The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2053-30

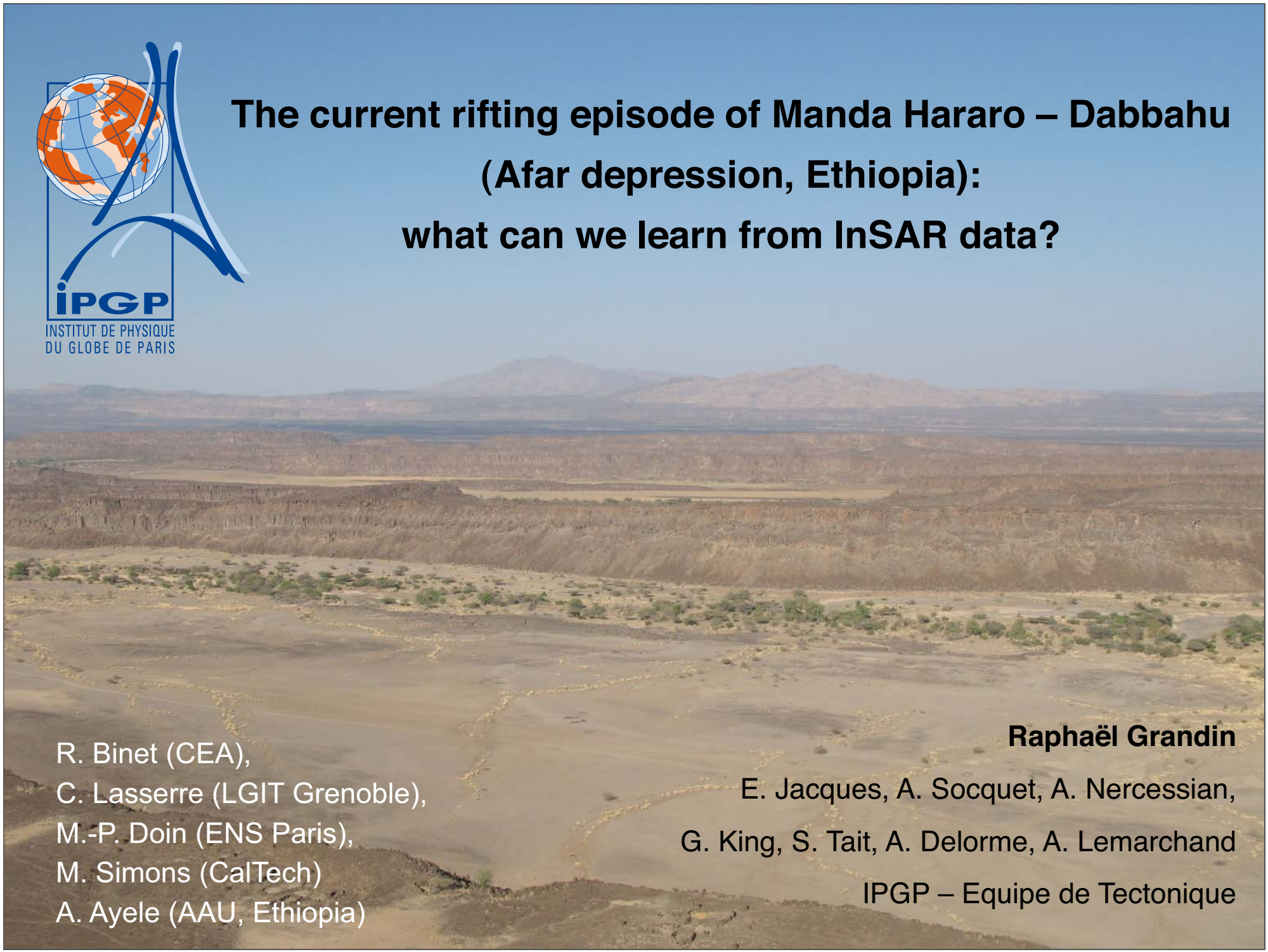
Advanced Workshop on Evaluating, Monitoring and Communicating Volcanic and Seismic Hazards in East Africa

17 - 28 August 2009

The current rifting episode of Manda Hararo-Dabbhu (Afar depression, Ethiopia): what can we learn from InSAR data?

Raphael Grandin
Institut de Physique du Globe de Paris
France

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it



The current rifting episode of Manda Hararo – Dabbahu (Afar depression, Ethiopia): what can we learn from InSAR data?

Raphaël Grandin

E. Jacques, A. Socquet, A. Nercessian,

G. King, S. Tait, A. Delorme, A. Lemarchand

IPGP – Equipe de Tectonique

R. Binet (CEA),

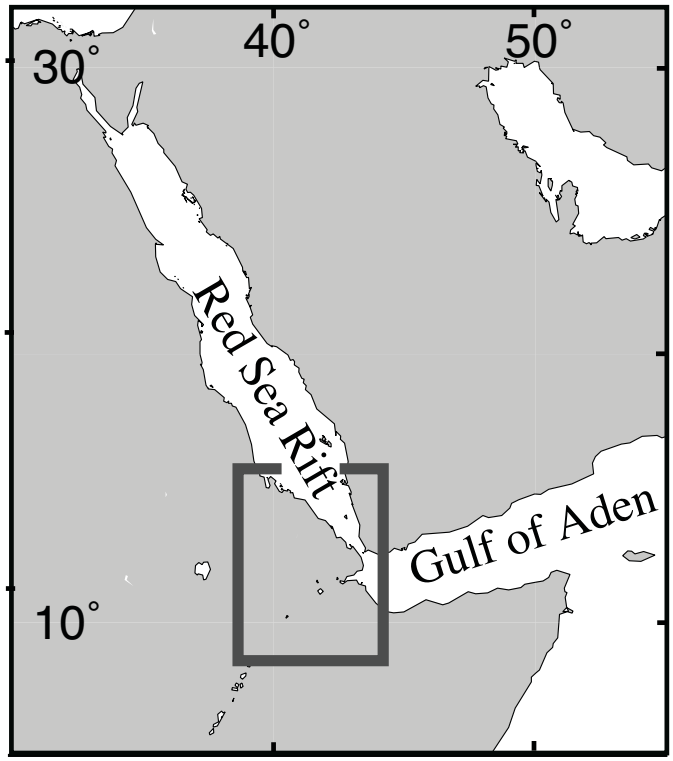
C. Lasserre (LGIT Grenoble),

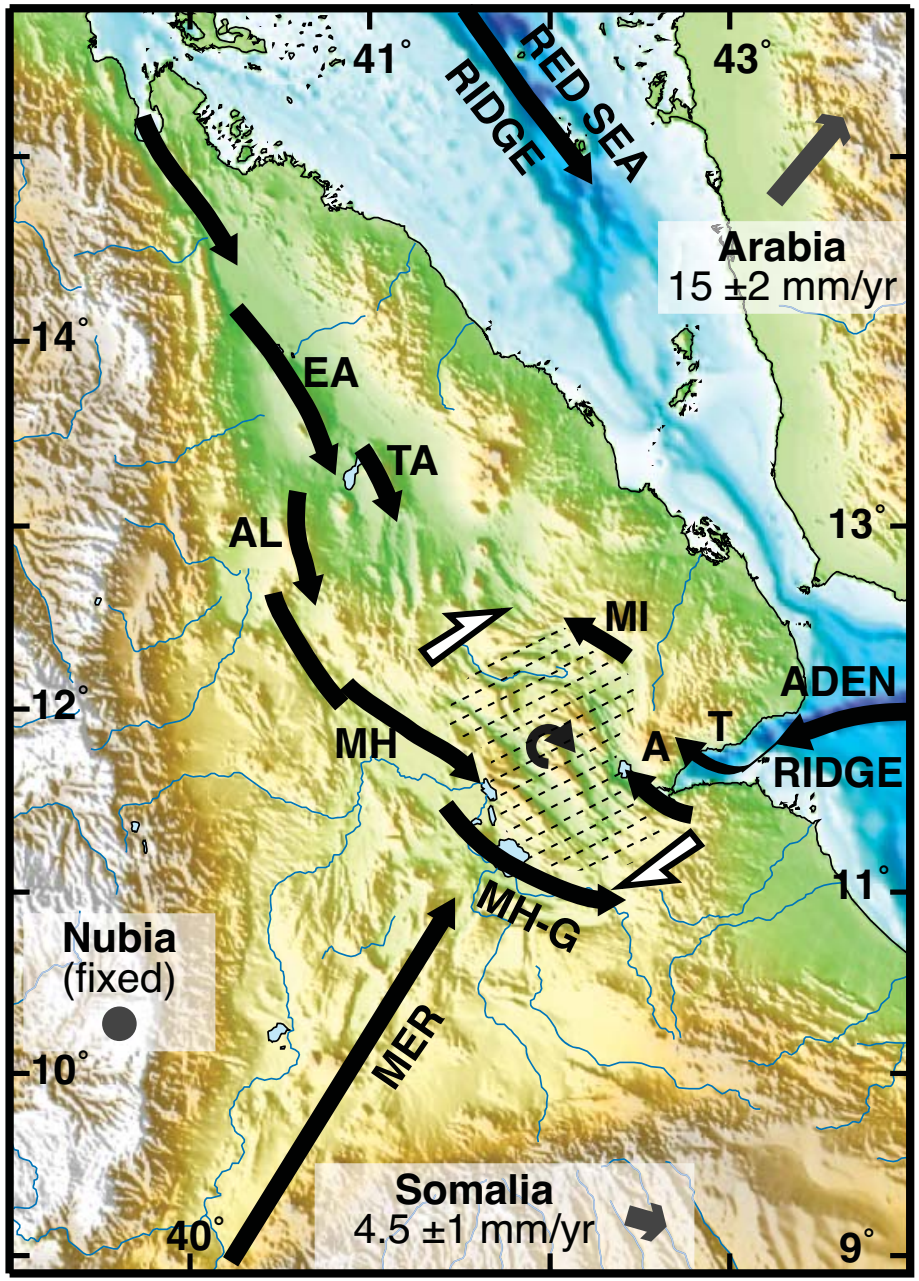
M.-P. Doin (ENS Paris),

M. Simons (CalTech)

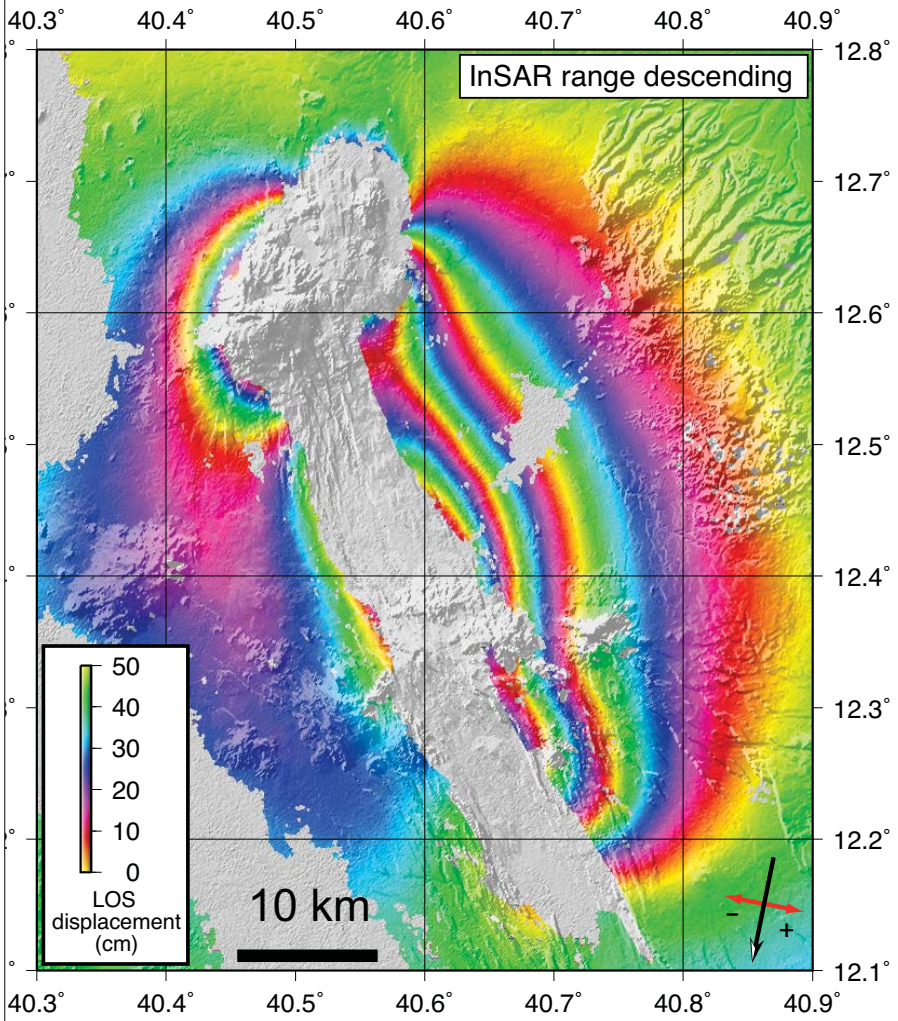
A. Ayele (AAU, Ethiopia)

The Afar depression: an hotspot-influenced triple junction





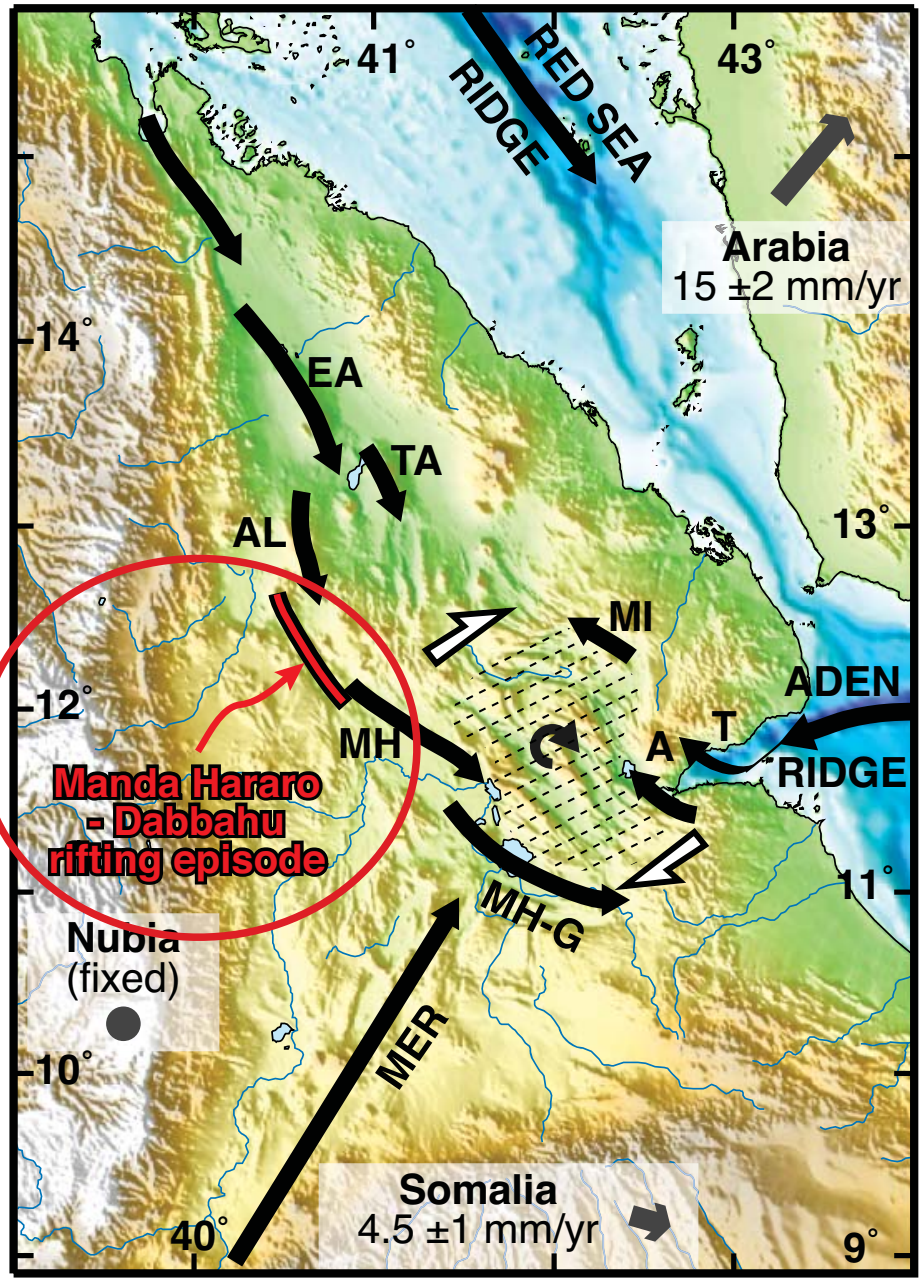
The Afar depression: an hotspot-influenced triple junction

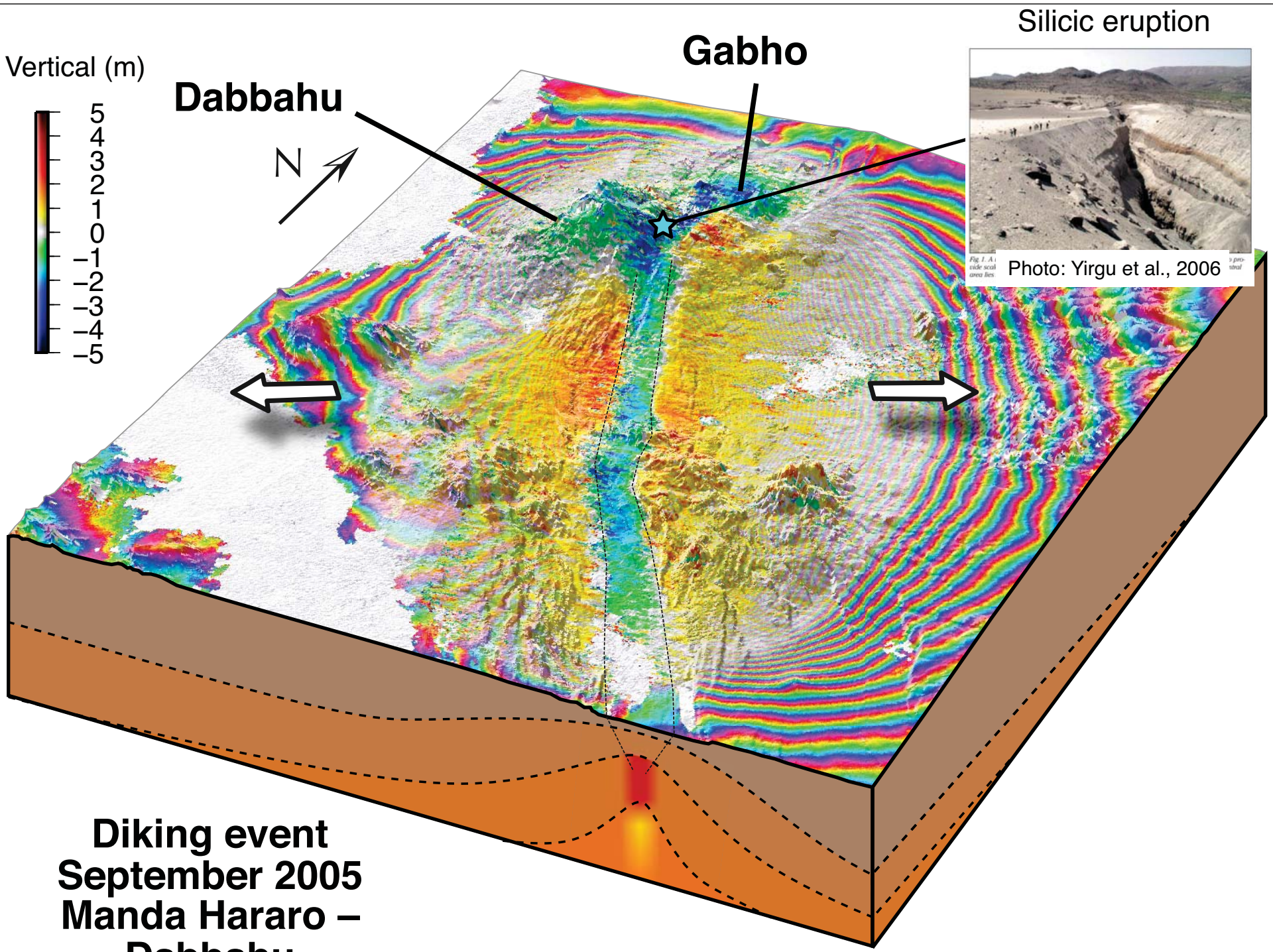


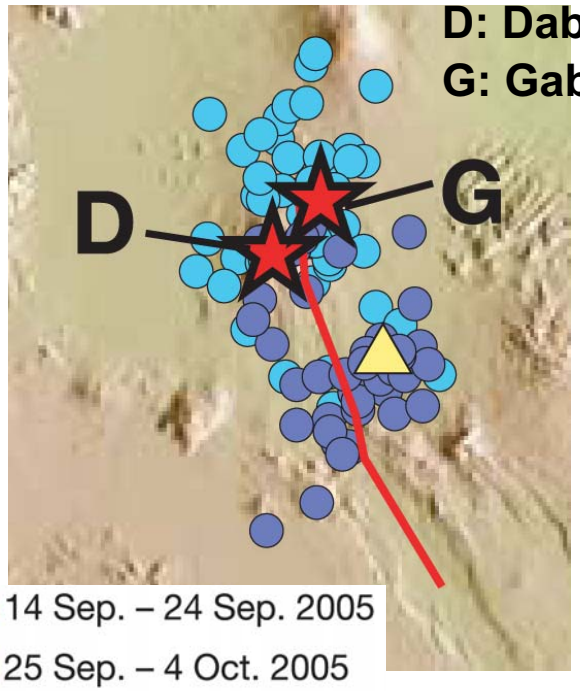
September 2005:

initiation of a rifting episode

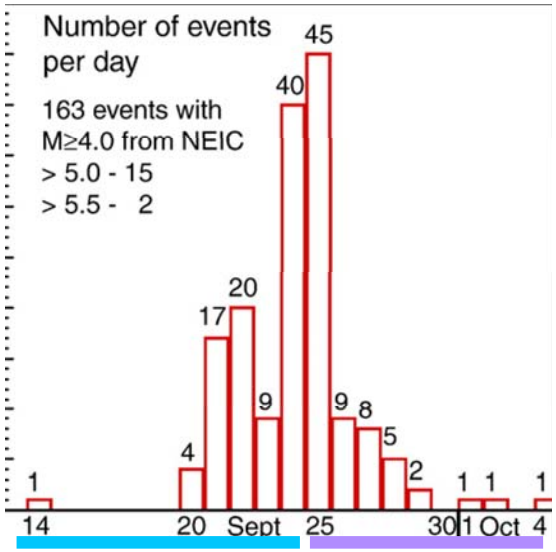
at Manda Hararo – Dabbahu



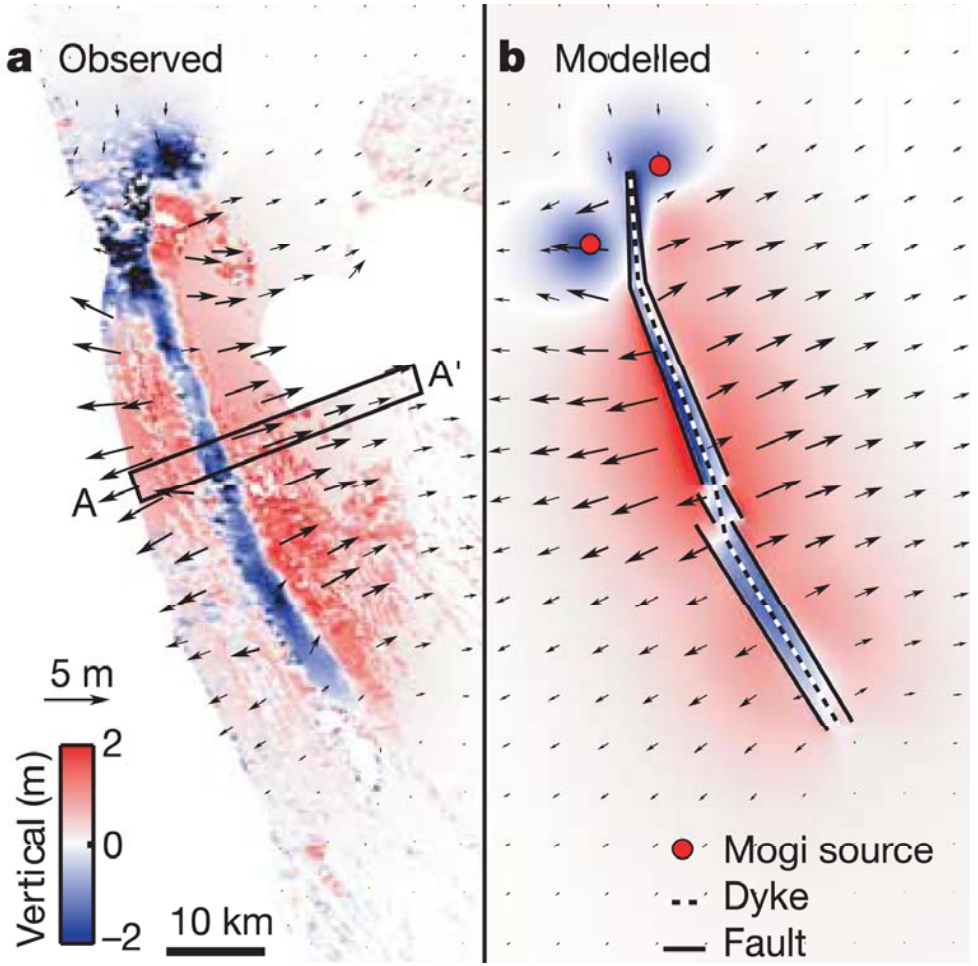

Vertical (m)
5
4
3
2
1
0
−1
−2
−3
−4
−5
Dabbahu
Gabho
N
Silicic eruption
Photo: Yirgu et al., 2006
Diking event
September 2005
Manda Hararo –
Dabbahu



[Wright et al., Nature, 2006]



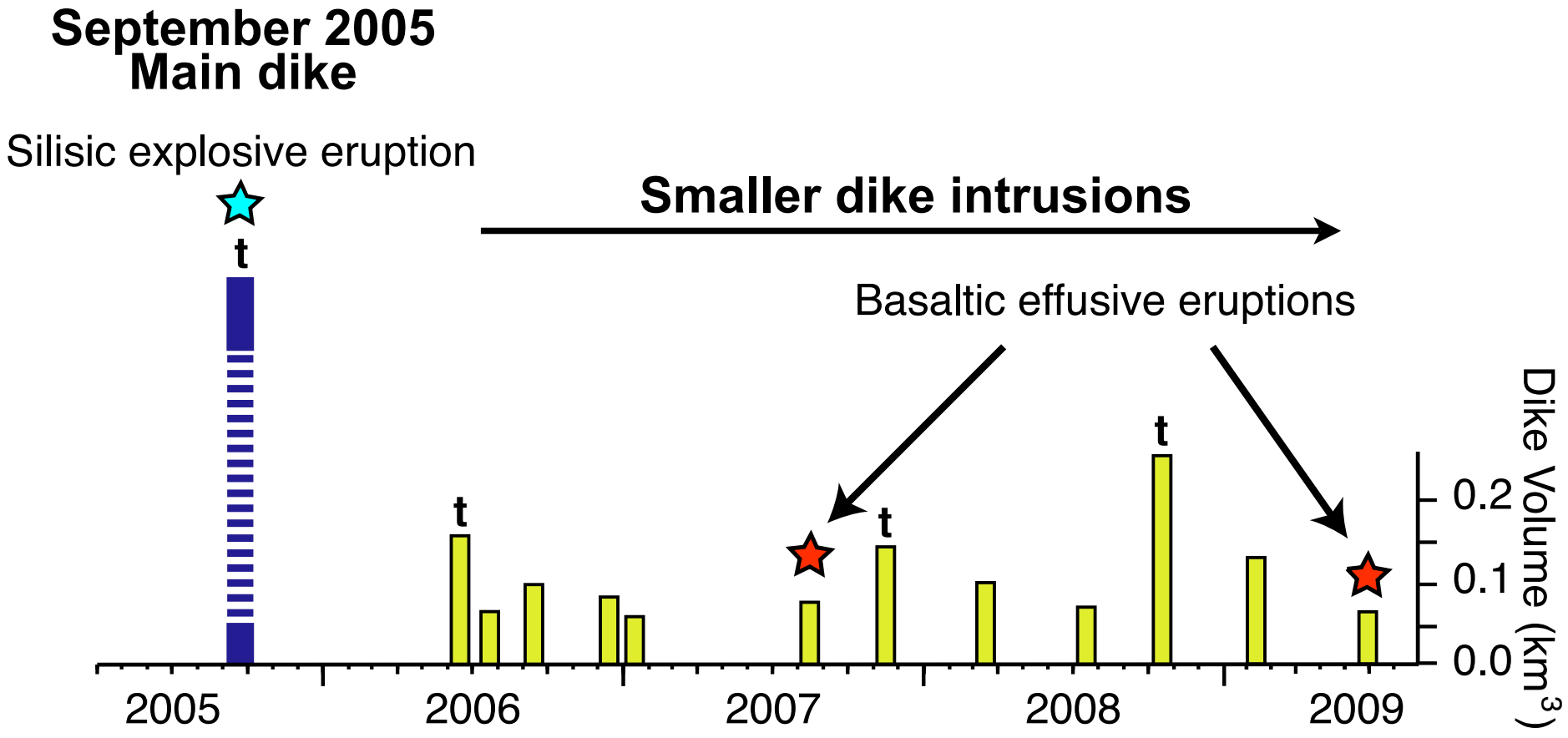
[Ayele et al., EPSL, 2007]



[Wright et al., Nature, 2006]

Lateral dike intrusion originating from magma chamber at the Northern tip of the segment??

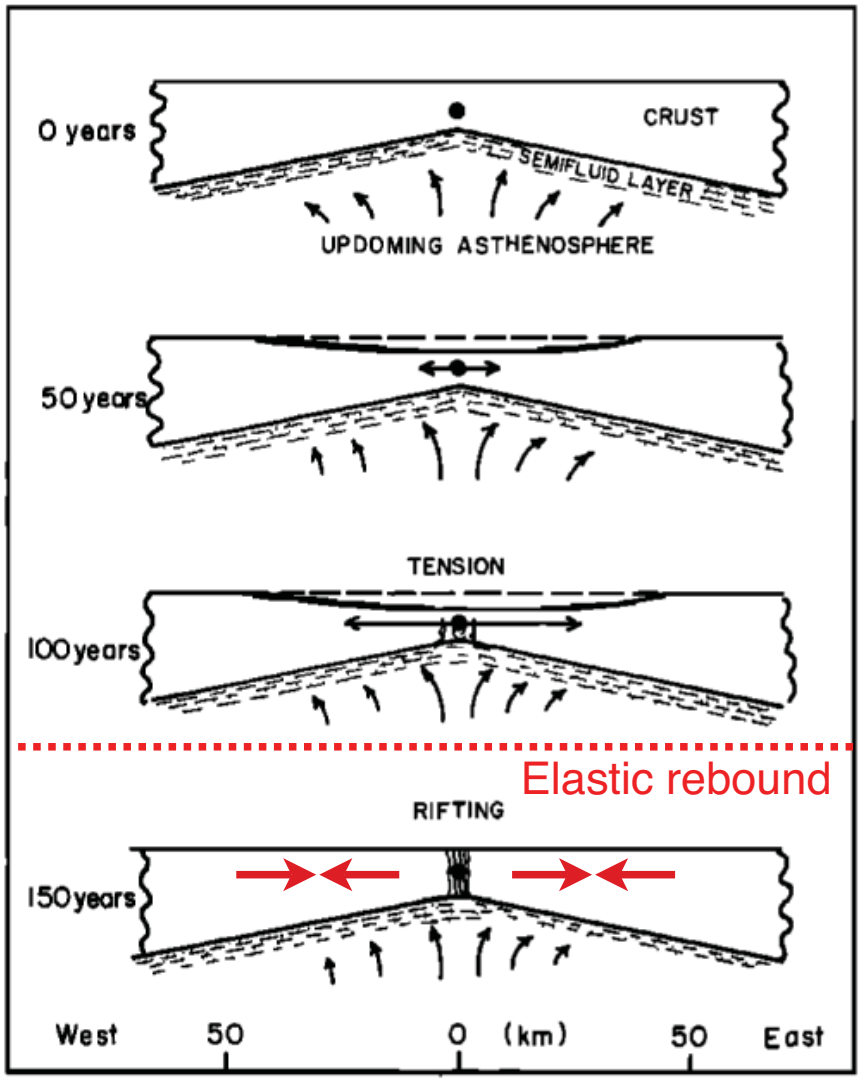
Repeated intrusions in Manda Hararo – Dabbahu rift in 2005 - 2006 - 2007 - 2008 - 2009



12 dikes since 2005

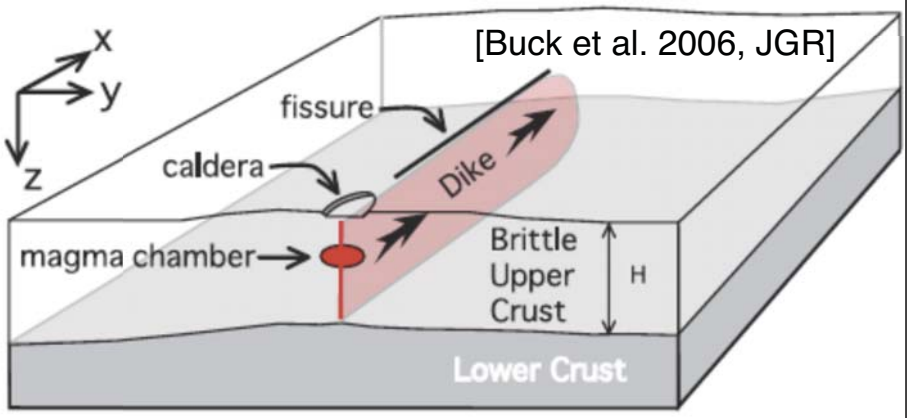
Only 3 eruptions...

The magmato-tectonic cycle



[Bjornsson 1985, JGR]

Fig. 8. A model of episodic crustal rifting in NE Iceland. Tension is gradually built up in the axial rift zone by ridge push force and is released every few 100 years in a rifting episode. Arrows proportional to deviatoric stress in the crust.



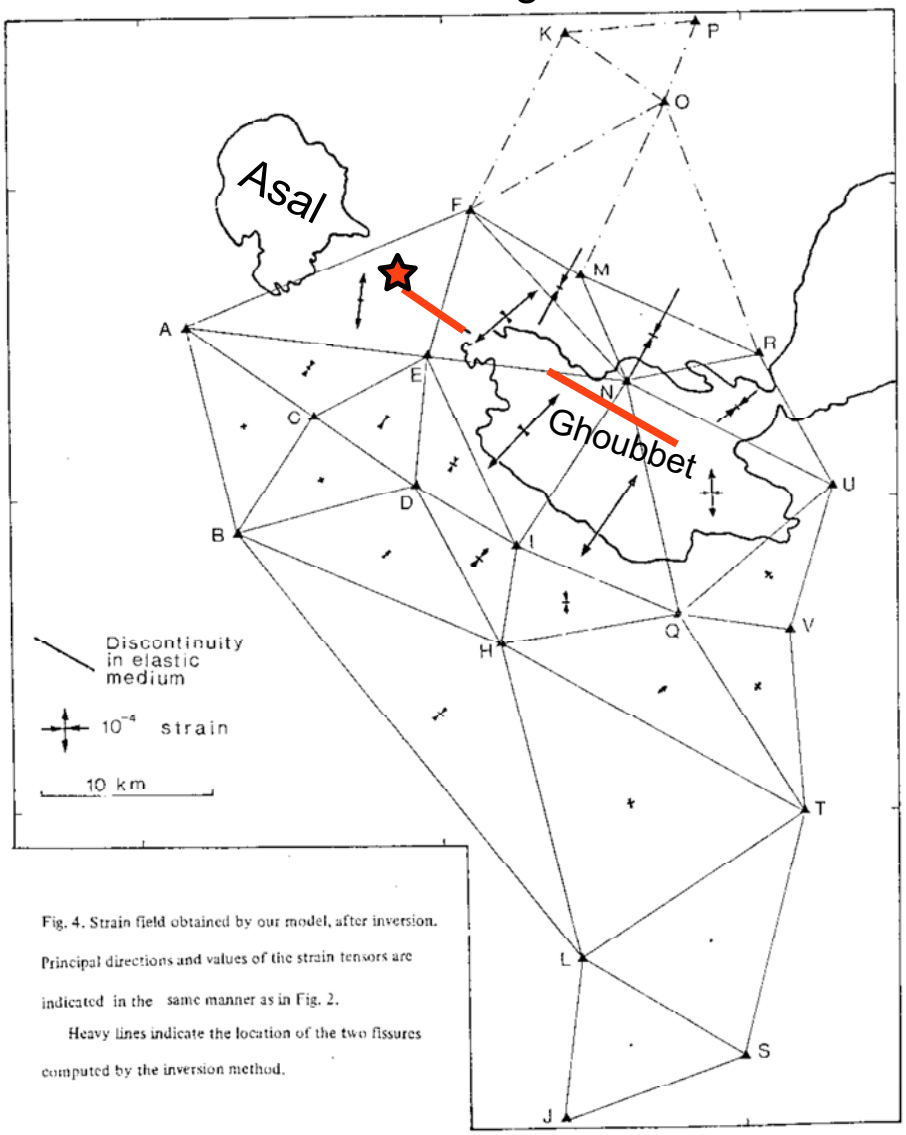
[Buck et al. 2006, JGR]

Extension is relieved during
a "**rifting episode**"
Recurrence time ~ 100 yrs
Duration ~ several months/years

A rifting episode is made
of a series of
"**diking events**"
Recurrence time ~ several months
Duration ~ several hours/days

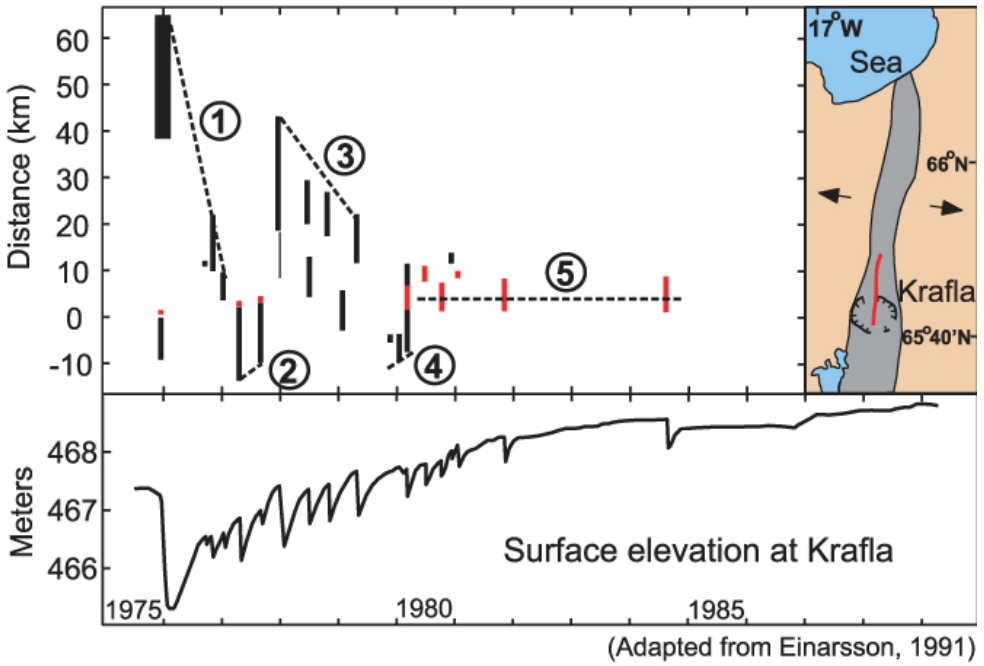
Known examples of previous rifting episodes in similar magmato-tectonic environments

1978 Asal Rifting Crisis



[Tarantola et al., EPSL, 1979]

1975-1984 Krafla Rifting Episode



[Einarsson et al., 1991]

Asal (Djibouti, Afar) 1978
Volume ~ 0.2 km3
Duration: several months?

Krafla (Iceland) 1975
Volume ~ 0.6 km3 (minimum)
Durée: 9 years

Main Questions

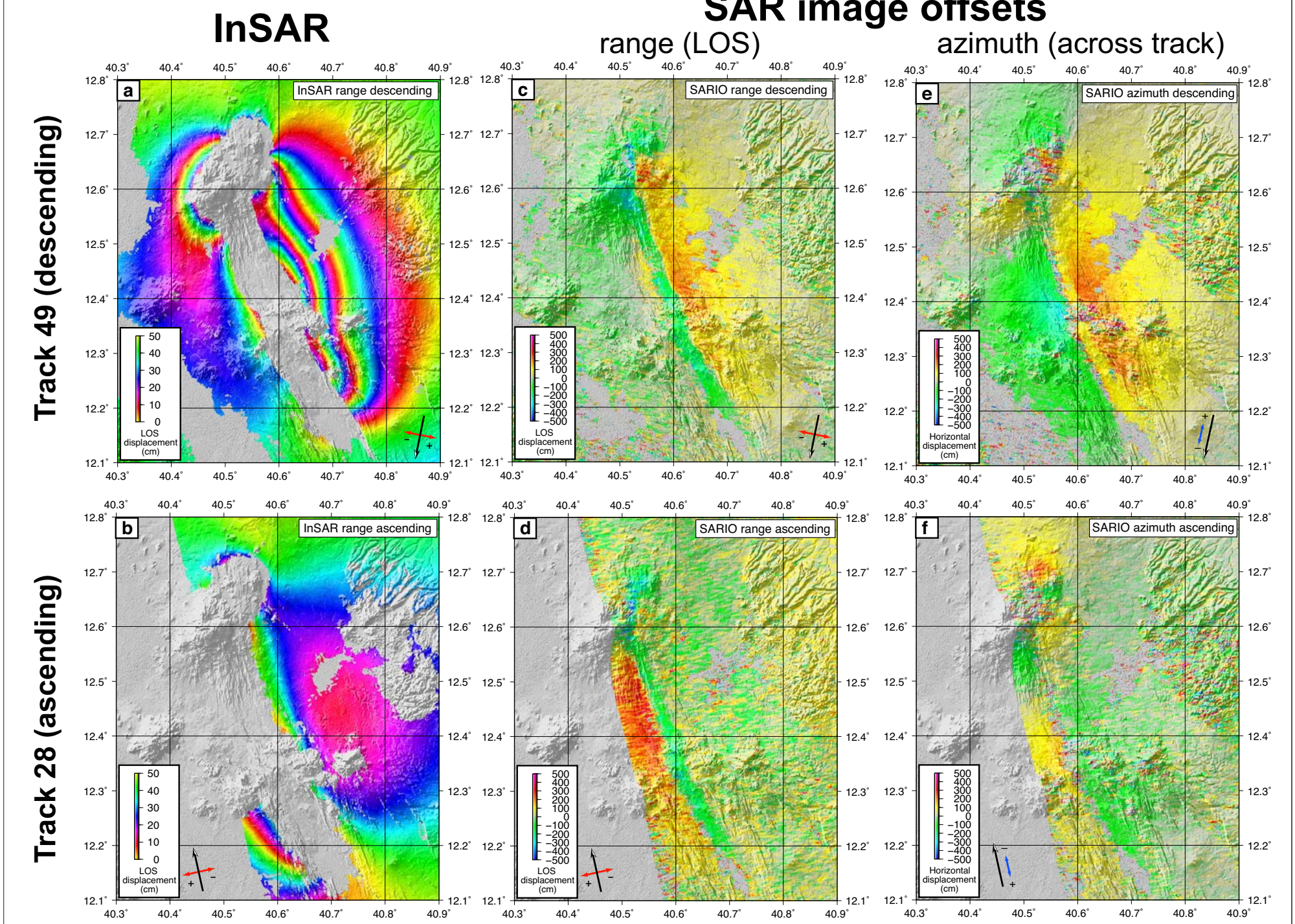
* What was the amount of opening in September 2005 during the main rifting event?
* Where does the magma come from?
* Why several dikes, not just one?
* What does it tell us about rifting processes at Mid-Oceanic Ridges?

Outline

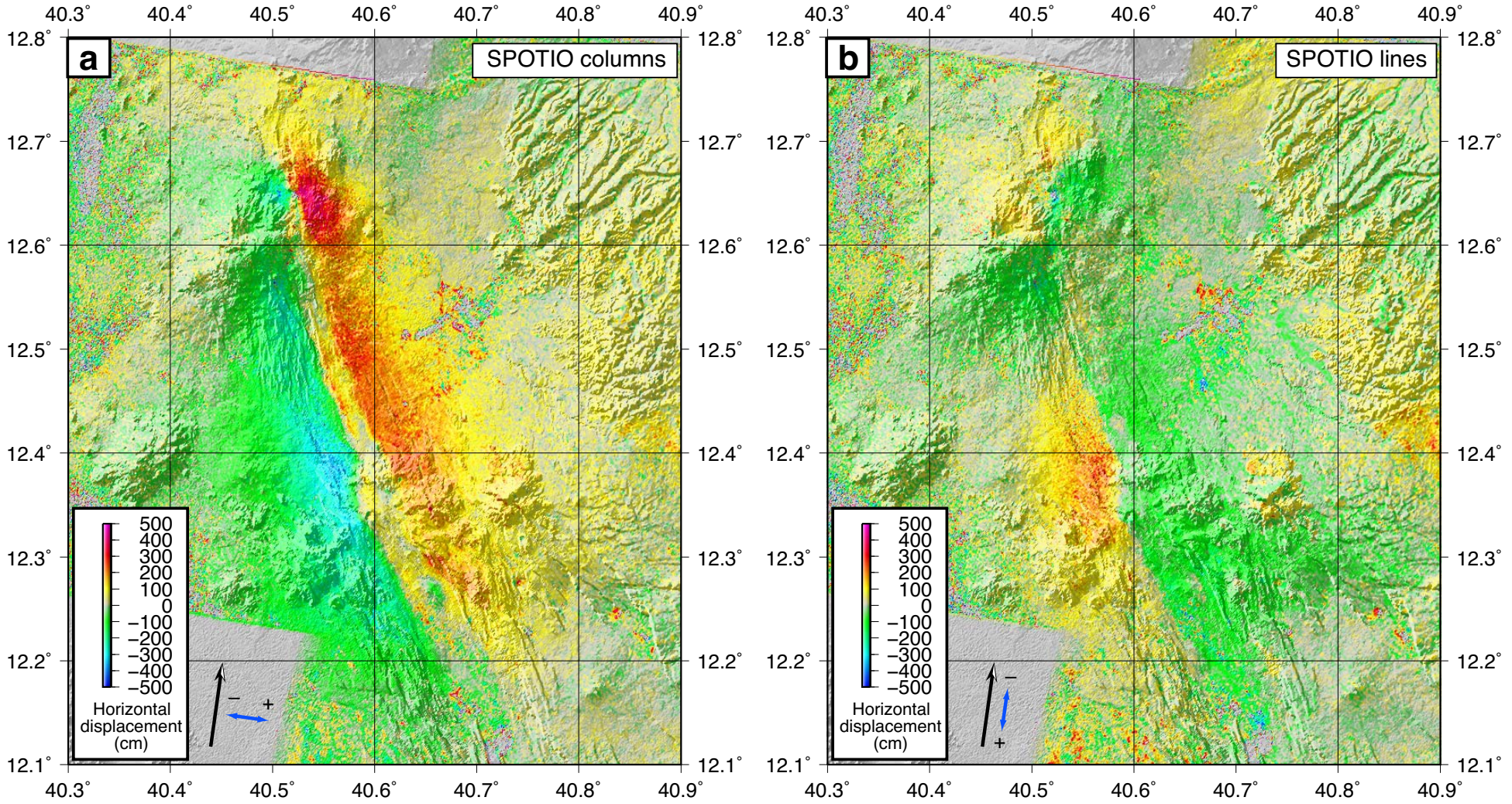
1) The main dike seen by remote sensing
2) Subsequent intrusions of 2006-2009
3) Inter-dike deformation time-series
4) Back to the main rifting event...
5) Conclusions

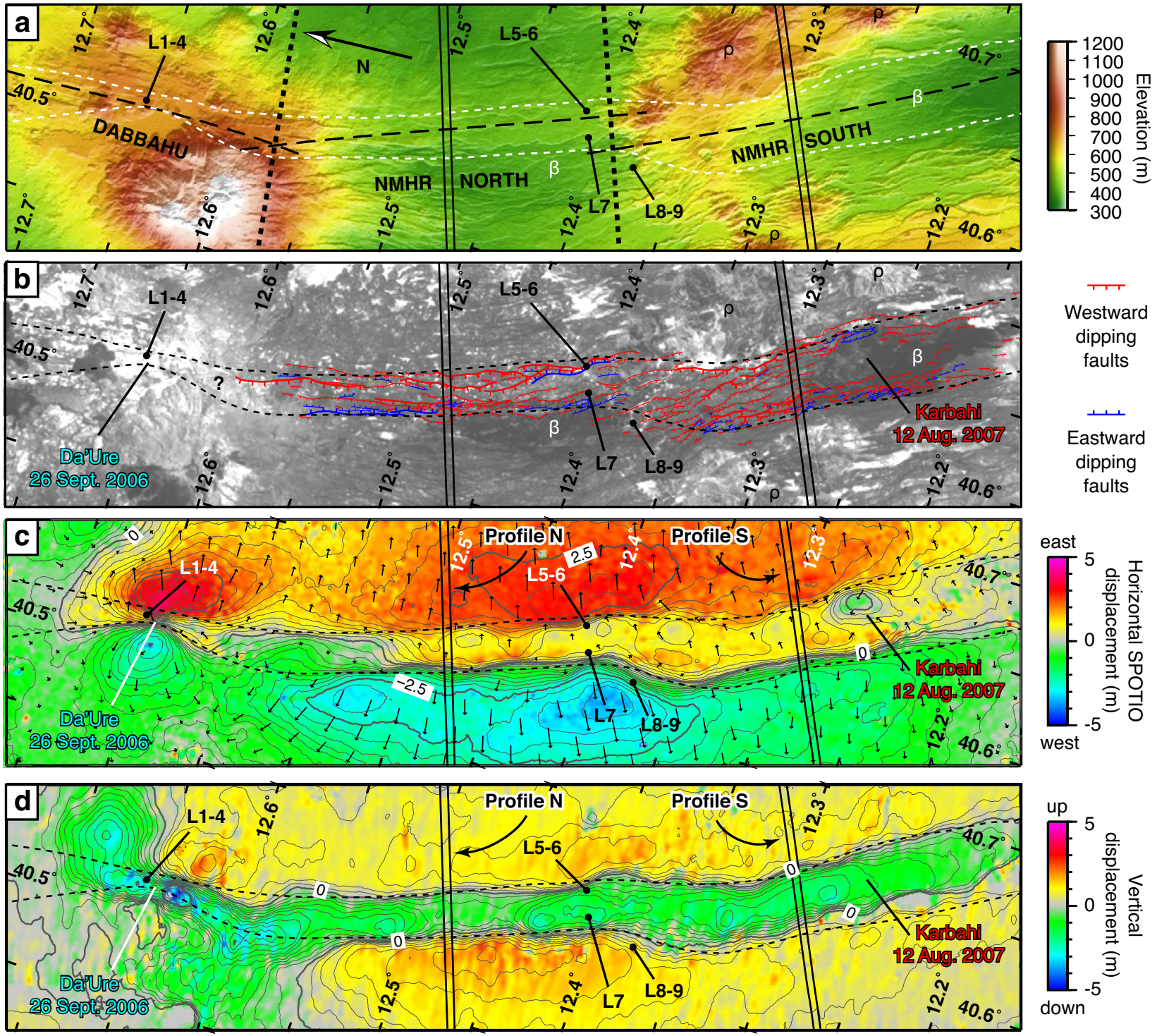
1

September 2005 rifting event

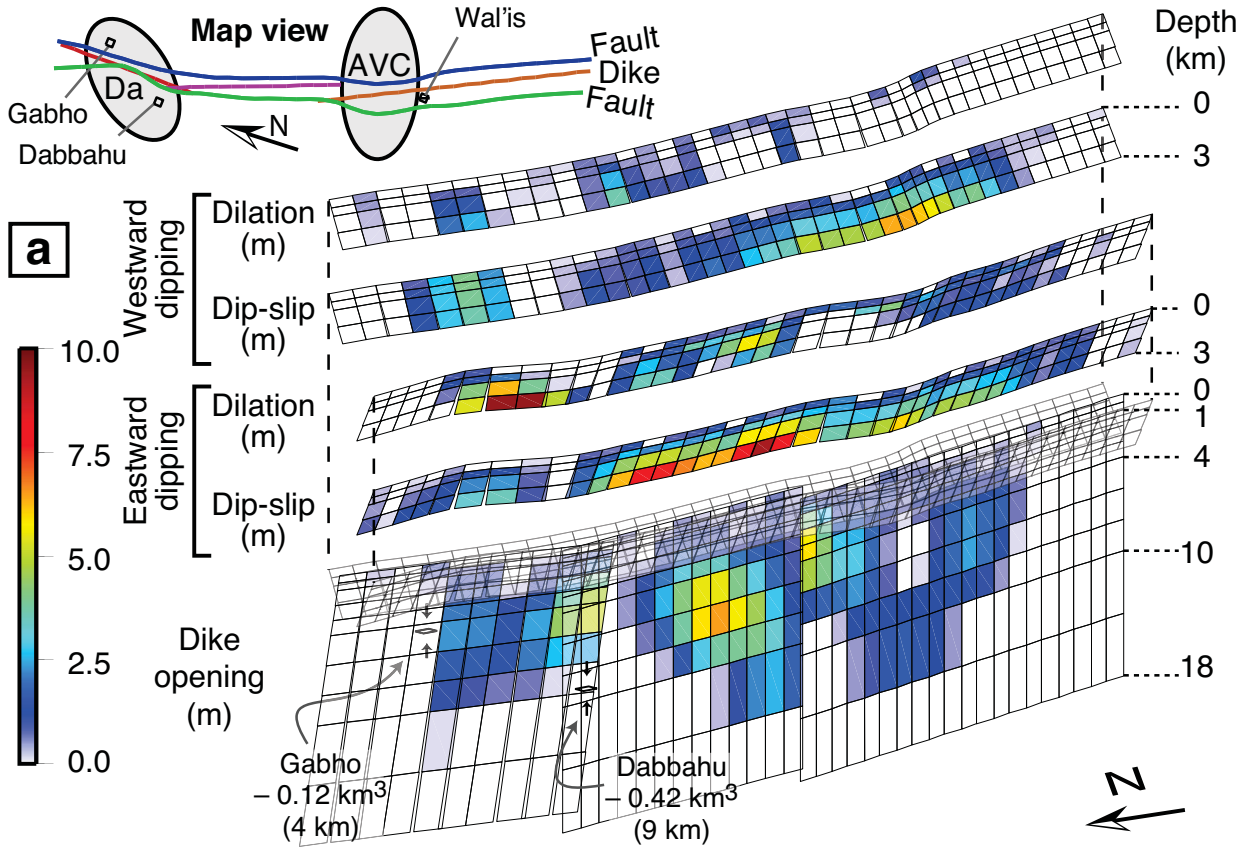

InSAR
SAR image offsets
range (LOS)
azimuth (across track)
Track 49 (descending)
Track 28 (ascending)
a
InSAR range descending
b
InSAR range ascending
c
SARIO range descending
d
SARIO range ascending
e
SARIO azimuth descending
f
SARIO azimuth ascending
LOS displacement (cm)
Horizontal displacement (cm)
40.3° 40.4° 40.5° 40.6° 40.7° 40.8° 40.9°
12.8° 12.7° 12.6° 12.5° 12.4° 12.3° 12.2° 12.1°

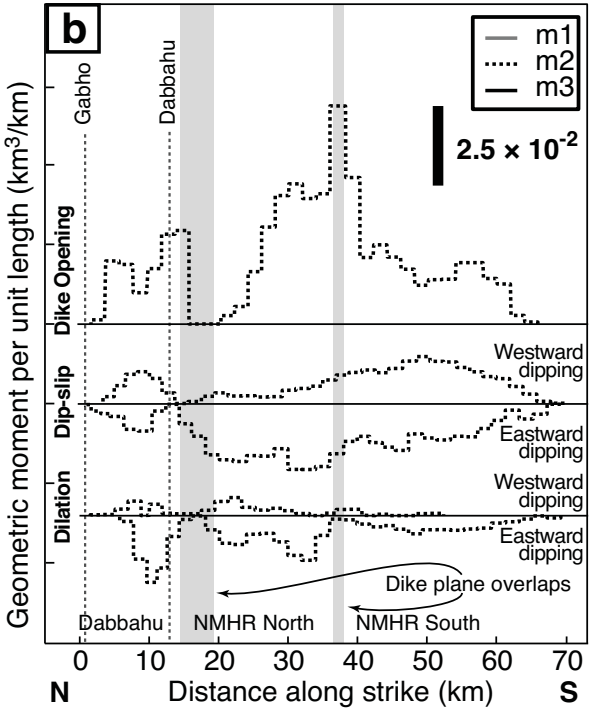
Sub-pixel correlation of SPOT 10m-resolution images




a
b
c
d
L1-4
L5-6
L7
L8-9
N
DABBAHU
NMHR
NORTH
NMHR
SOUTH
β
ρ
12.7°
12.6°
12.5°
12.4°
12.3°
12.2°
40.5°
40.6°
40.7°
Da'Ure
26 Sept. 2006
Karbahi
12 Aug. 2007
Profile N
Profile S
2.5
-2.5
0
1200
1100
1000
900
800
700
600
500
400
300
Elevation (m)
Westward dipping faults
Eastward dipping faults
east
west
5
0
-5
Horizontal SPOTIO displacement (m)
up
down
Vertical displacement (m)

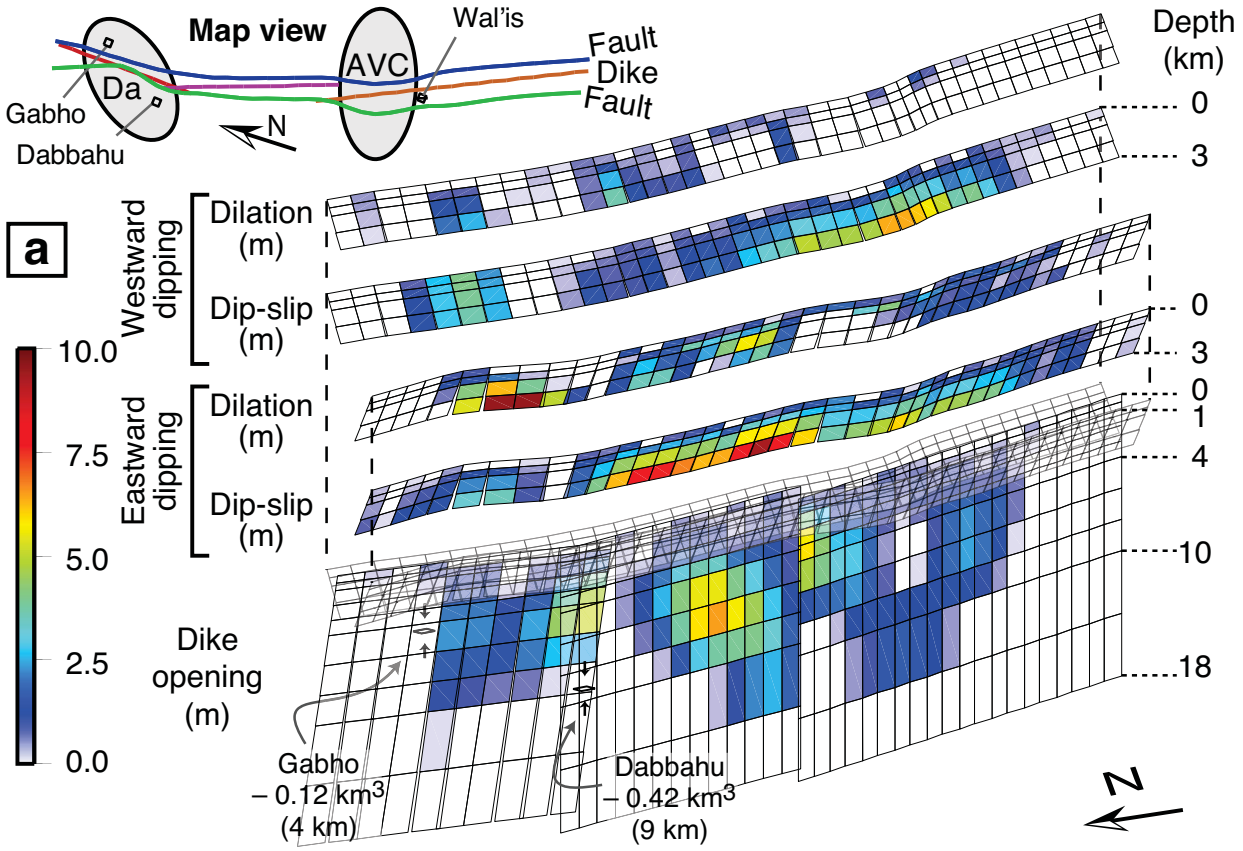
Inversion results

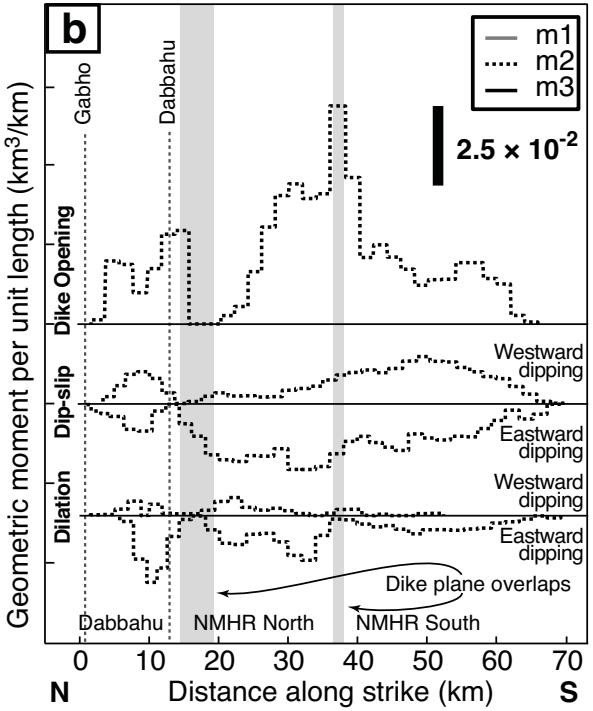




Dike volume = 1.9 km^3
Height = 10-12 km
Average opening = 5m
Peak opening at 7 km depth

Inversion results



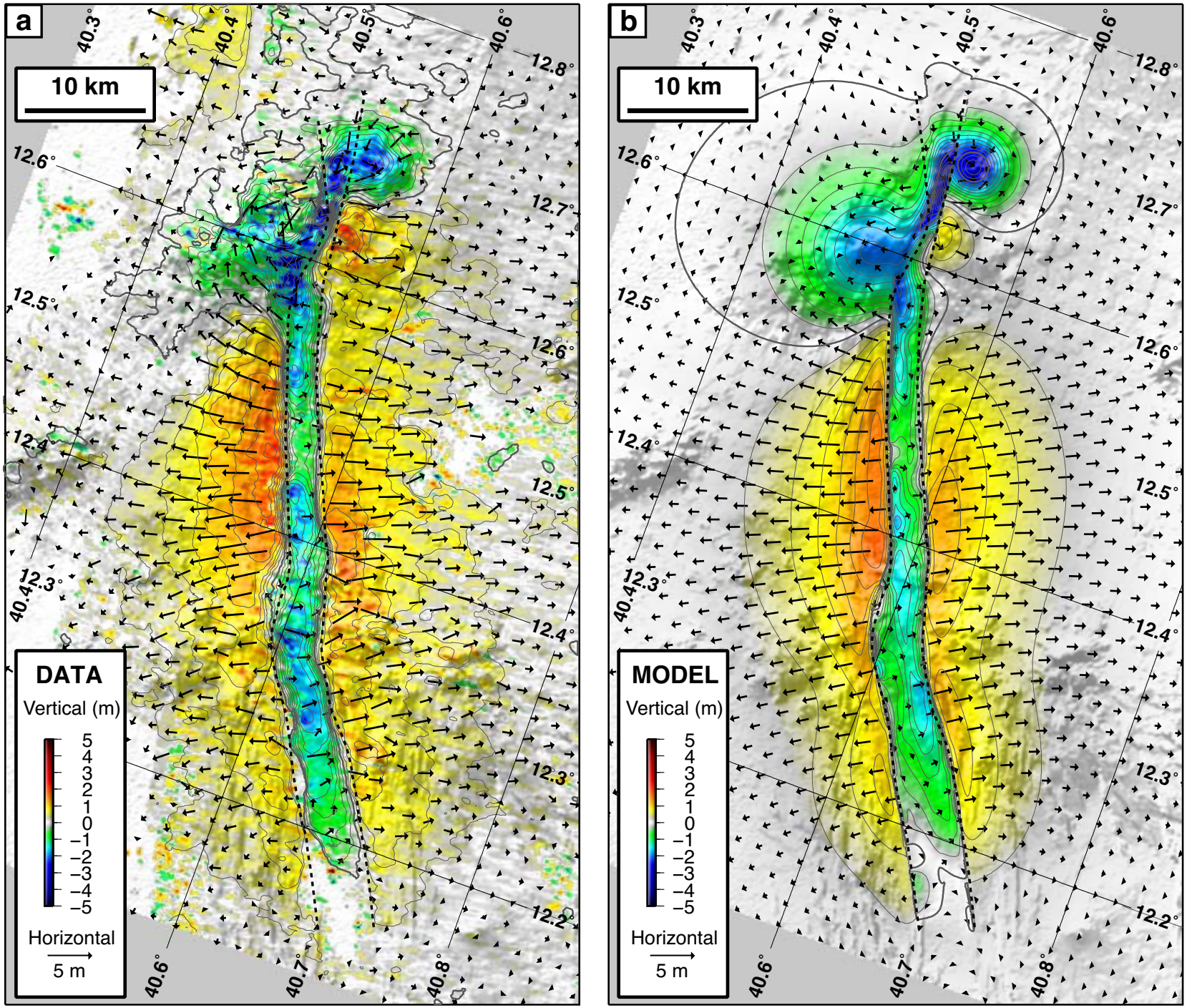


Dike volume = 1.9 km^3
Height = 10-12 km
Average opening = 5m
Peak opening at 7 km depth

The dike is made of 3 segments

Significant dilation occurs at shallow depth

Horizontal deformation is asymmetric


a
10 km
DATA
Vertical (m)
5
4
3
2
1
0
−1
−2
−3
−4
−5
Horizontal
5 m
b
10 km
MODEL
Vertical (m)
5
4
3
2
1
0
−1
−2
−3
−4
−5
Horizontal
5 m

Problems raised by the September 2005 dike

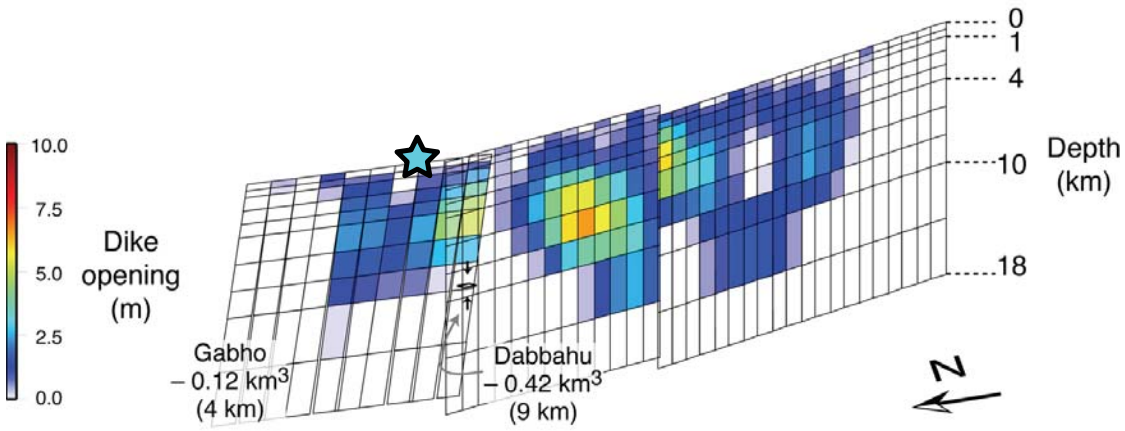
From geodetic inversions:

opening ~ 3 - 5 m

length ~ 50 - 65 km

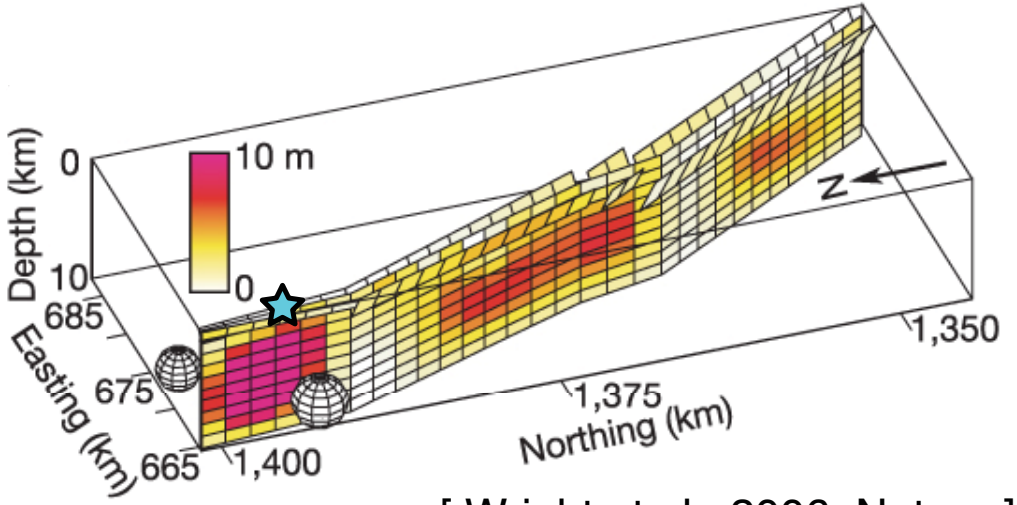
height ~ 10 km

➡ volume ~ 1.0 - 2.5 km3



... but only ~20% comes from magma chambers at Dabbahu and Gabho...

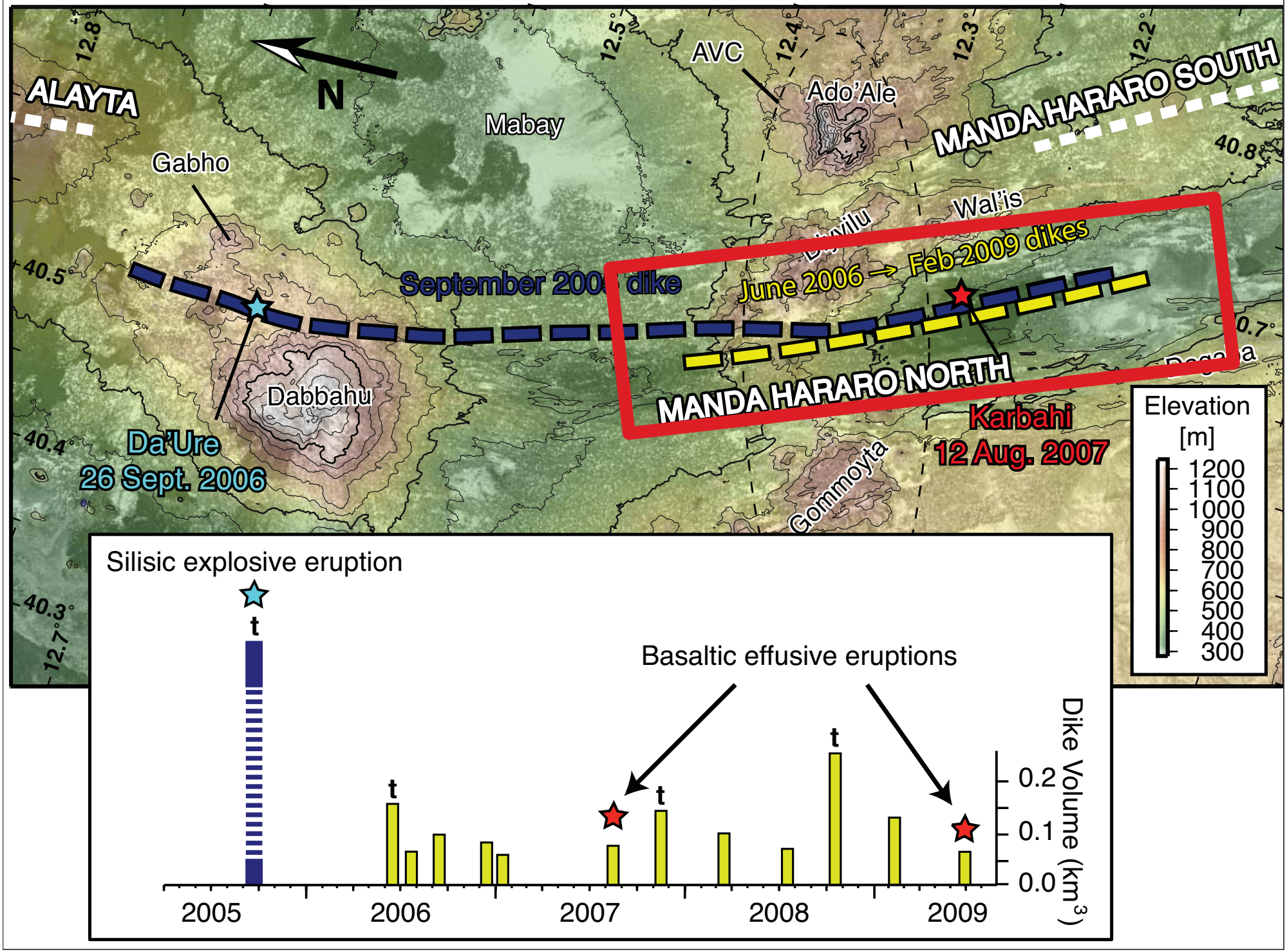
... magma pathway along the dike is not clearly imaged in the opening distributions...

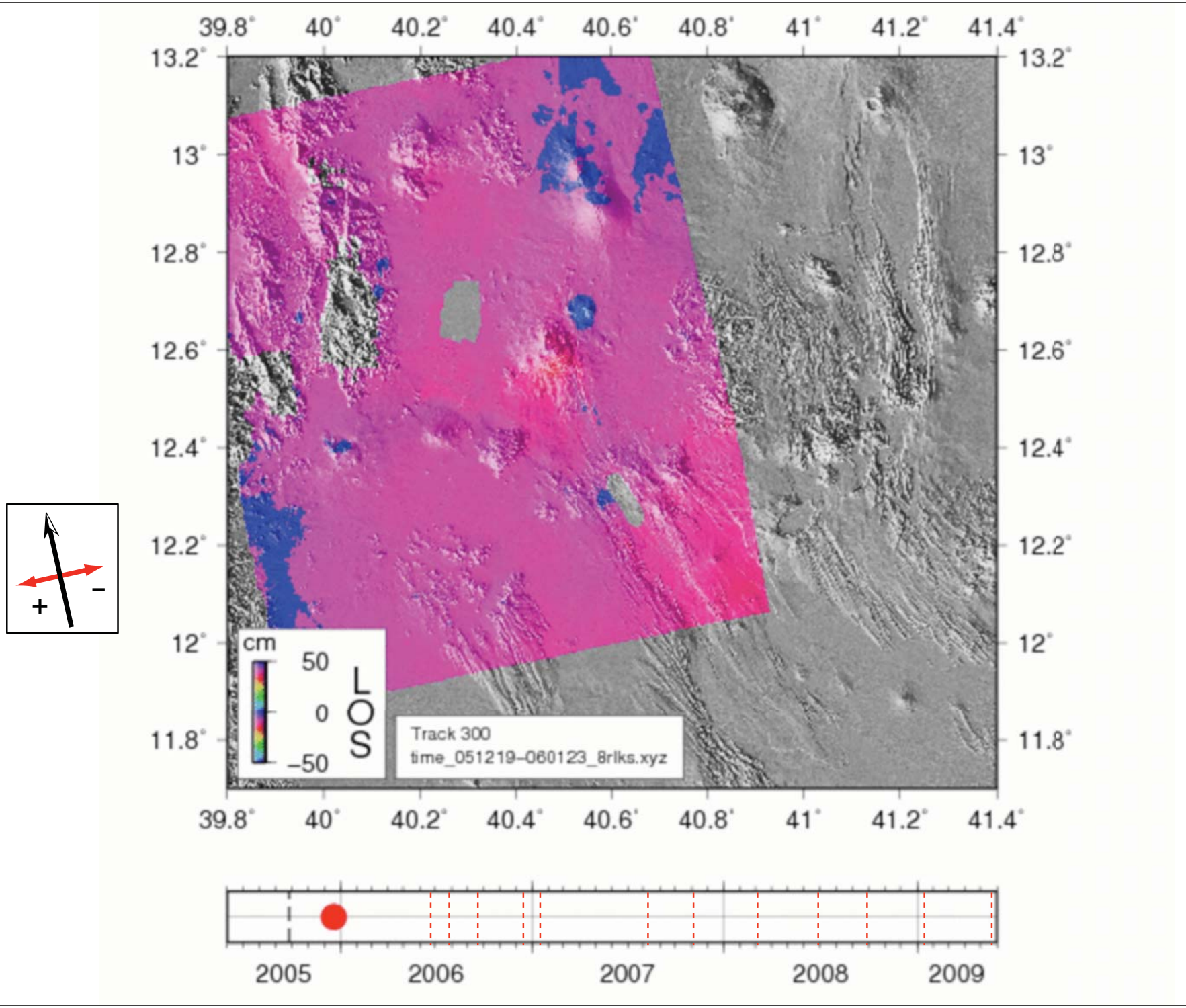


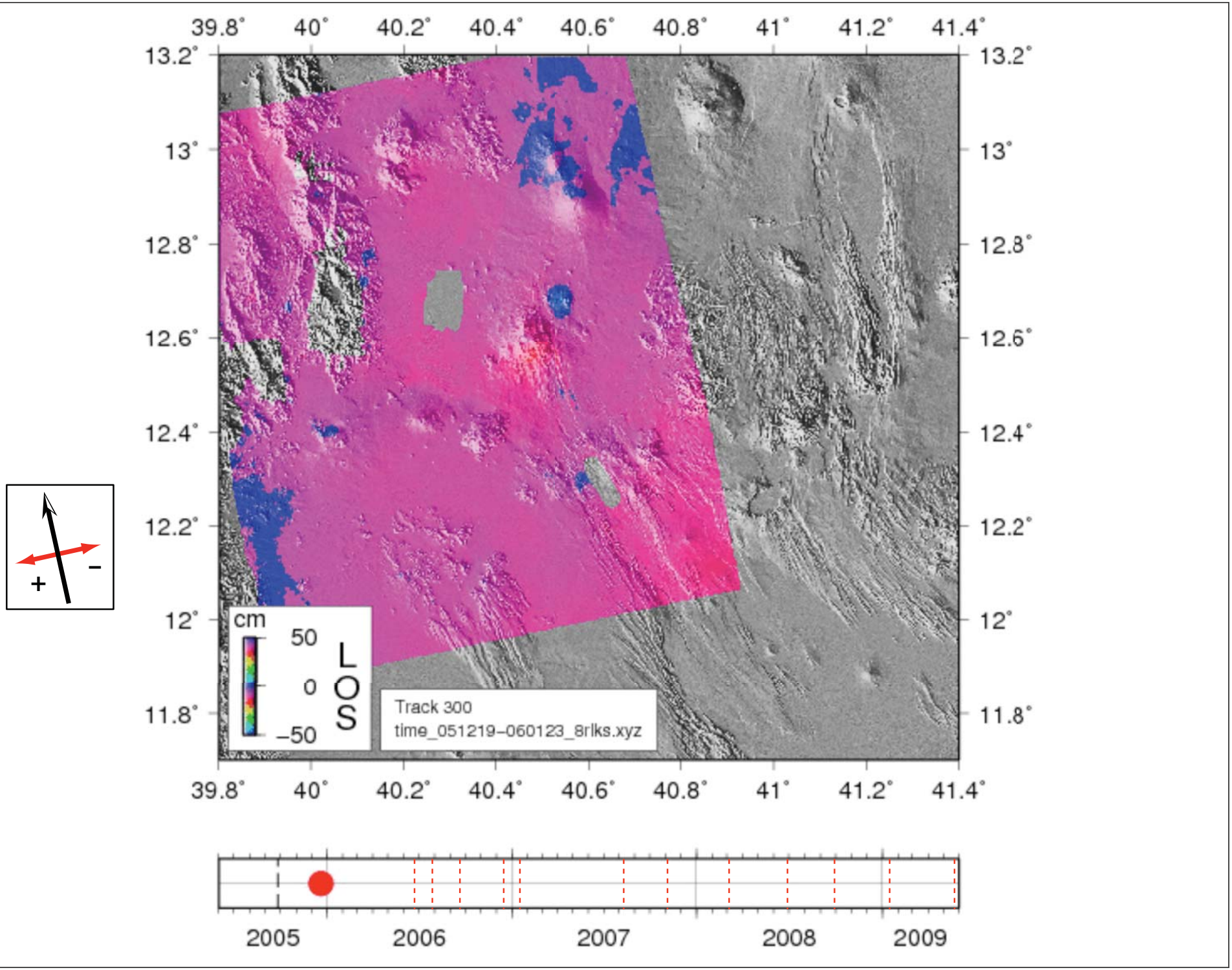
[Wright et al., 2006, Nature]

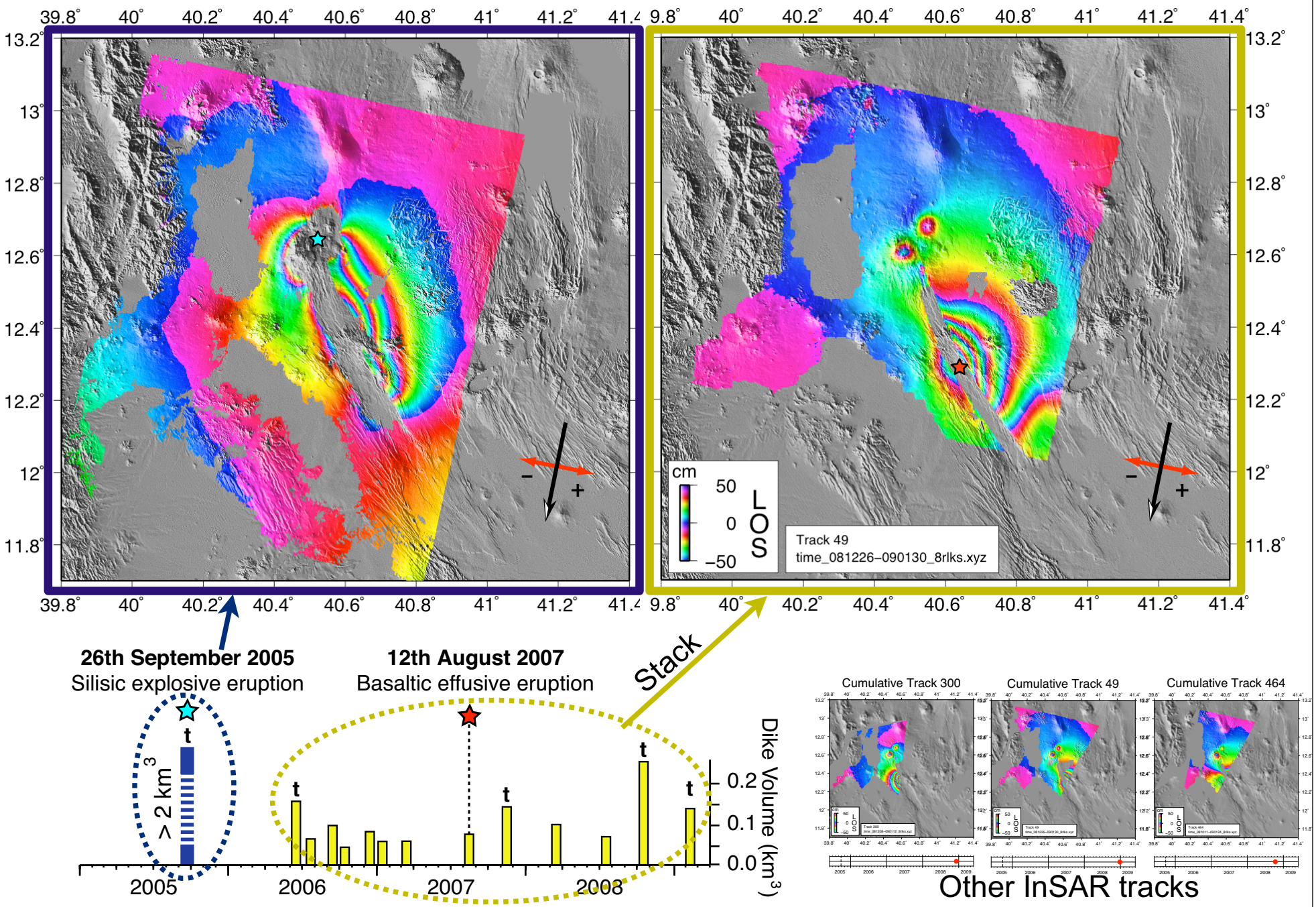
2

The rifting events of 2006-2009


ALAYTA
N
Mabay
AVC
Ado'Ale
MANDA HARARO SOUTH
Gabho
Wal'is
June 2006 → Feb 2009 dikes
September 2005 dike
MANDA HARARO NORTH
Dabbahu
Da'Ure
26 Sept. 2006
Karbahi
12 Aug. 2007
Gommoyta
Elevation [m]
1200
1100
1000
900
800
700
600
500
400
300
12.8
12.5
12.4
12.3
12.2
40.8
40.5
40.4
40.3
12.7
Silisic explosive eruption
t
Basaltic effusive eruptions
t
t
t
2005
2006
2007
2008
2009
Dike Volume (km3)
0.2
0.1
0.0


39.8°
40°
40.2°
40.4°
40.6°
40.8°
41°
41.2°
41.4°
13.2°
13°
12.8°
12.6°
12.4°
12.2°
12°
11.8°
+
–
cm
50
0
–50
LOS
Track 300
time_051219–060123_8rlks.xyz
2005
2006
2007
2008
2009


39.8°
40°
40.2°
40.4°
40.6°
40.8°
41°
41.2°
41.4°
13.2°
13°
12.8°
12.6°
12.4°
12.2°
12°
11.8°
+
–
cm
50
0
–50
LOS
Track 300
time_051219–060123_8rlks.xyz
2005
2006
2007
2008
2009


39.8° 40° 40.2° 40.4° 40.6° 40.8° 41° 41.2° 41.4°
13.2° 13° 12.8° 12.6° 12.4° 12.2° 12° 11.8°
cm
50
0
−50
LOS
Track 49
time_081226−090130_8rlks.xyz
26th September 2005
Silisic explosive eruption
12th August 2007
Basaltic effusive eruption
Stack
> 2 km3
t
2005
2006
2007
2008
Dike Volume (km3)
0.2
0.1
0.0
Cumulative Track 300
Cumulative Track 49
Cumulative Track 464
Other InSAR tracks

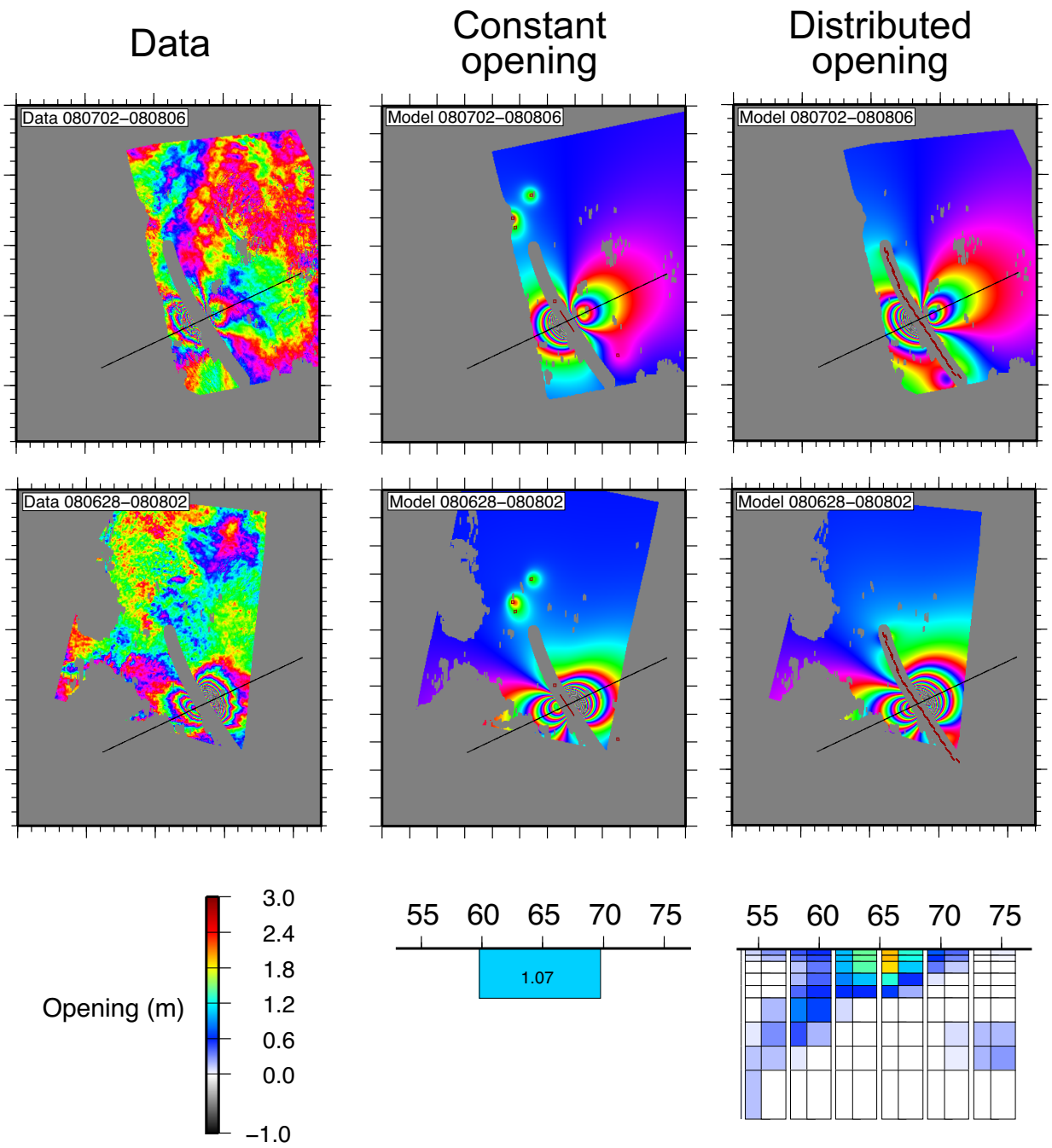
Inversion of geodetic data for dike intrusions

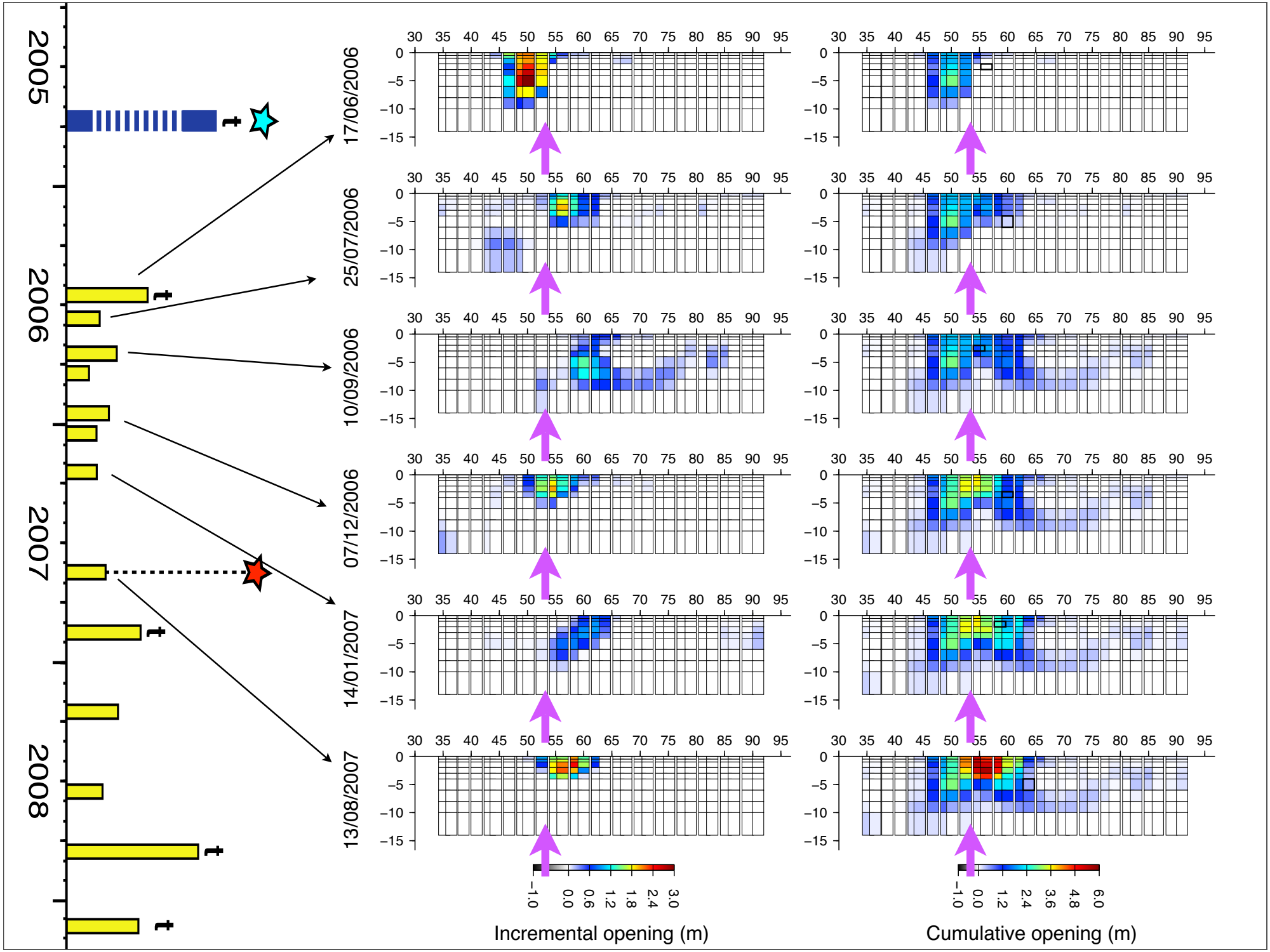
Combining ascending and descending tracks helps resolving the H/V ambiguity

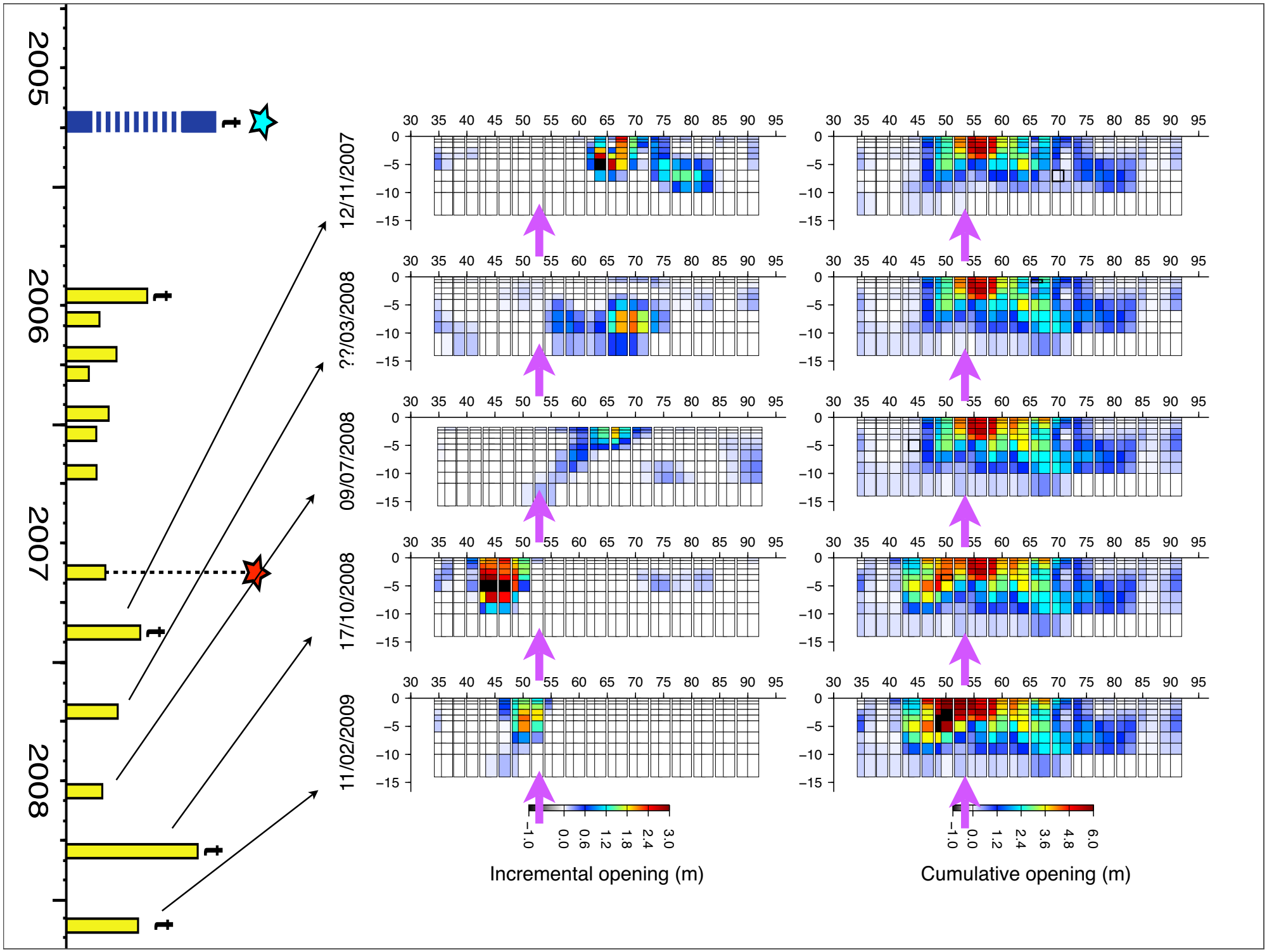
Step 1:
Non-linear inversion of the geometry of the dike [Tarantola & Valette, 1982]

Step 2:
Linear inversion of opening on a discretized dike plane to constrain the “shape” of the dike

Example: July 9th, 2008 dike

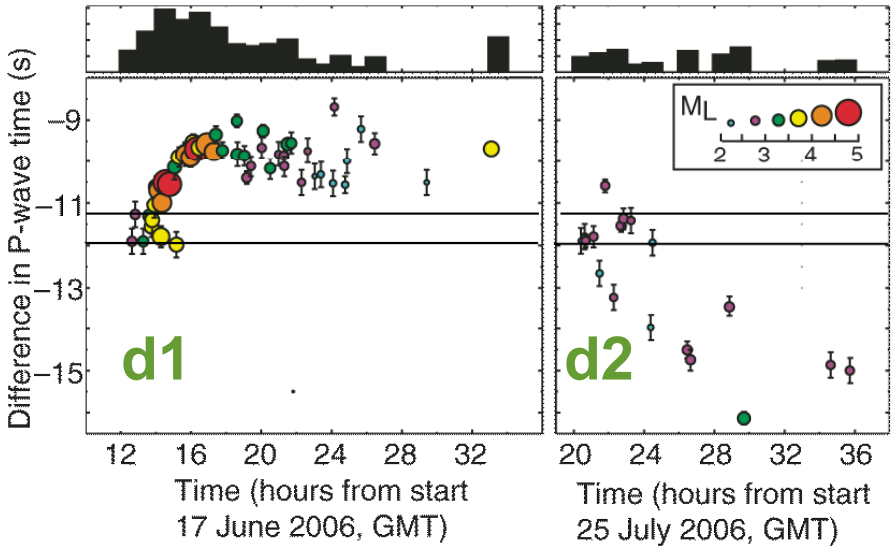



2005
2006
2007
2008
17/06/2006
25/07/2006
10/09/2006
07/12/2006
14/01/2007
13/08/2007
30 35 40 45 50 55 60 65 70 75 80 85 90 95
0 −5 −10 −15
−1.0 0.0 0.6 1.2 1.8 2.4 3.0
Incremental opening (m)
−1.0 0.0 1.2 2.4 3.6 4.8 6.0
Cumulative opening (m)

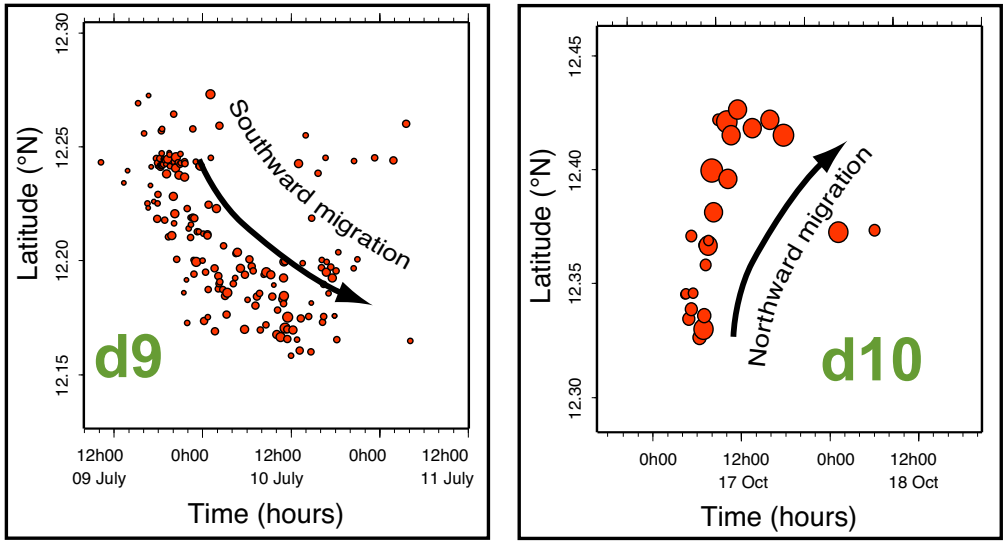

2005
2006
2007
2008
12/11/2007
??/03/2008
09/07/2008
17/10/2008
11/02/2009
Incremental opening (m)
Cumulative opening (m)

Migration of seismicity during dike emplacement

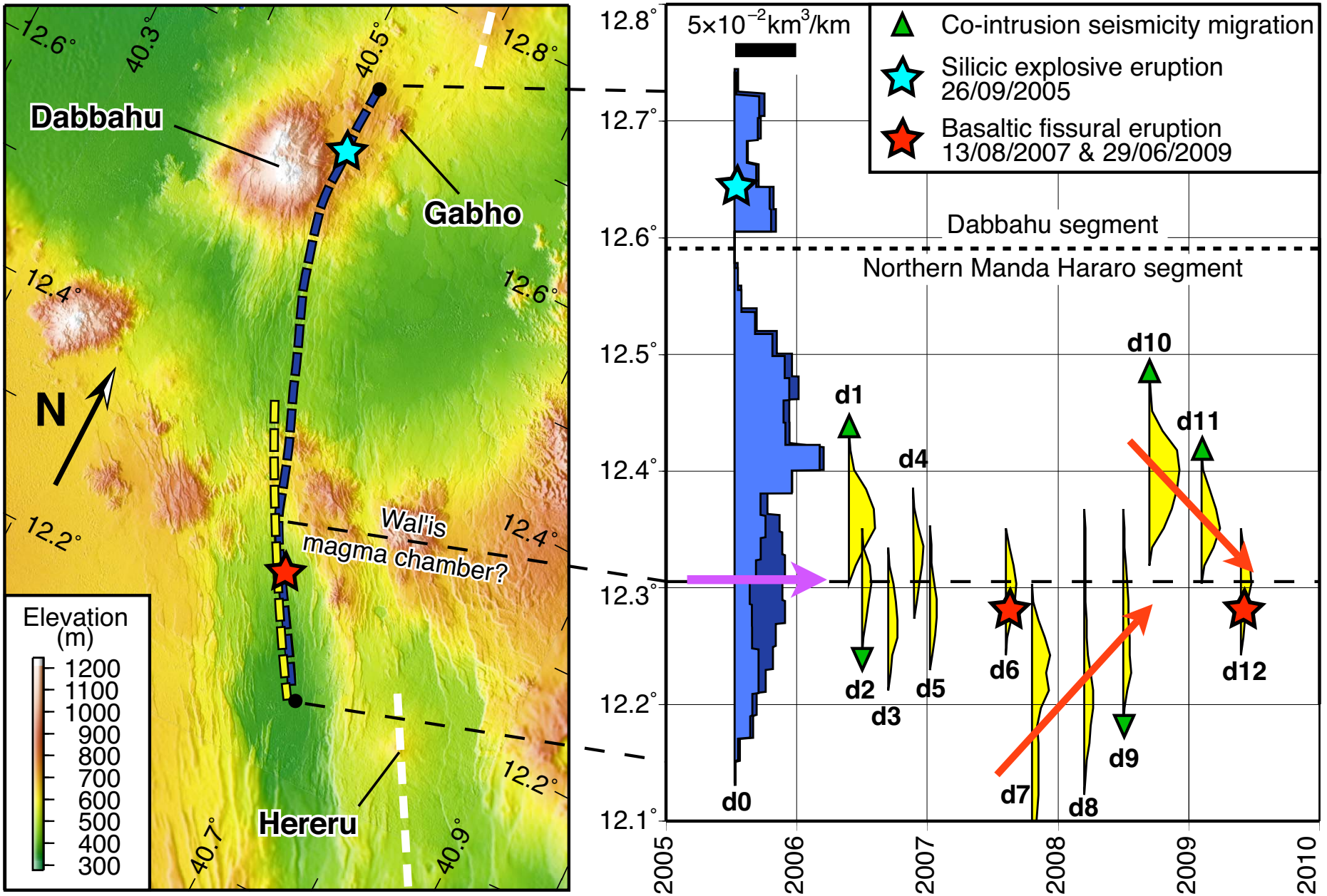
[Keir et al., 2009]

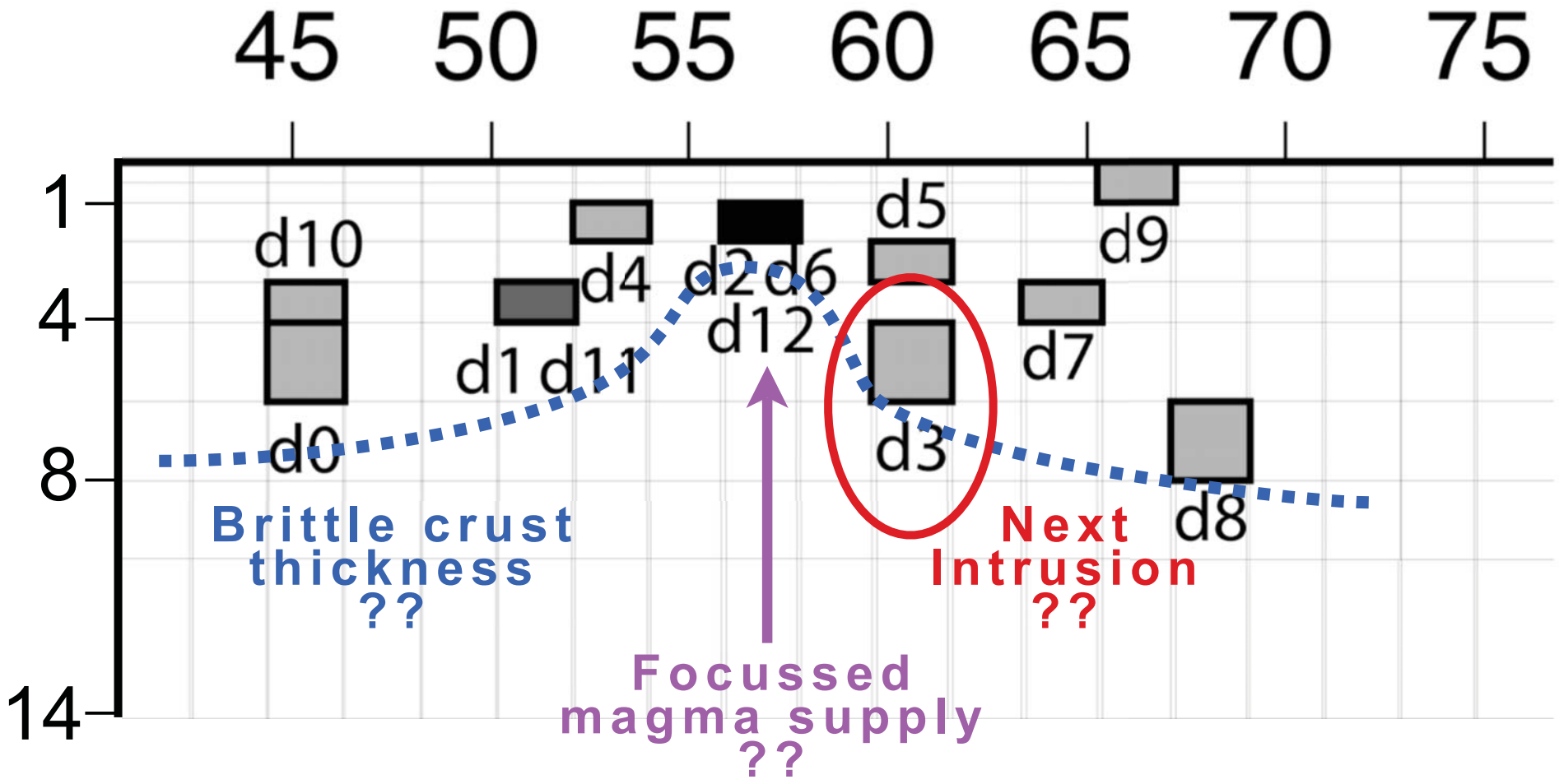


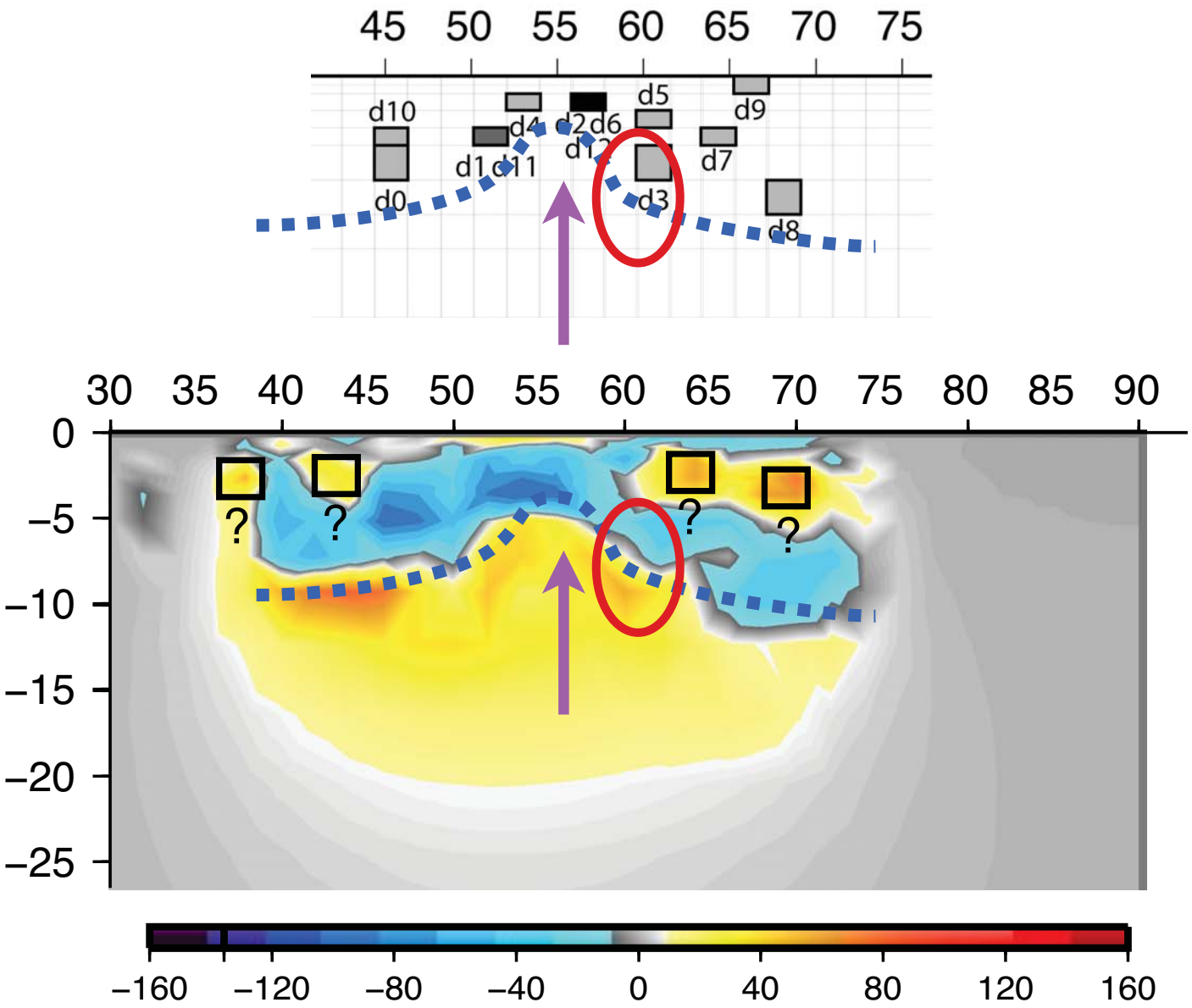
IPGP/AAU local seismic array



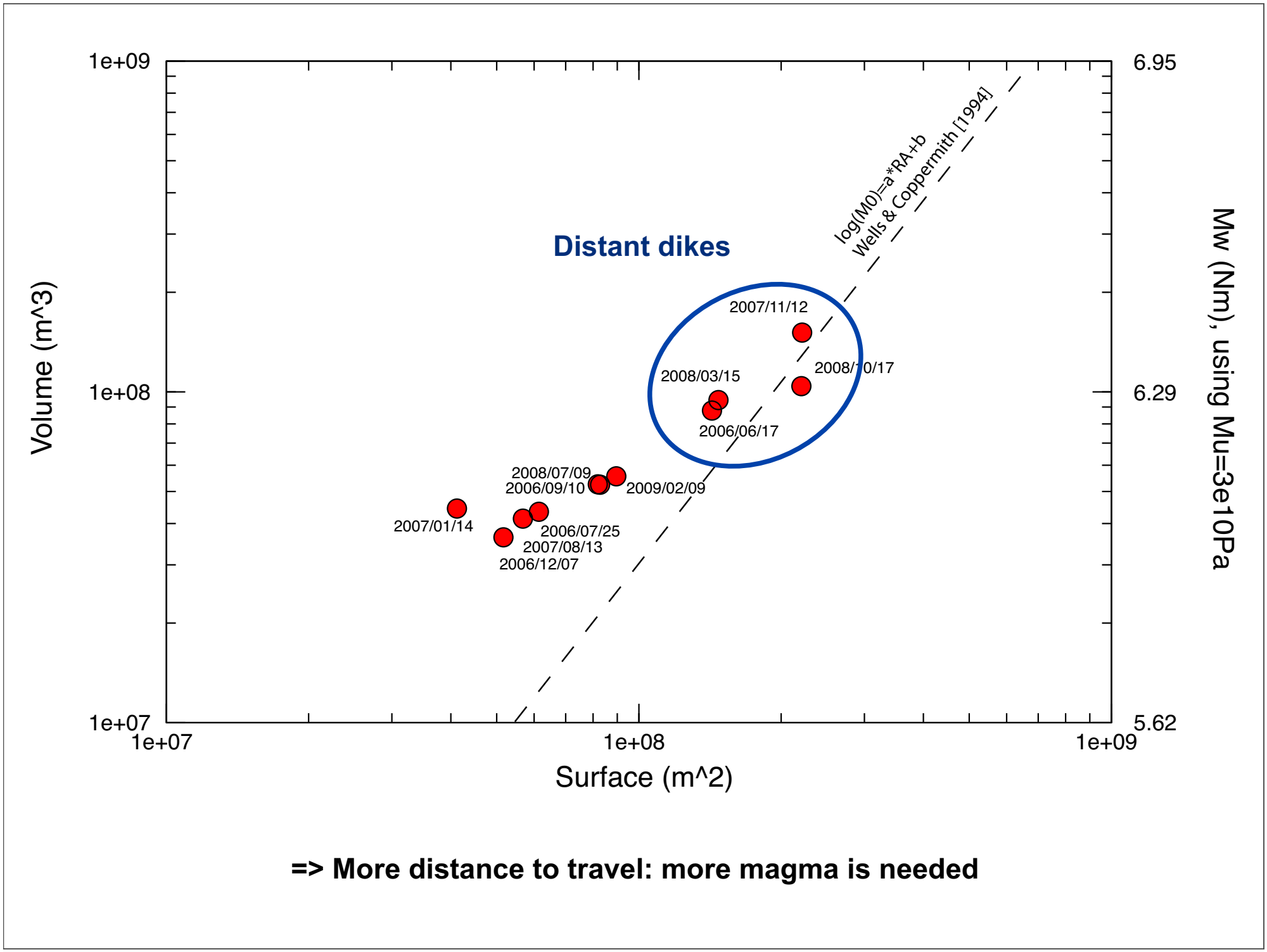
Repeated intrusions in Manda Hararo – Dabbahu rift in 2005 - 2006 - 2007 - 2008 - 2009




45
50
55
60
65
70
75
1
4
8
14
d10
d0
d1
d11
d4
d2
d6
d12
d5
d3
d7
d9
d8
Brittle crust thickness ??
Focussed magma supply ??
Next Intrusion ??



[Nelly Mazzoni, MSc, IPGP]

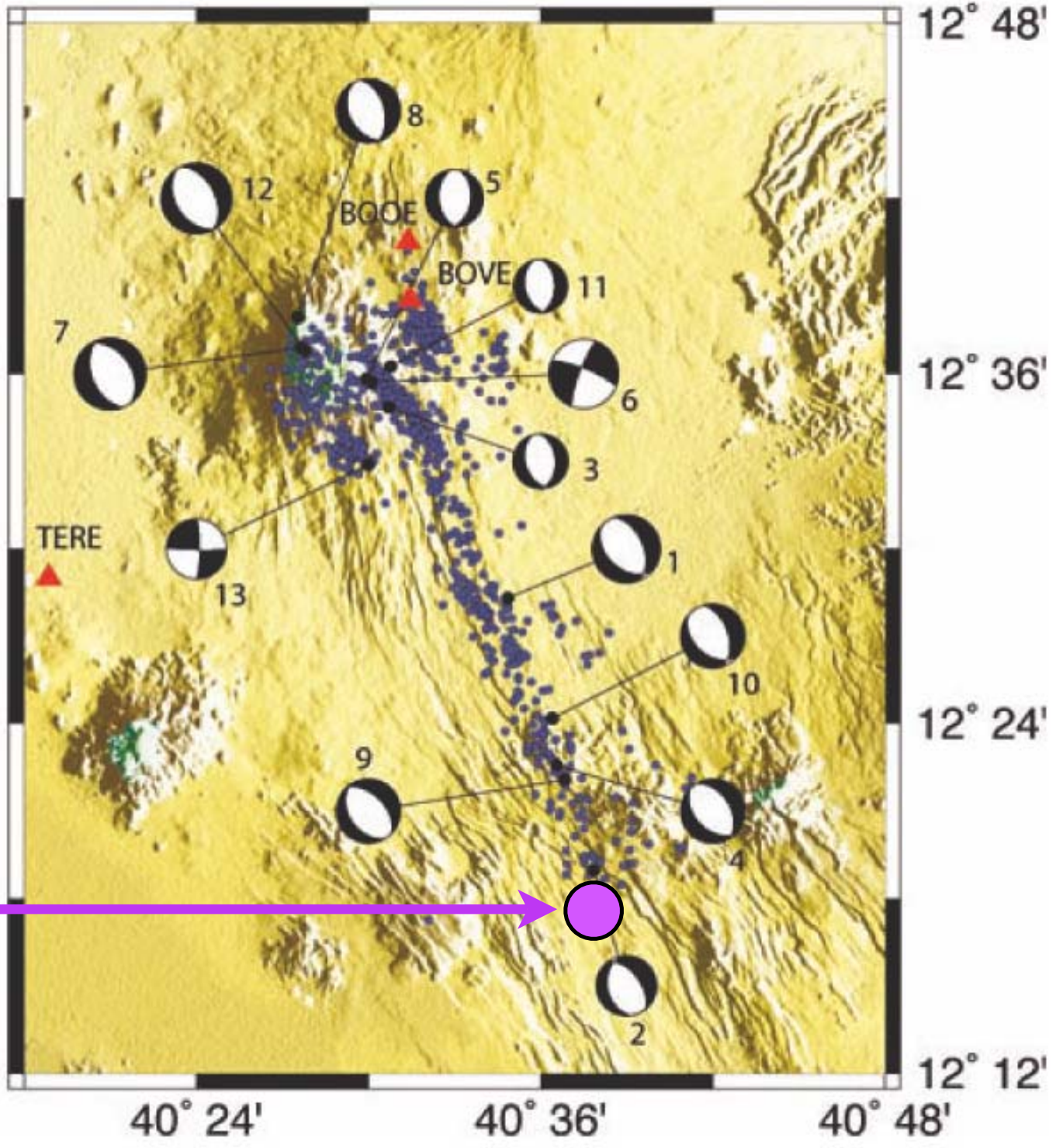


=> More distance to travel: more magma is needed

3

Transient deformation between dike intrusions

[Ebinger et al., 2008]

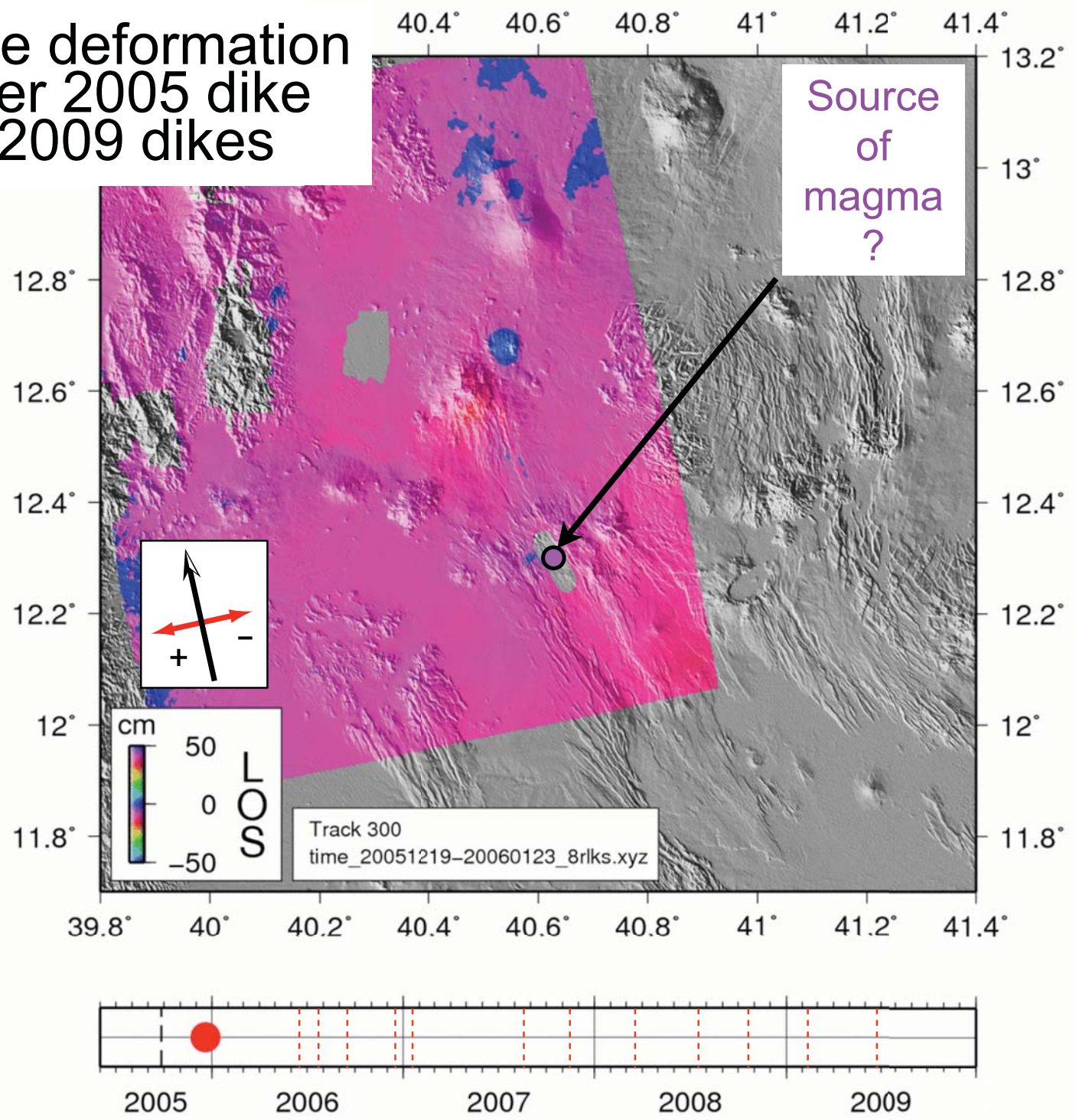


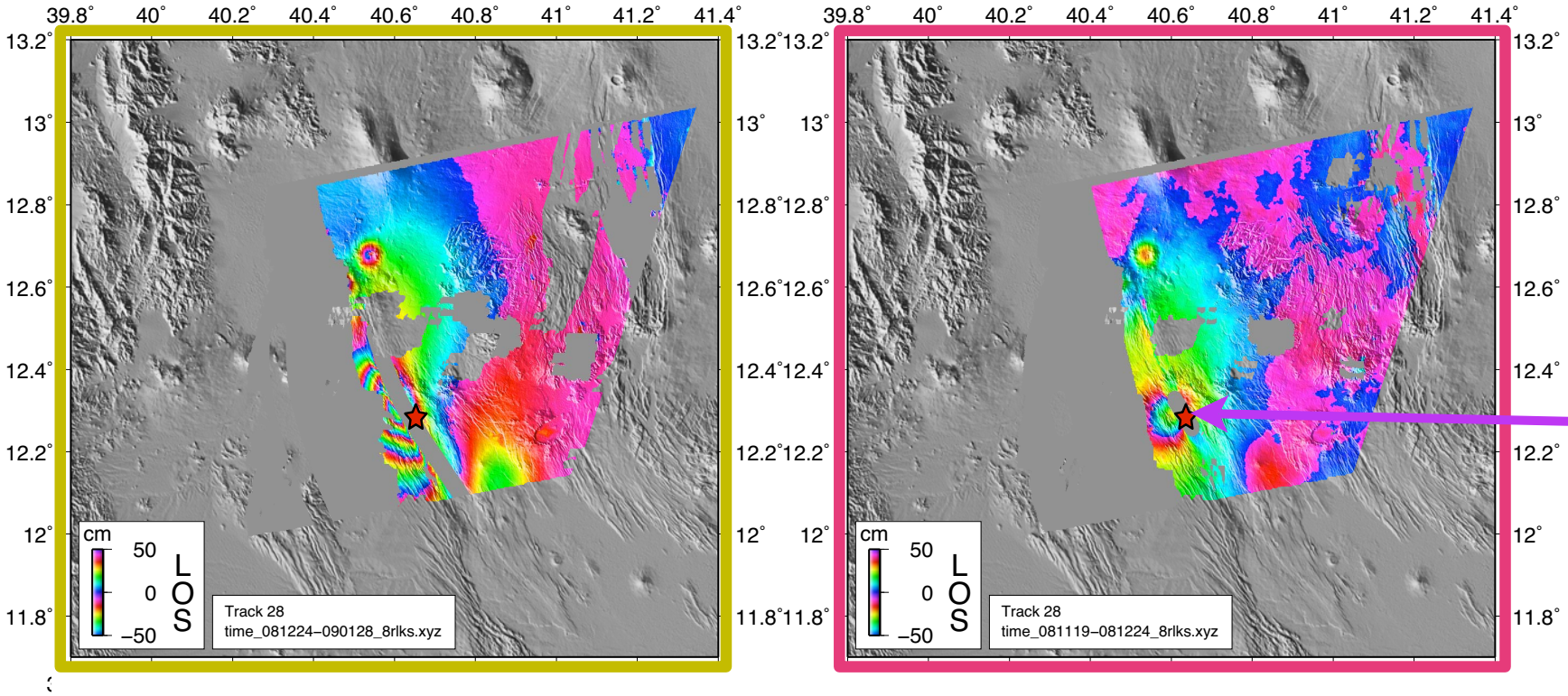
Source of magma ?

InSAR cumulative deformation since September 2005 dike without 2006-2009 dikes

Transient deformation between dike intrusions suggest the presence of a deep (> 10 km depth) source of deformation at the centre of the segment

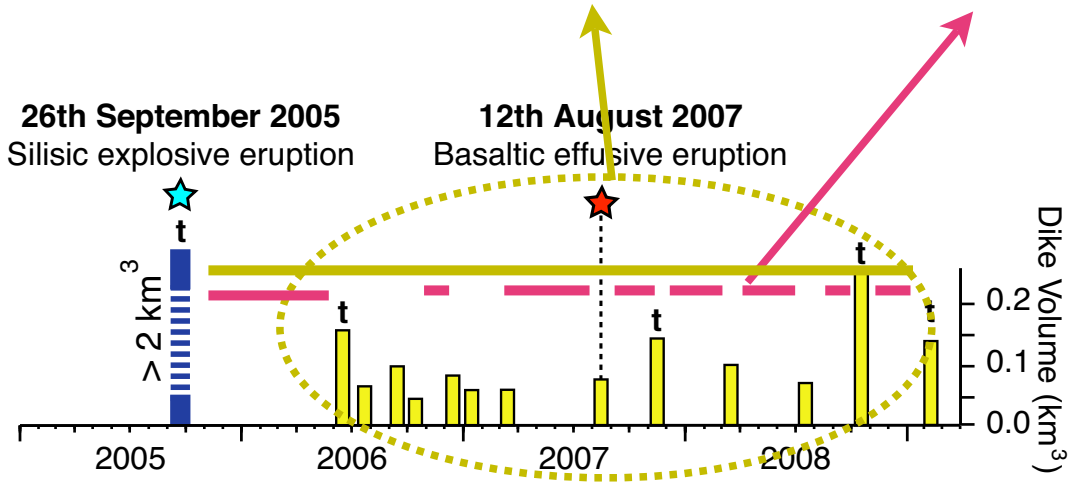
Length of the source: < 10 km





total deformation

inter-diking deformation only



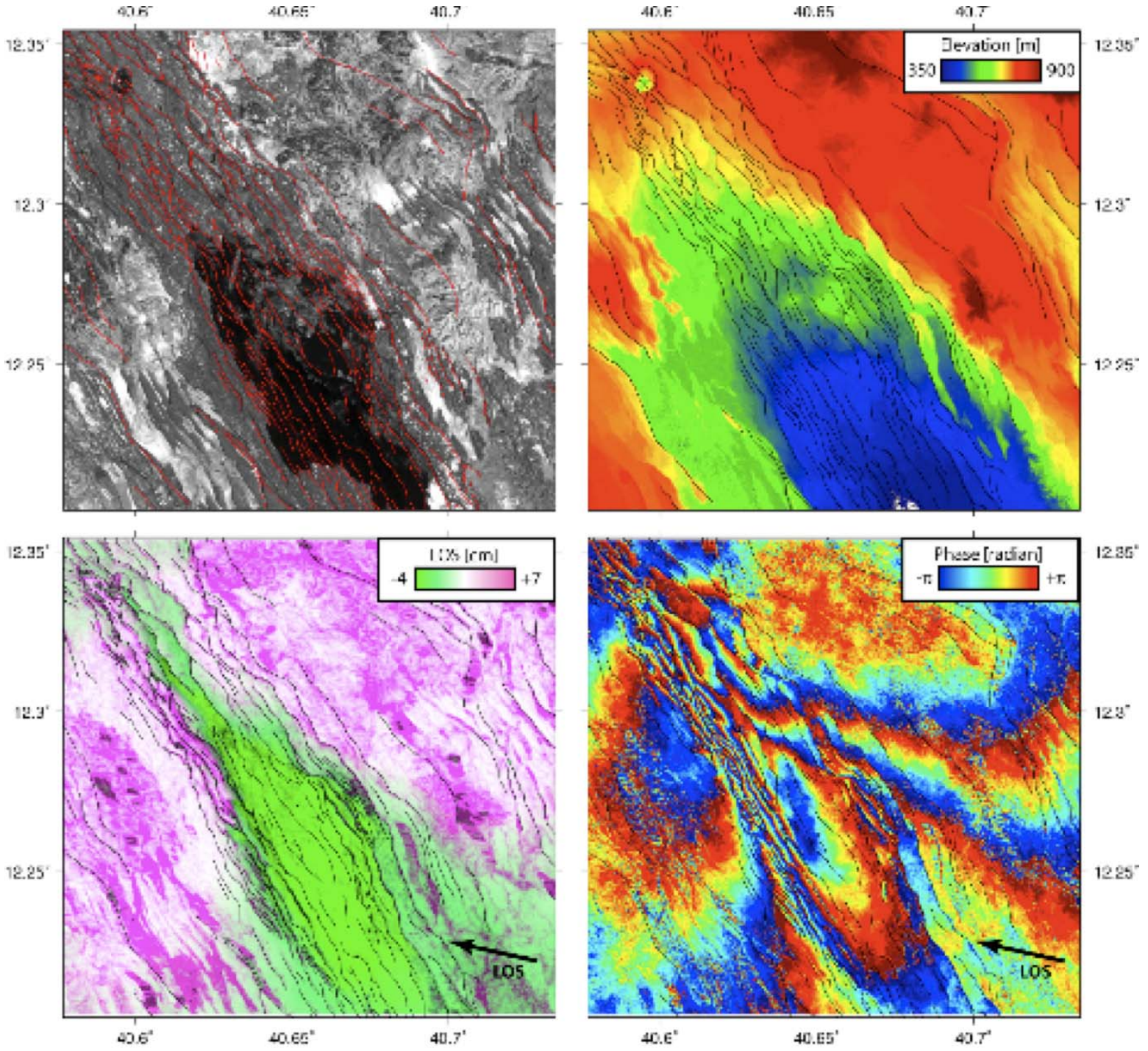
Transient deformation between dike intrusions suggest the presence of a deep (> 10 km depth) source of deformation at the centre of the segment

Length of the source < 10 km

High resolution InSAR processing

- Detailed mapping
⇨ tectonic analysis

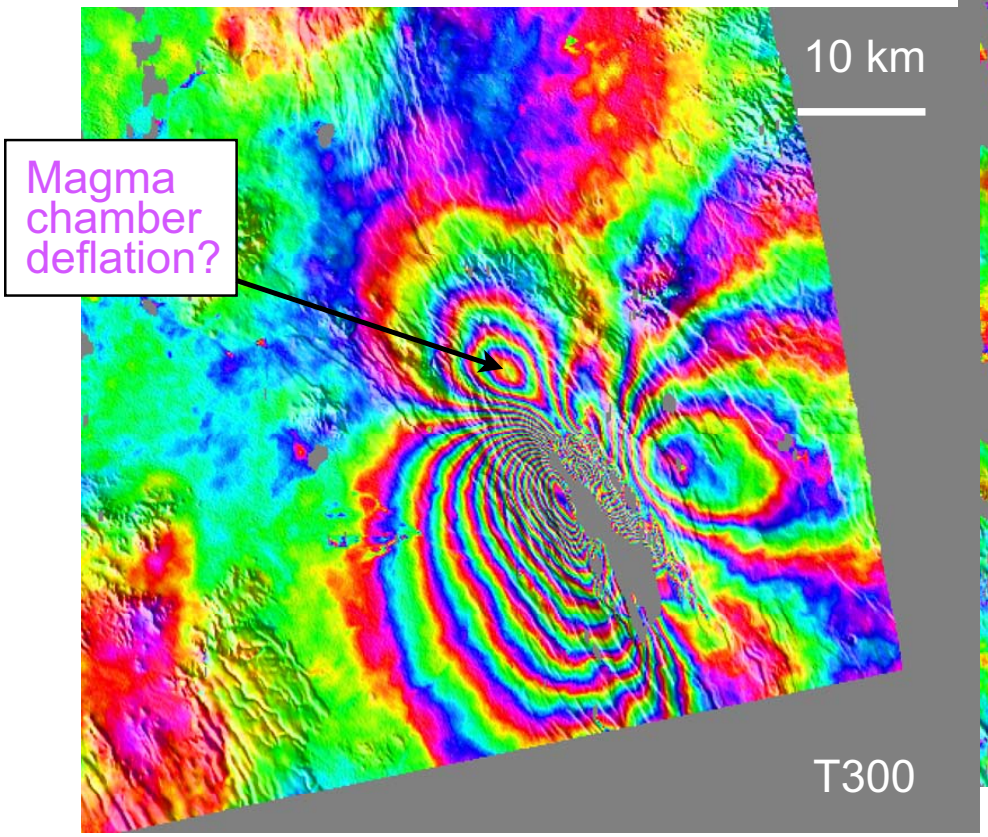
- Geometry and kinematic behavior of faults/fissures
⇨ constraints for mechanical modeling



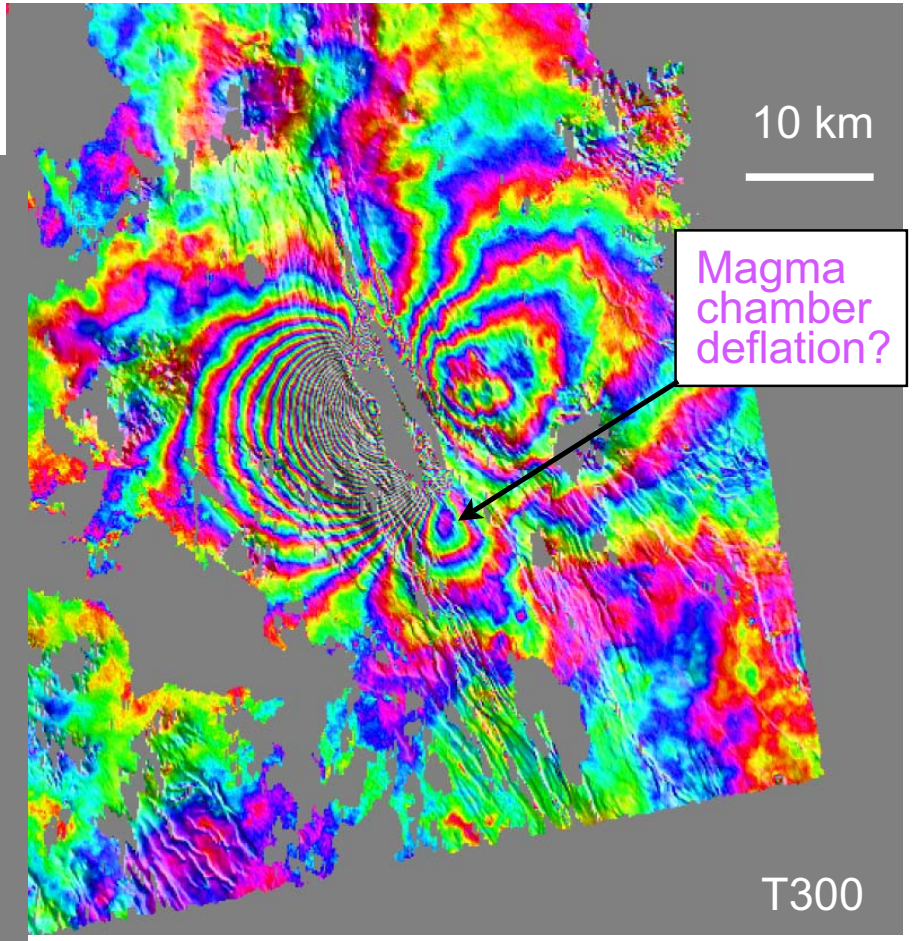
4

Back to the main rifting event...

Central magma chamber deflation during a dike intrusion captured by InSAR



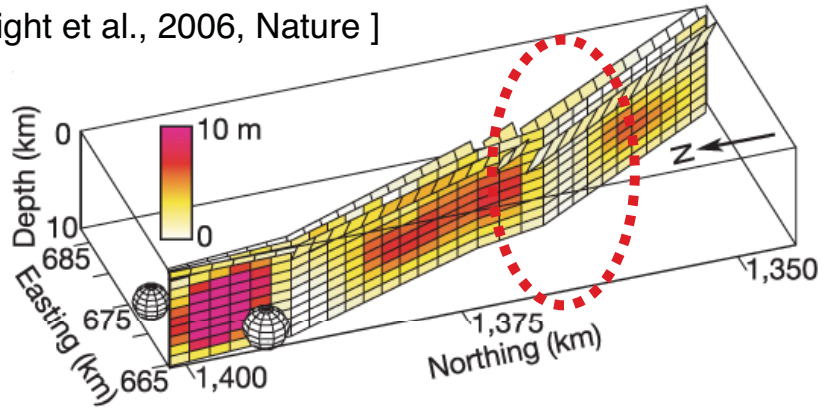
November 2007 dike:
southernmost dike

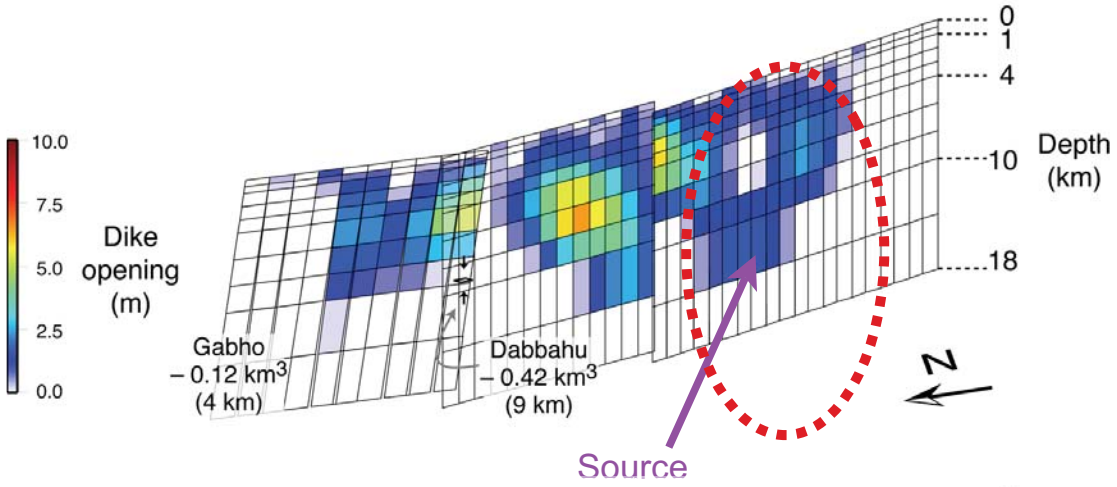


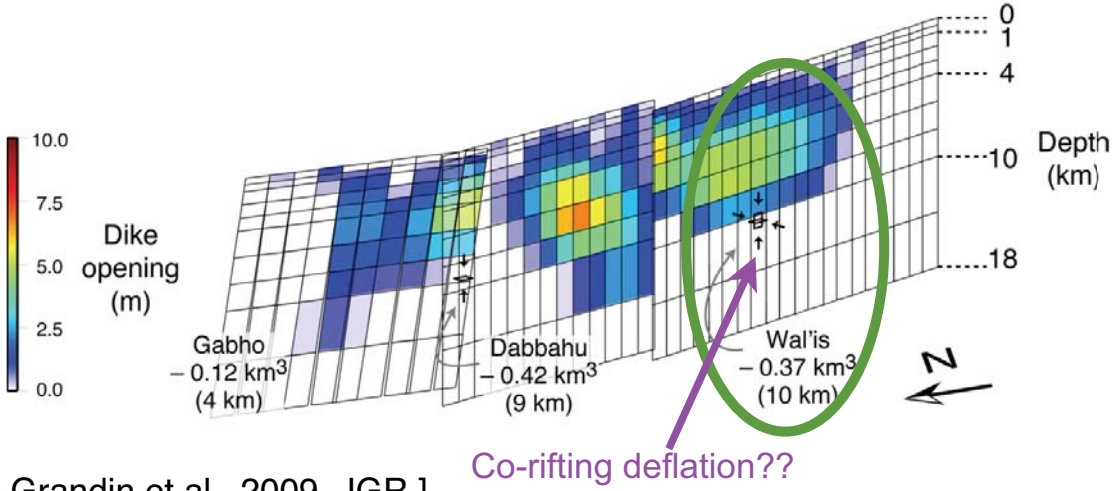
October 2008 dike:
northernmost dike

Elastic modeling => depth > 10-15 km

[Wright et al., 2006, Nature]



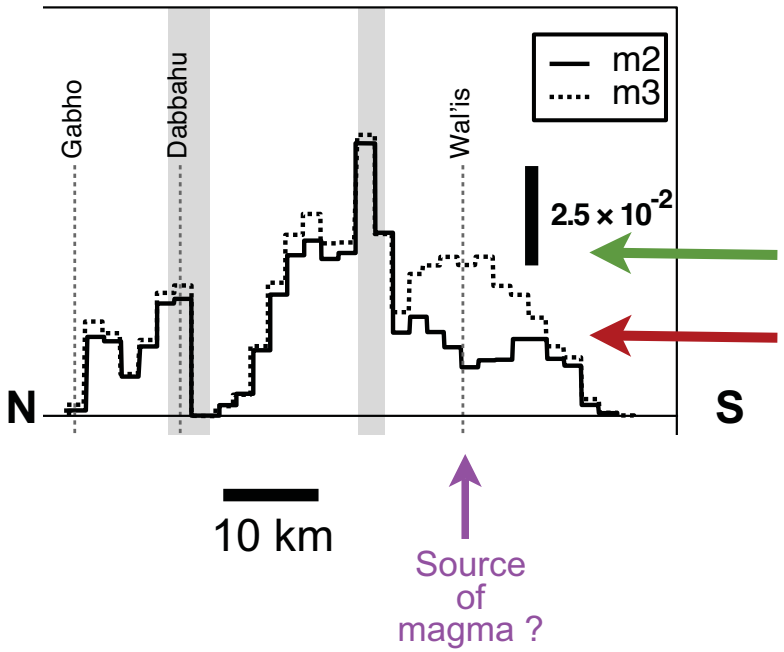




[Grandin et al., 2009, JGR]

What happened there during the September 2005 rifting event?

Average thickness
of the September 2005 dike
along the rift



Strong influence of a deep deflation on the solution of the inversion of co-rifting geodetic data

Conclusions

Source of magma: at the centre of the rift

➡ Compatible observations at slow-spreading MOR

Limited magma availability

➡ Small or no overpressure of the main magma reservoir implies a large tectonic stress deficit at the onset of rifting => magma is emplaced “passively” into the dikes

Strong (thick?) crust at the Wal’is rift axis

➡ Recent localization of magma-assisted extension

A few remaining problems...

Time needed to solidify a 5m-thick dike > 1 year

➡ What prevents the whole crack from dilating during magma surge?

Strong heterogeneity of the normal stress change on the dike

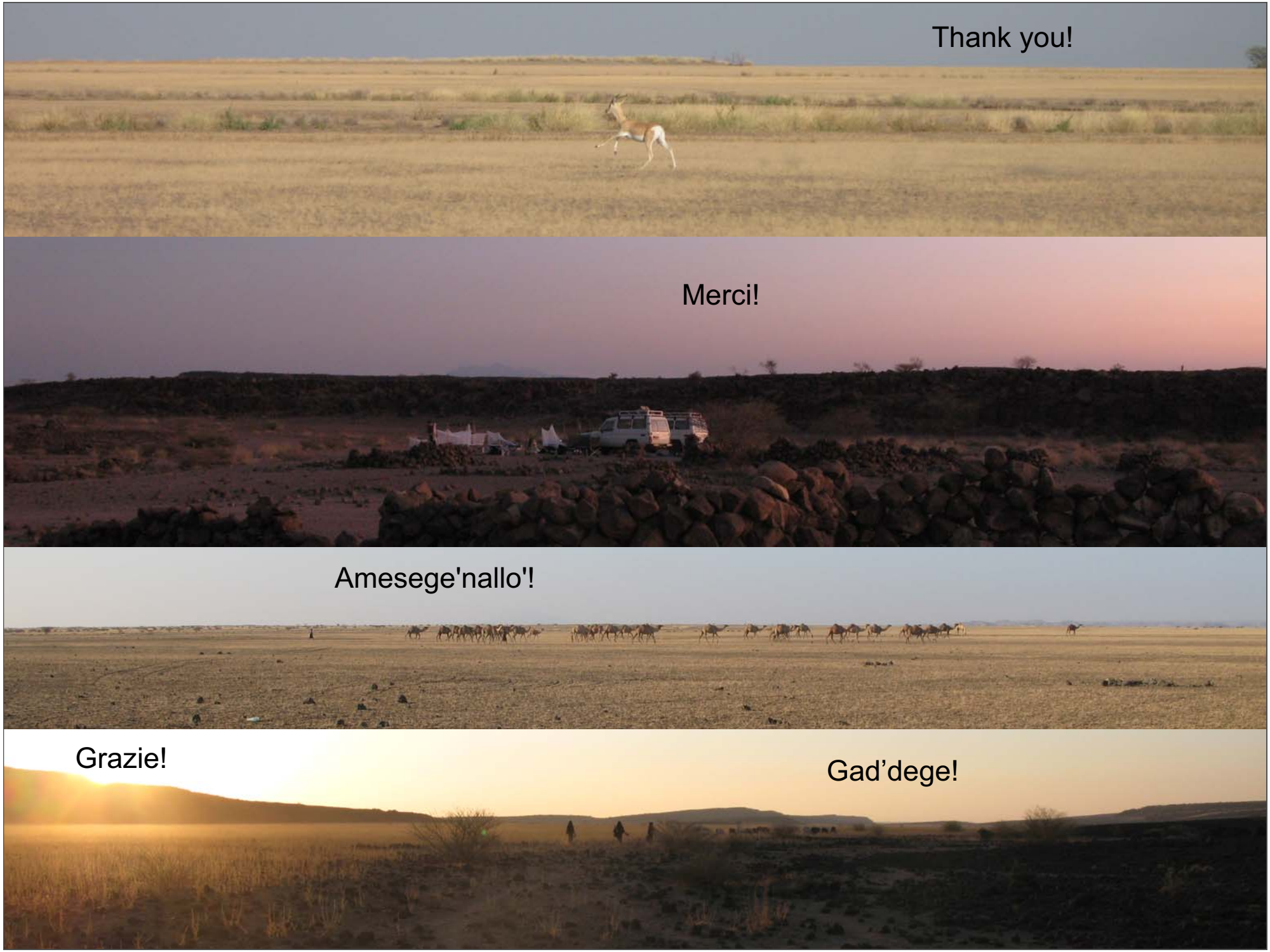
➡ What were the initial stress conditions?

Response of the central plumbing system

➡ What is the nature of the deep process that generates transient deformation (diking, viscous flow...)?

No transient deformation observed (with InSAR..) prior to injection

➡ What triggers the rifting episode? What controls the size of it?


Thank you!
Merci!
Amesege'nallo'!
Grazie!
Gad’dege!