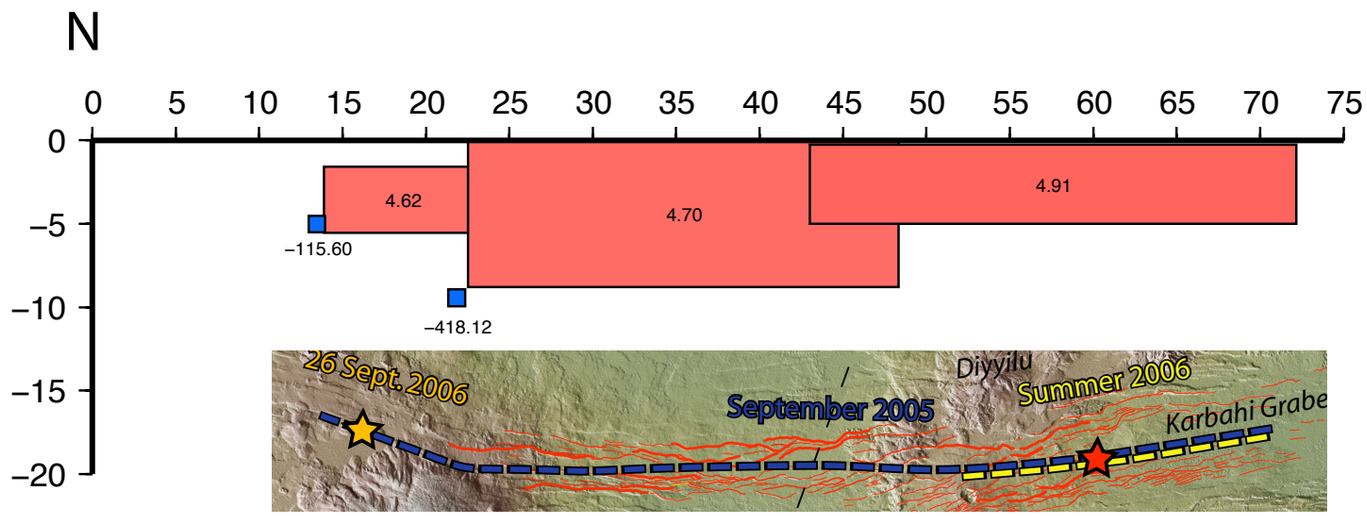
- opening
- position (longitude and latitude)
- width (bottom and top depths)
- length
- orientation (dip and strike)

Data sets used:

- InSAR descending
- InSAR ascending
- SARIO azimuth descending

- **31 parameters**
- **5936 data points**





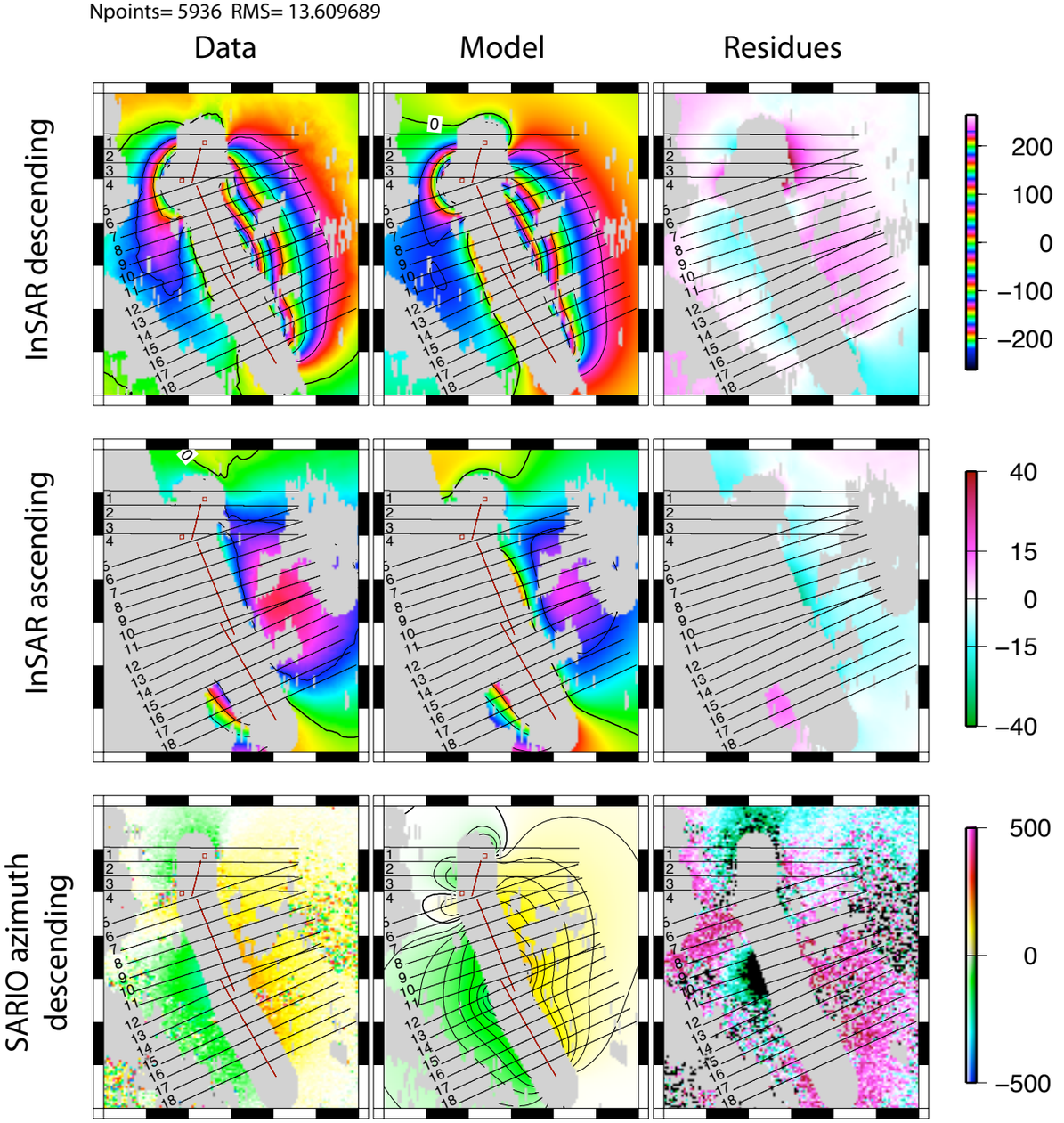
➪ Dike volume ~ 1.9 km^3

➪ Magmatic chamber deflation ~ 0.5 km^3

Comparison with Summer 2006 intrusion events

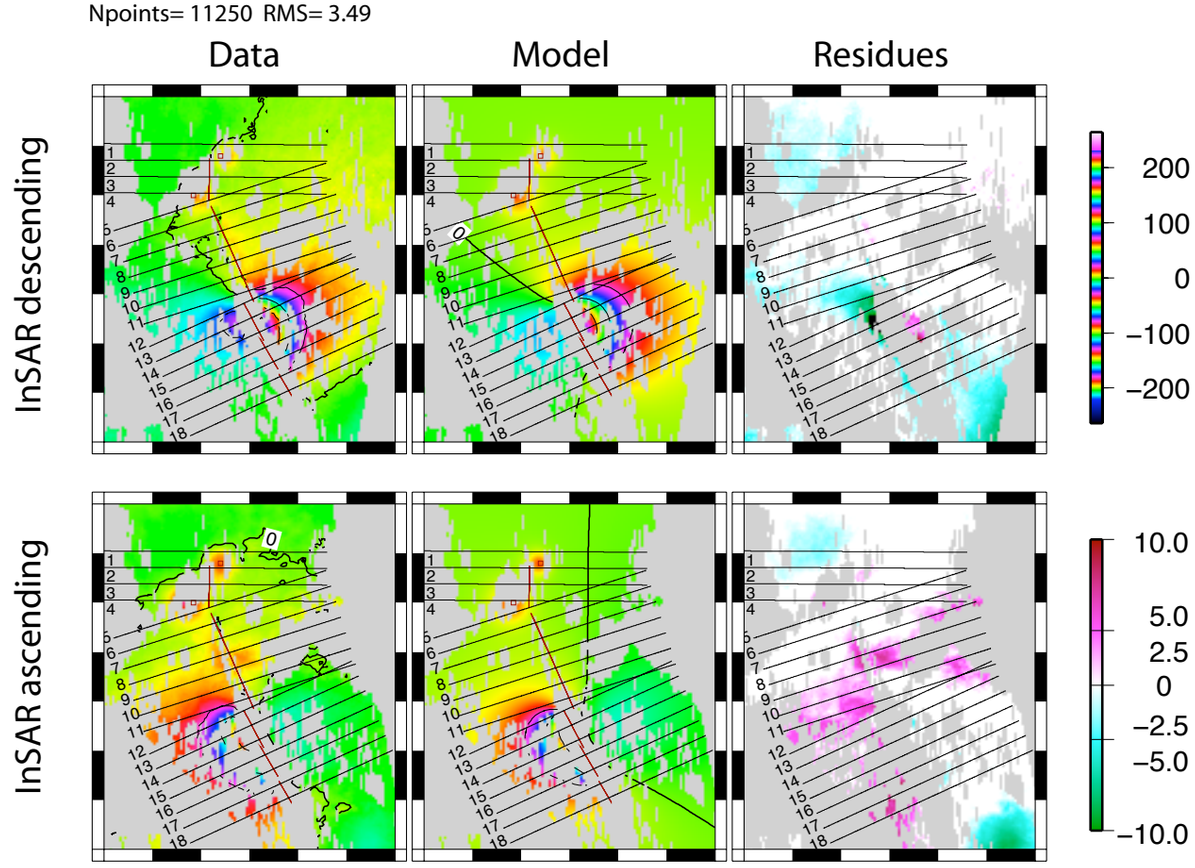
Late September 2005

Npoints= 5936 RMS= 13.609689



June 17th 2006

Npoints= 11250 RMS= 3.49

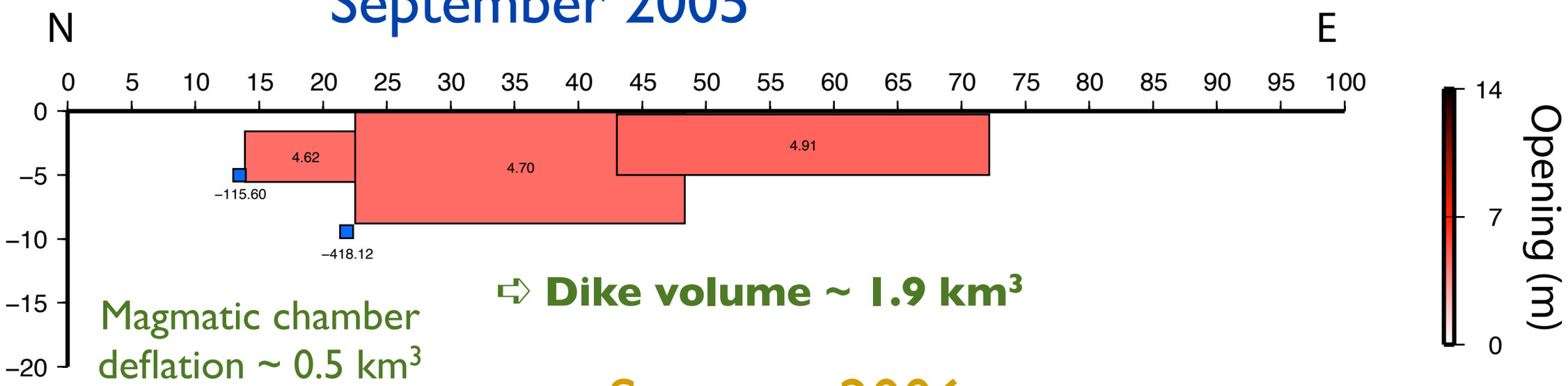


September 2005

Summer 2006

Comparison with Summer 2006 intrusion events (2)

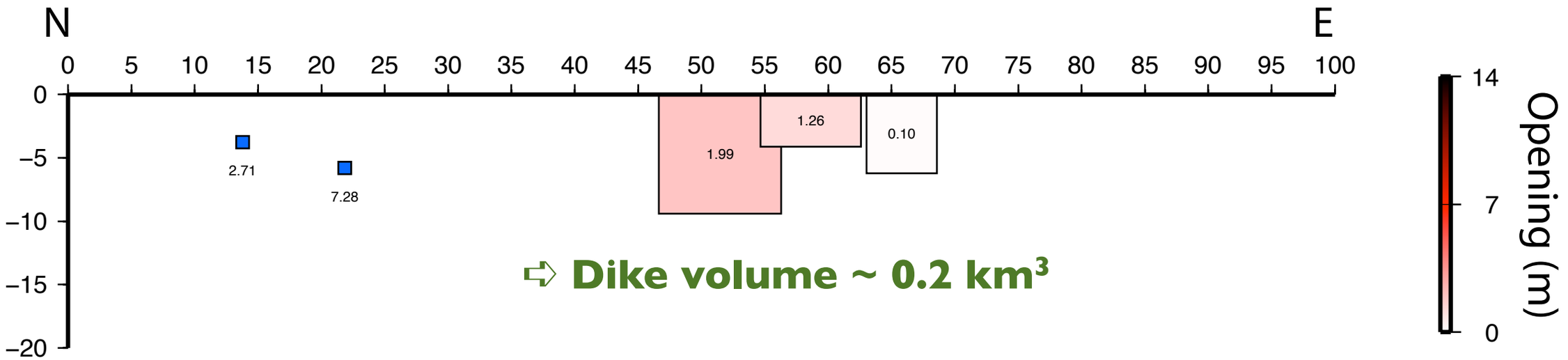
September 2005



Magmatic chamber deflation ~ 0.5 km³

➪ **Dike volume ~ 1.9 km³**

Summer 2006



➪ **Dike volume ~ 0.2 km³**

Inversion #2

Geometry:

- 8 dike segments
- 2 sills
- 30 faults (15 on each side)

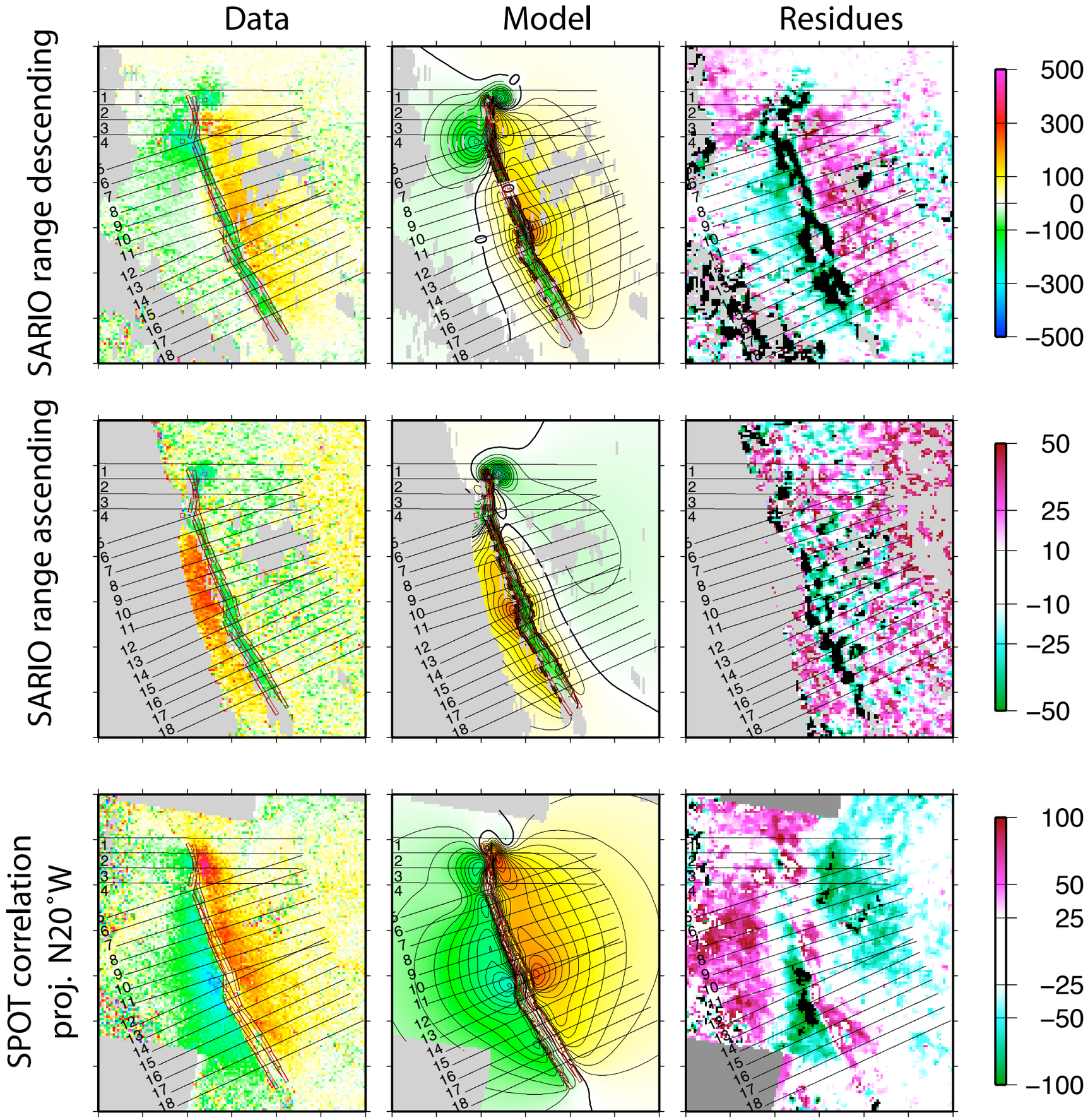
Inverted parameters (for the faults):

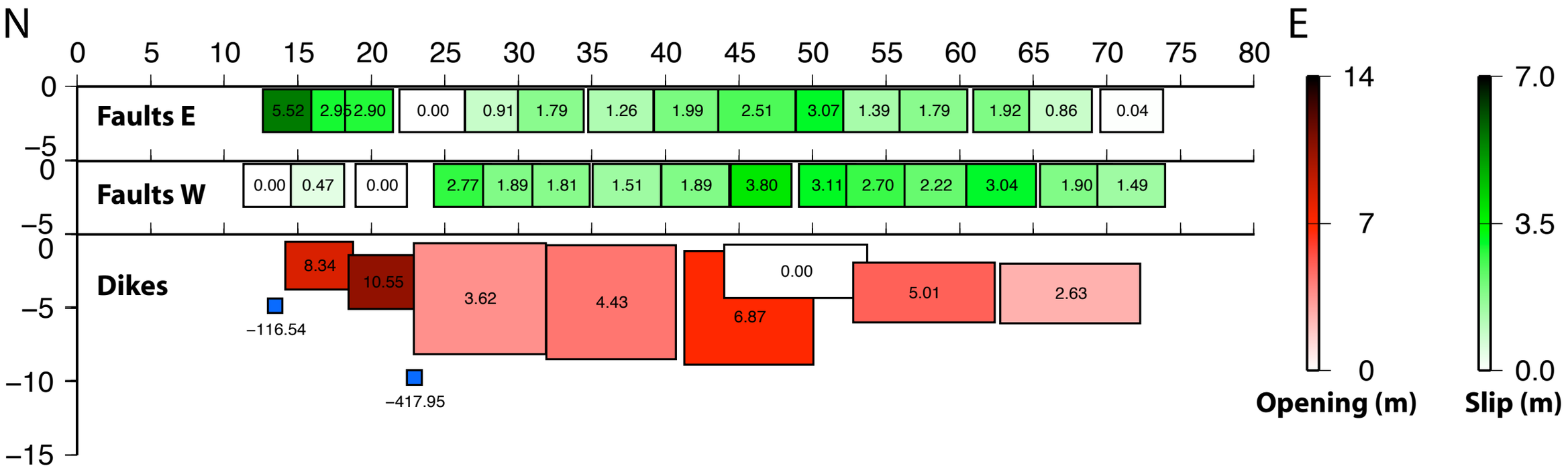
- slip
- position (longitude and latitude)

Data set used:

- InSAR, SARIO range and SARIO azimuth descending
- InSAR, SARIO range and SARIO azimuth ascending
- SPOT offsets

- **138 parameters**
- **7024 data points**





➪ Greatest opening along the Dabbahu segment, but at shallow depth only ⇒ smaller volume

➪ Asymmetric slip along Dabba'hu segment

➪ Opening is maximum at the junction between the northern segment and the southern segment

Inversion #3

Geometry:

- 315 dike segments
- 2 sills
- 320 faults (160 on each side)

Data sets used:

- InSAR, SARIO range and SARIO azimuth descending
- InSAR, SARIO range and SARIO azimuth ascending
- SPOT offsets

- **957 parameters**
- **7024 data points**

Inverted parameters (for the faults):

- slip and opening

Inverted parameters (for the dikes):

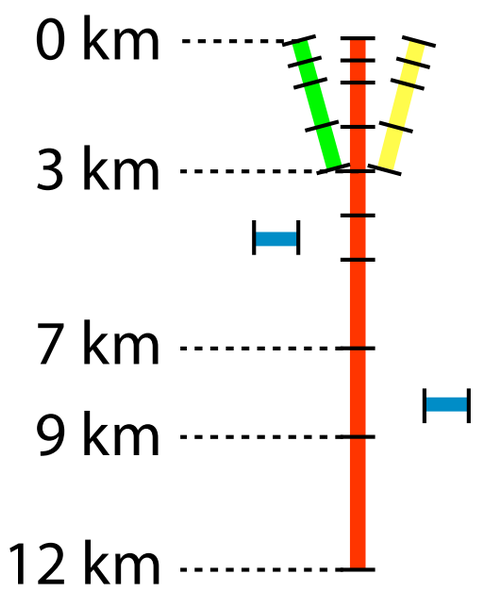
- opening

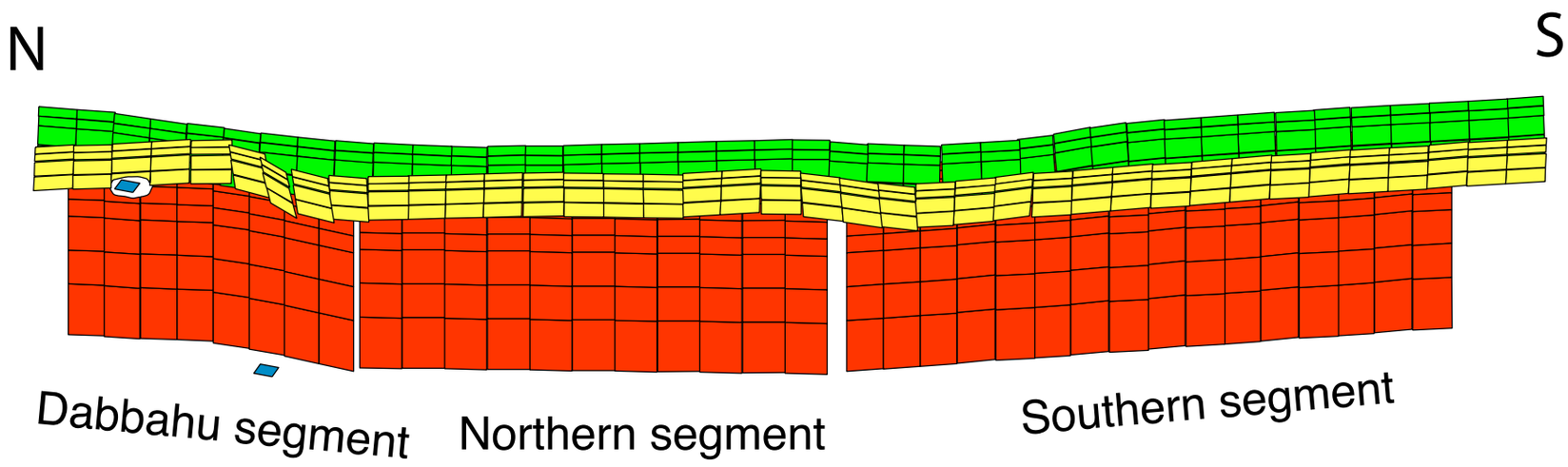
Inverted parameters (for the sills):

- closure

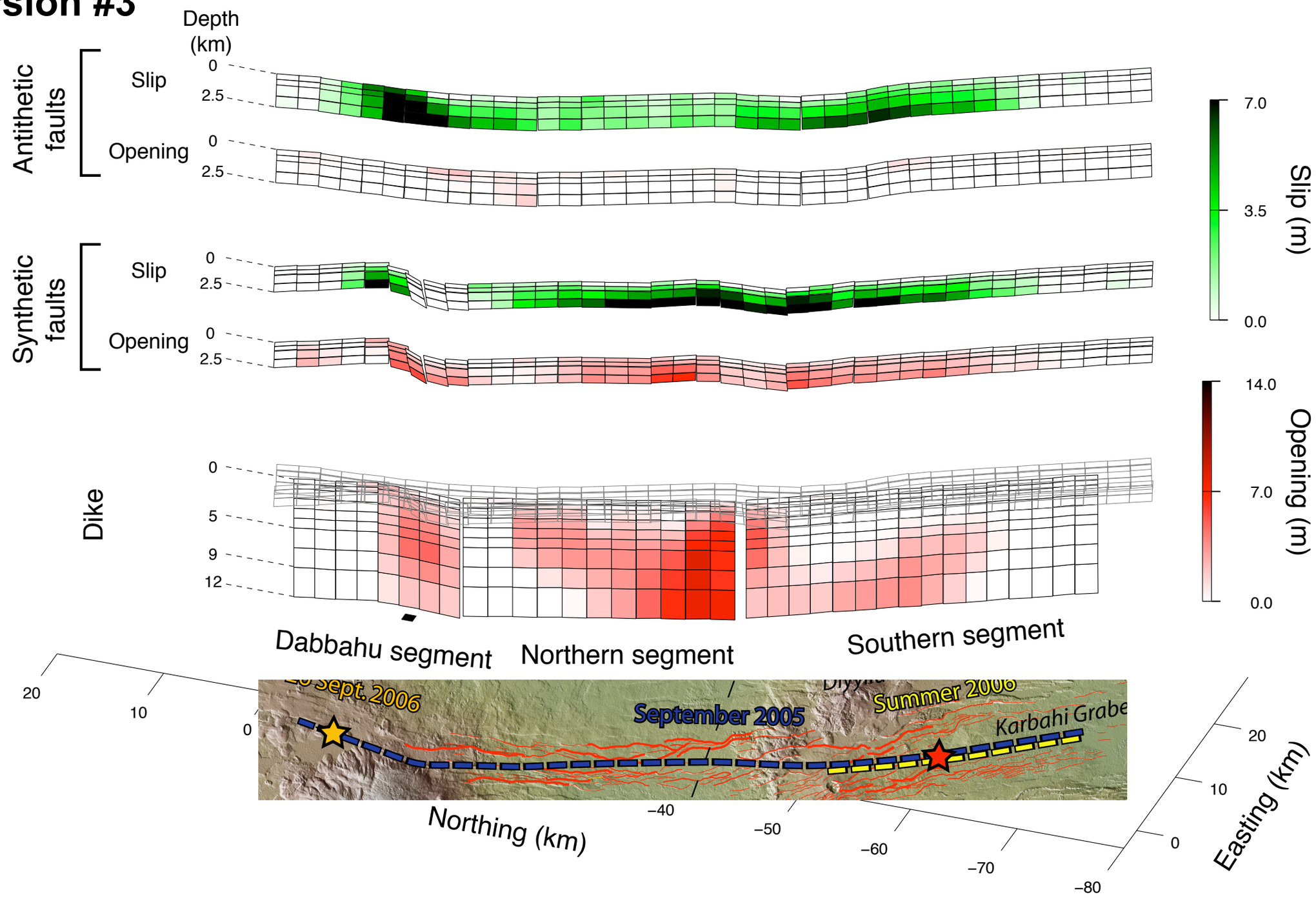
Additional constraints:

- non-negativity
- Laplacian smoothing (Menke, 1984)





Inversion #3

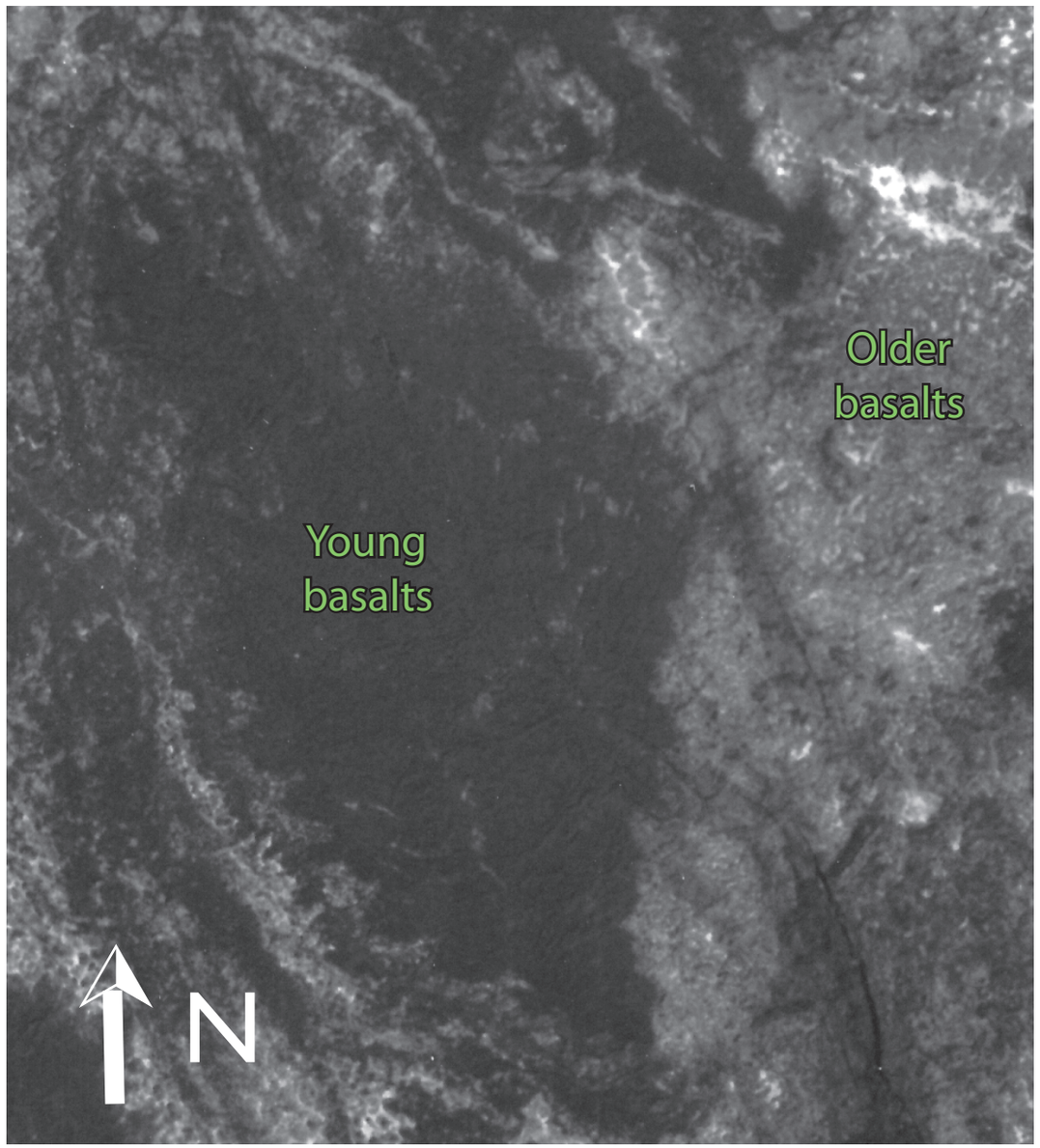


➪ Asymmetric slip along the Dabbahu segment

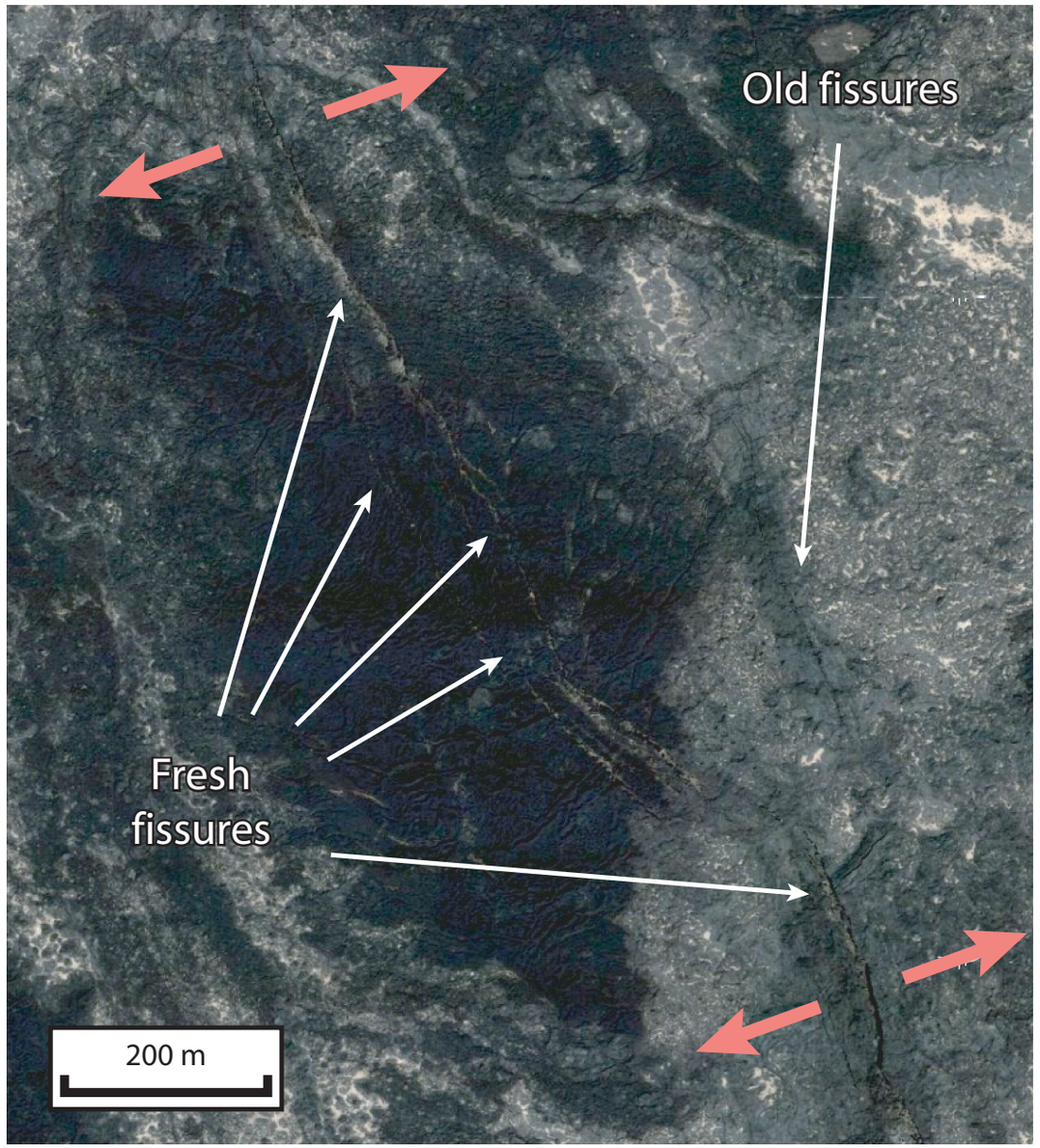
➪ Opening is deepest at the junction between northern and southern segments

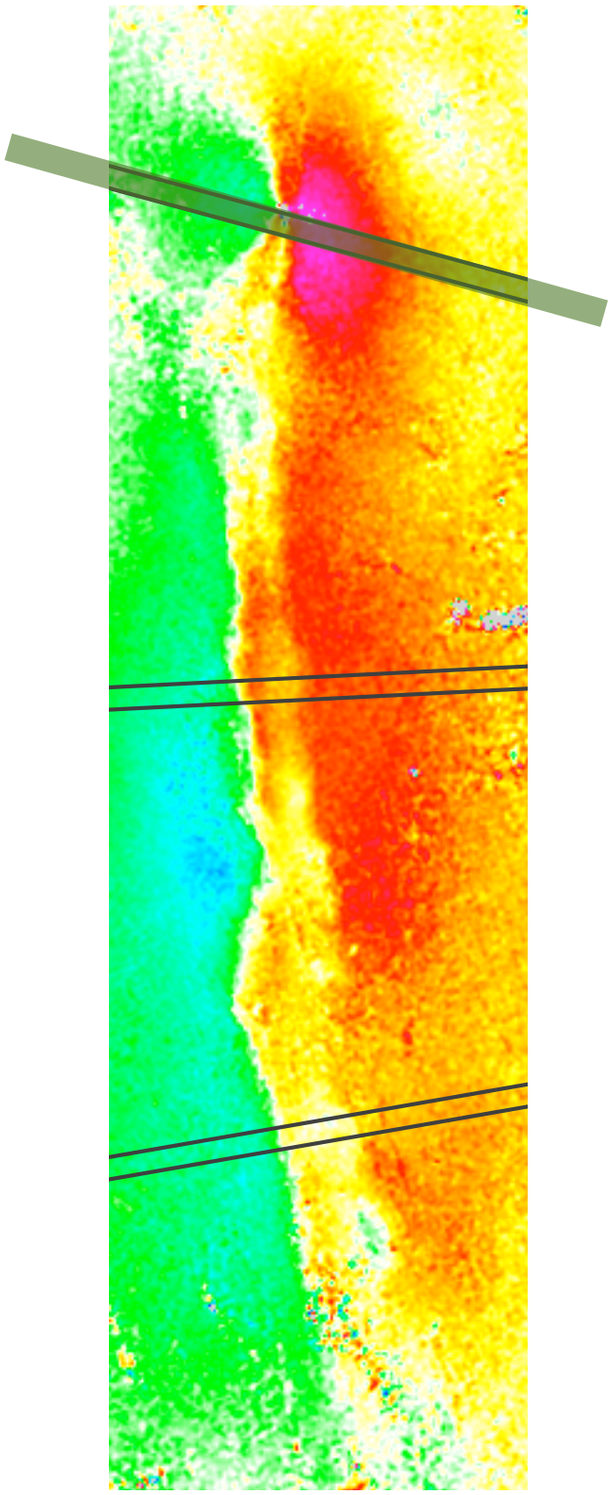
➪ Significant opening on, or close to, synthetic faults (eastward dipping)

Aerial photography
1994

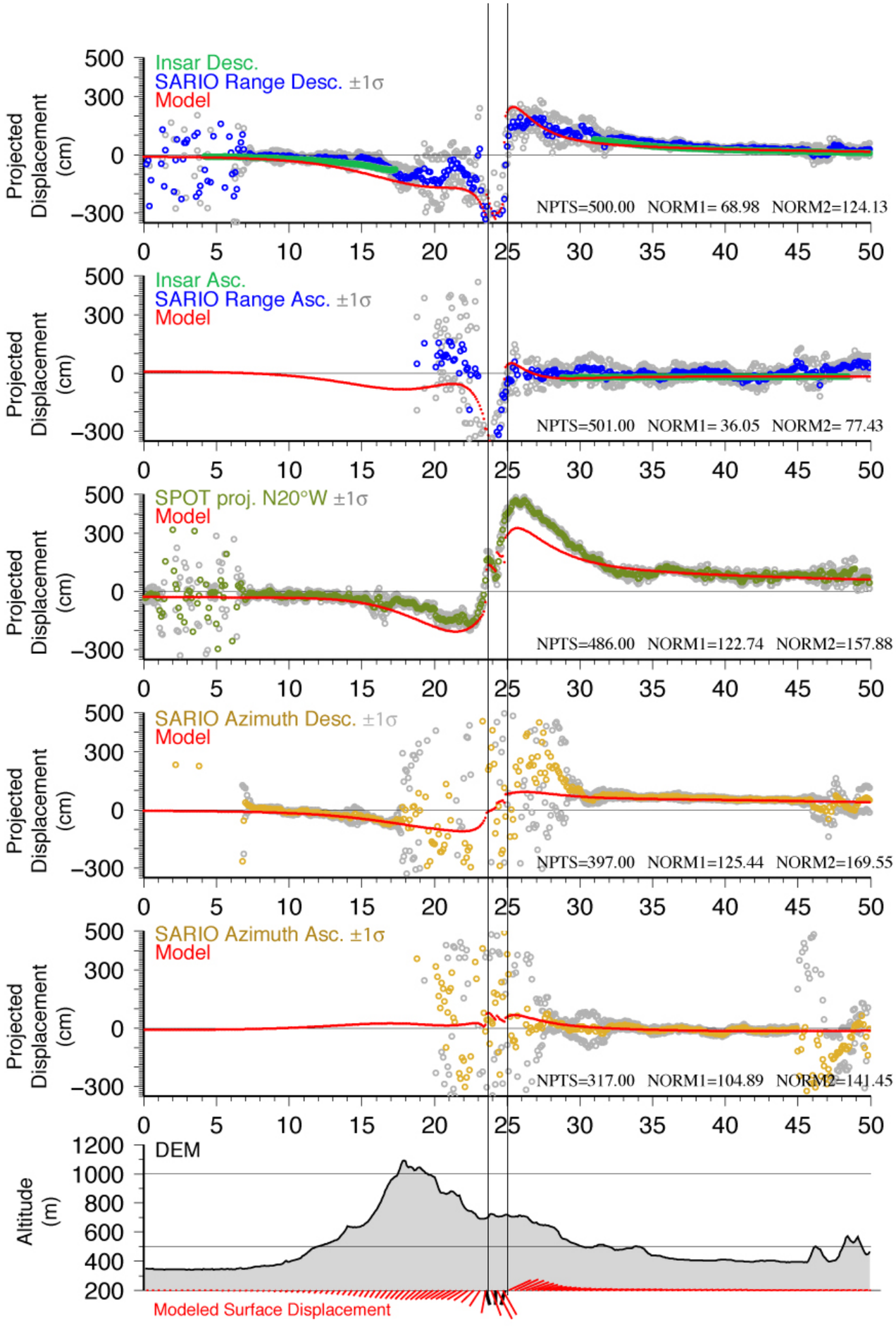


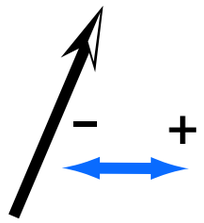
Quickbird image
2006





a


Insar Desc.
SARIO Range Desc. ±1σ
Model
NPTS=500.00 NORM1= 68.98 NORM2=124.13
Insar Asc.
SARIO Range Asc. ±1σ
Model
NPTS=501.00 NORM1= 36.05 NORM2= 77.43
SPOT proj. N20°W ±1σ
Model
NPTS=486.00 NORM1=122.74 NORM2=157.88
SARIO Azimuth Desc. ±1σ
Model
NPTS=397.00 NORM1=125.44 NORM2=169.55
SARIO Azimuth Asc. ±1σ
Model
NPTS=317.00 NORM1=104.89 NORM2=141.45
DEM
Modeled Surface Displacement
Projected Displacement (cm)
Altitude (m)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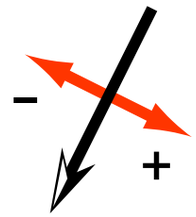
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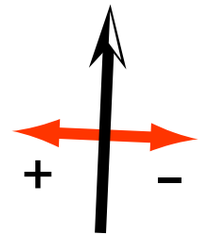
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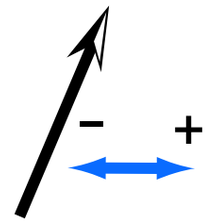
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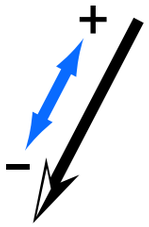
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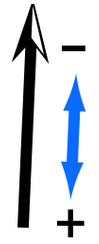
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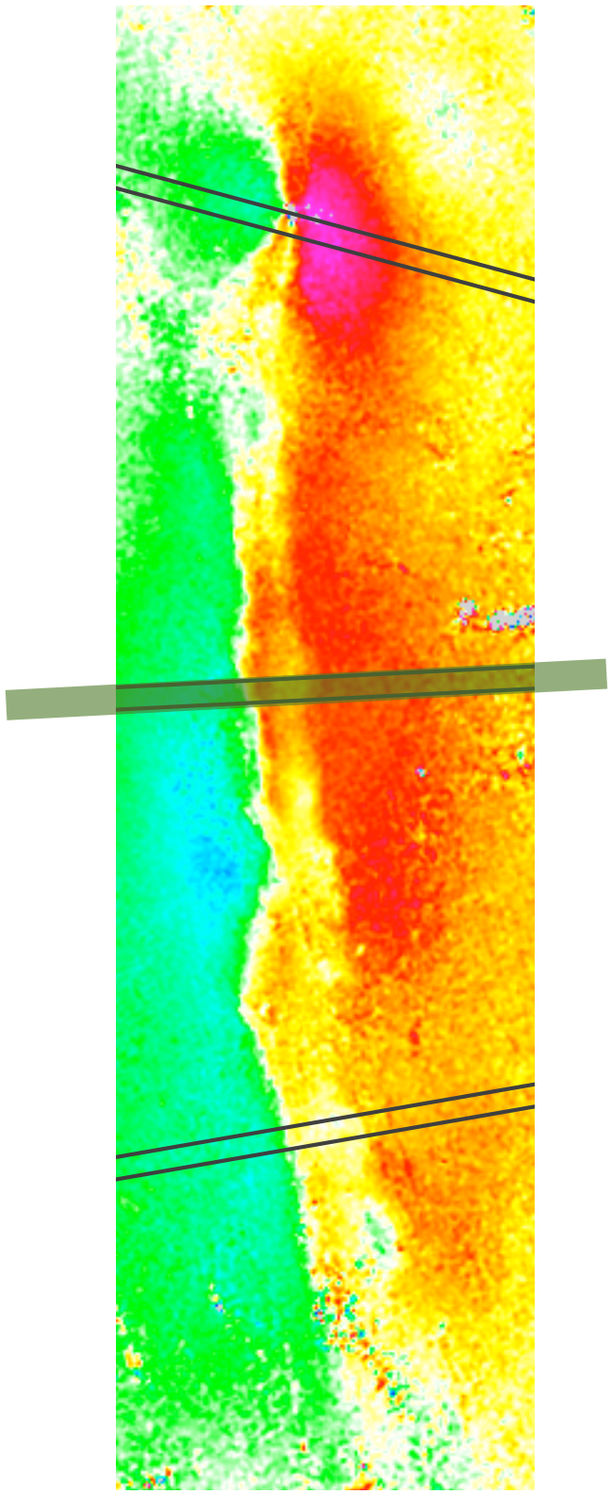

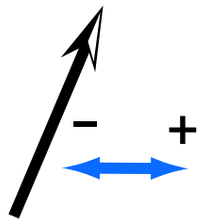
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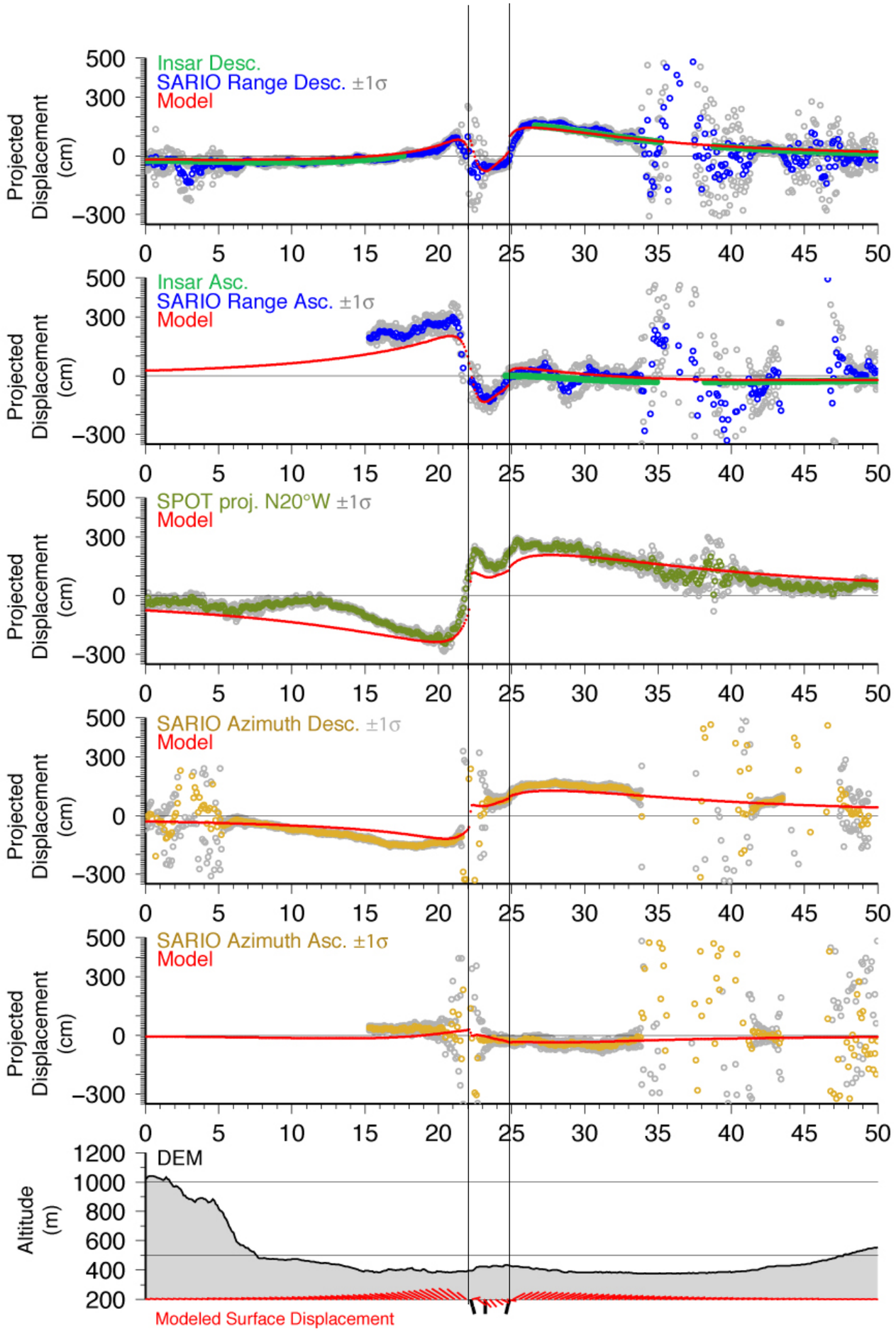
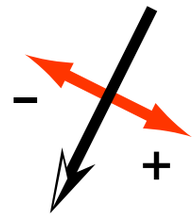

Insar Desc.
SARIO Range Desc. ±1σ
Model
Insar Asc.
SARIO Range Asc. ±1σ
Model
SPOT proj. N20°W ±1σ
Model
SARIO Azimuth Desc. ±1σ
Model
SARIO Azimuth Asc. ±1σ
Model
DEM
Modeled Surface Displacement
Projected Displacement (cm)
Altitude (m)
500
300
0
–300
1200
1000
800
600
400
200
0
5
10
15
20
25
30
35
40
45
50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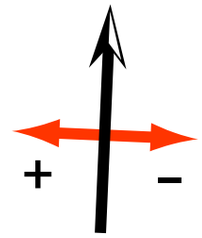
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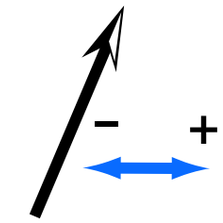
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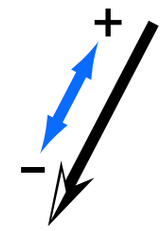
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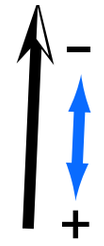
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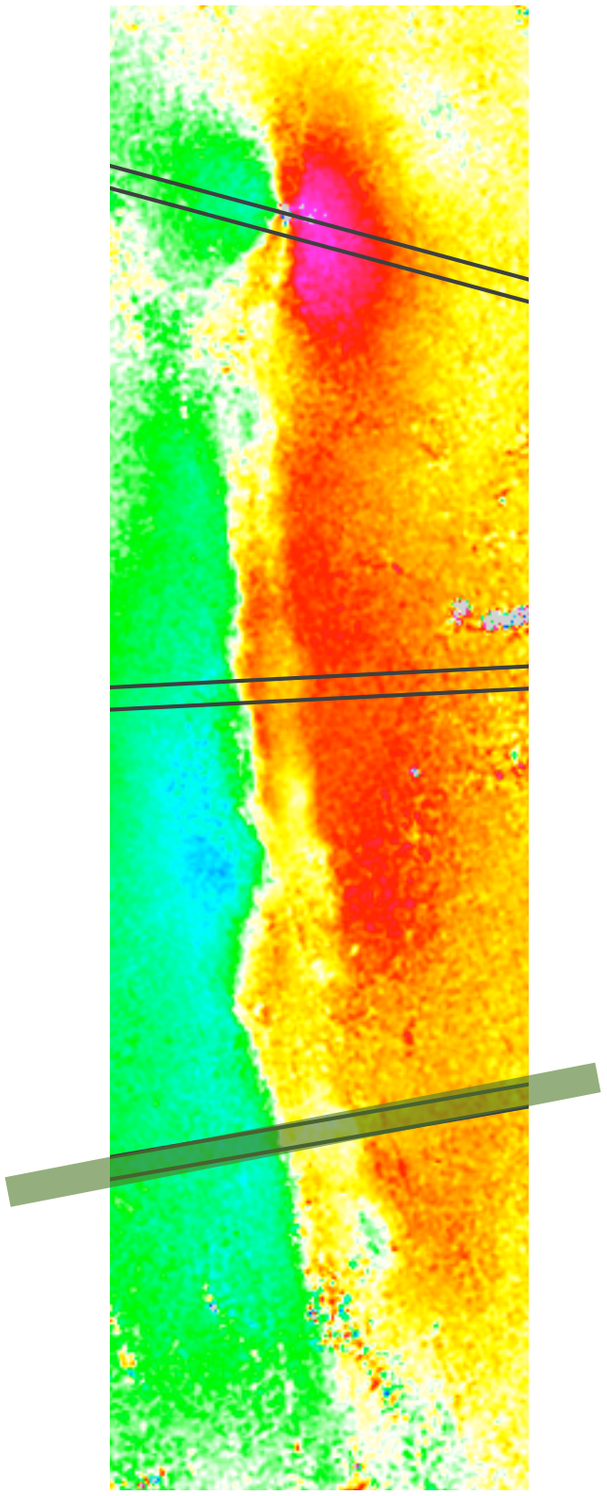

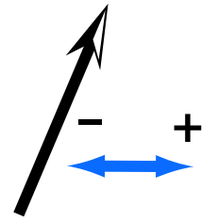
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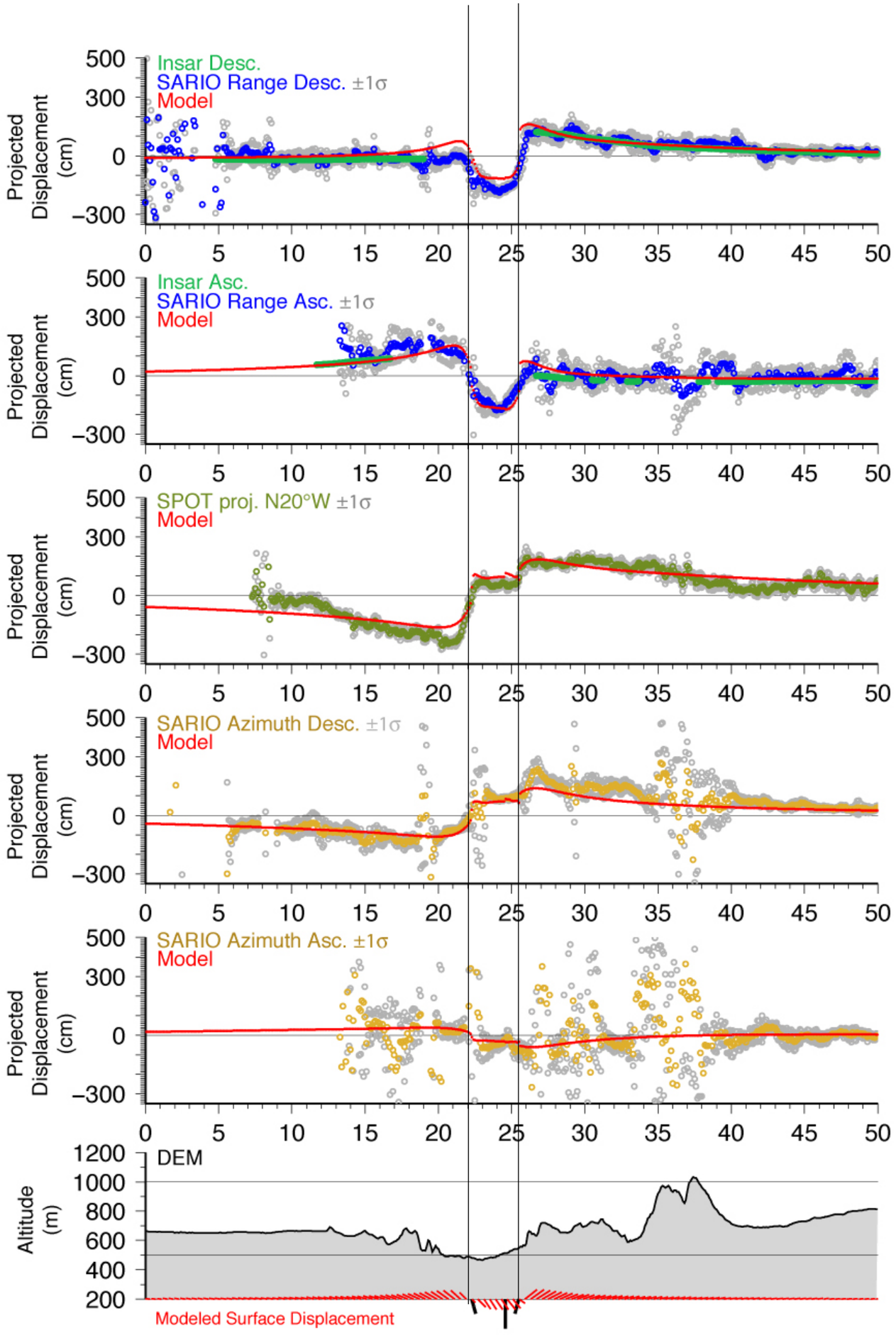
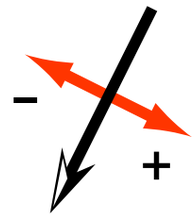

Insar Desc.
SARIO Range Desc. ±1σ
Model
Insar Asc.
SARIO Range Asc. ±1σ
Model
SPOT proj. N20°W ±1σ
Model
SARIO Azimuth Desc. ±1σ
Model
SARIO Azimuth Asc. ±1σ
Model
DEM
Modeled Surface Displacement
Projected Displacement (cm)
Altitude (m)
500
300
0
−300
1200
1000
800
600
400
200
0
5
10
15
20
25
30
35
40
45
50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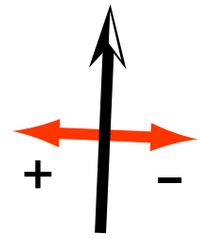
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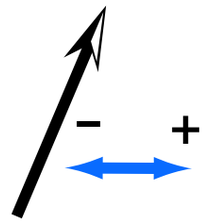
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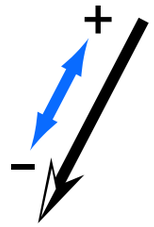
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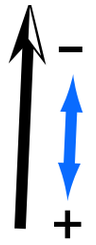
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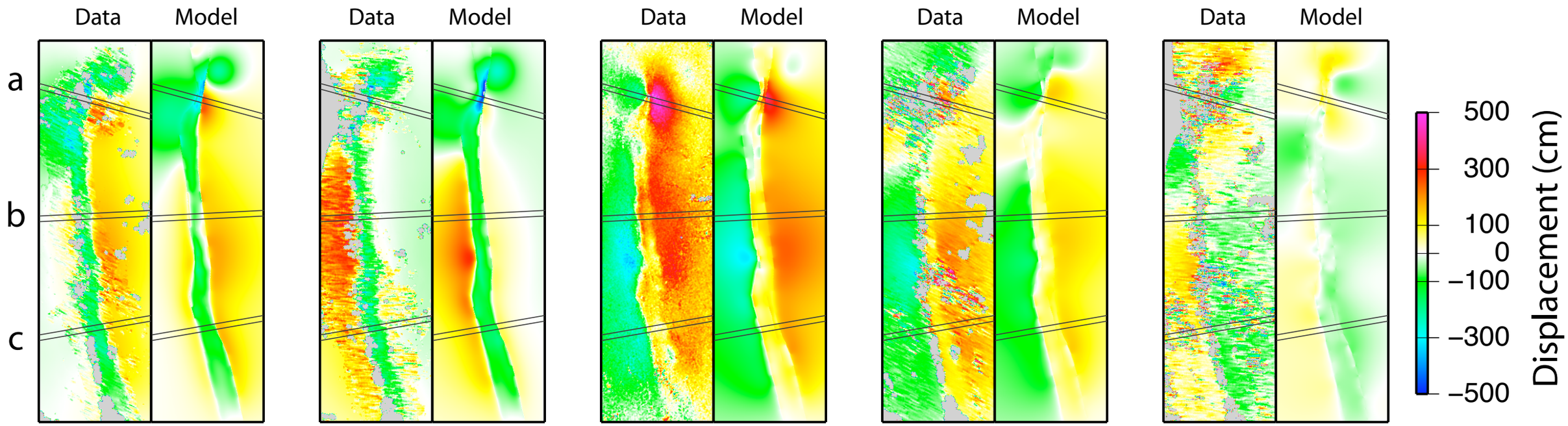
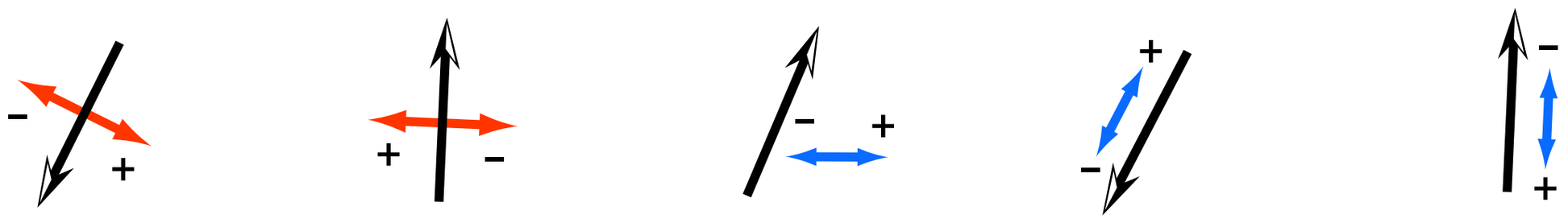
Inversion #3





➪ Explains most of the data set

➪ Robust result

but ... slight understimation of horizontal displacements

and ... several small scale problems

Summary & possible conclusions

➪ Dike volume ~ 1.9 km^3

➪ Magmatic chamber deflation ~ 0.5 km^3

➪ Requires another source for at least 2/3 of the basaltic magma

➪ Shallow opening west of Dabba'hu, with asymmetric slip

➪ Importance of segmentation

➪ Shallow silisic dike originating from the Gabho magmatic chamber?

➪ Largest and deepest opening at Ado'Ale

➪ Locus of basaltic magma input?

➪ Norhern segment: opening and slip at shallow depth on or close to synthetic (eastward dipping) faults ; no opening on antithetic faults, with less slip

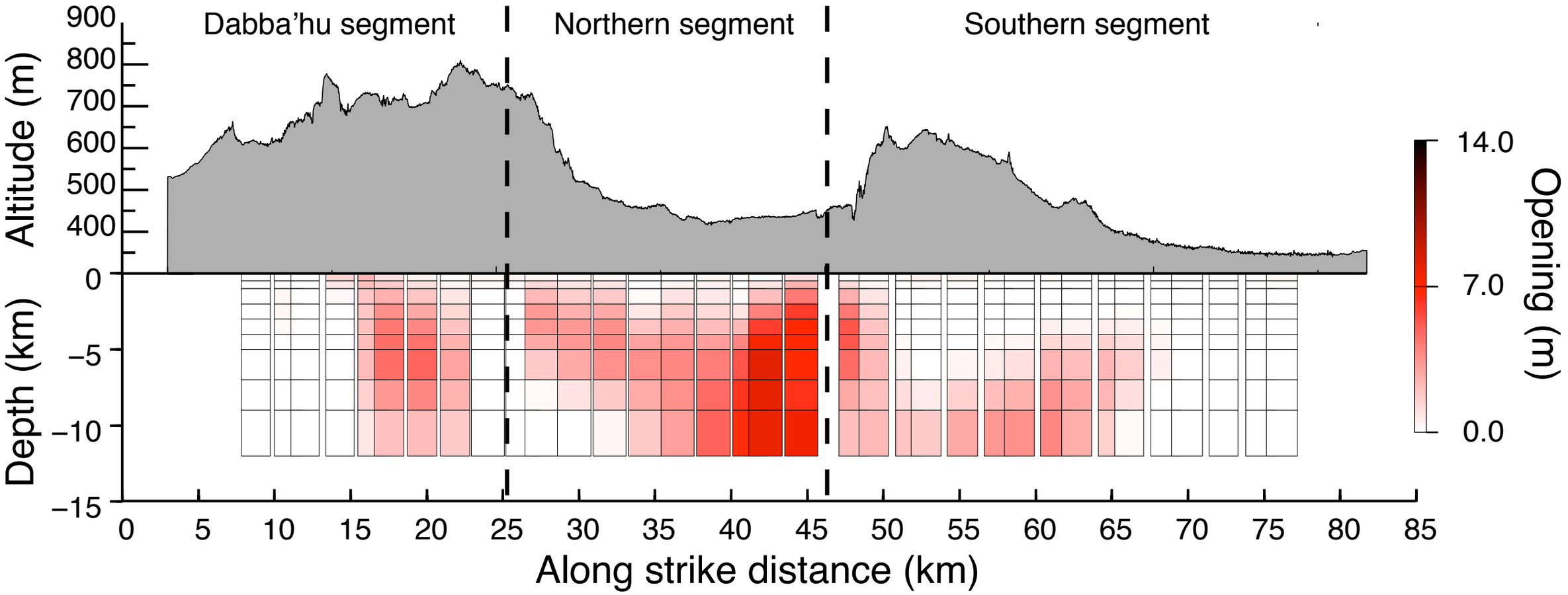
➪ Magma assisted faulting?

➪ Block rotations?

➪ Southern segment: more symmetrical behavior along the southern segment

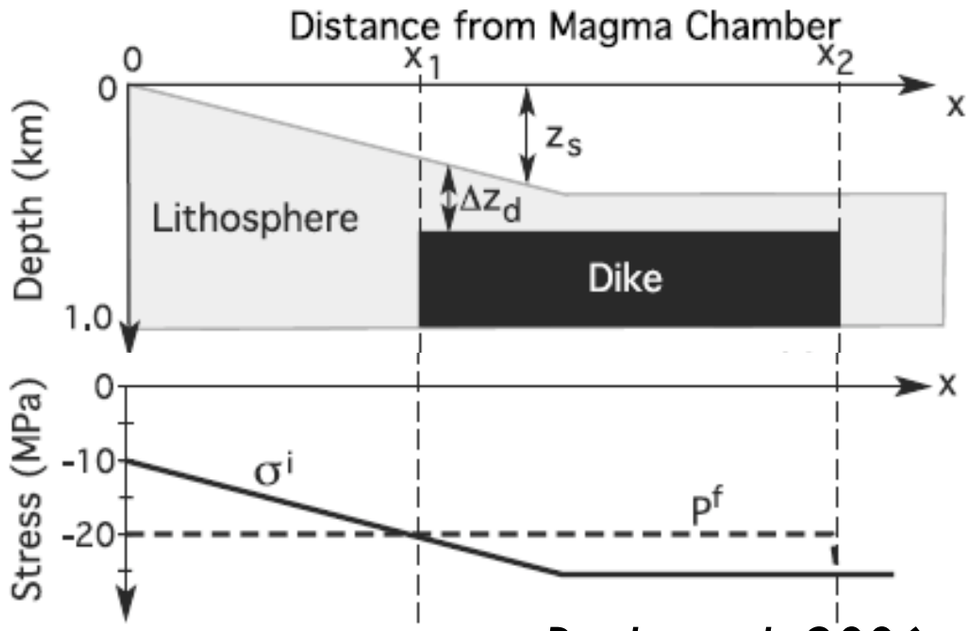
➪ Displacements observed at the surface are conditionned by the location of the dike with respect to the rift axis

Along strike topography VS opening



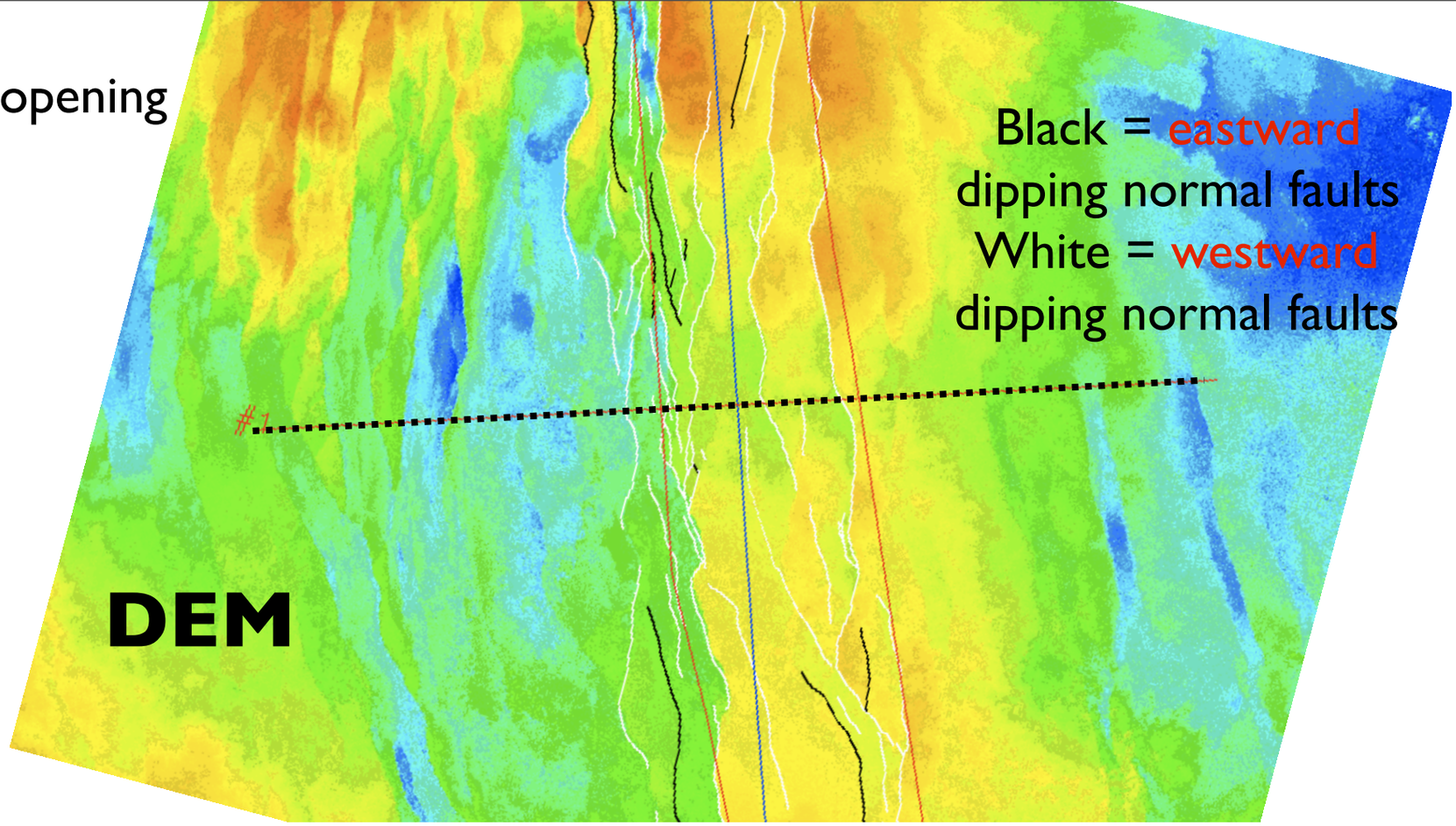
High topography = stress barrier for the dike?

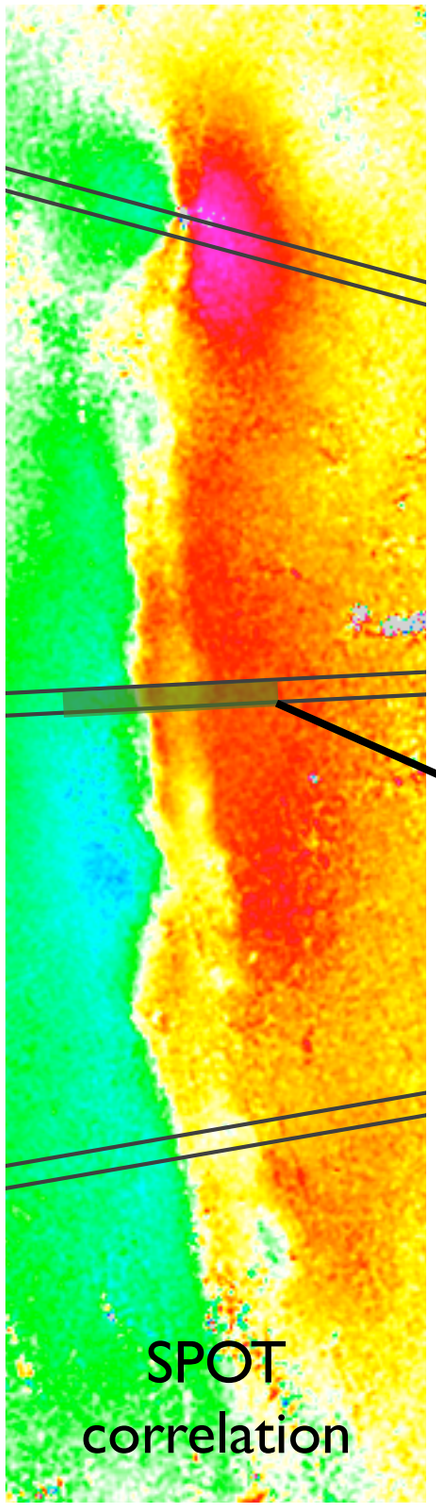
➪ If so, when and how is extension accomodated in areas where opening is "bottlenecked"?

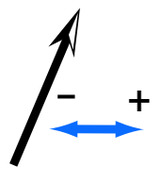


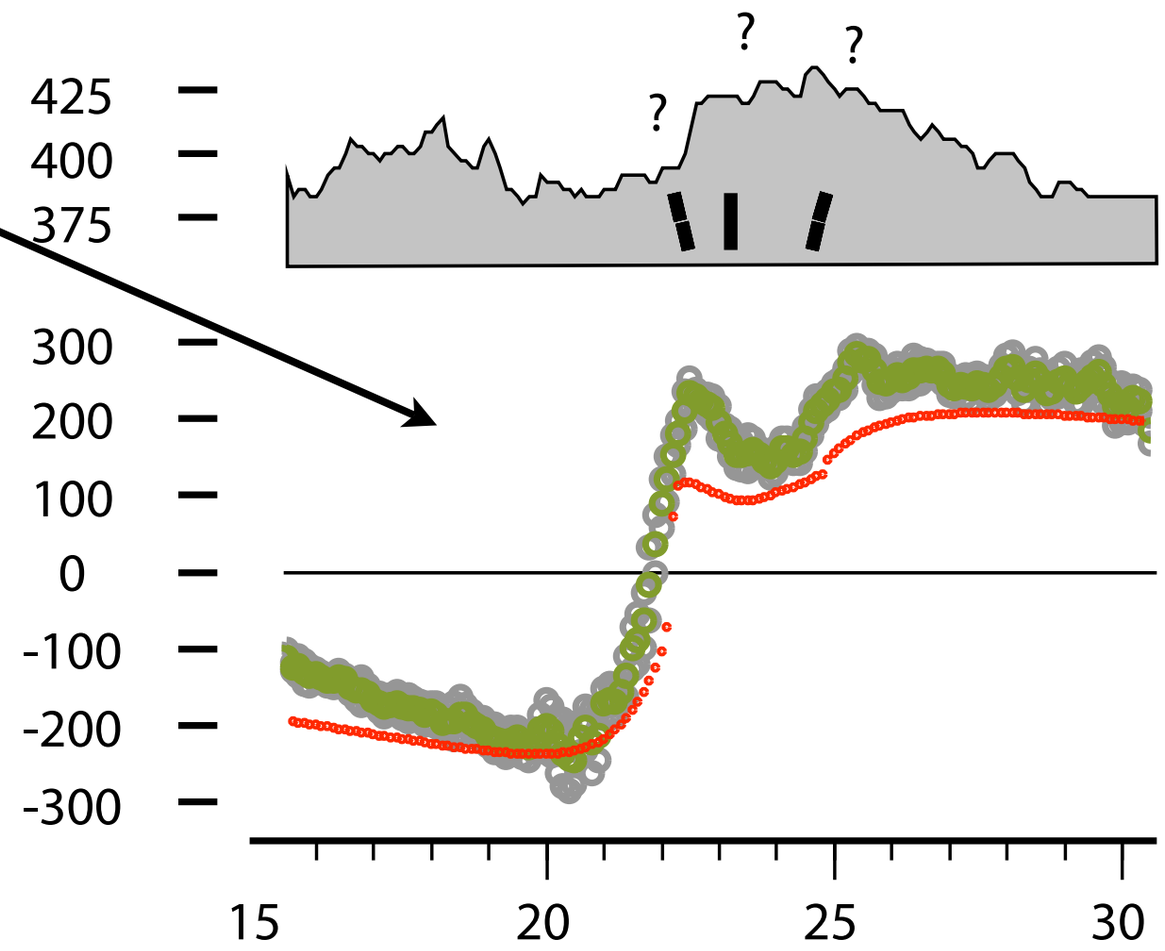
Buck et al., 2006

Rift perpendicular topography VS opening





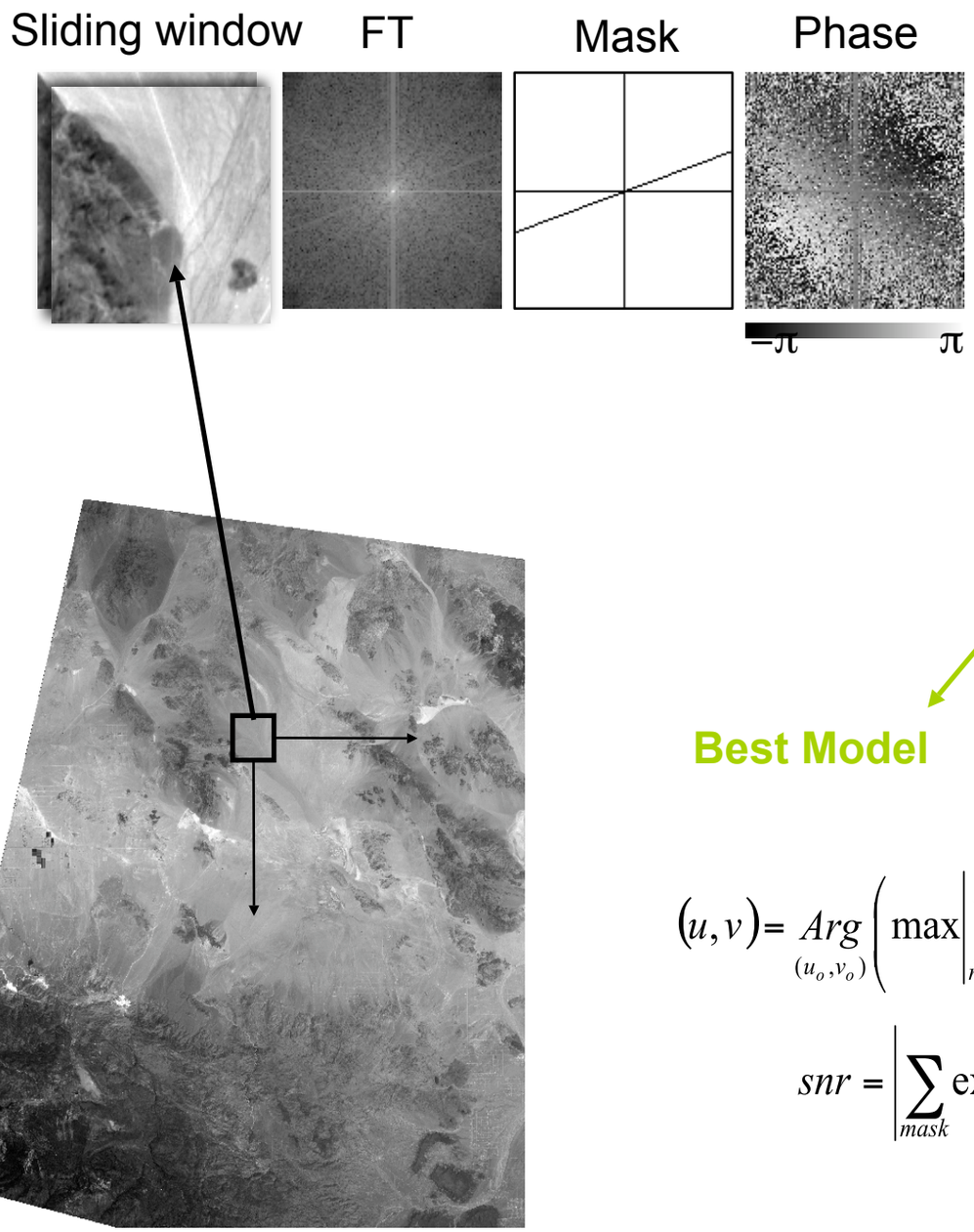




Thank you for your attention!

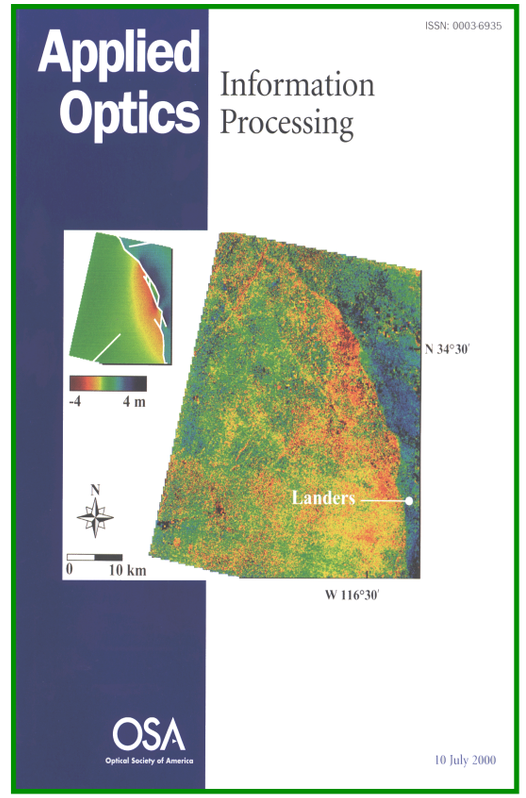
Sub-pixel correlation of optical images: principle

$$I_2(c,l) = I_1(c+u_0, l+v_0)$$
$$TF(I_2) = TF(I_1).e^{2i\pi(w_c u_0 + w_l v_0)}$$



$$(u,v) = \underset{(u_o,v_o)}{Arg}\left(\max\left|\sum_{mask}\exp[i.\Phi]\exp[-2\pi i.(w_c.u_o + w_l.v_o)]\right|\right)$$

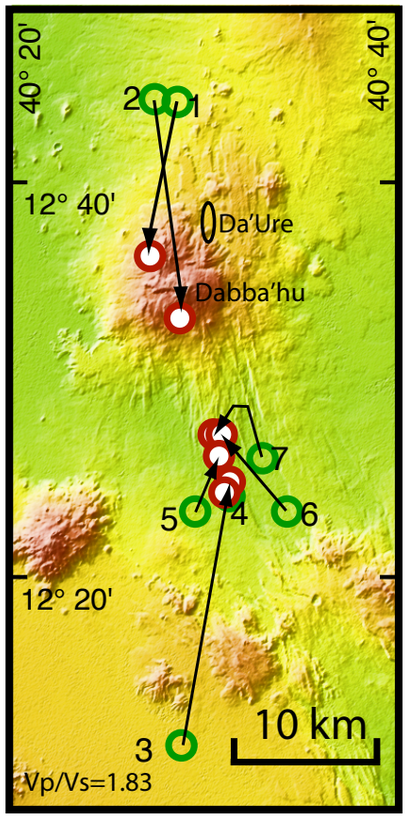
$$snr = \left|\sum_{mask}\exp[i.\Phi]\exp[-2\pi i.(w_c.u + w_l.v)]\right|$$

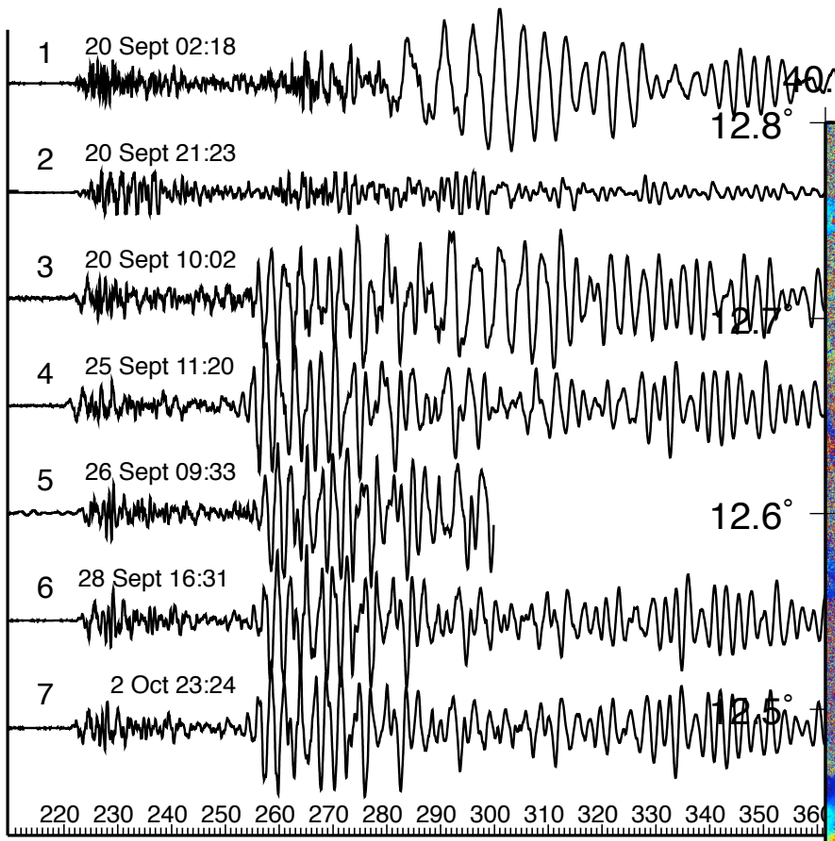


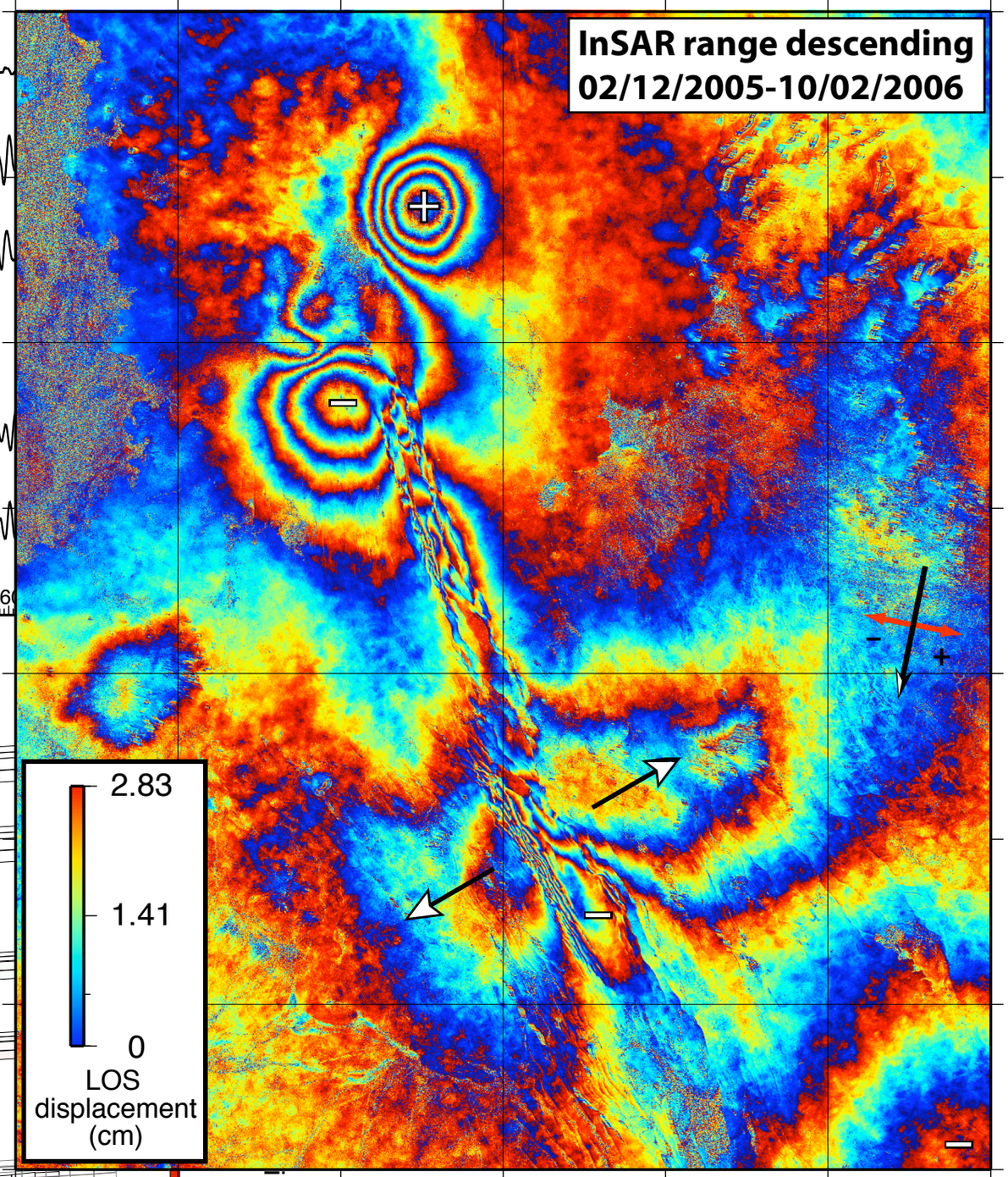
Landers

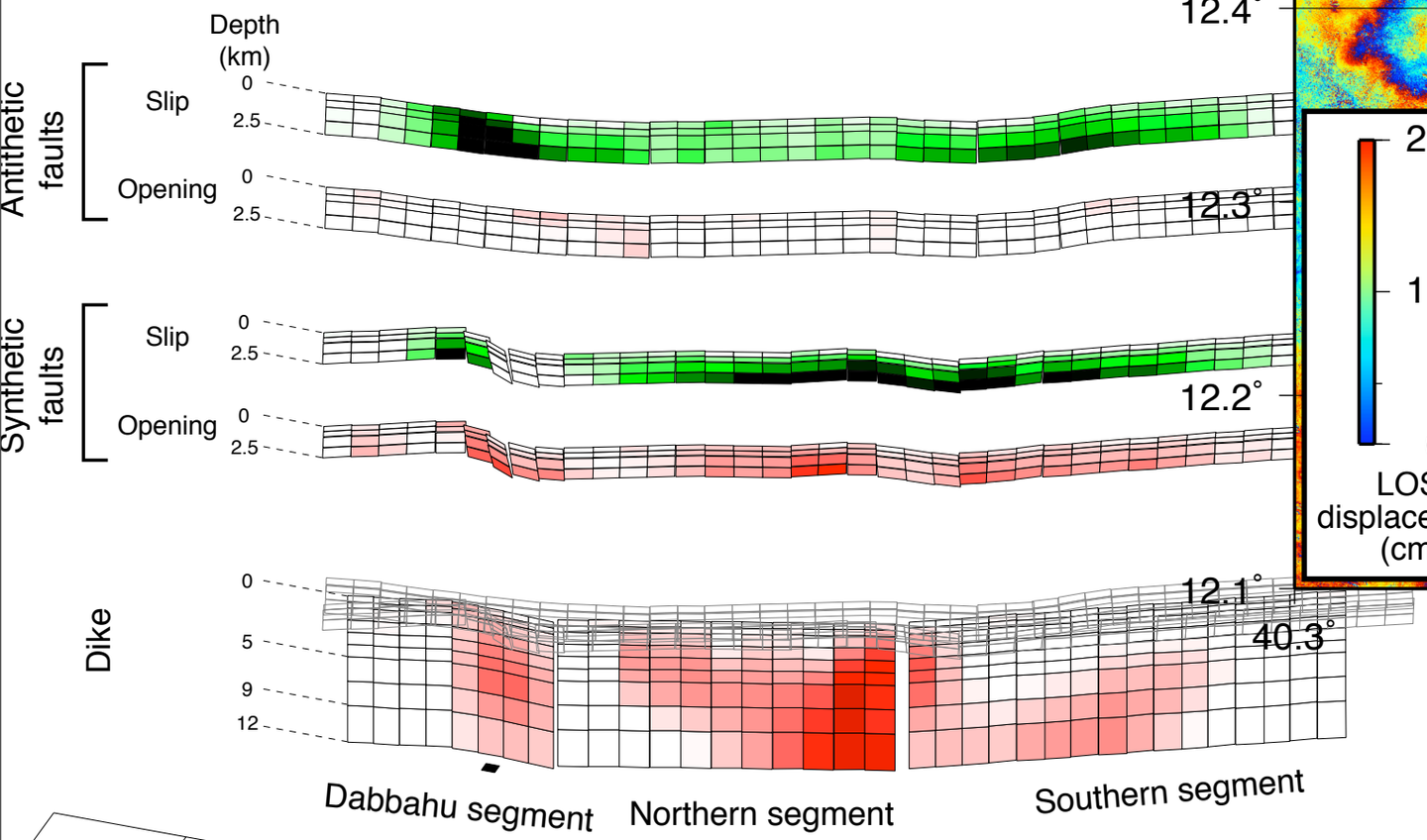
Michel, Van Puymbroeck, Binet

Segmentation

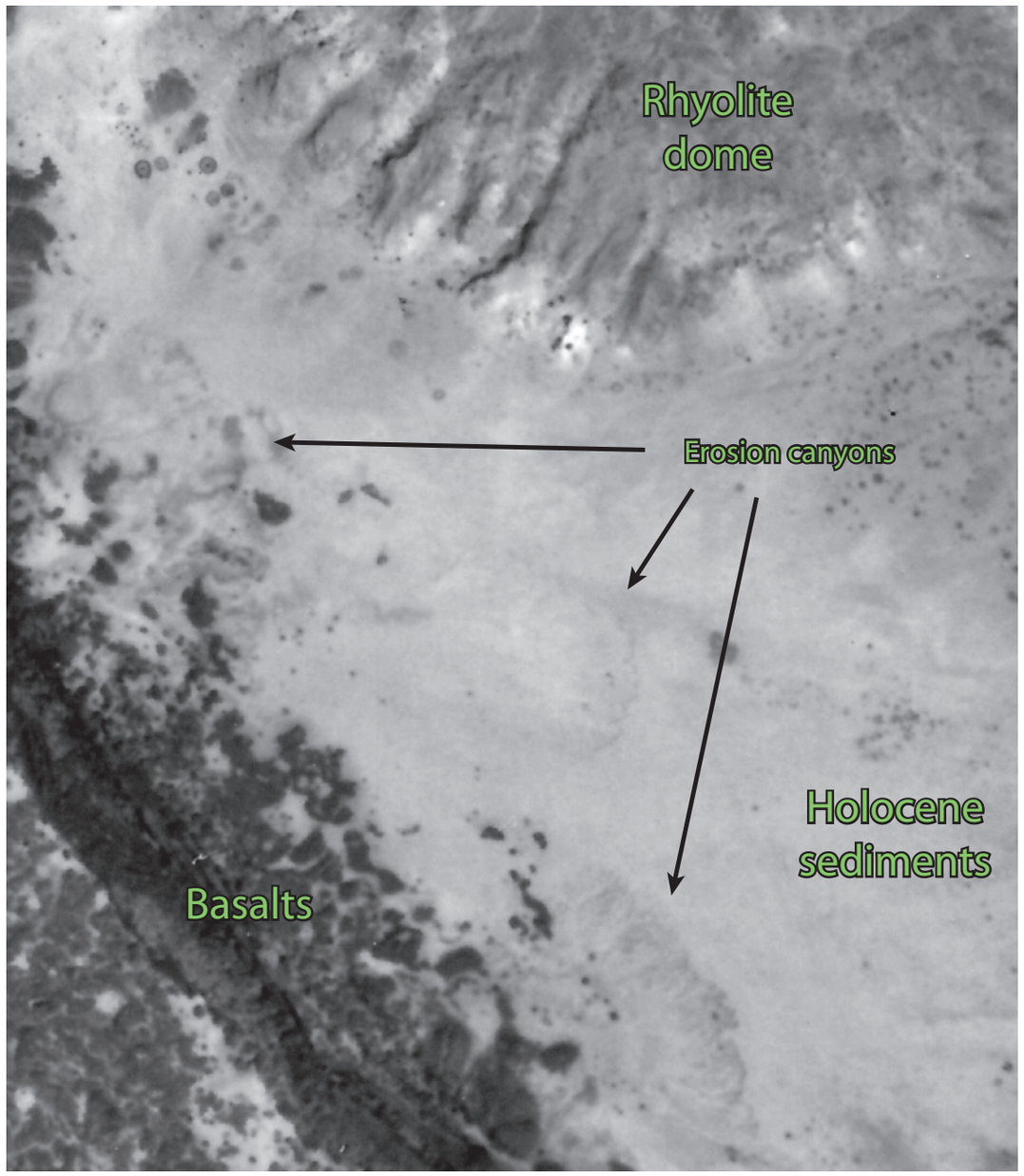




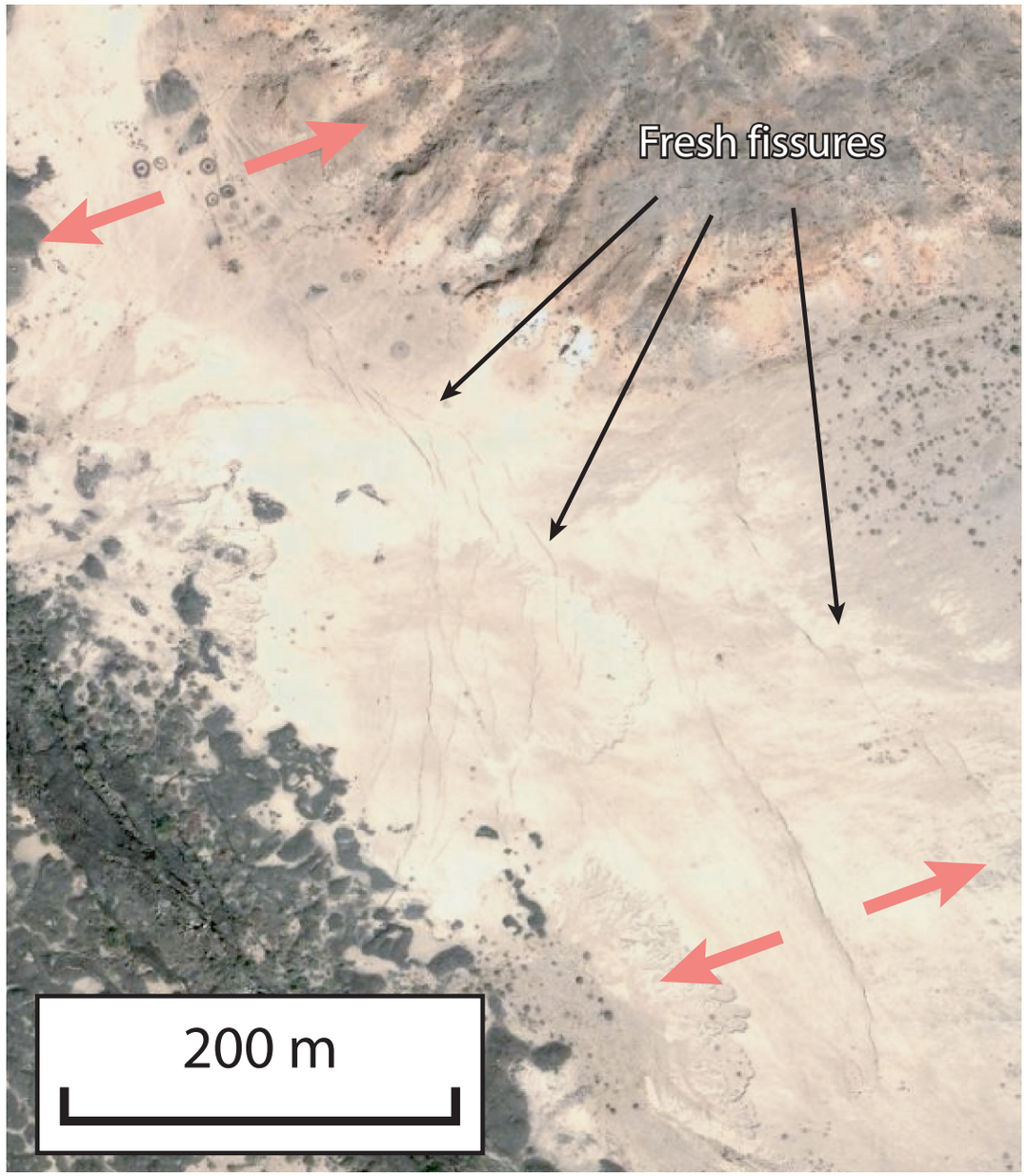




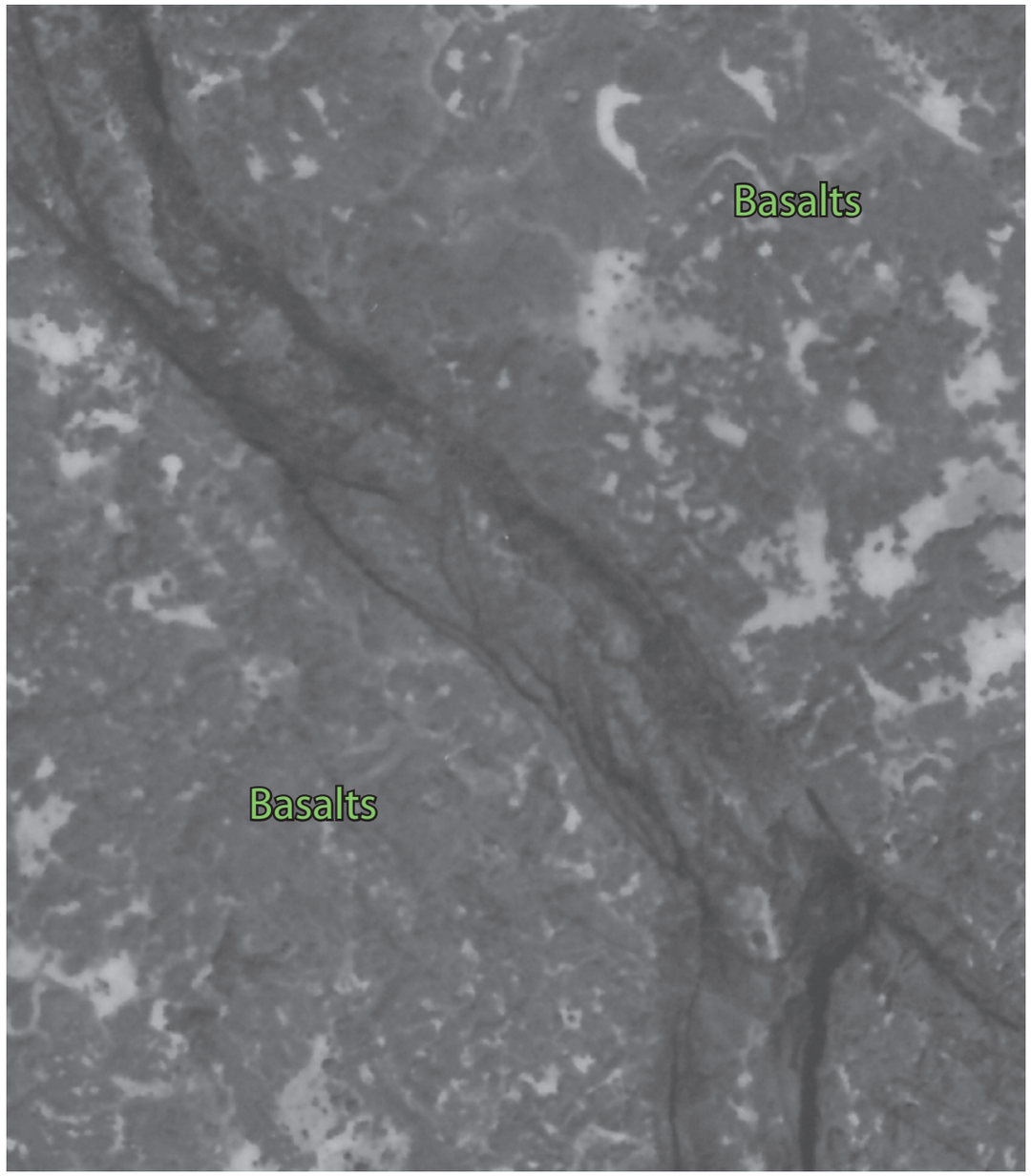
Aerial photography
1994



Quickbird image
2006



Aerial photography
1994



Quickbird image
2006