The Abdus Salam
International Centre
for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2464-19

Earthquake Tectonics and Hazards on the Continents

17 - 28 June 2013

the Afar

T. J. Wright

University of Leeds
UK

Witnessing the birth of an Ocean? The ongoing rifting episode in Afar, Ethiopia

Tim Wright
University of Leeds, UK
Plus collaborators from the Afar Rift Consortium

Afar Rift Consortium

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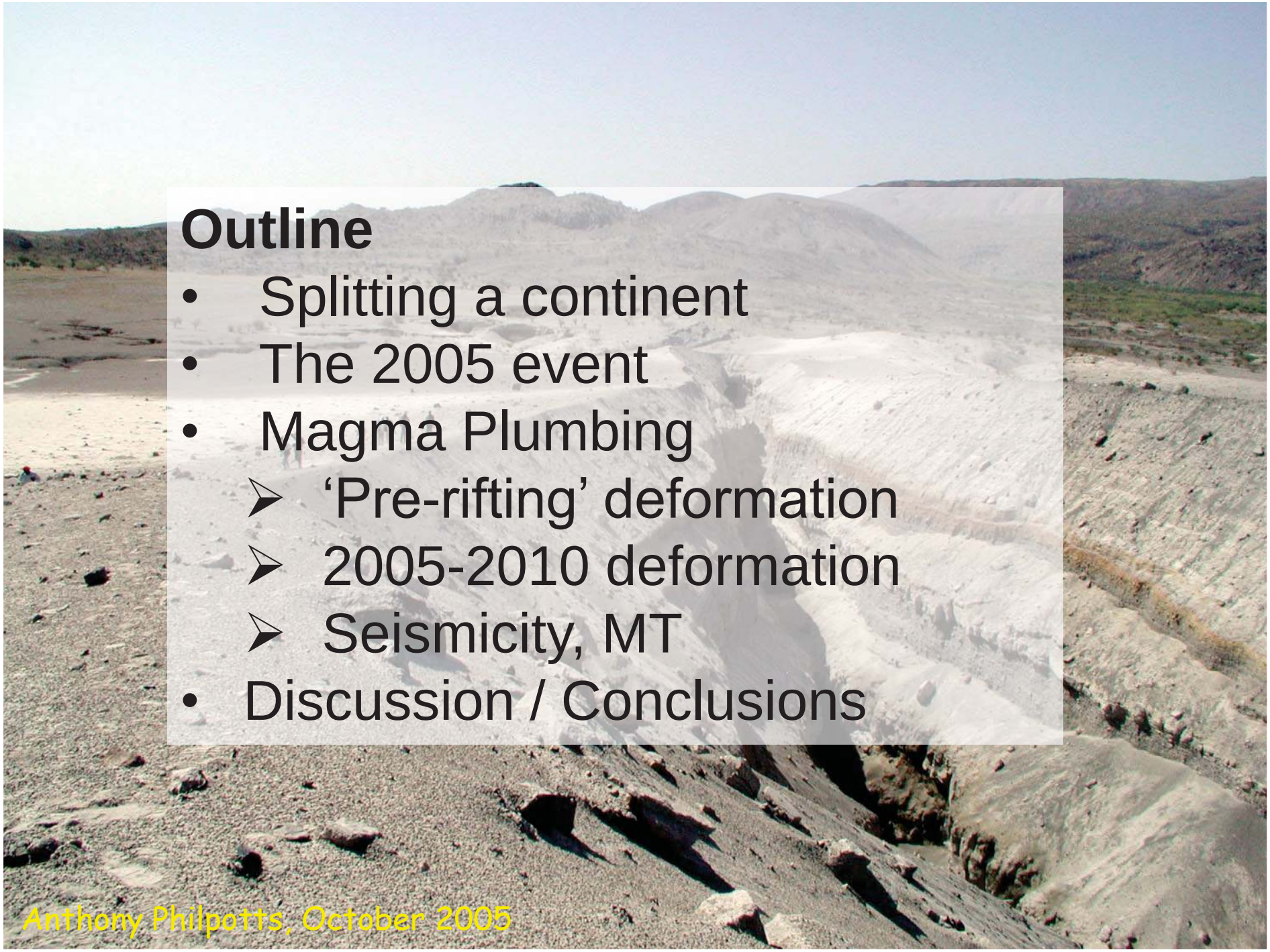
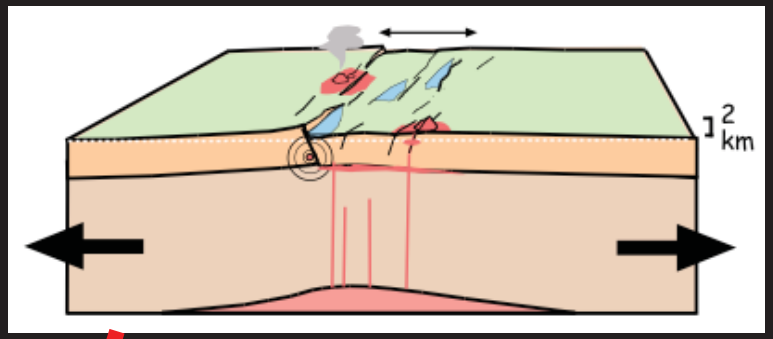
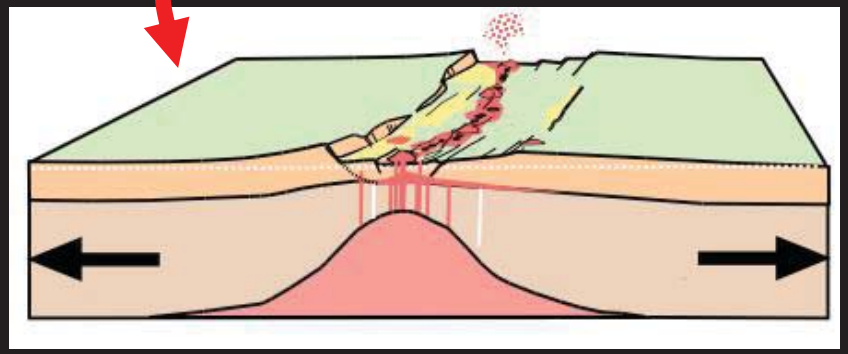
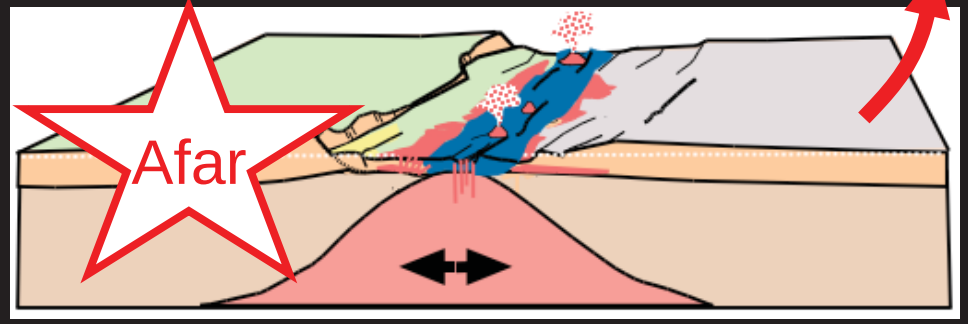
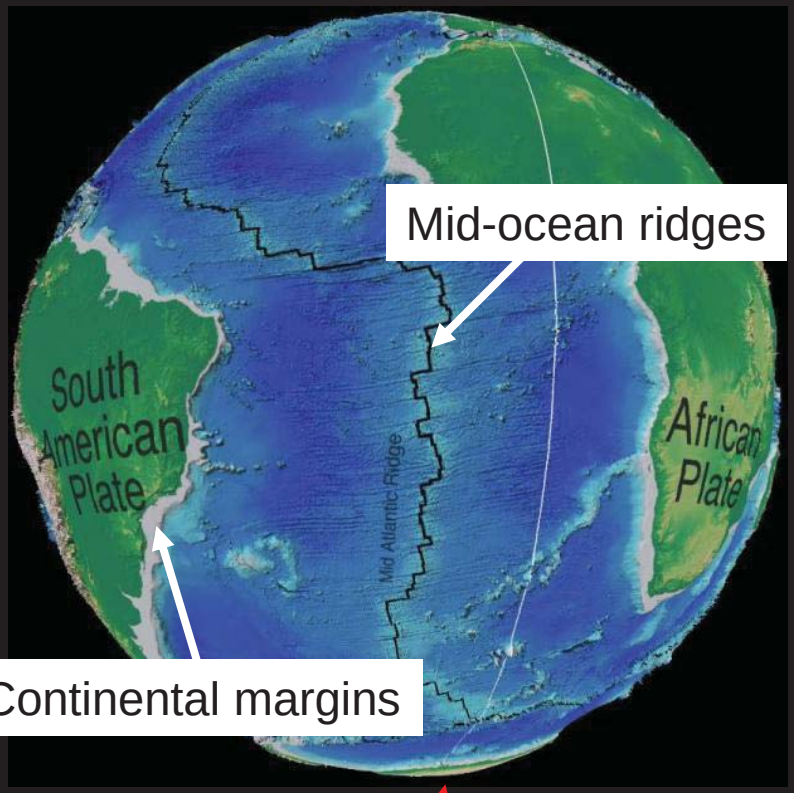

Outline
• Splitting a continent
• The 2005 event
• Magma Plumbing
➢ ‘Pre-rifting’ deformation
➢ 2005-2010 deformation
➢ Seismicity, MT
• Discussion / Conclusions
Anthony Philpotts, October 2005

Splitting a continent and forming a new ocean

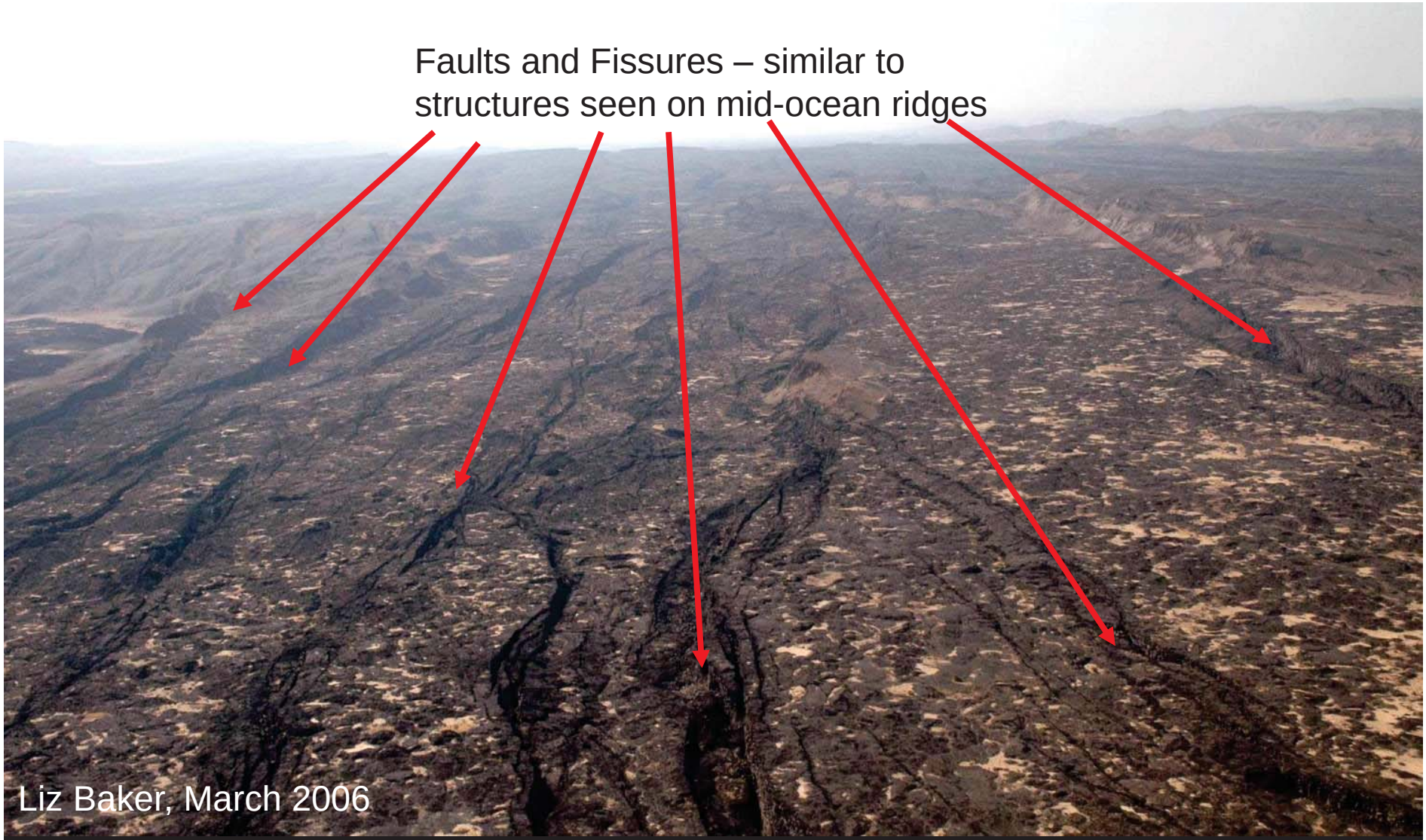






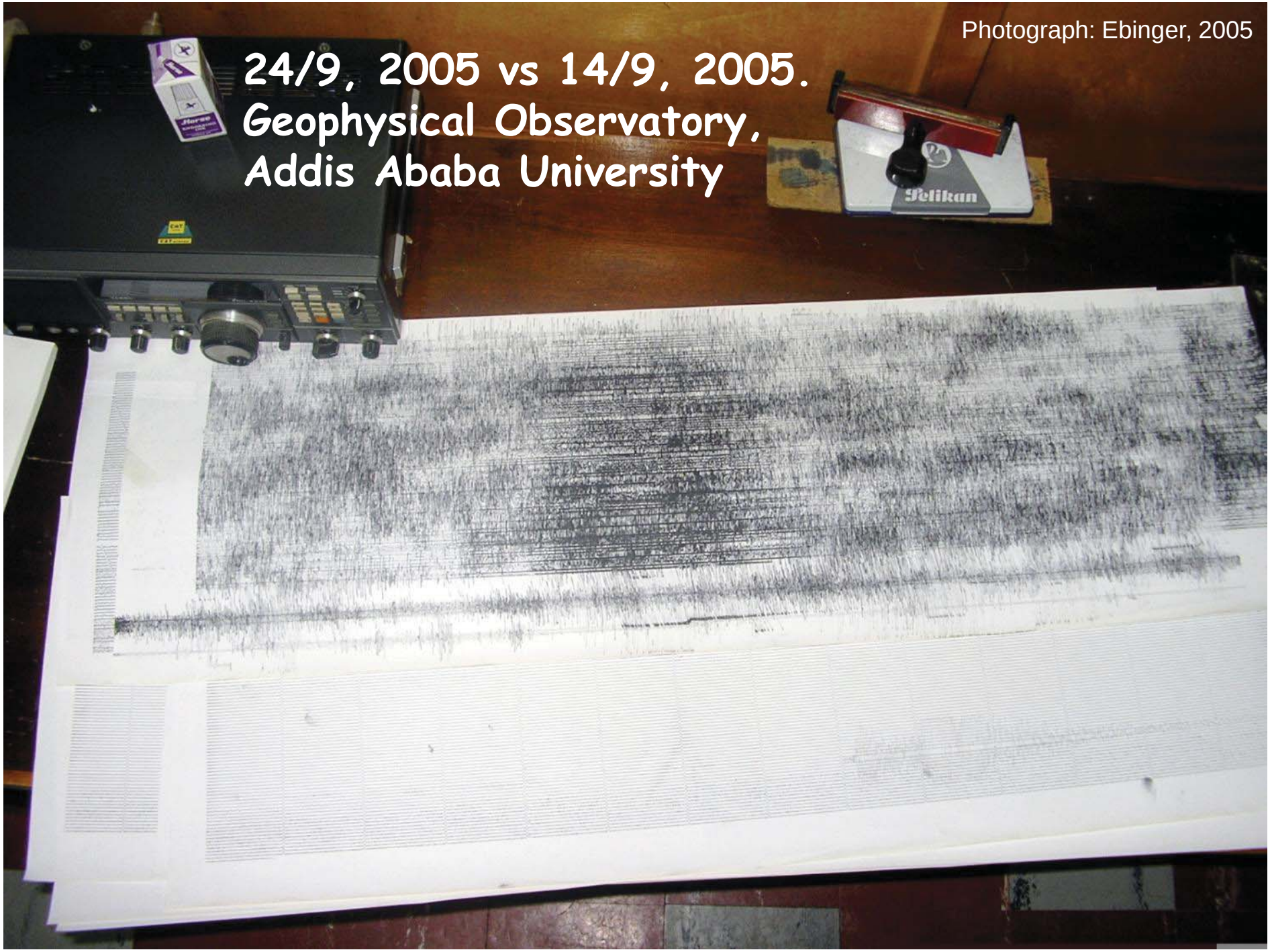


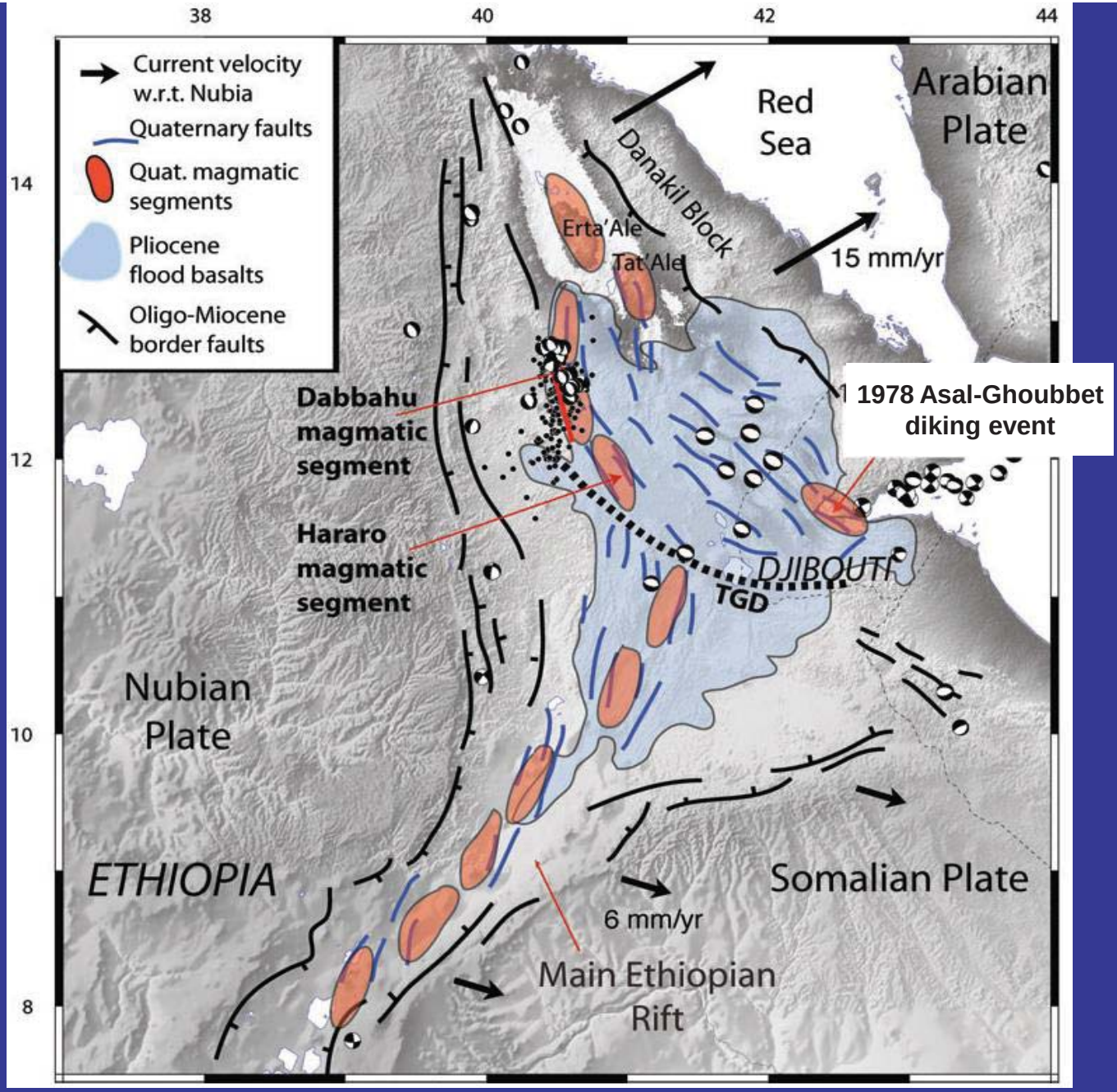
Figures modified from Ebinger (2005)



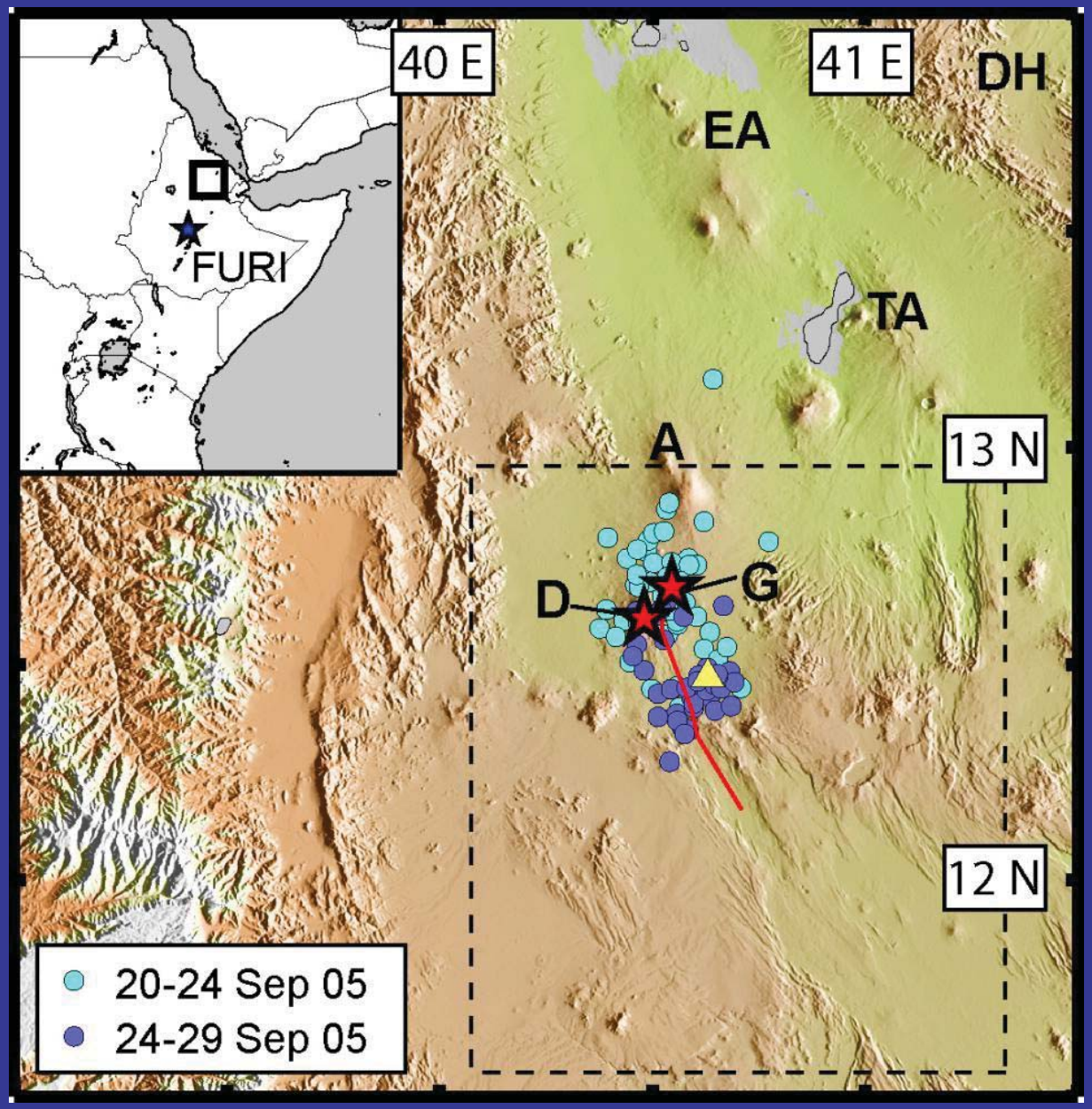
Afar is the only place on Earth today where the final stages of continental rupture and the beginning of seafloor spreading are occurring above sea level.


Photograph: Ebinger, 2005
ON EW & NS
Power & Heat are off
Atalay Ayele , Geophysical Observatory, Addis Ababa University


24/9, 2005 vs 14/9, 2005.
Geophysical Observatory,
Addis Ababa University
Photograph: Ebinger, 2005
Pelikan



From Ebinger et al., GJI 2008



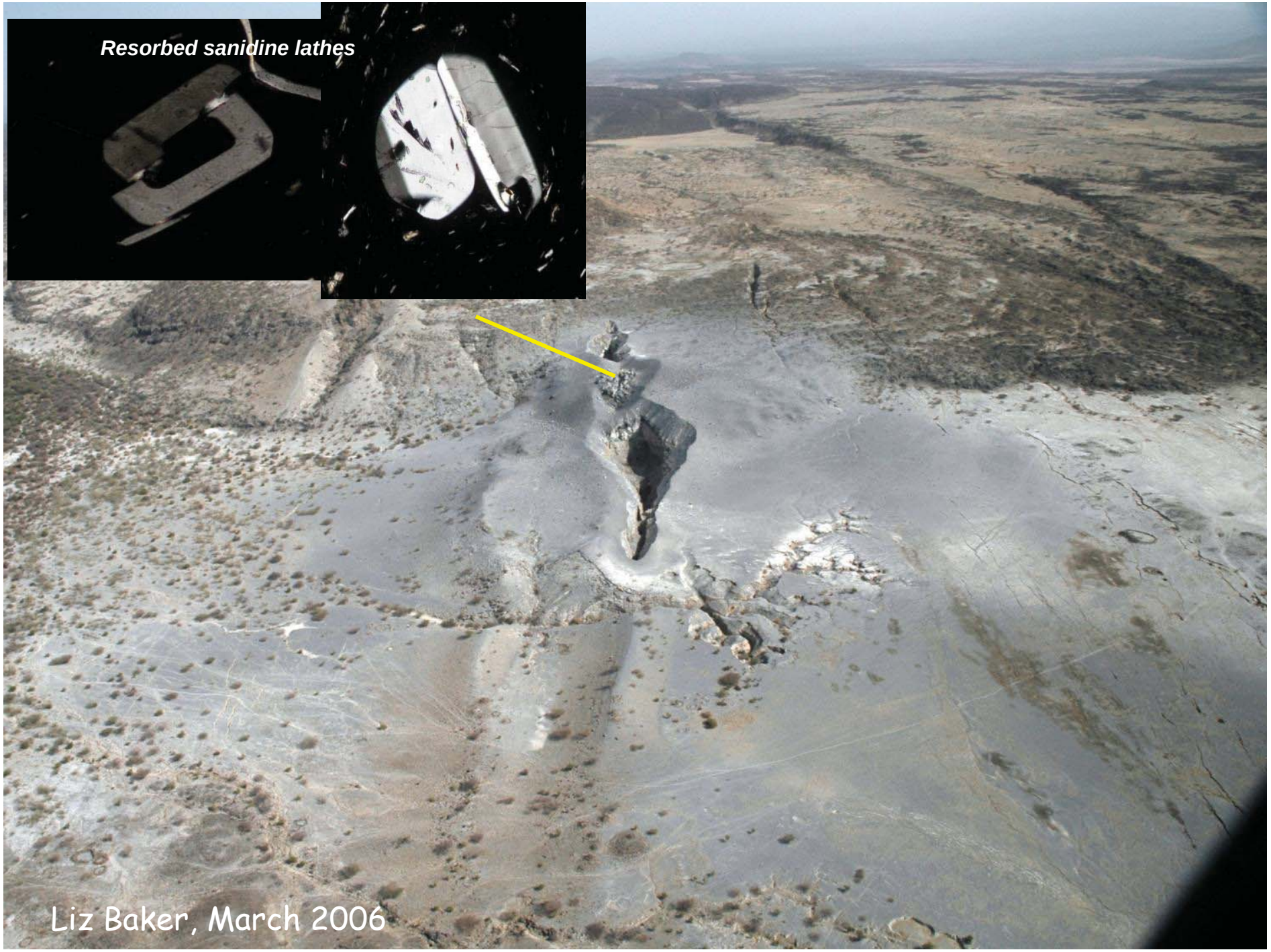
20/9/2005 to 8/10/2005

162 earthquakes (m_b < 5.7) detected by NEIC.

Relocated by Anna Stork


Liz Baker, March 2006


Anthony Philpotts, October 2005

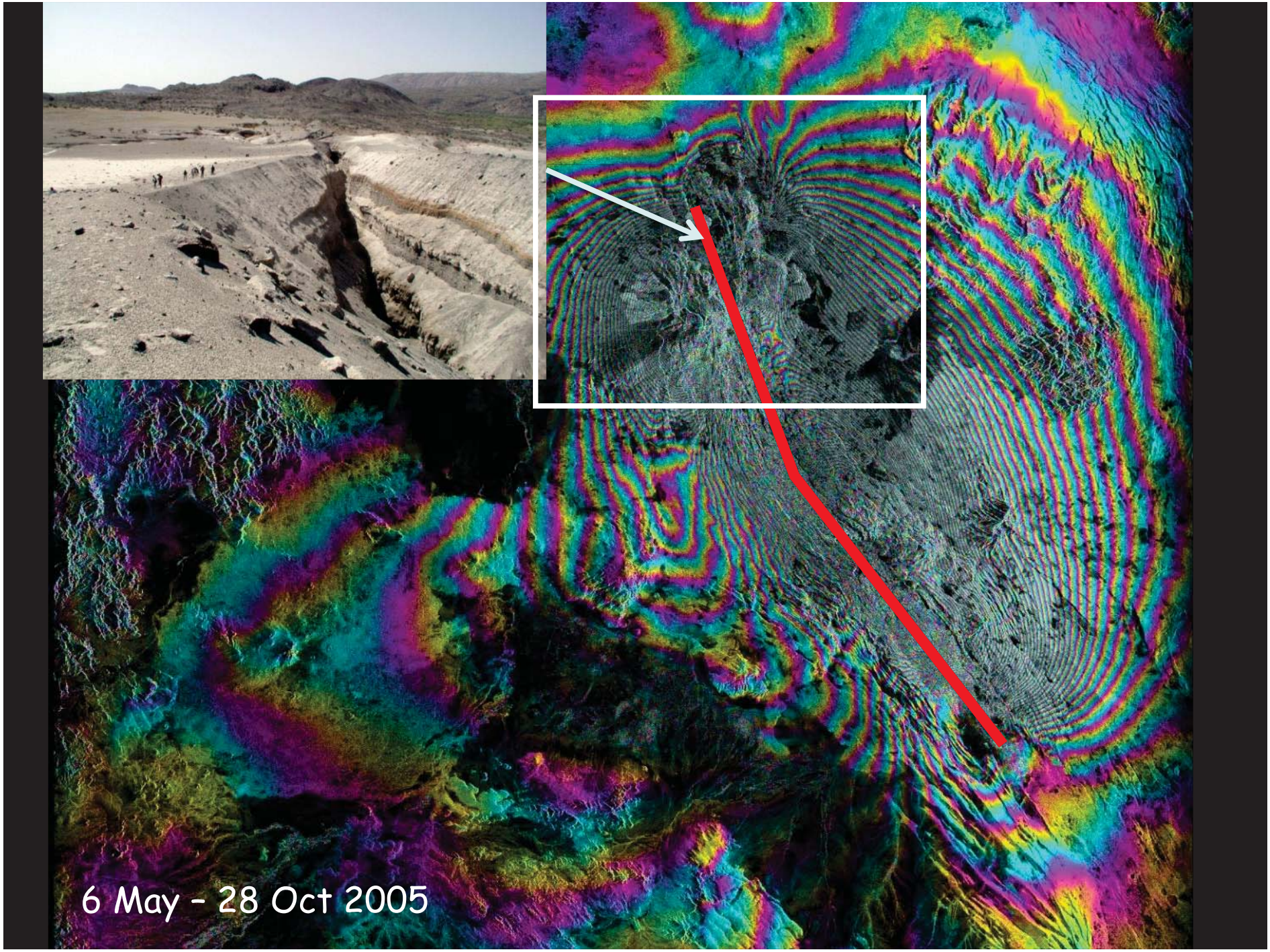

Resorbed sanidine lathes
Liz Baker, March 2006

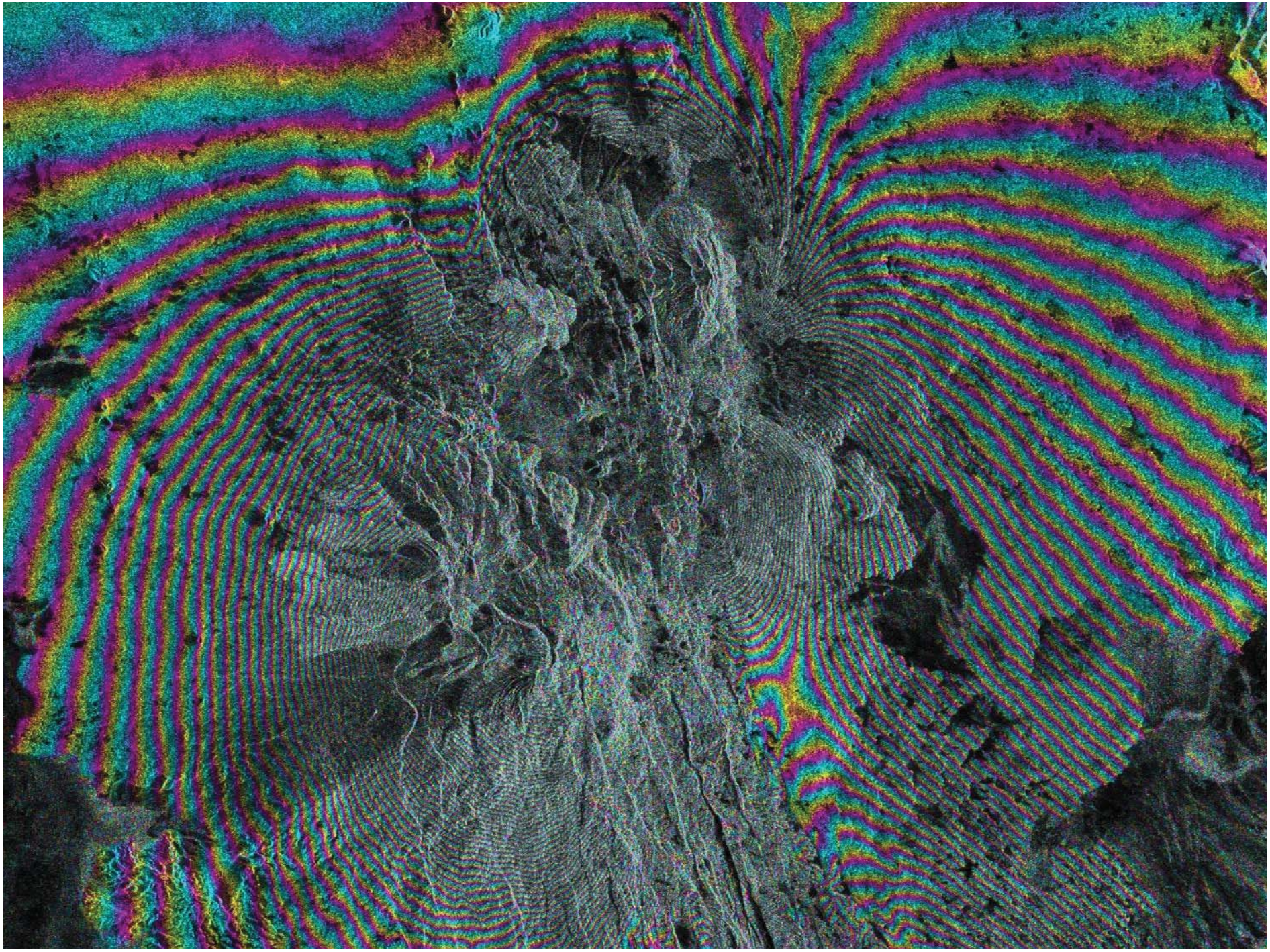

Liz Baker, March 2006

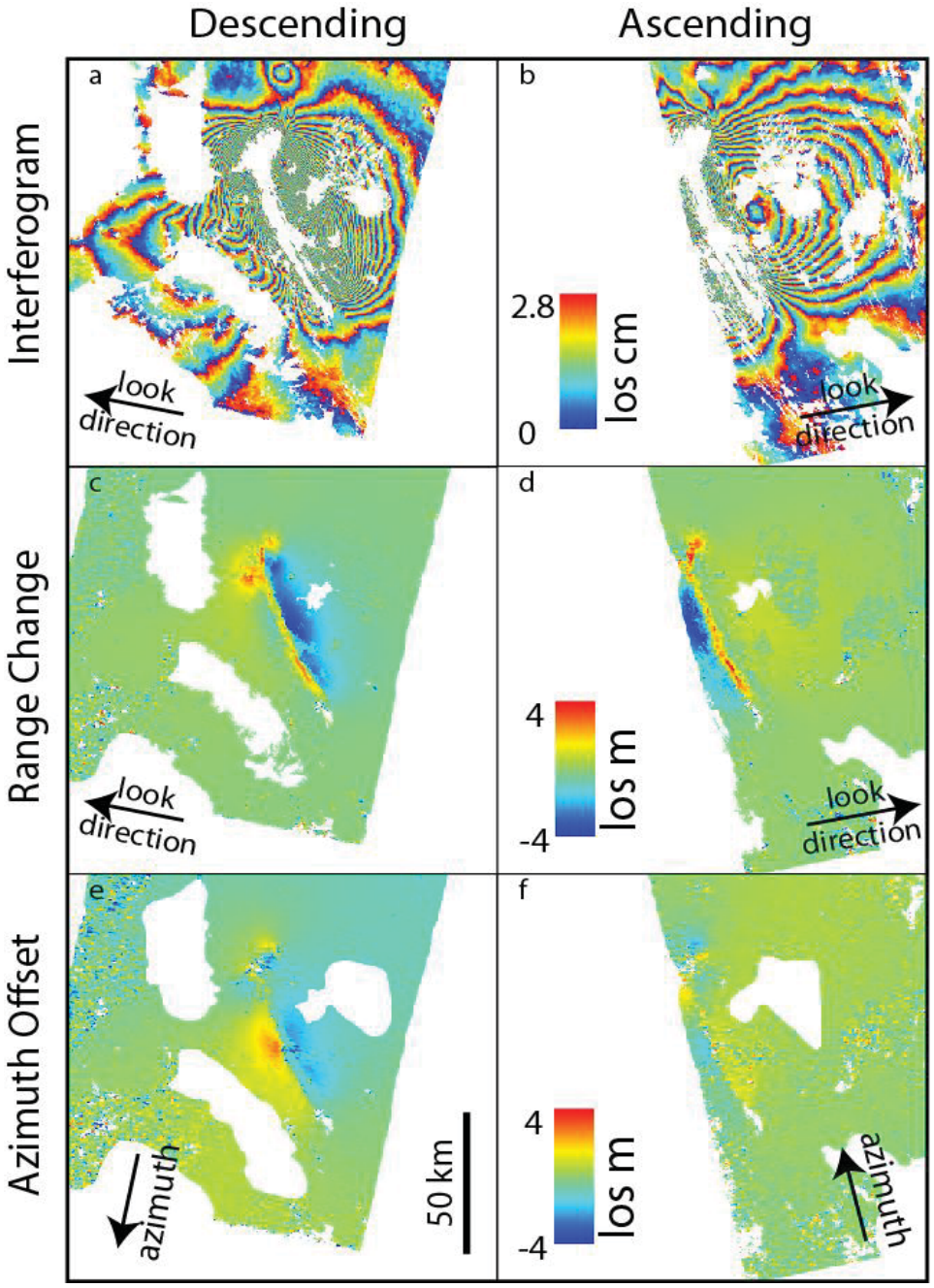

James Hammond, Jan 2006


Liz Baker, March 2006


Liz Baker, March 2006

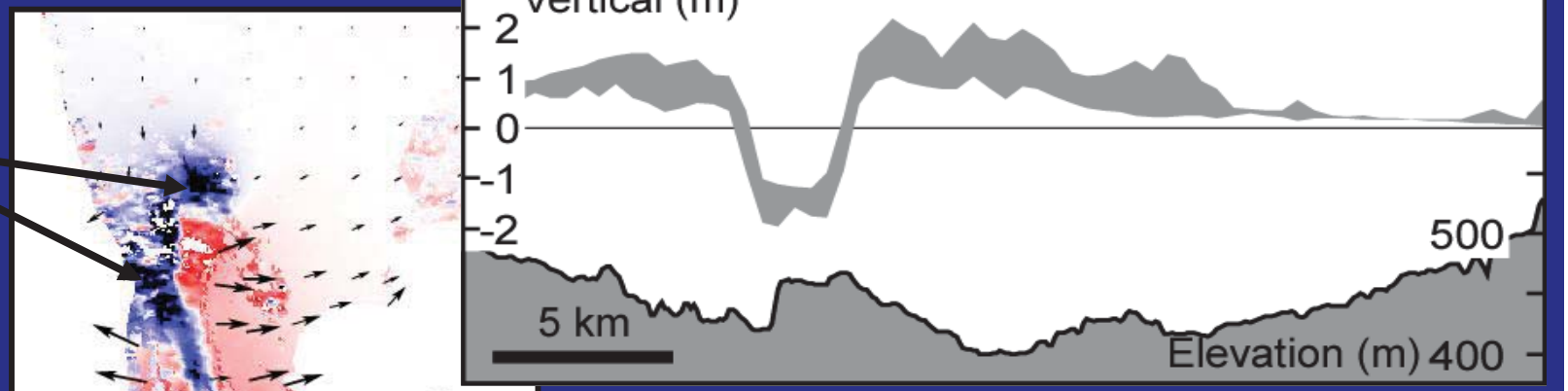

6 May – 28 Oct 2005



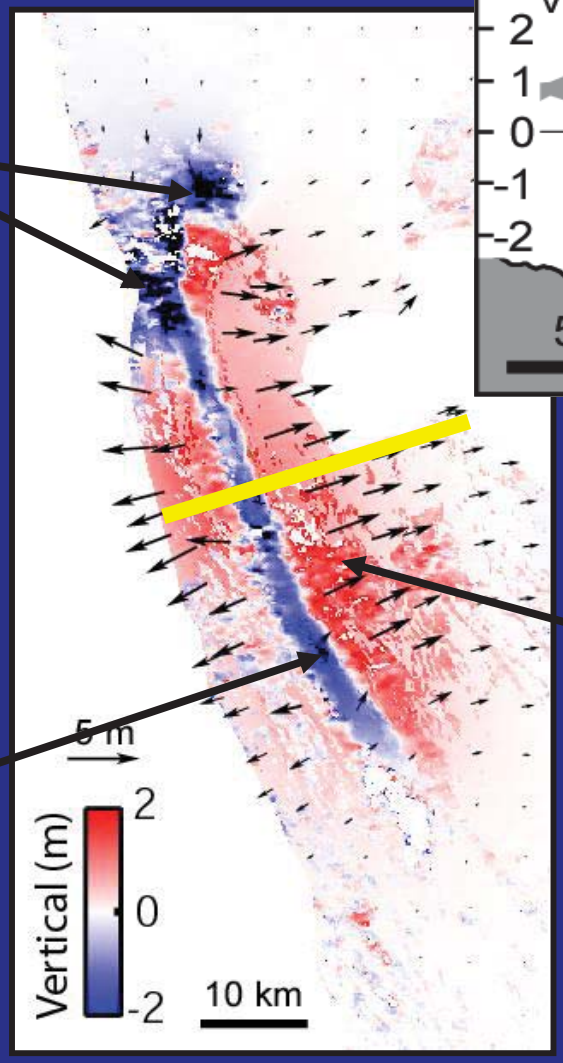


Can combine all data to produce 3D deformation field for rifting event.

3D displacements measured from radar data

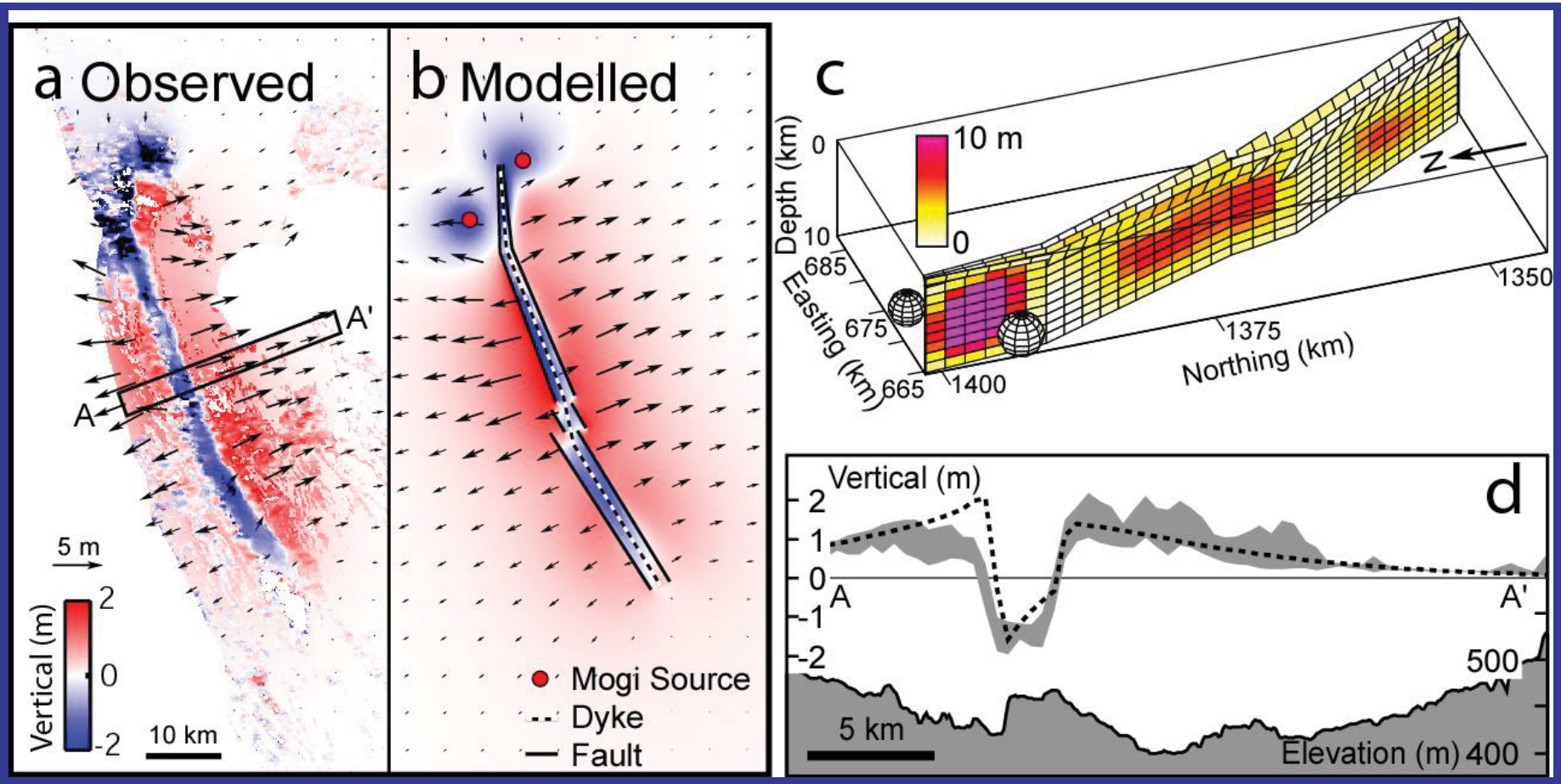


Deflating Magma Chambers



Collapsed Zone along Rift

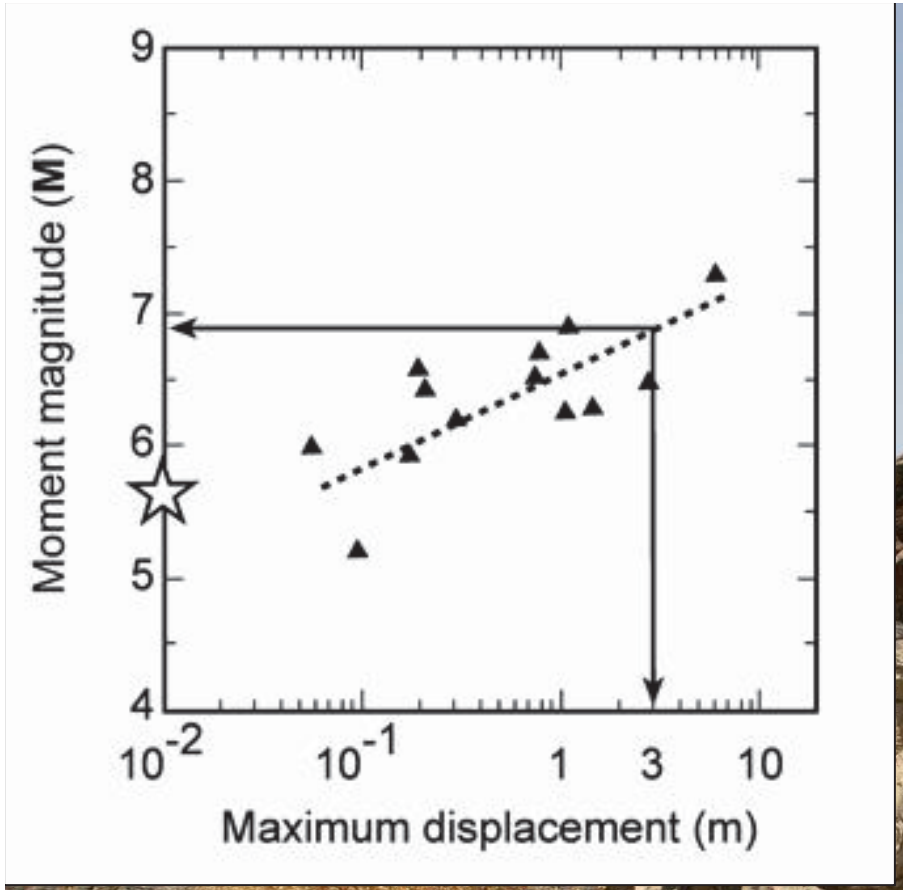
~Symmetrical spreading and flanking uplift



Wright et al., *Nature* 2006

- 2.5 km^3 magma intruded along dyke (Mt St Helens 1980 1.2 km^3; Krafla ~ 1 km^3 total).
- ~0.5 km^3 sourced from Dabbahu and Gabho volcanoes at North.
- Earthquakes can be responsible for < 7 % of moment release.
- Entire rift segment active in single episode.


pre-existing scarp ~ 18m
~3m throw
Eastern Flank (courtesy J. Rowland)

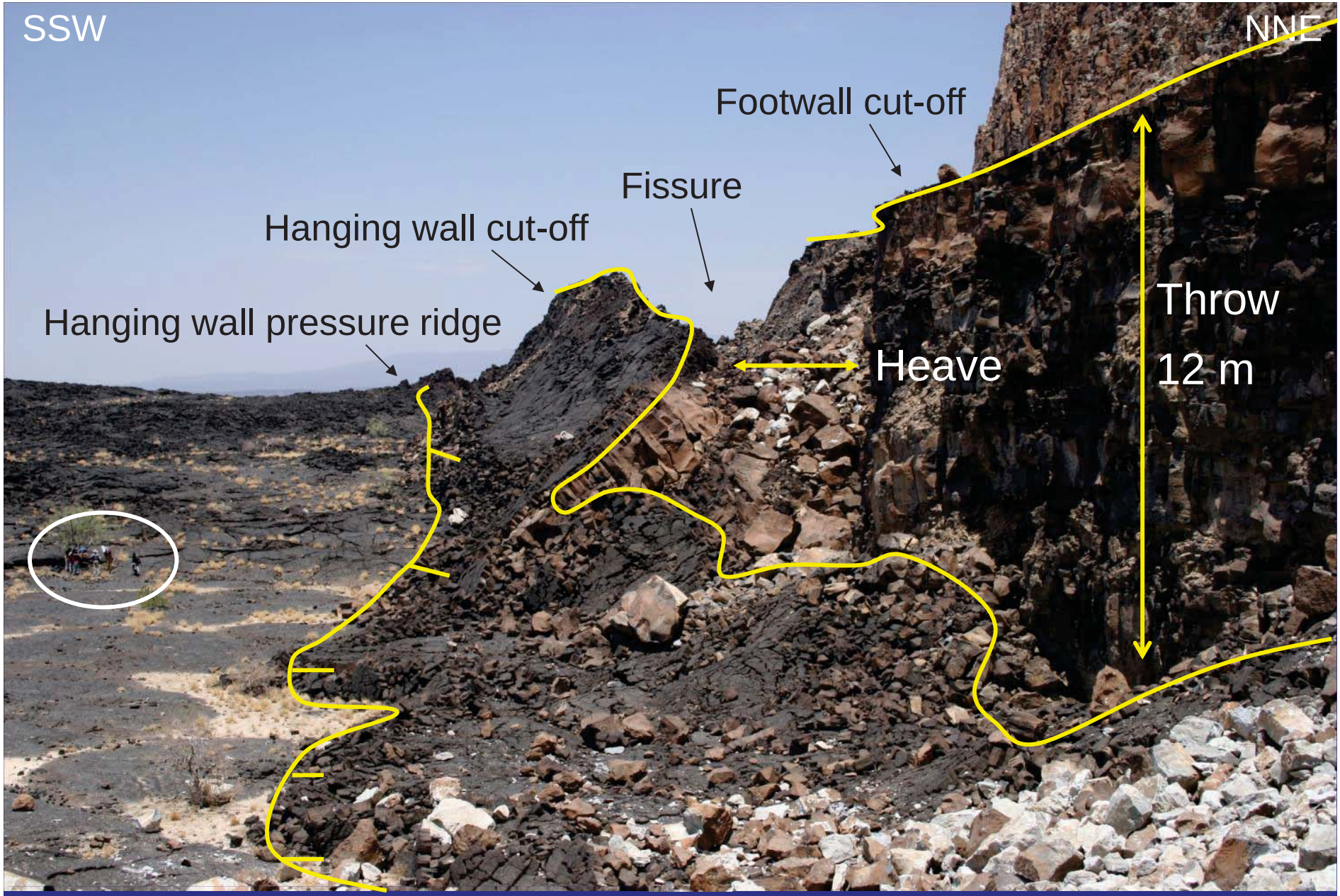


pre-existing scarp

3m

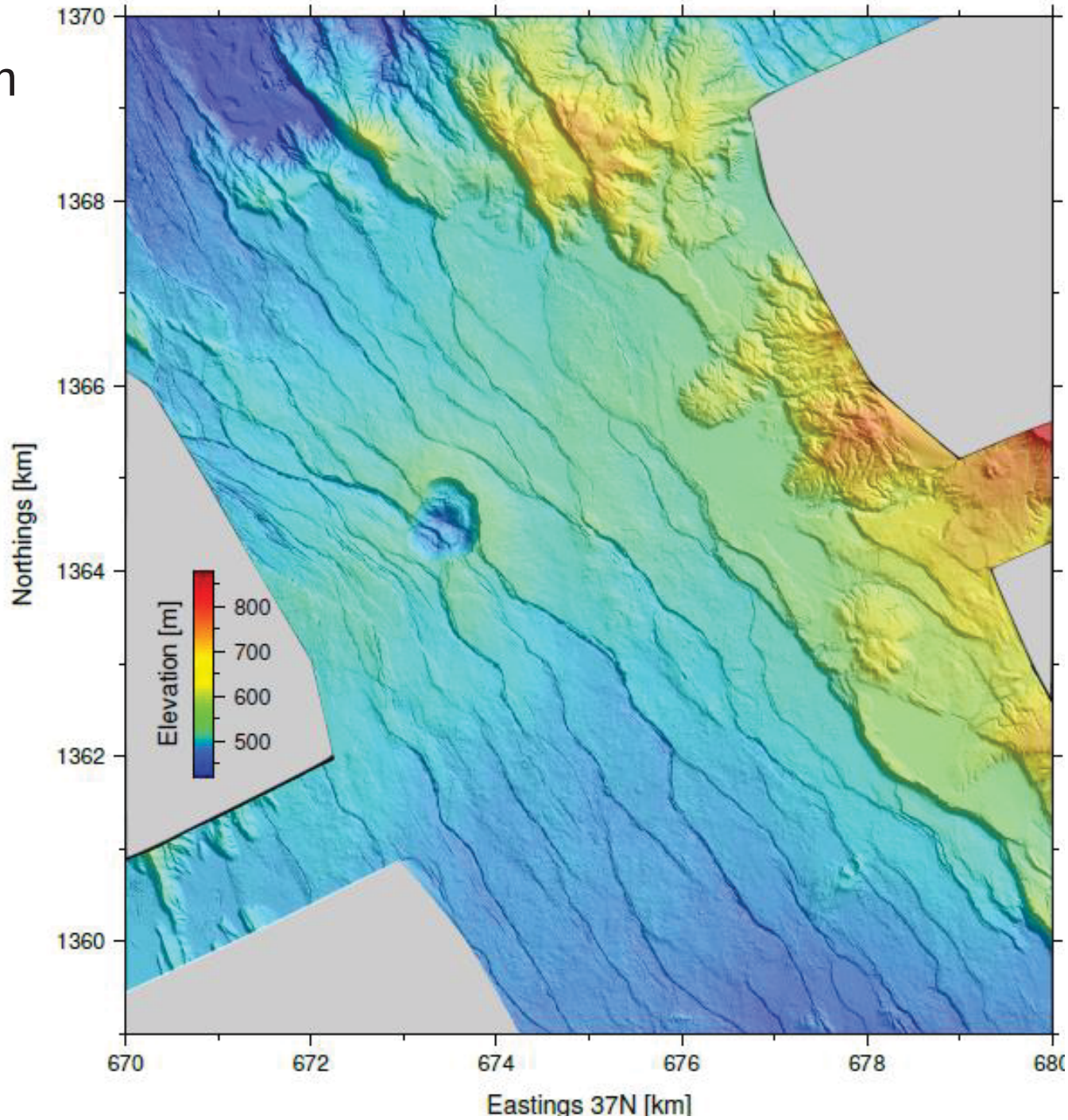
1-2m

Eastern Flank (courtesy J. Rowland)



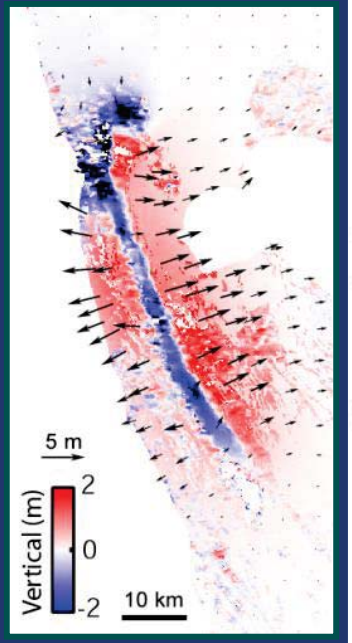
Morphology of normal faults

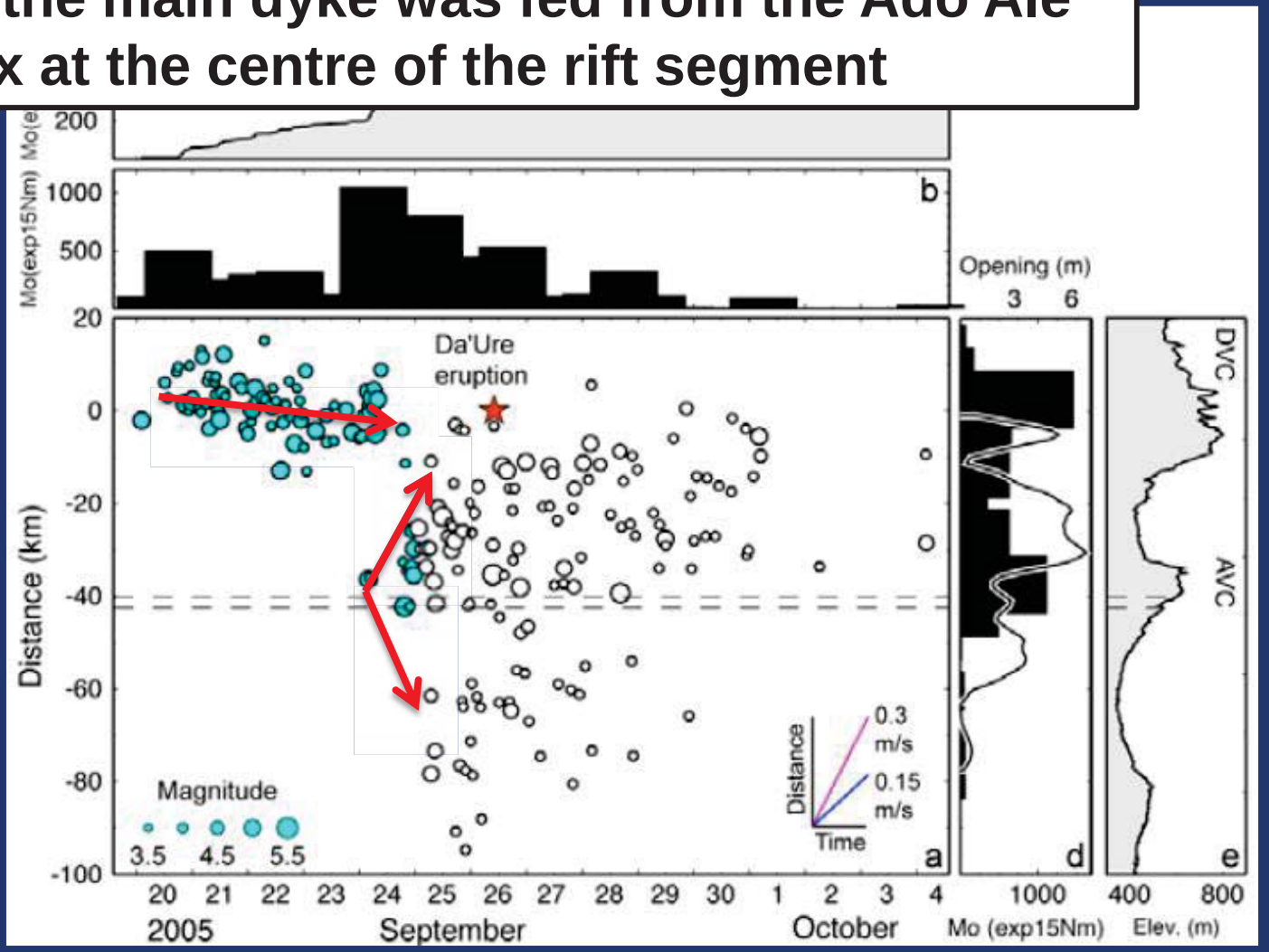
Topography from
LiDAR
~1 m resolution
October 2009



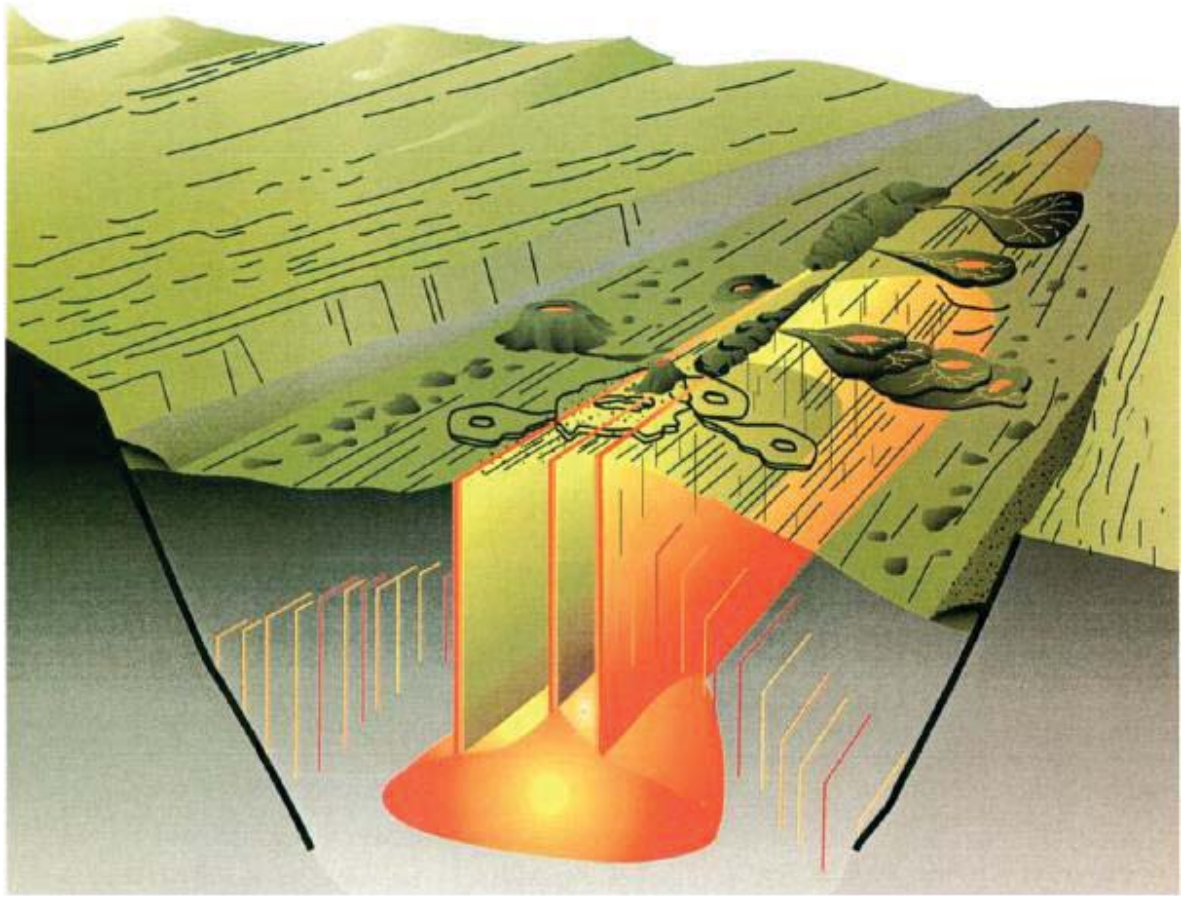
Ayele et al (GRL 2009) changes the story

Most of the main dyke was fed from the Ado Ale Complex at the centre of the rift segment

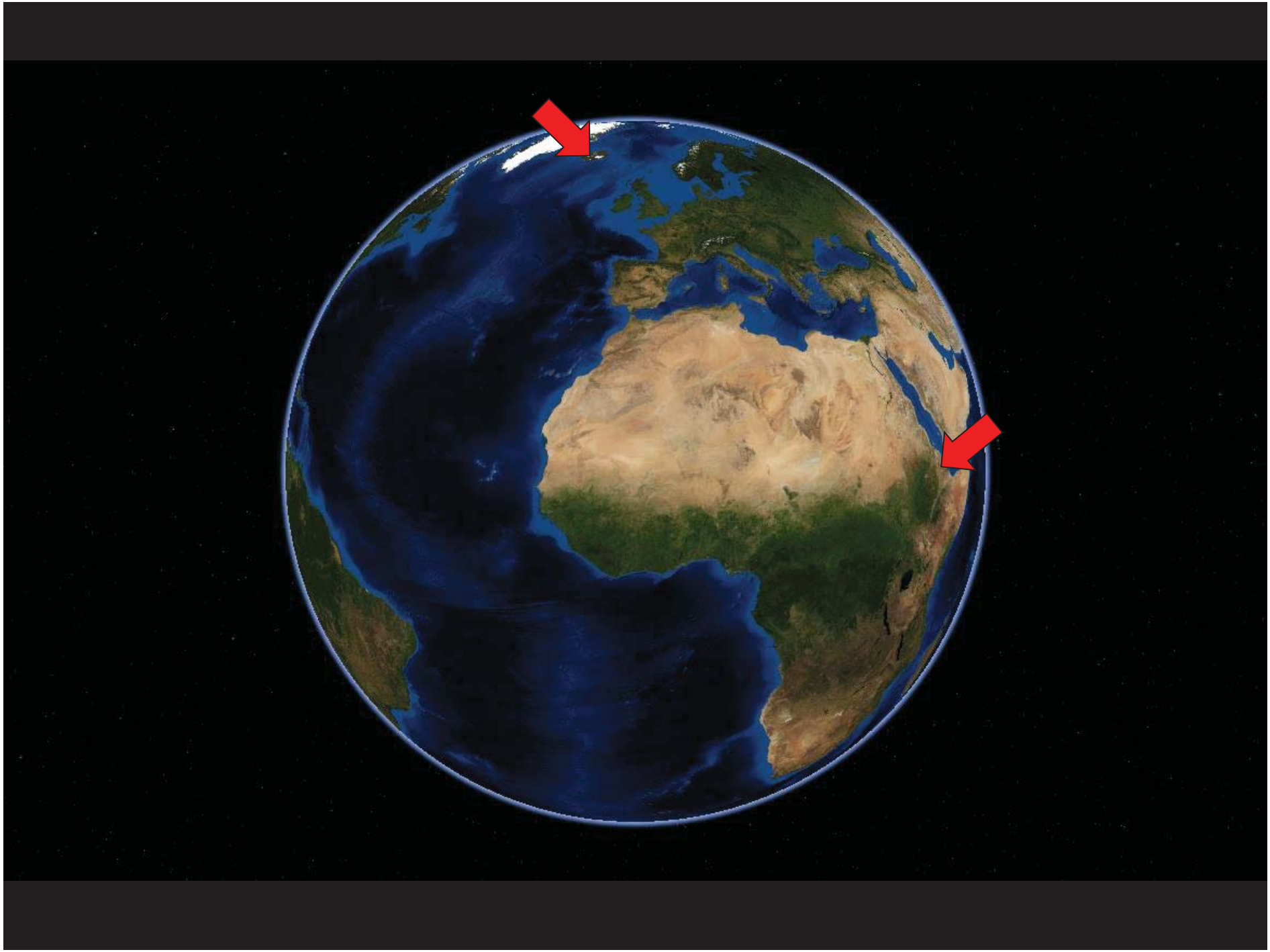


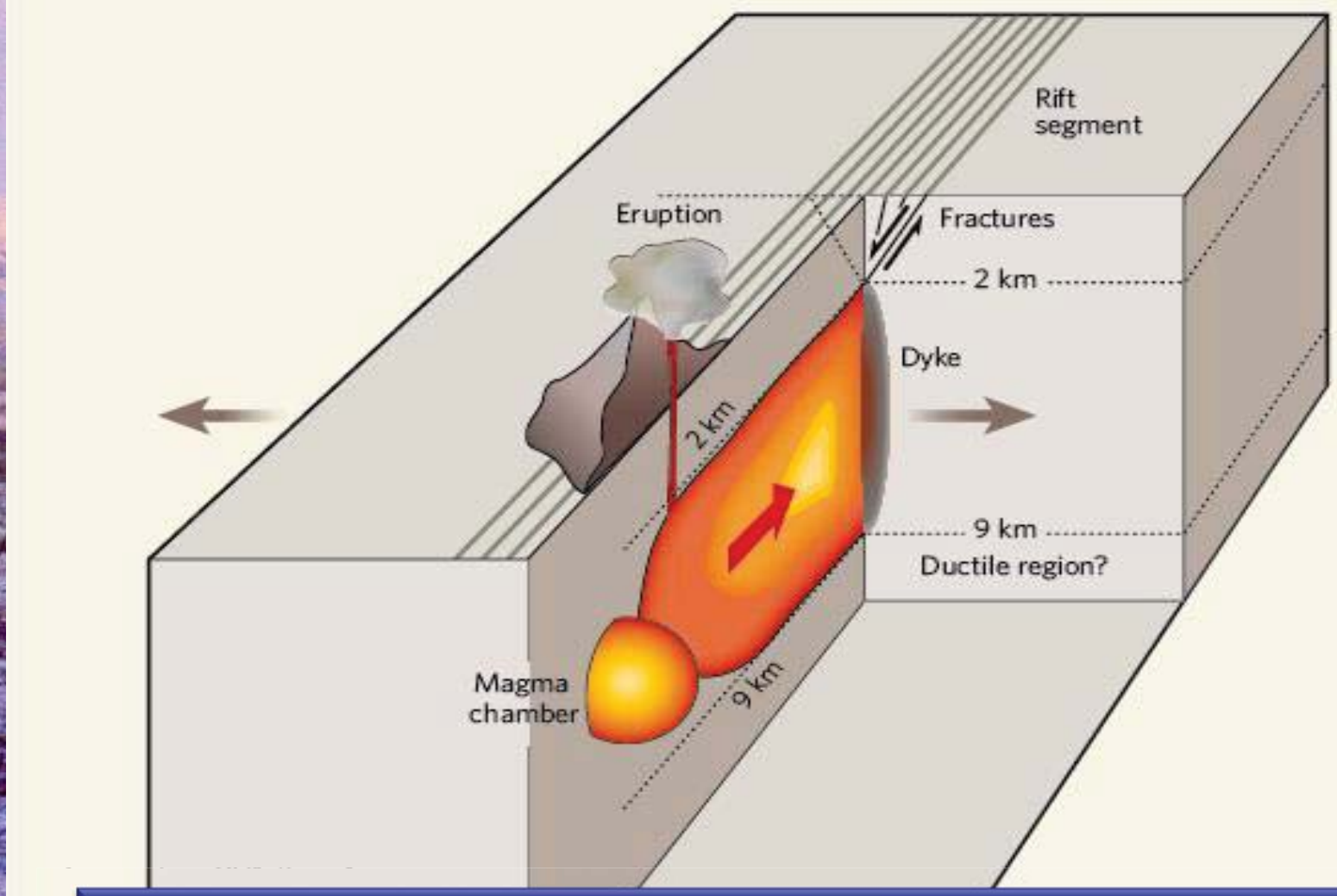


Mid-Atlantic Ridge – slow spreading rate
(Smith and Cann, JGR 1999)



Models derived from direct observations, but influenced dynamics at analogues above sea level (Hawaii, and …)



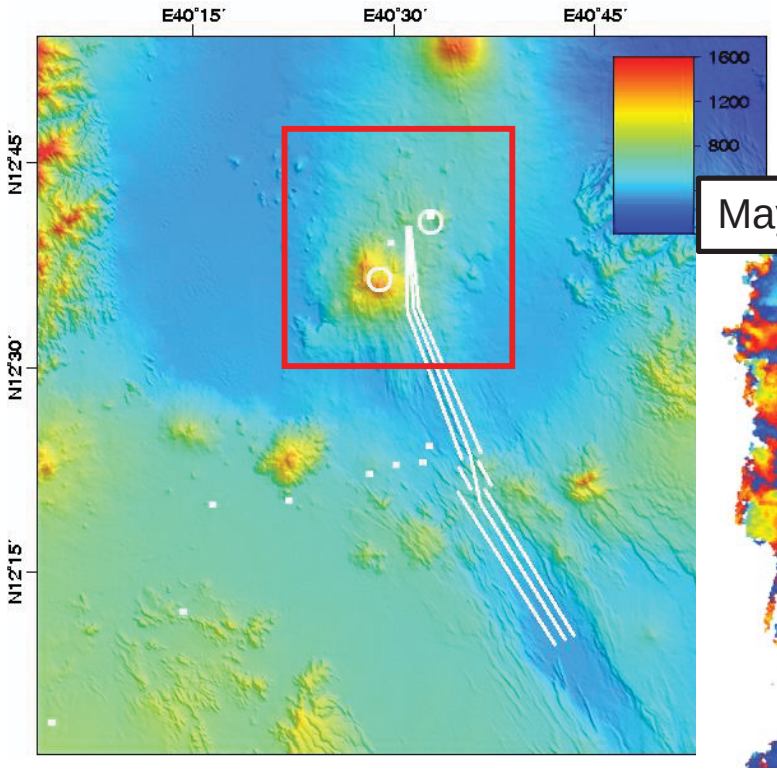


Is the plumbing system at Krafla a good analogue for Afar?

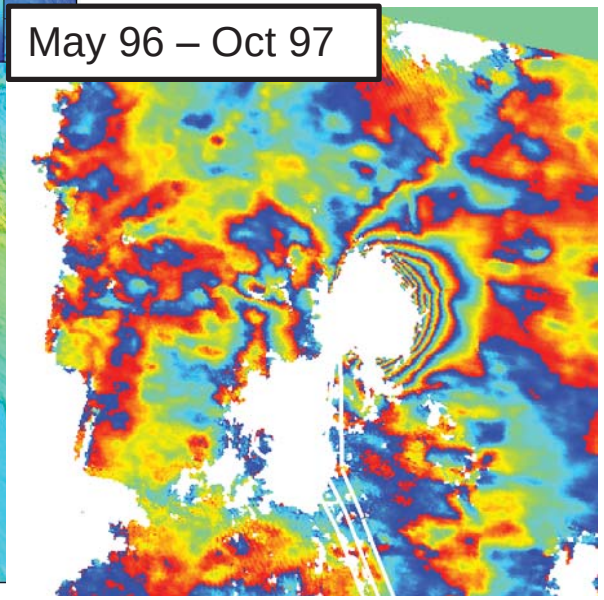
06

Thorarinsson September 8, 1977

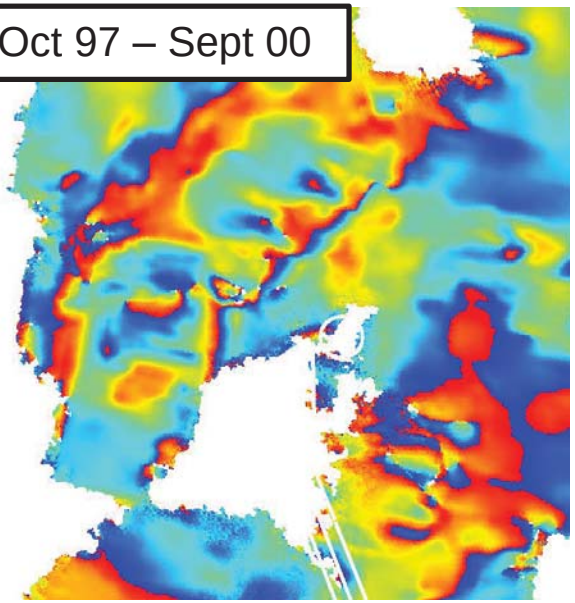
“Pre-episode” deformation



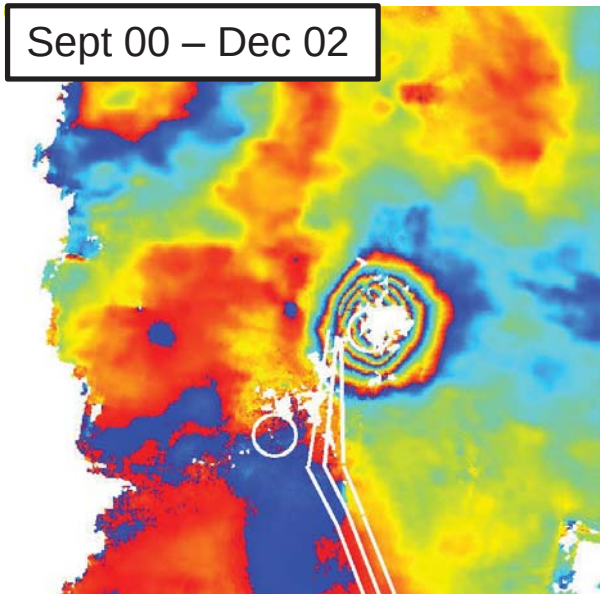
May 96 – Oct 97



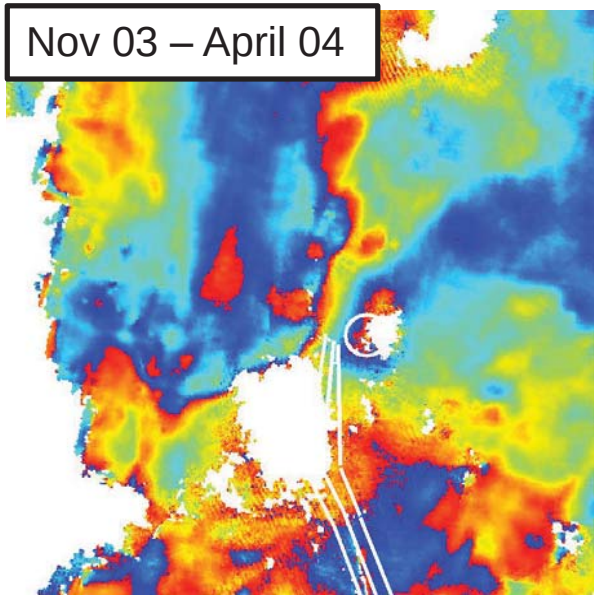
Oct 97 – Sept 00



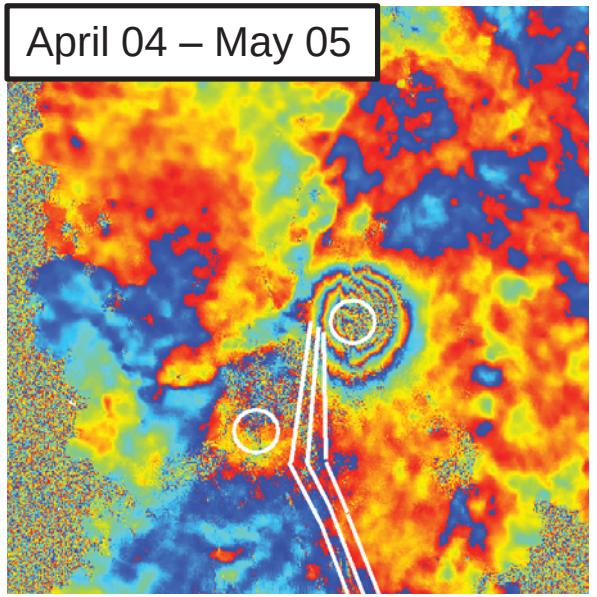
Sept 00 – Dec 02



Nov 03 – April 04



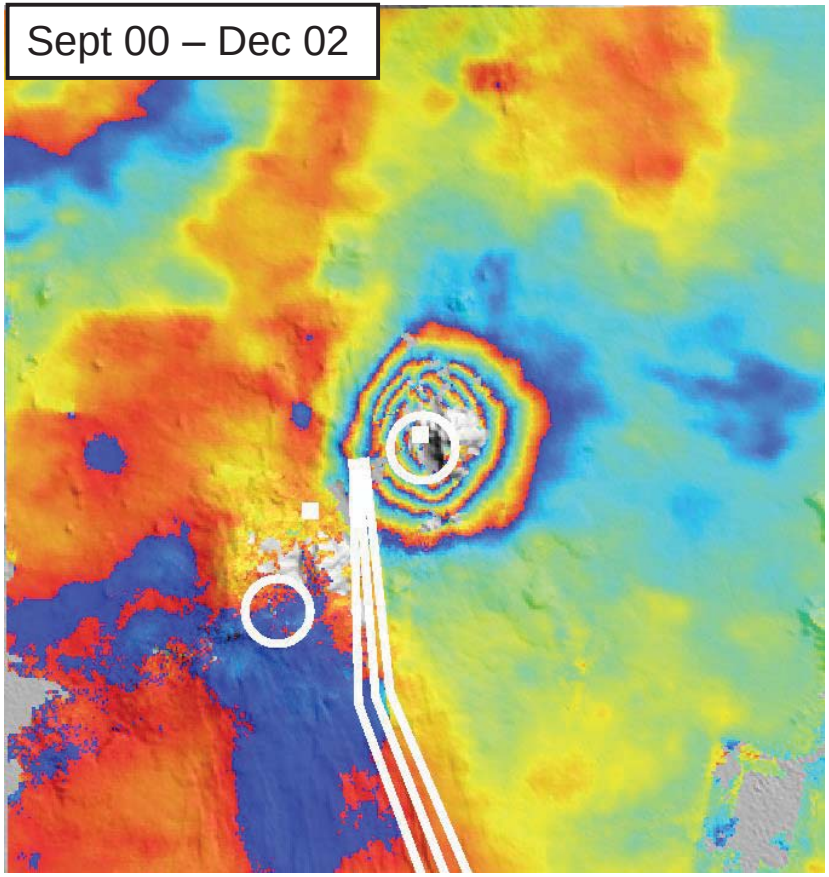
April 04 – May 05

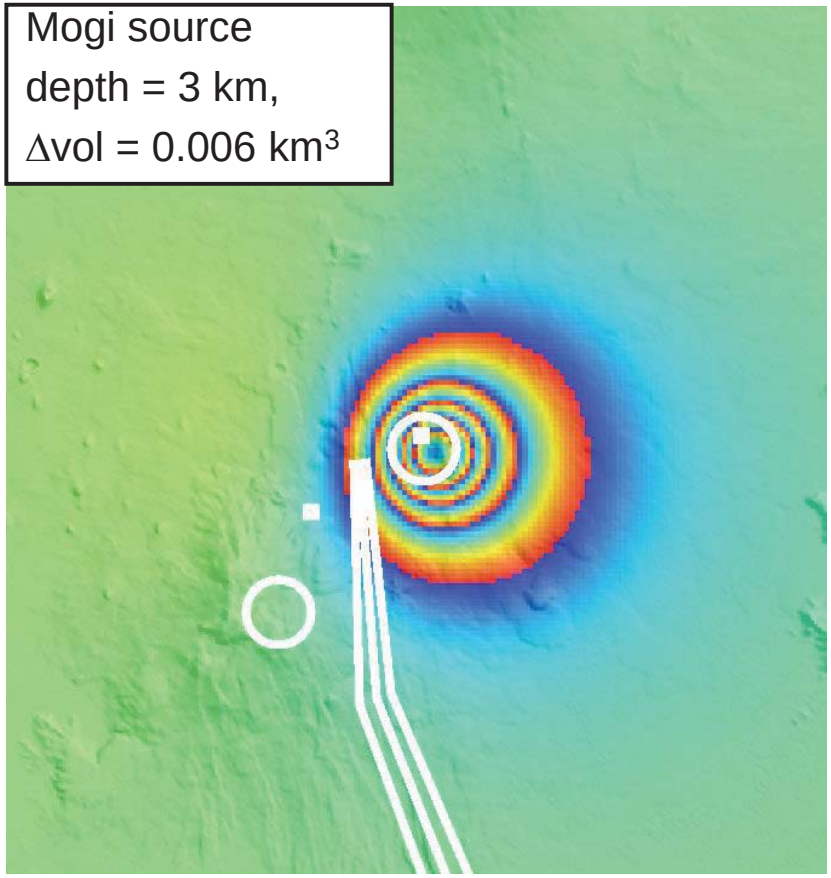


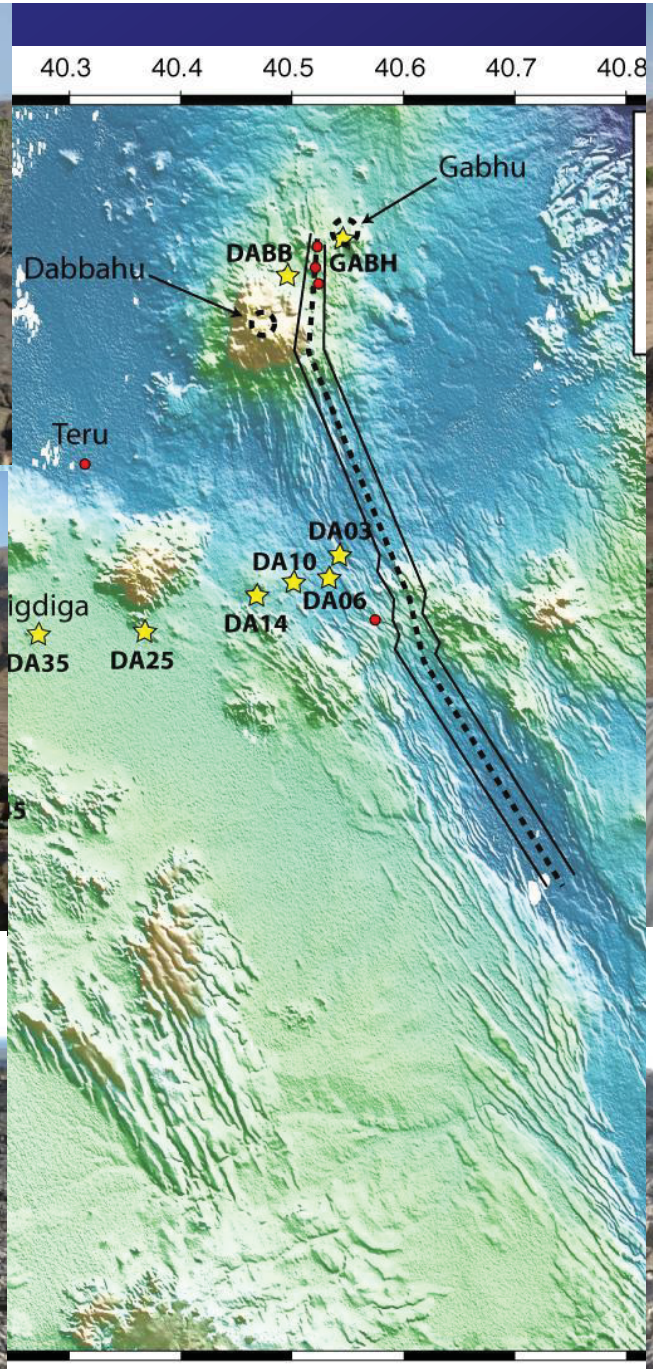
Episodic pre-episode deformation (uplift).

Events consistent with Magma chamber at ~3 km

Total influx Sept 00 – Sept 05 > 0.012 km^3






40.3
40.4
40.5
40.6
40.7
40.8
Gabhu
Dabbahu
DABB
GABH
Teru
DA03
DA10
DA06
DA14
igdiga
DA35
DA25

The Afar Rift Consortium

http://www.see.leeds.ac.uk/afar

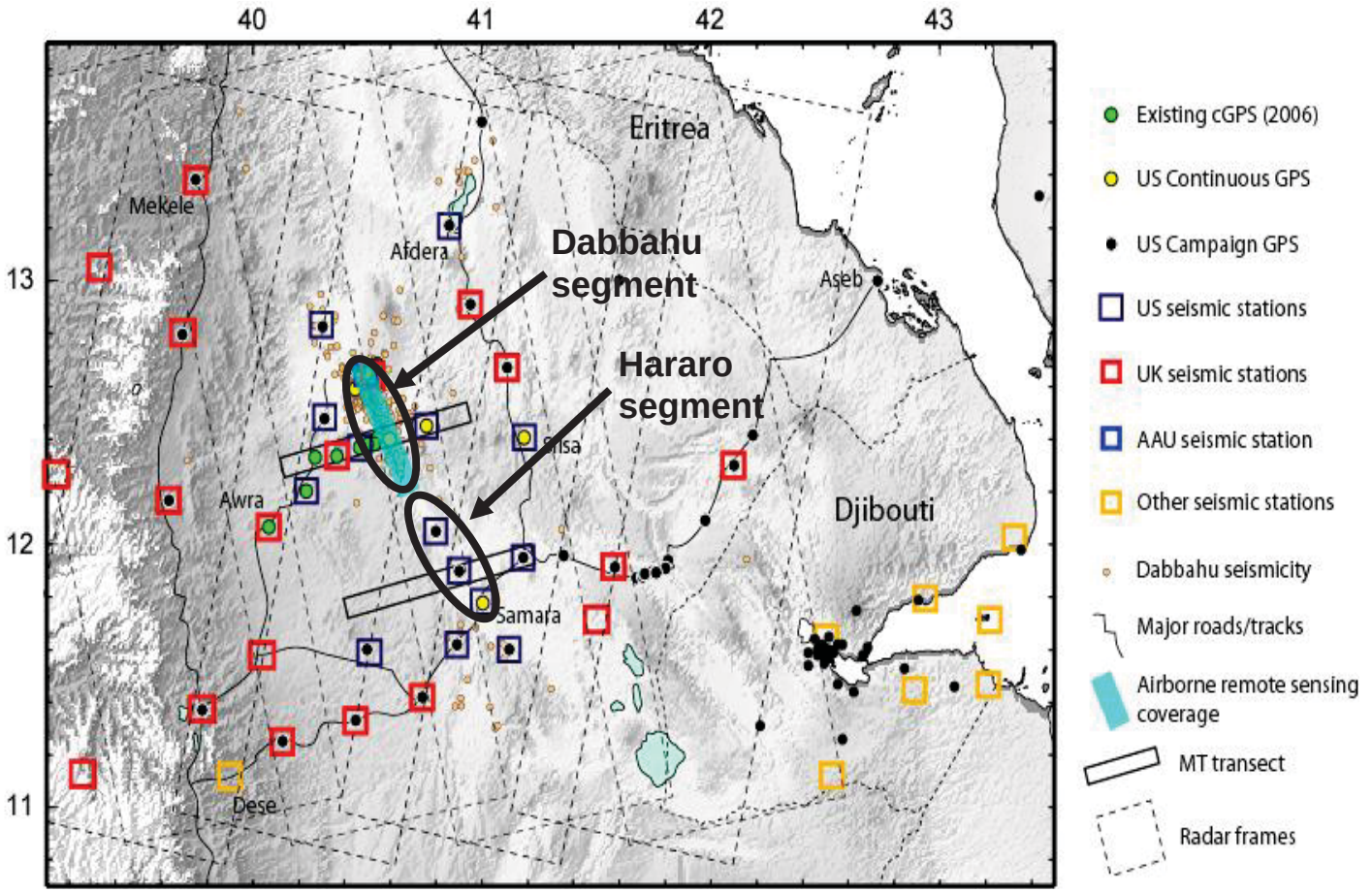
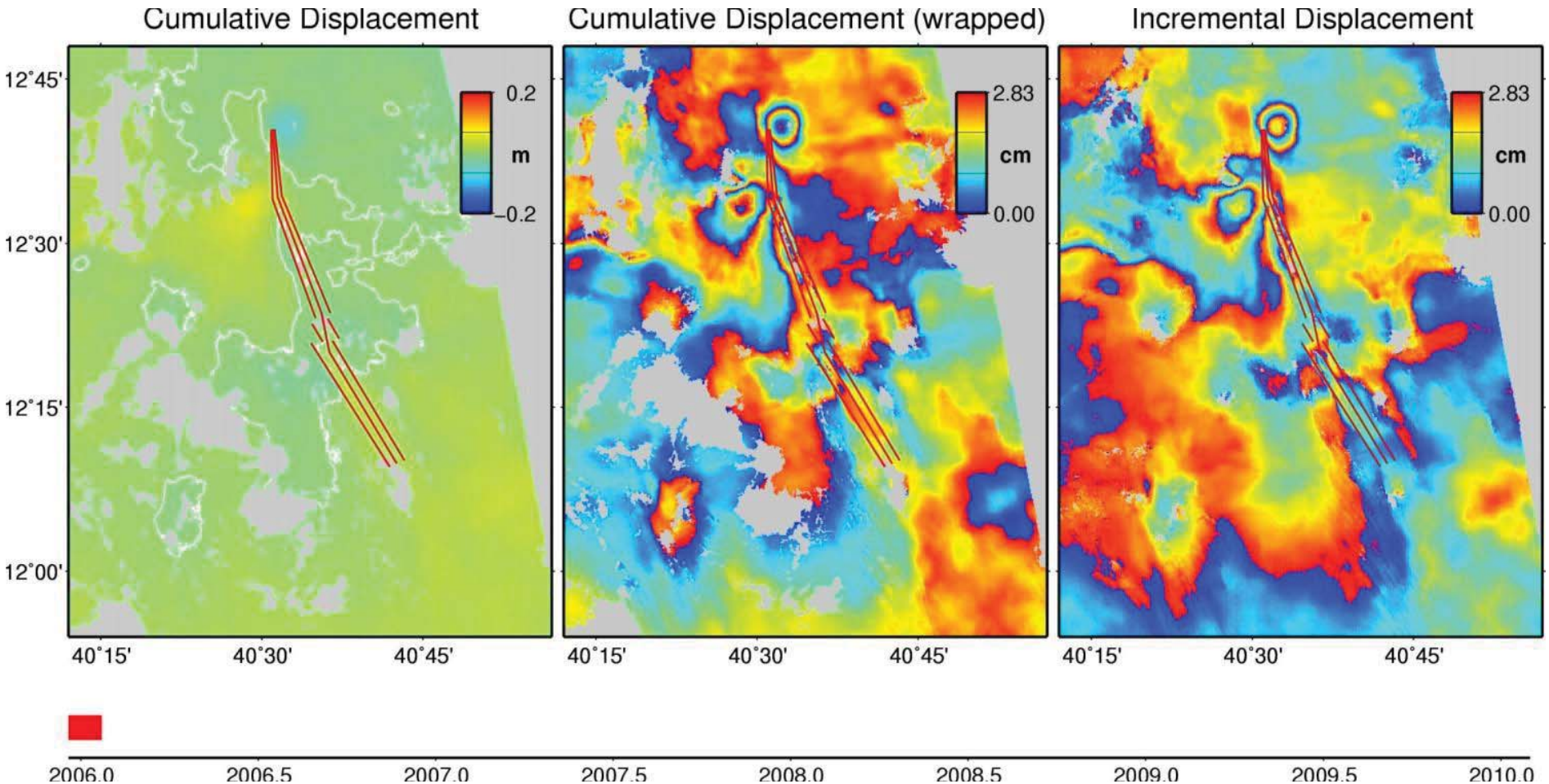


Photo: E. Calais, January 2006

Post-intrusion deformation – Track 300



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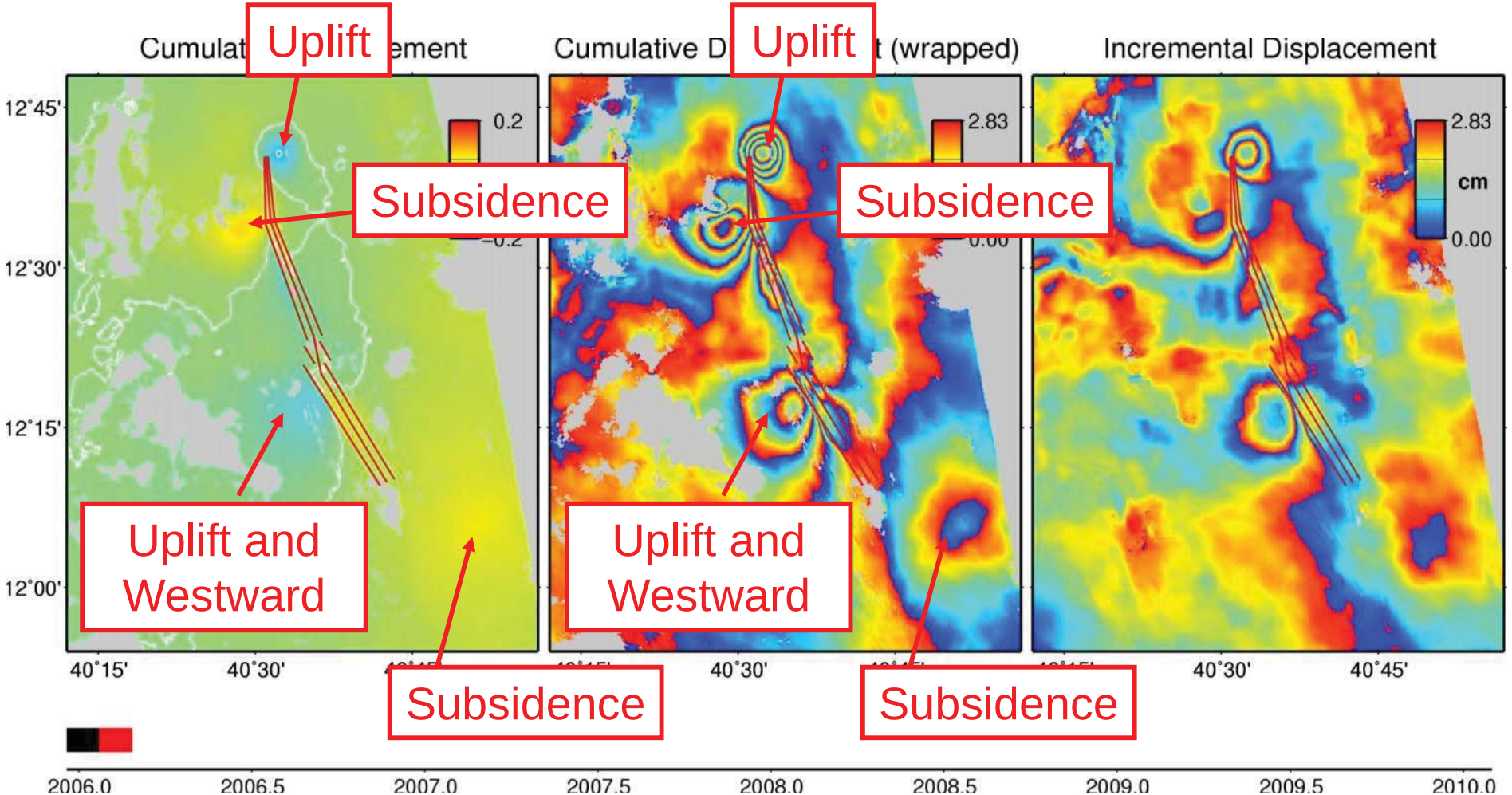

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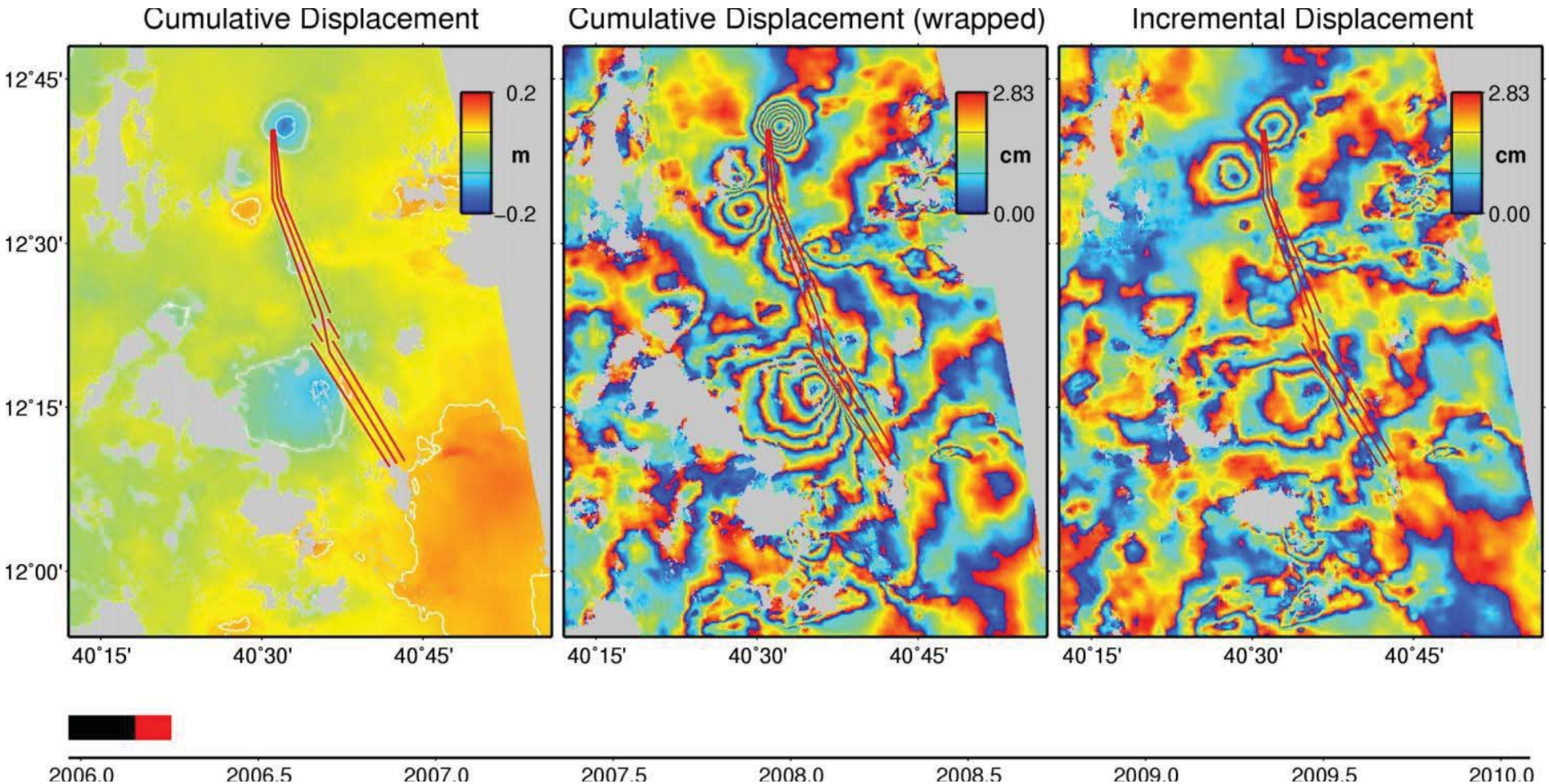
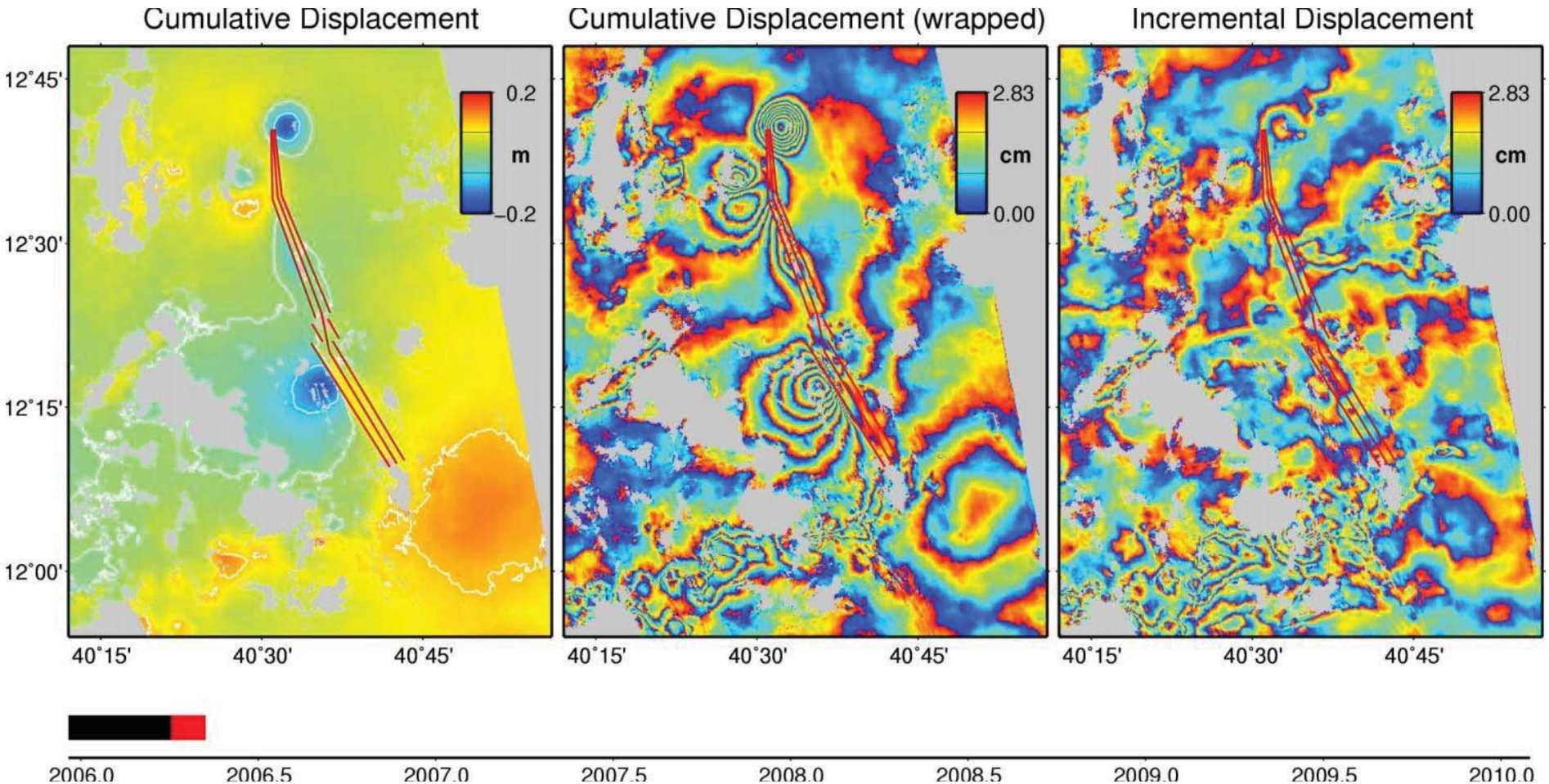


Post-intrusion deformation – Track 300



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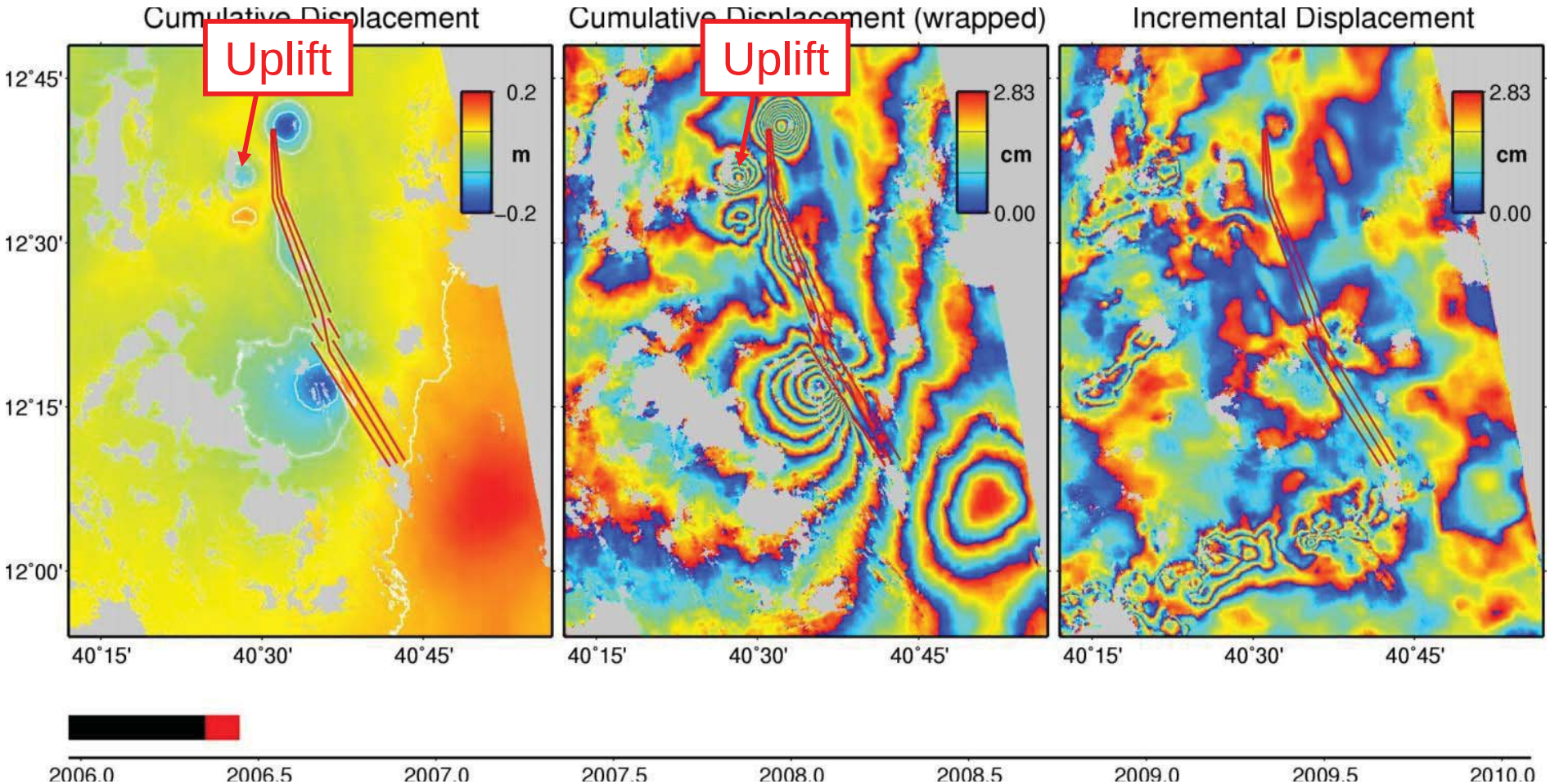
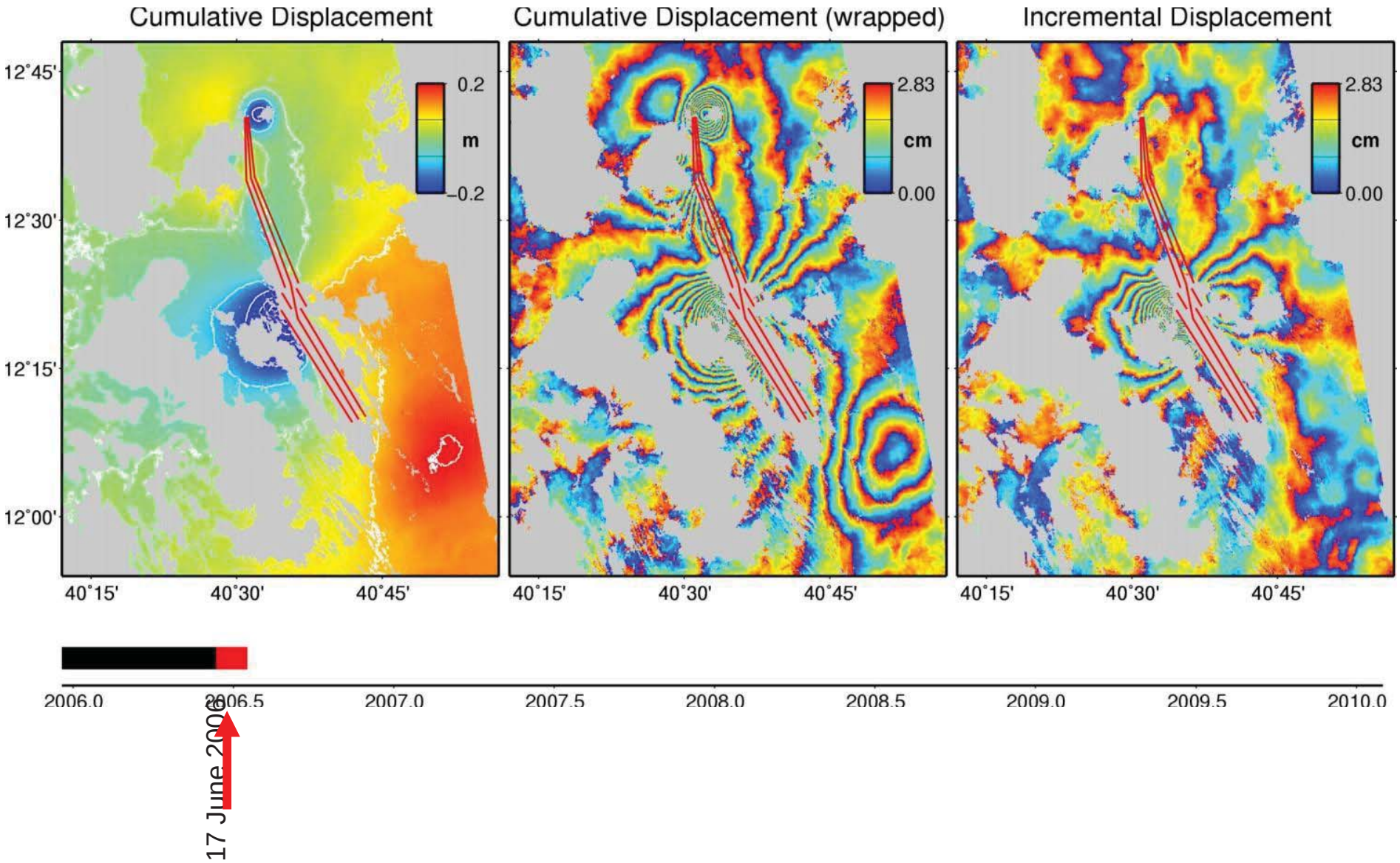
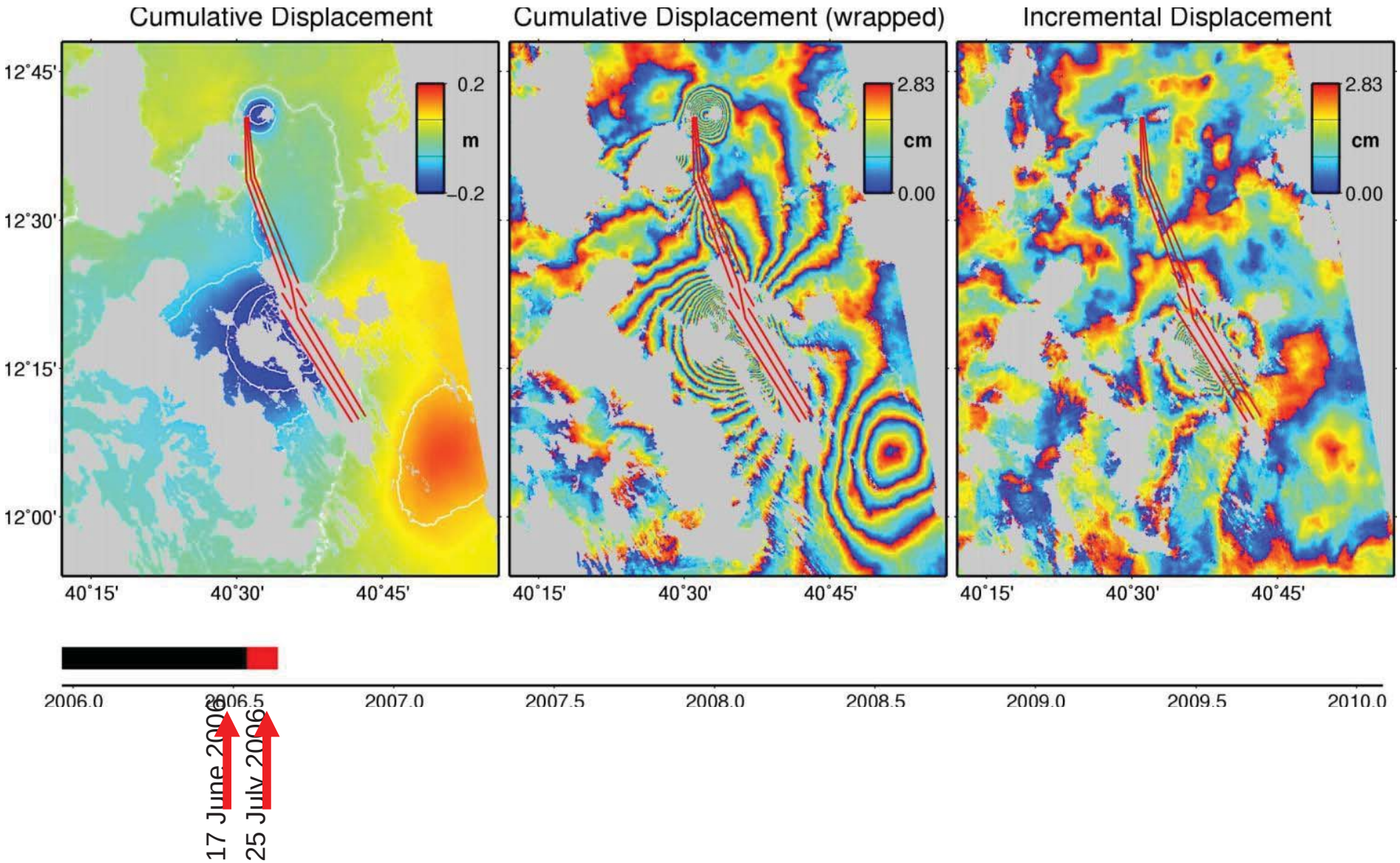


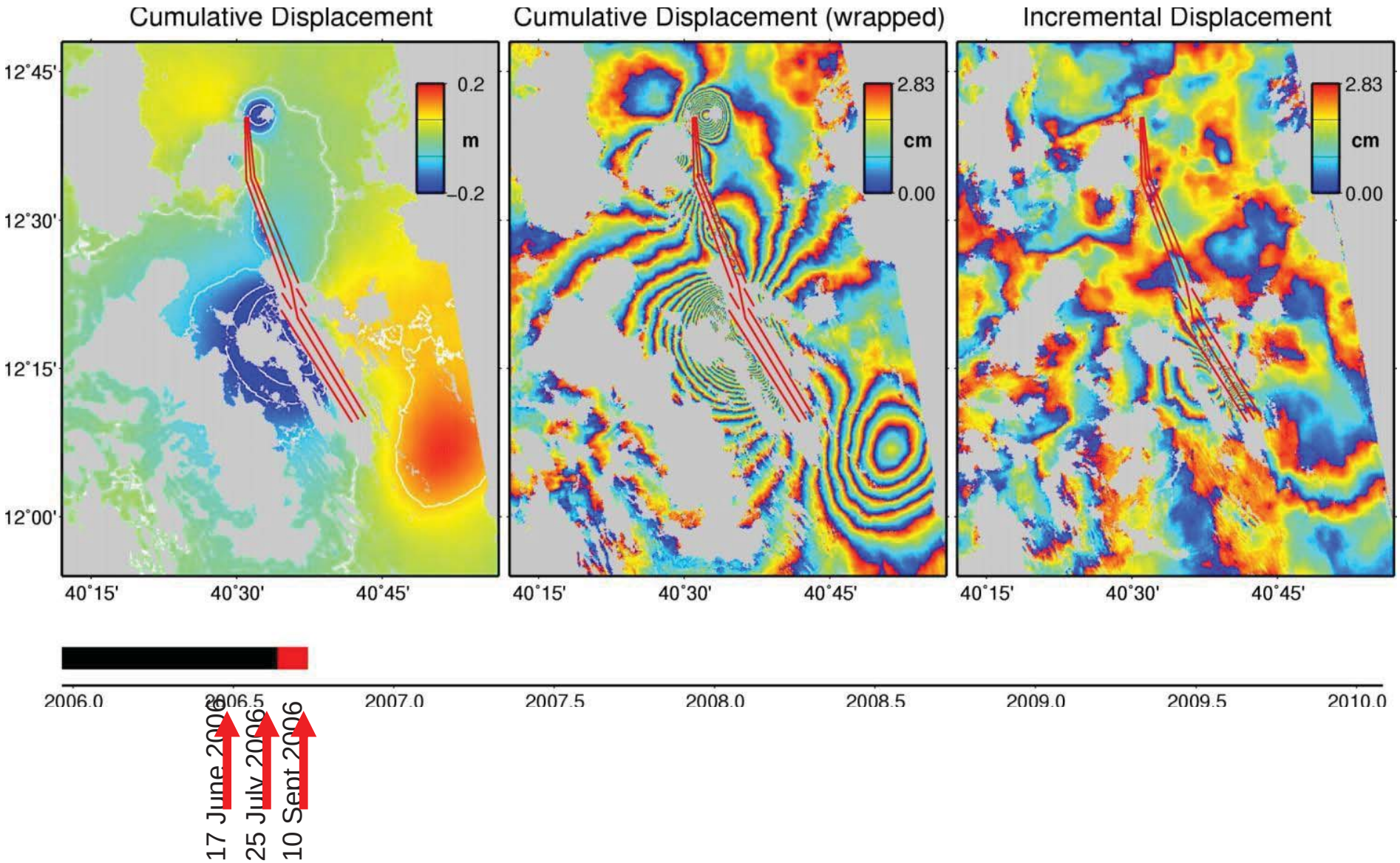
Post-intrusion deformation – Track 300



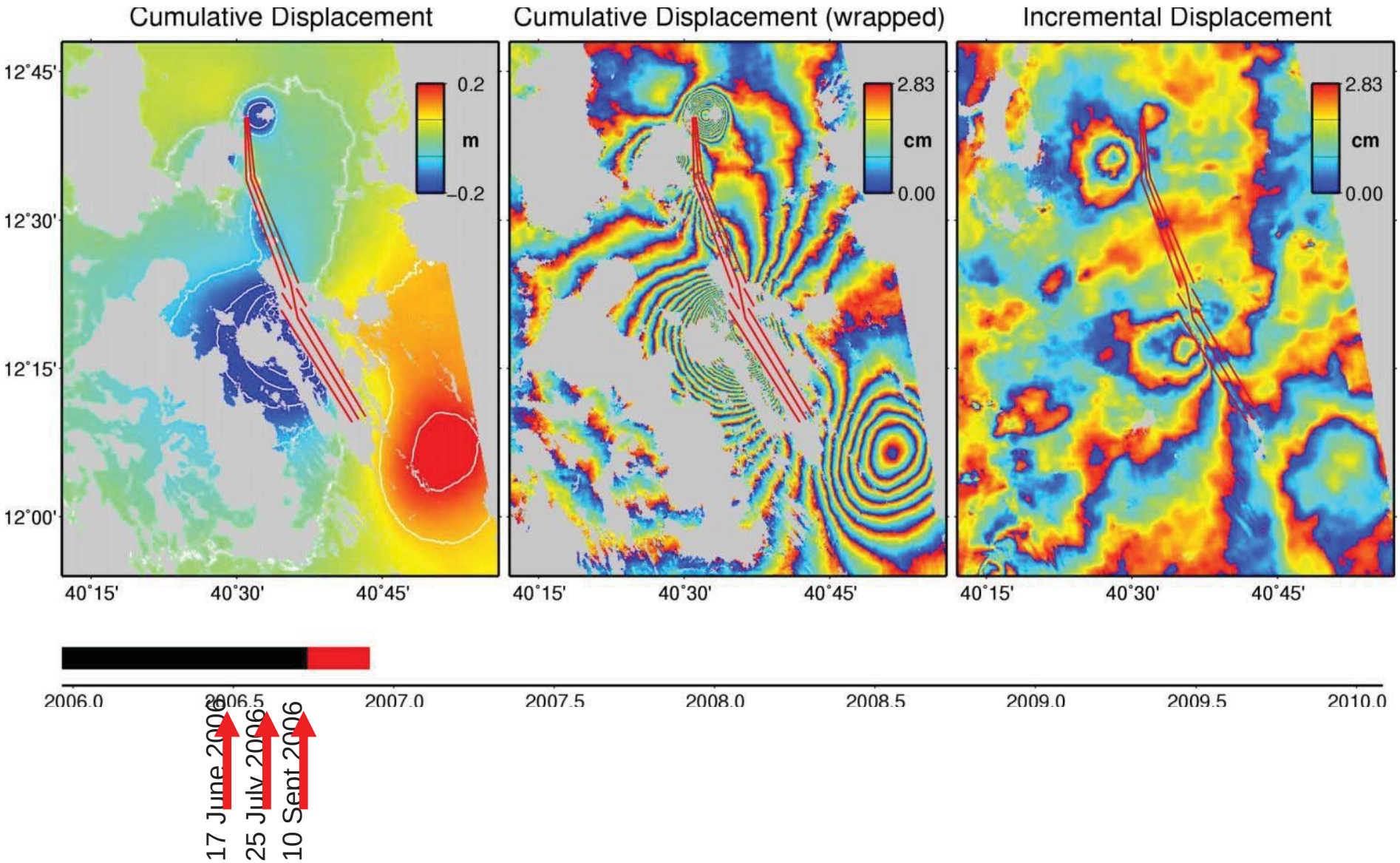
Post-intrusion deformation – Track 300



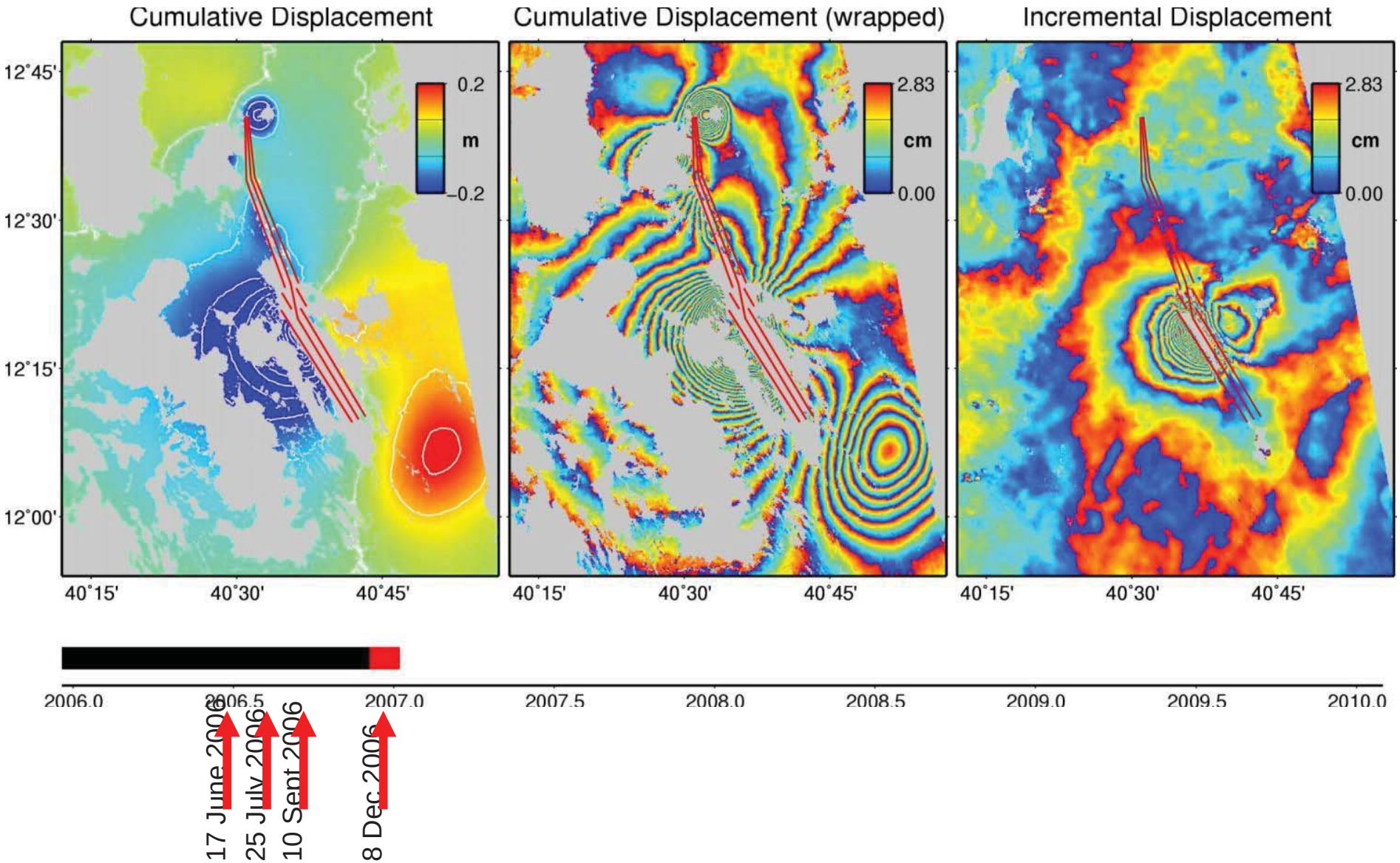
Post-intrusion deformation – Track 300



Post-intrusion deformation – Track 300



Post-intrusion deformation – Track 300



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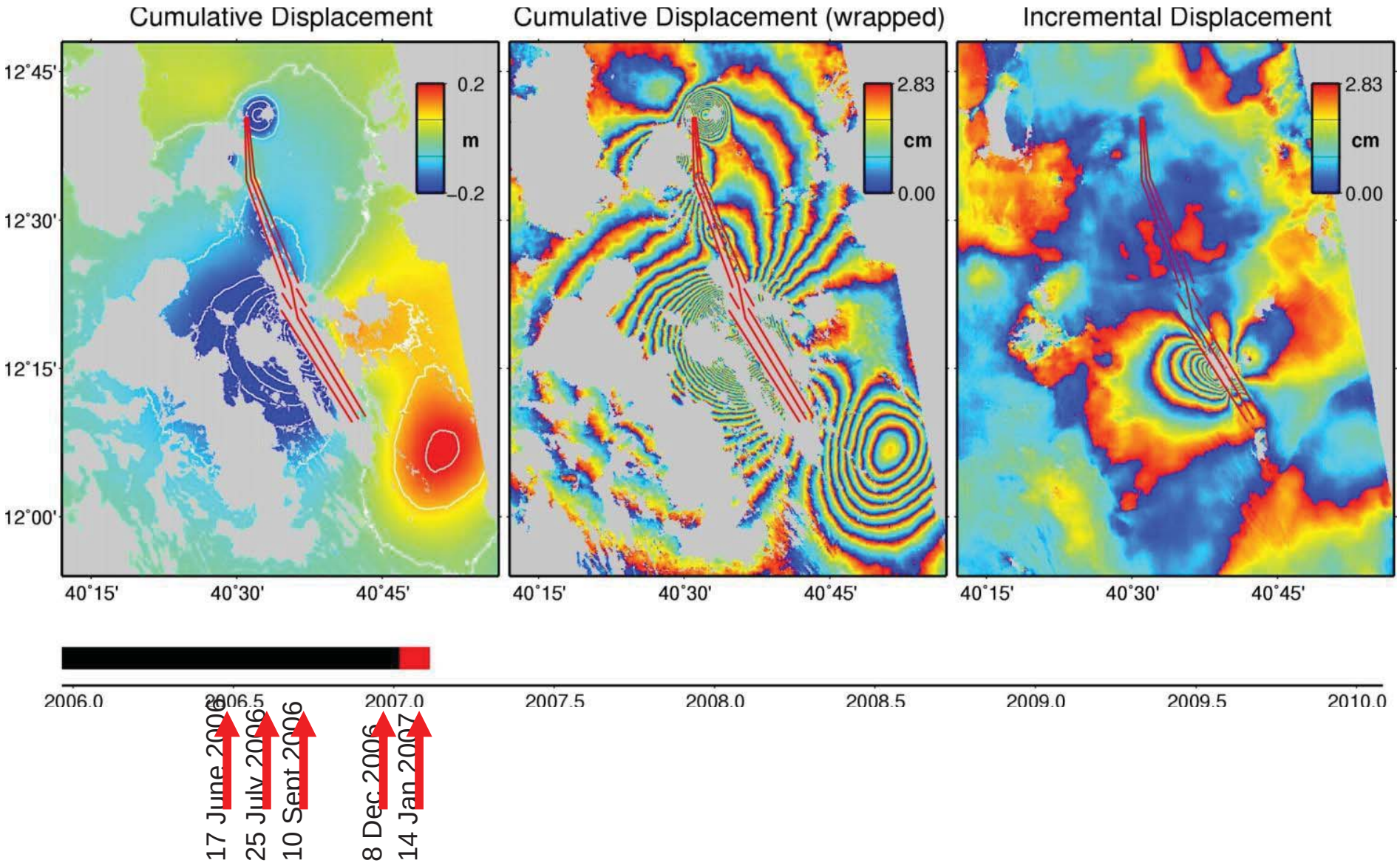

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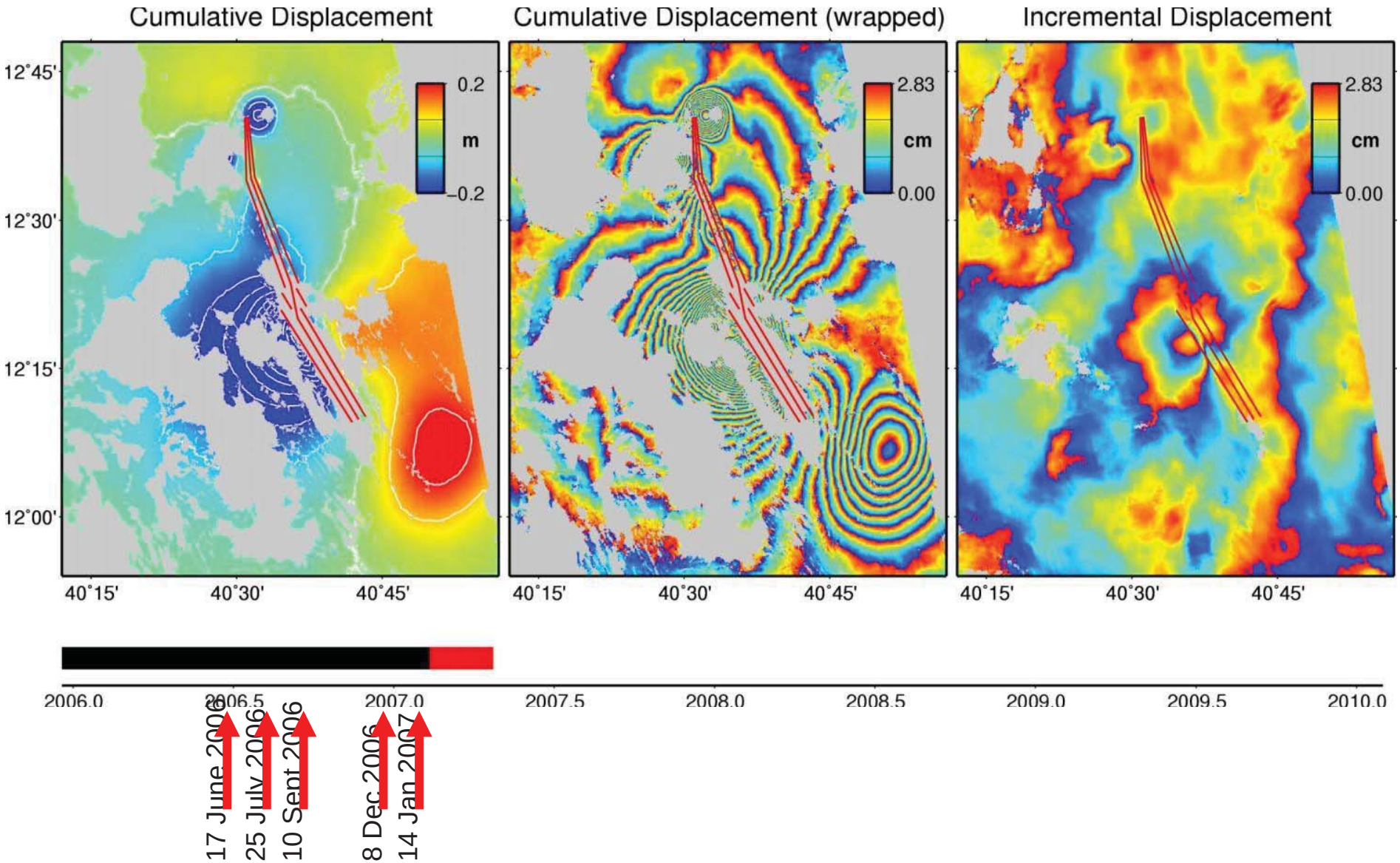

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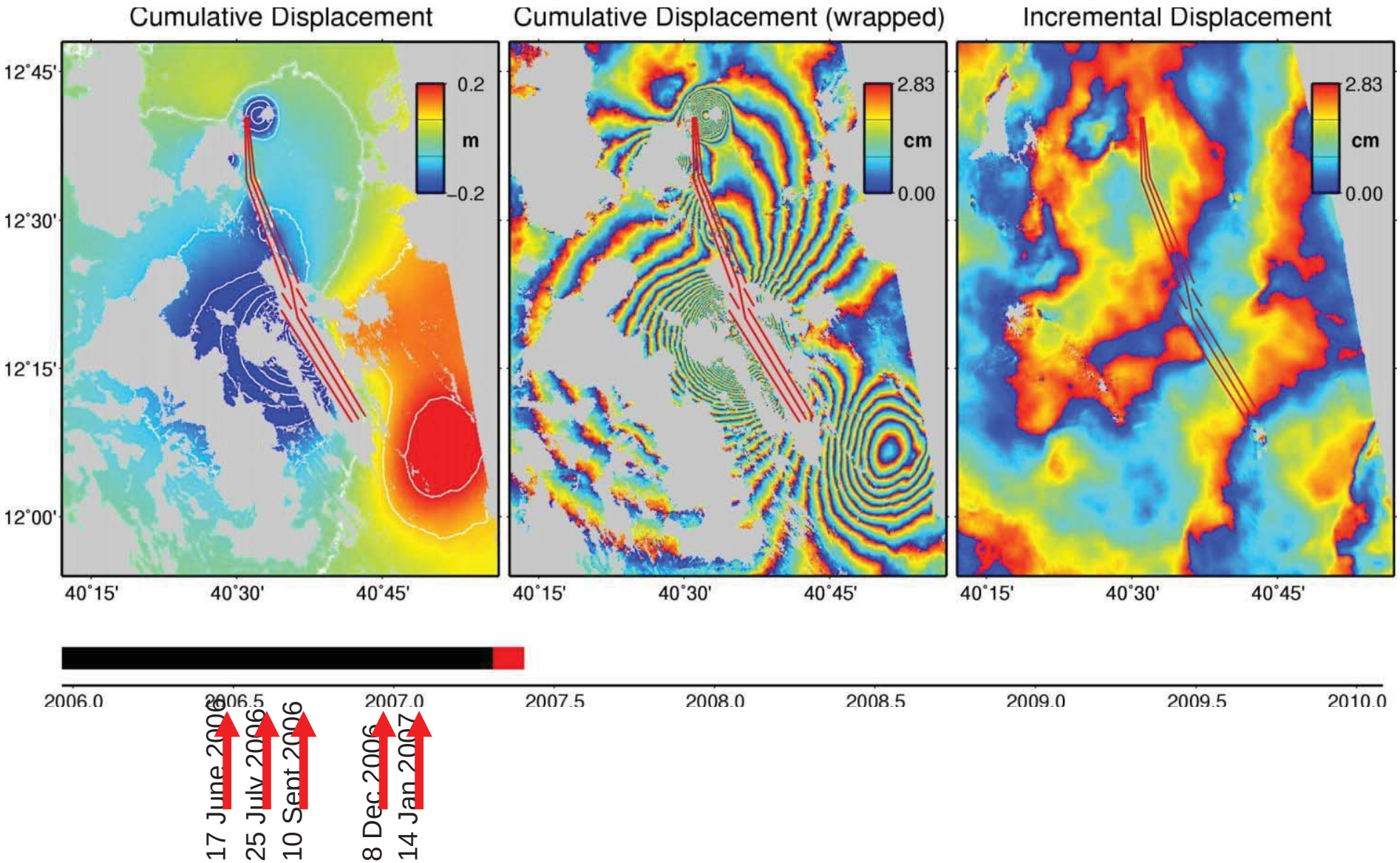

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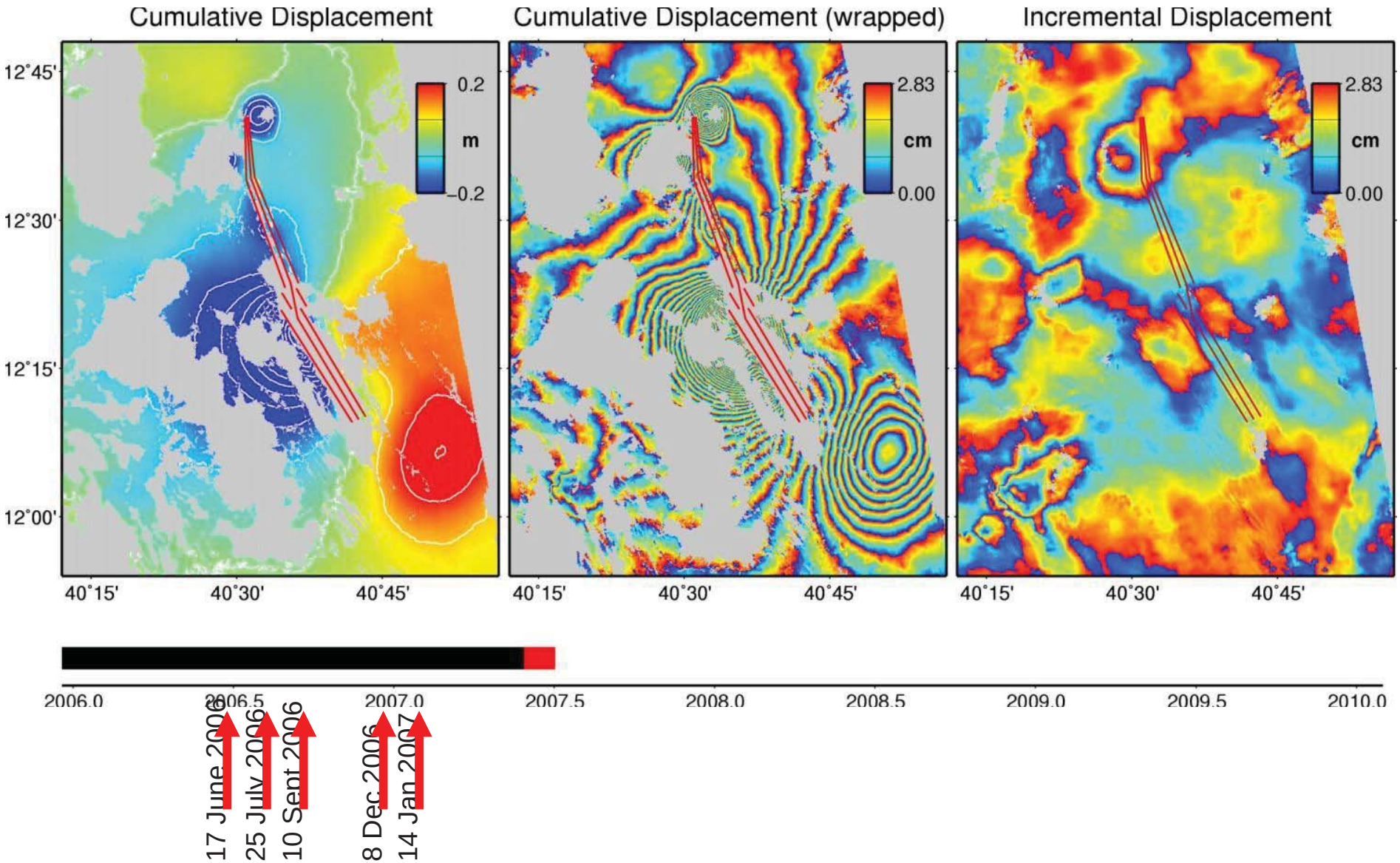

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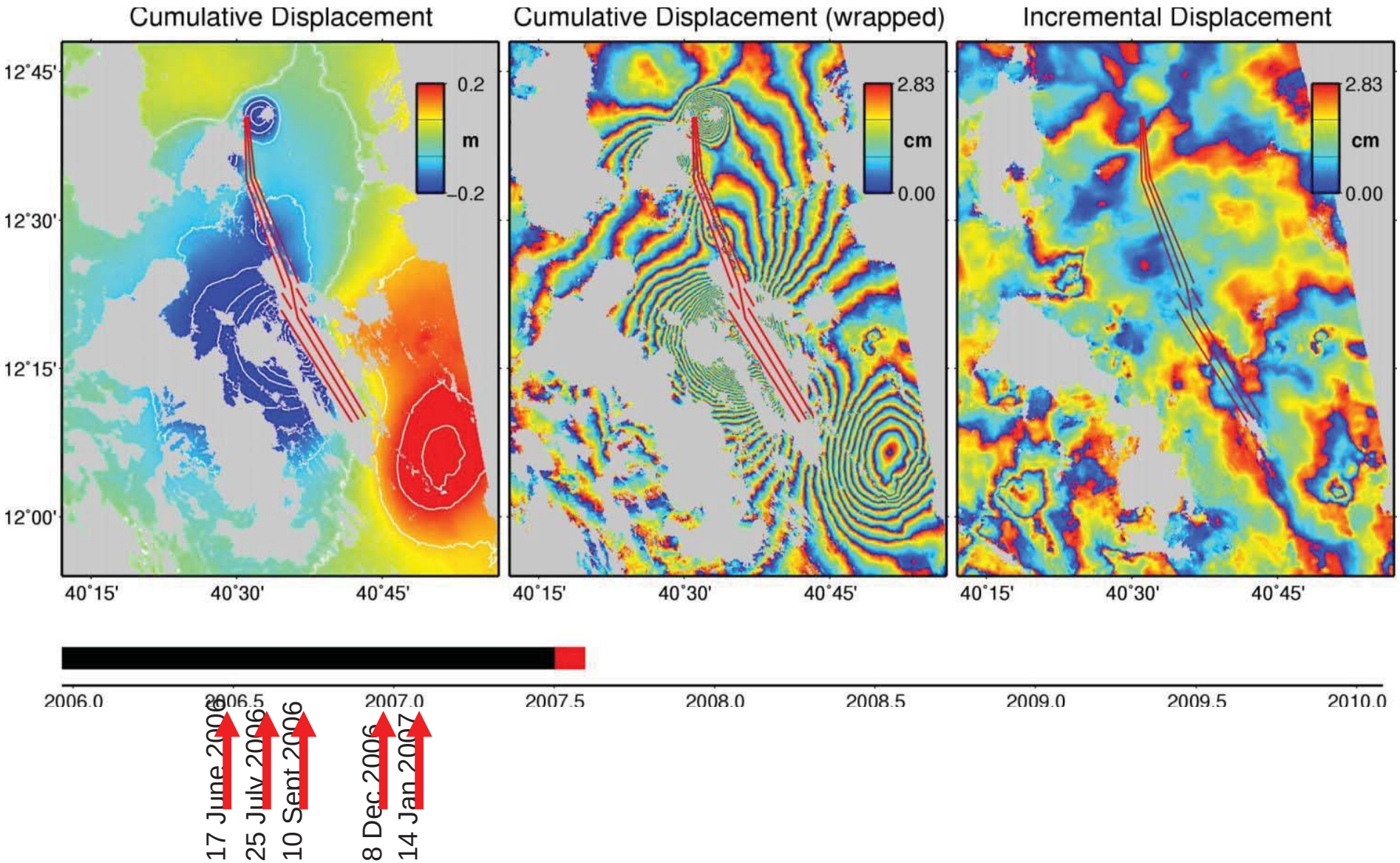

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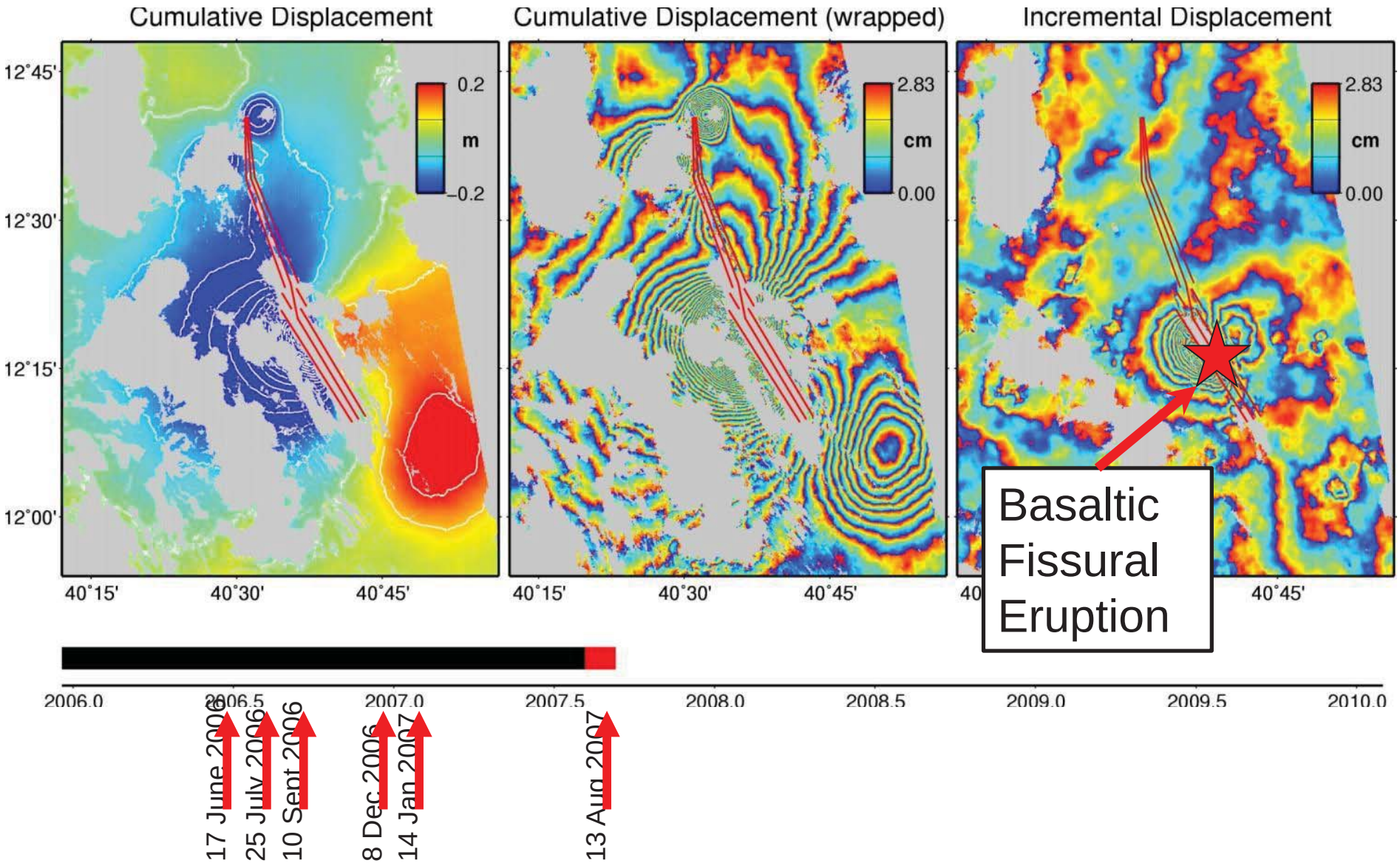

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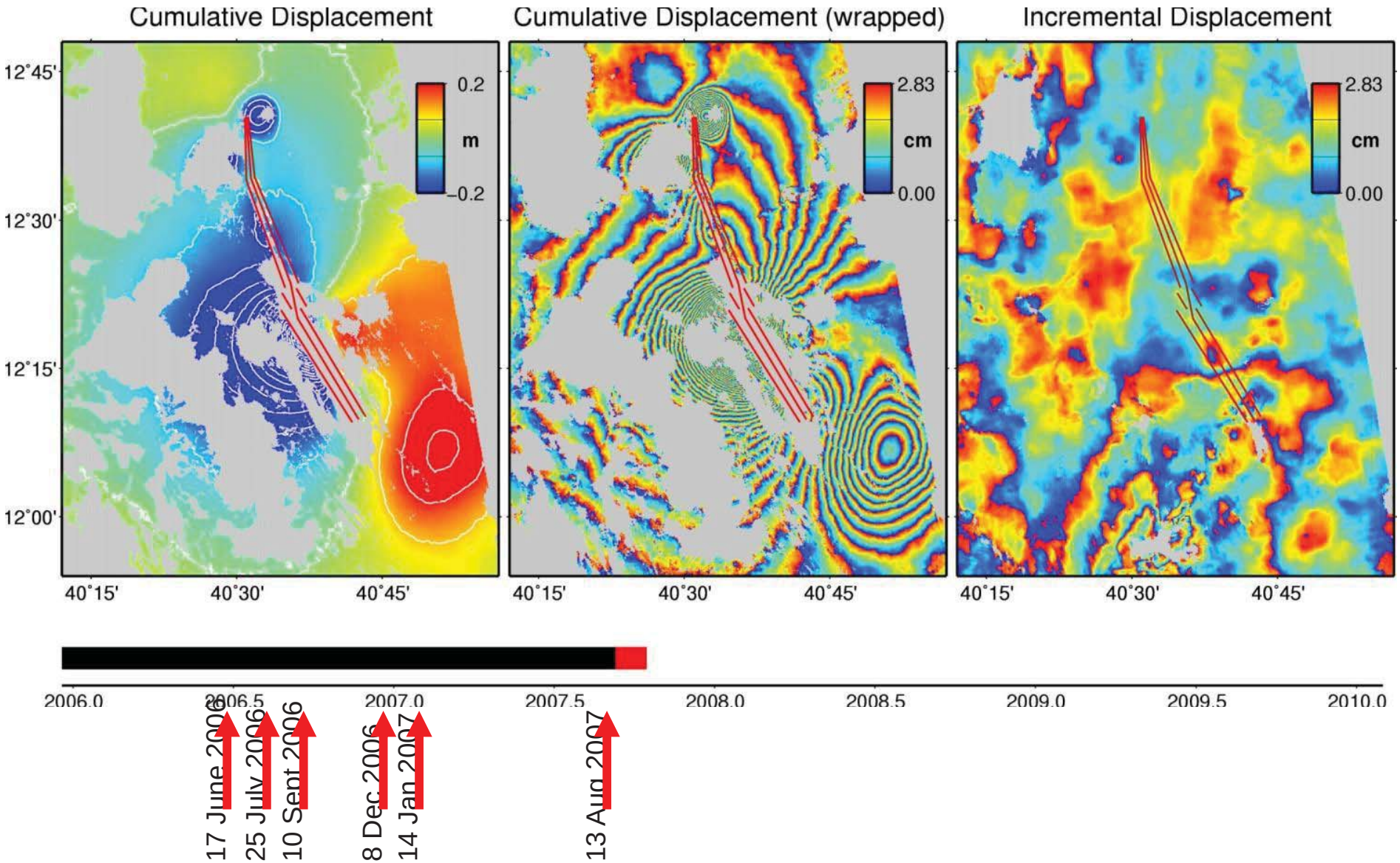

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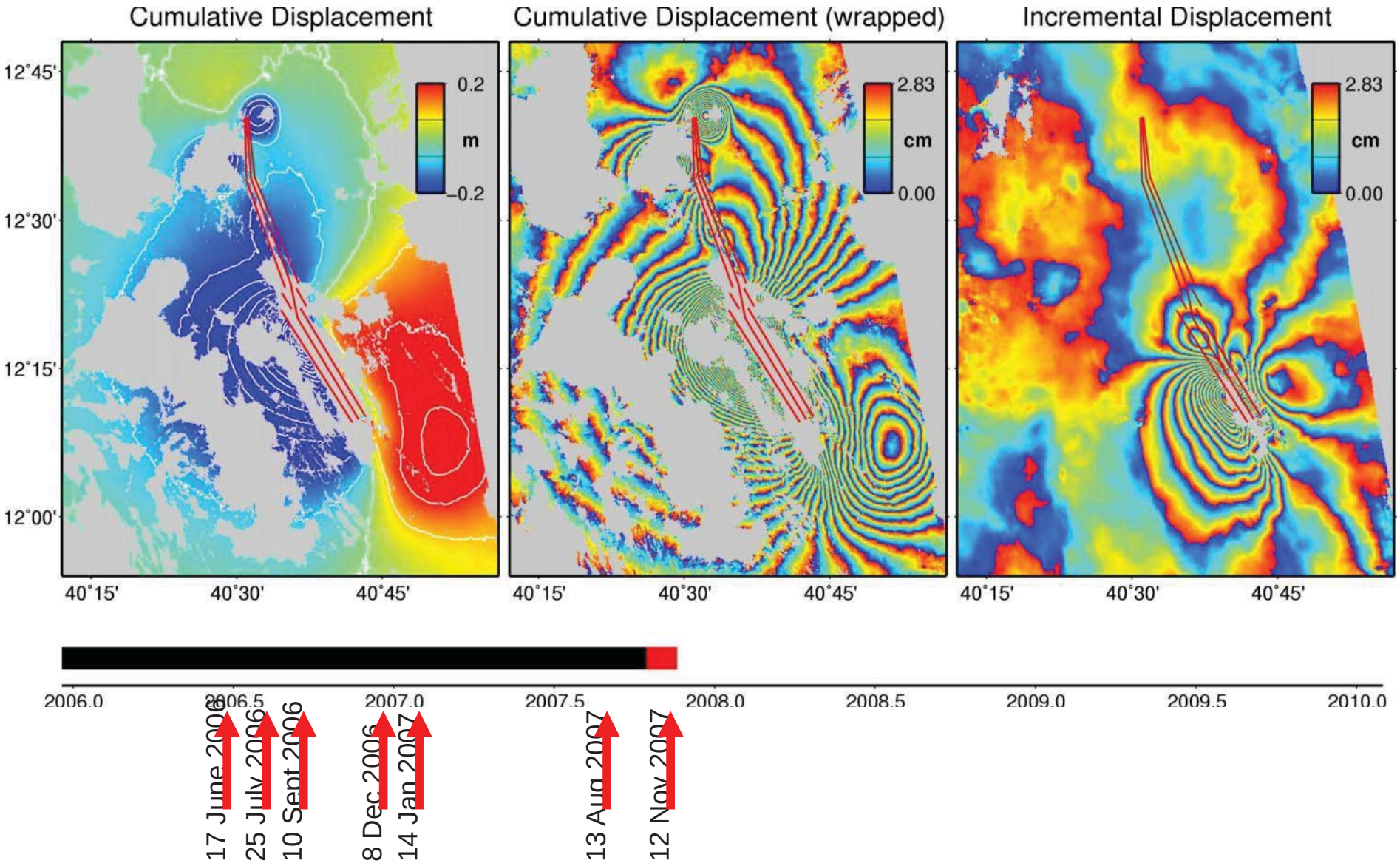
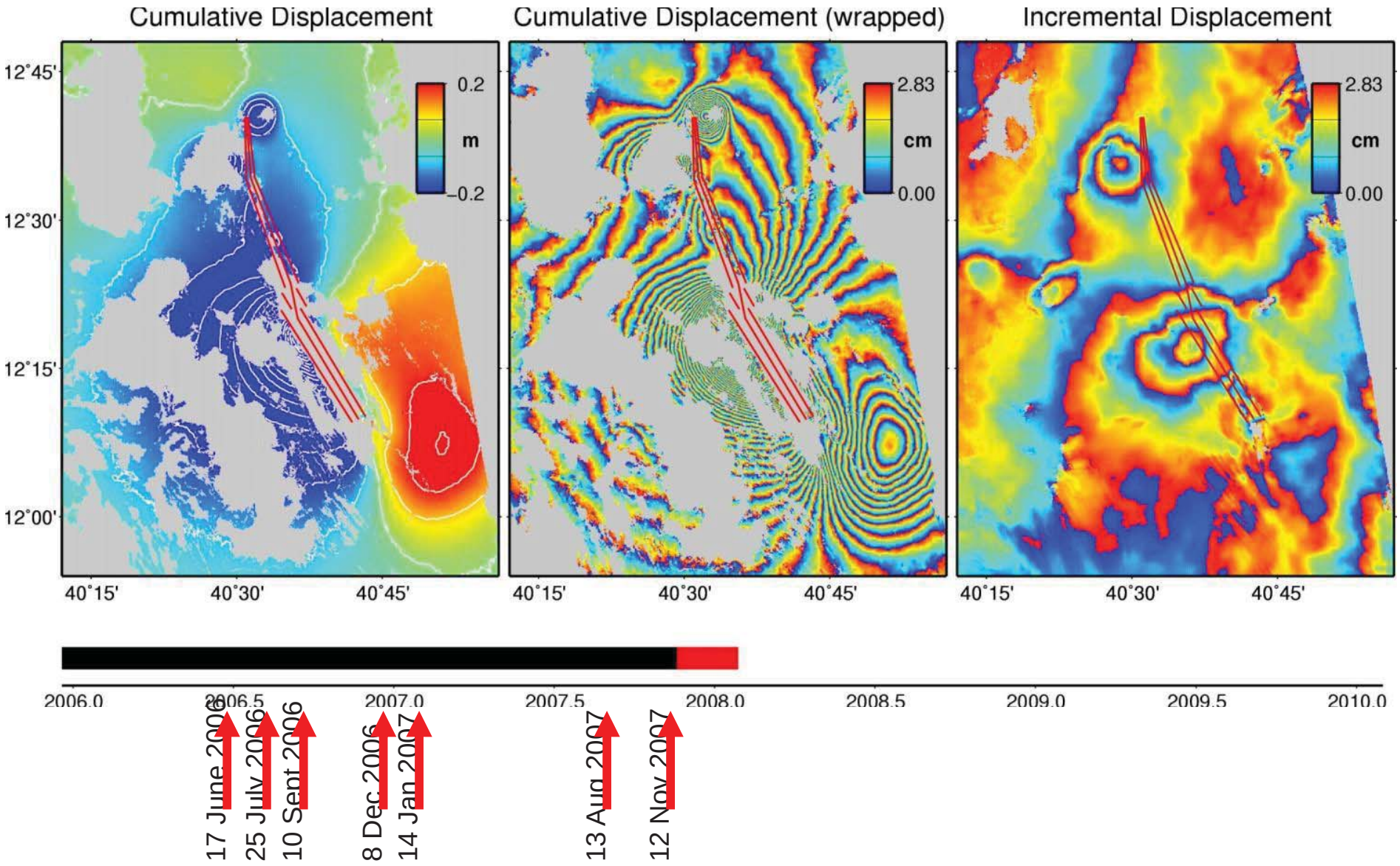
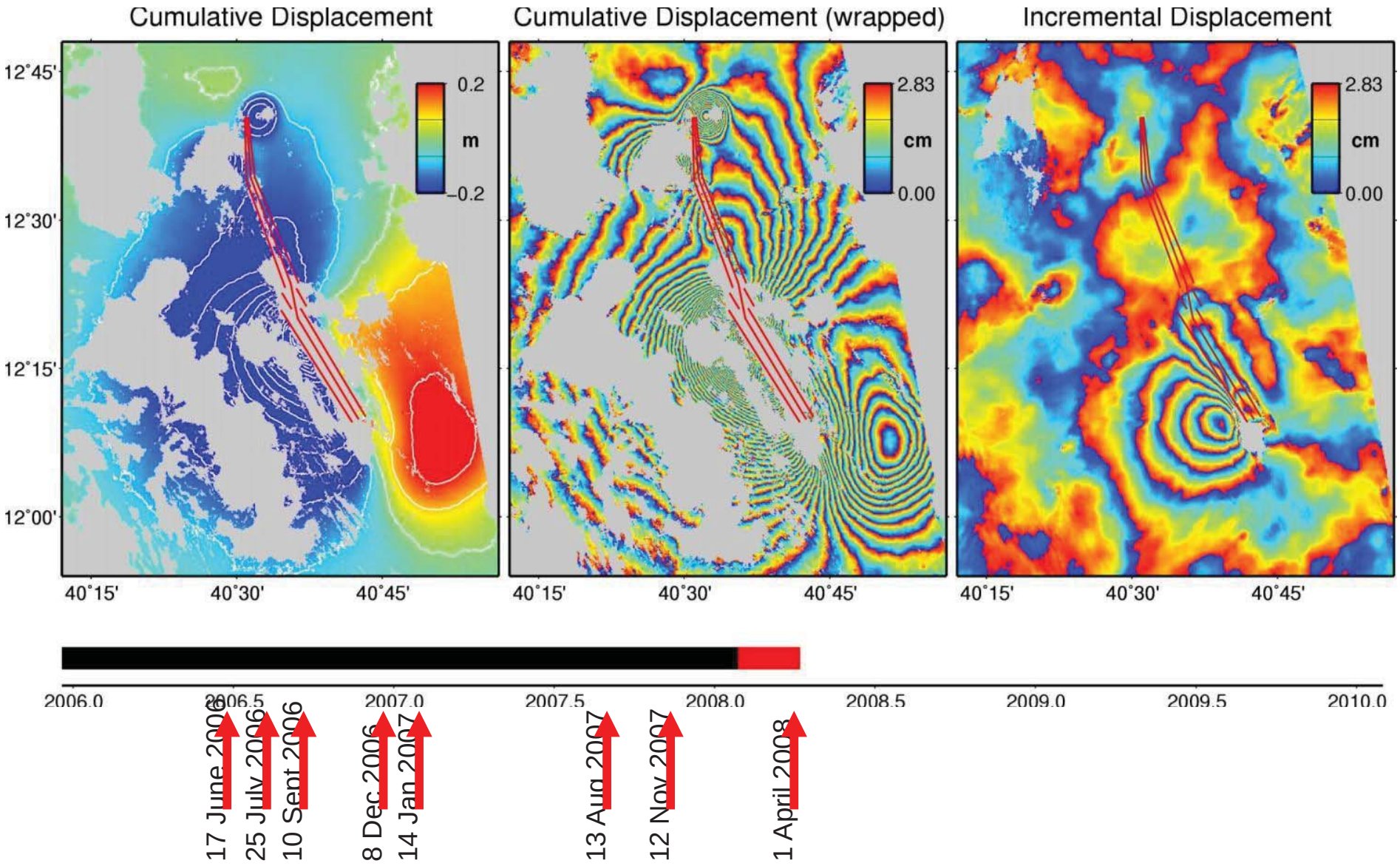


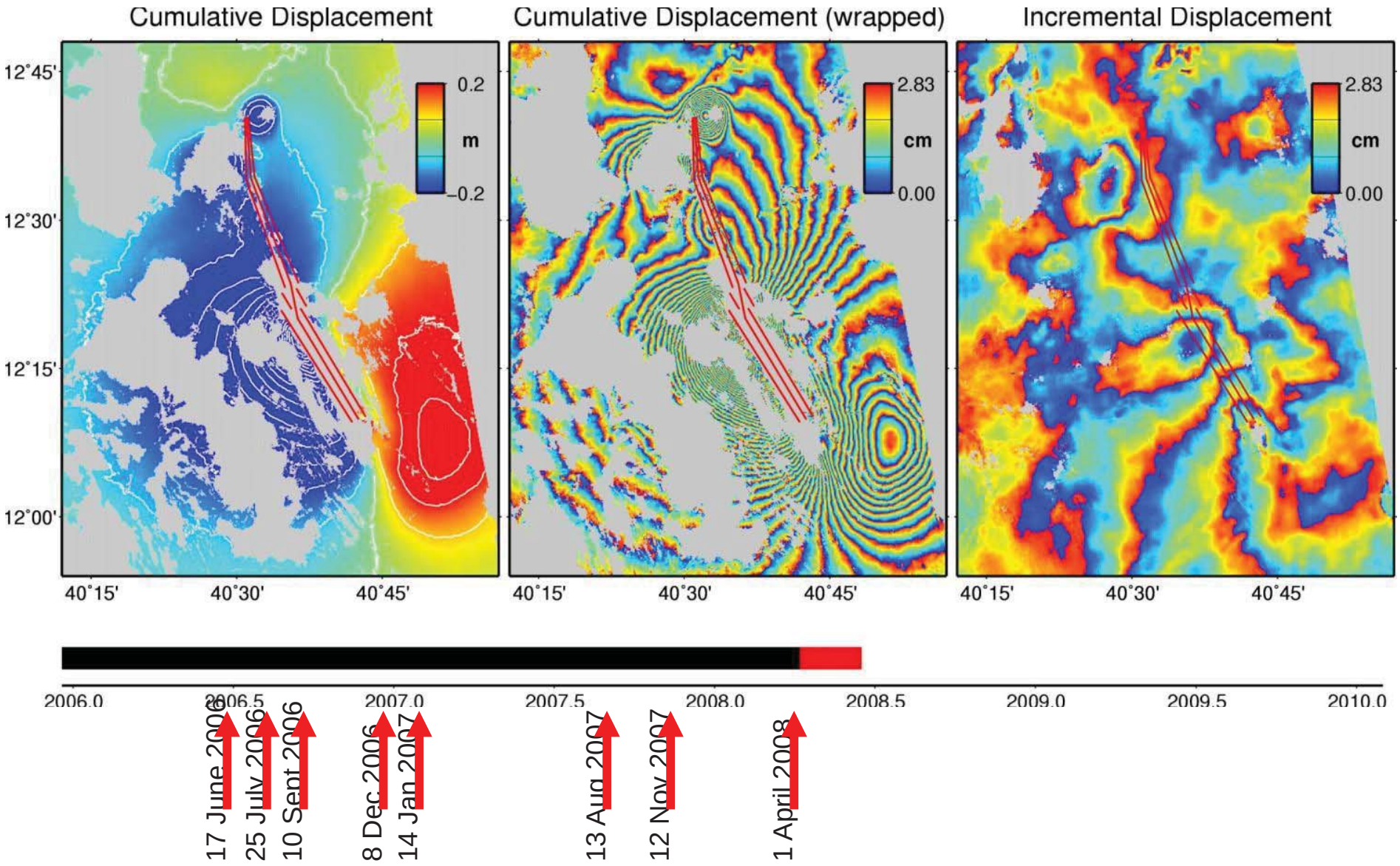
Post-intrusion deformation – Track 300



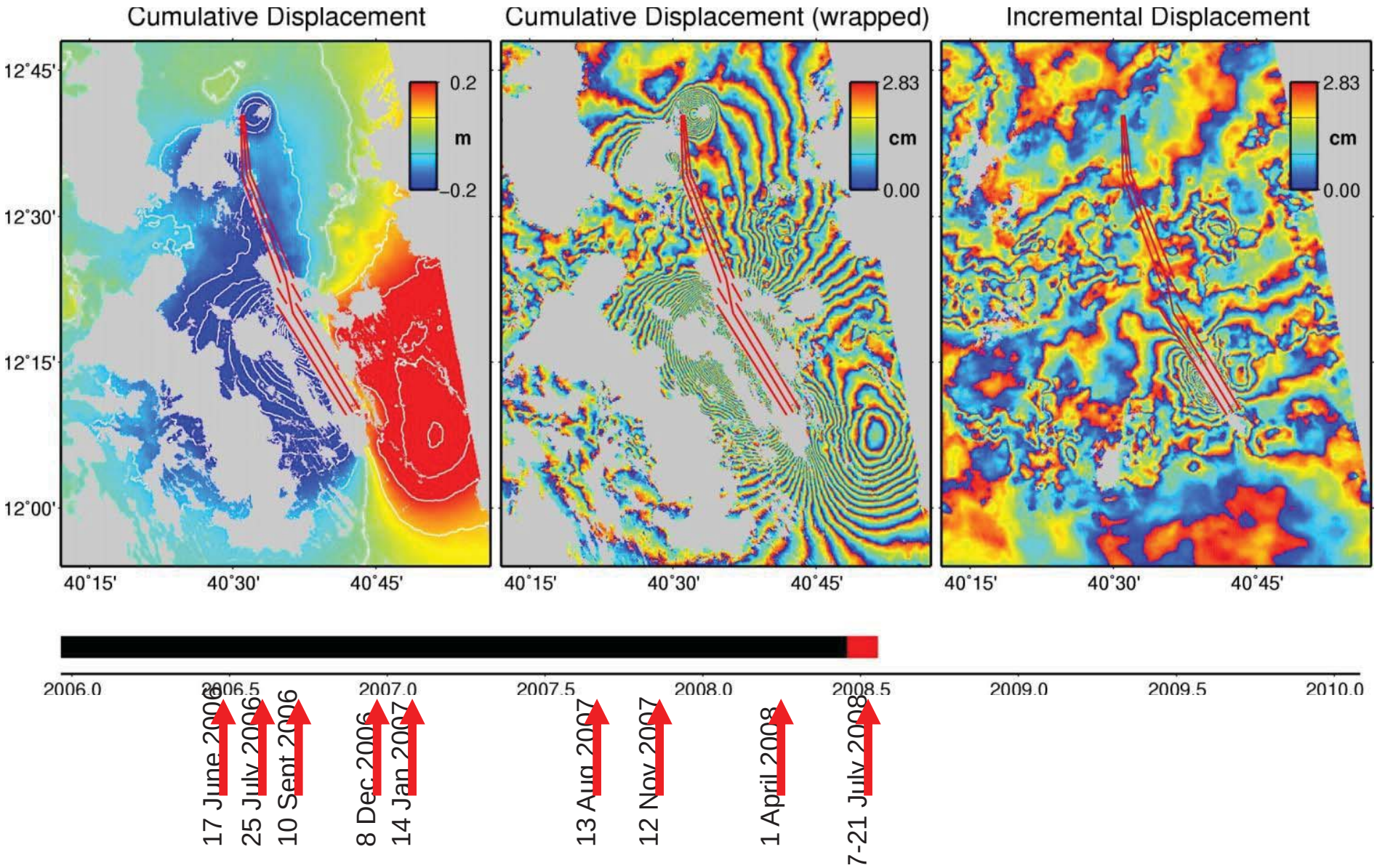
Post-intrusion deformation – Track 300



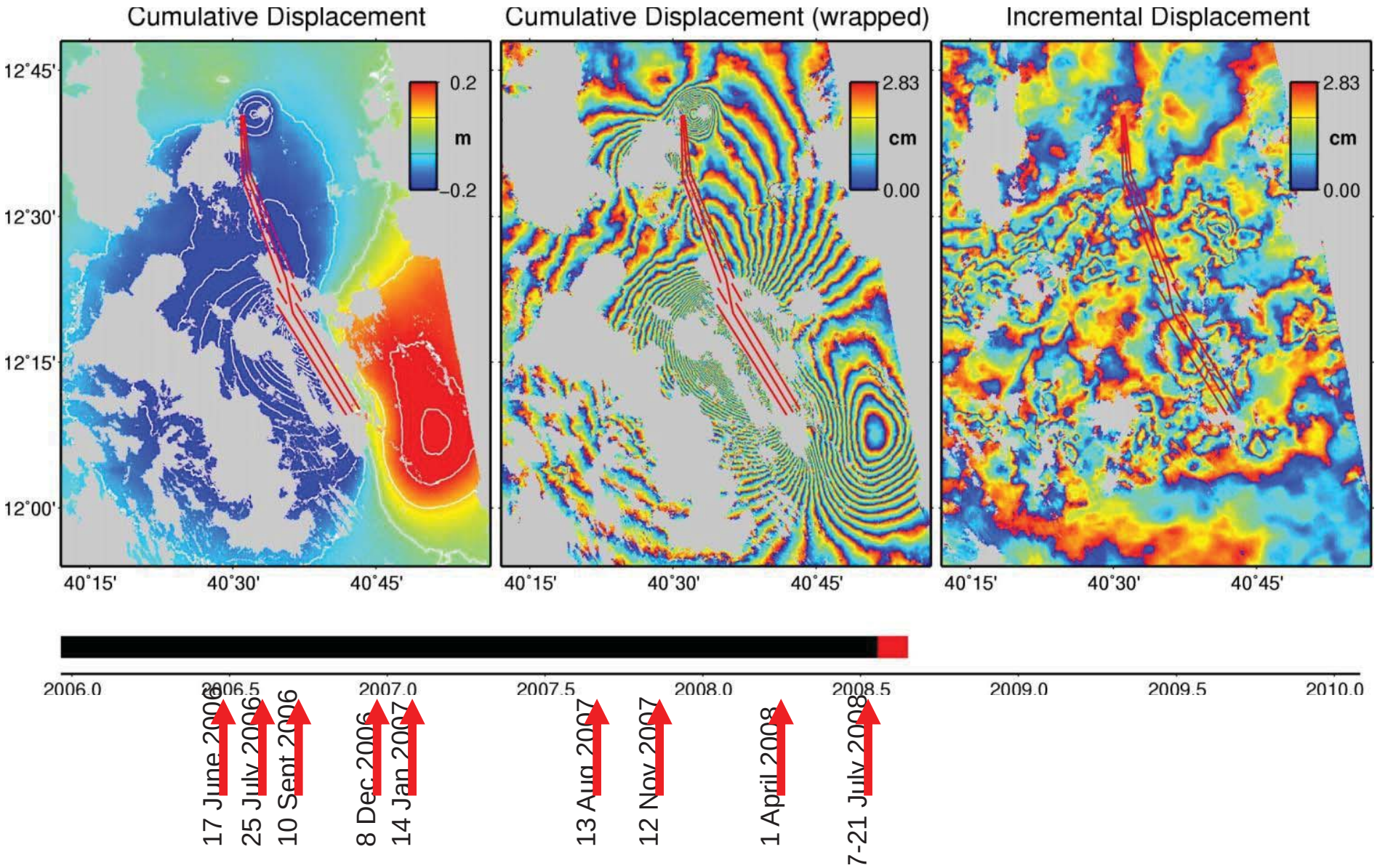
Post-intrusion deformation – Track 300



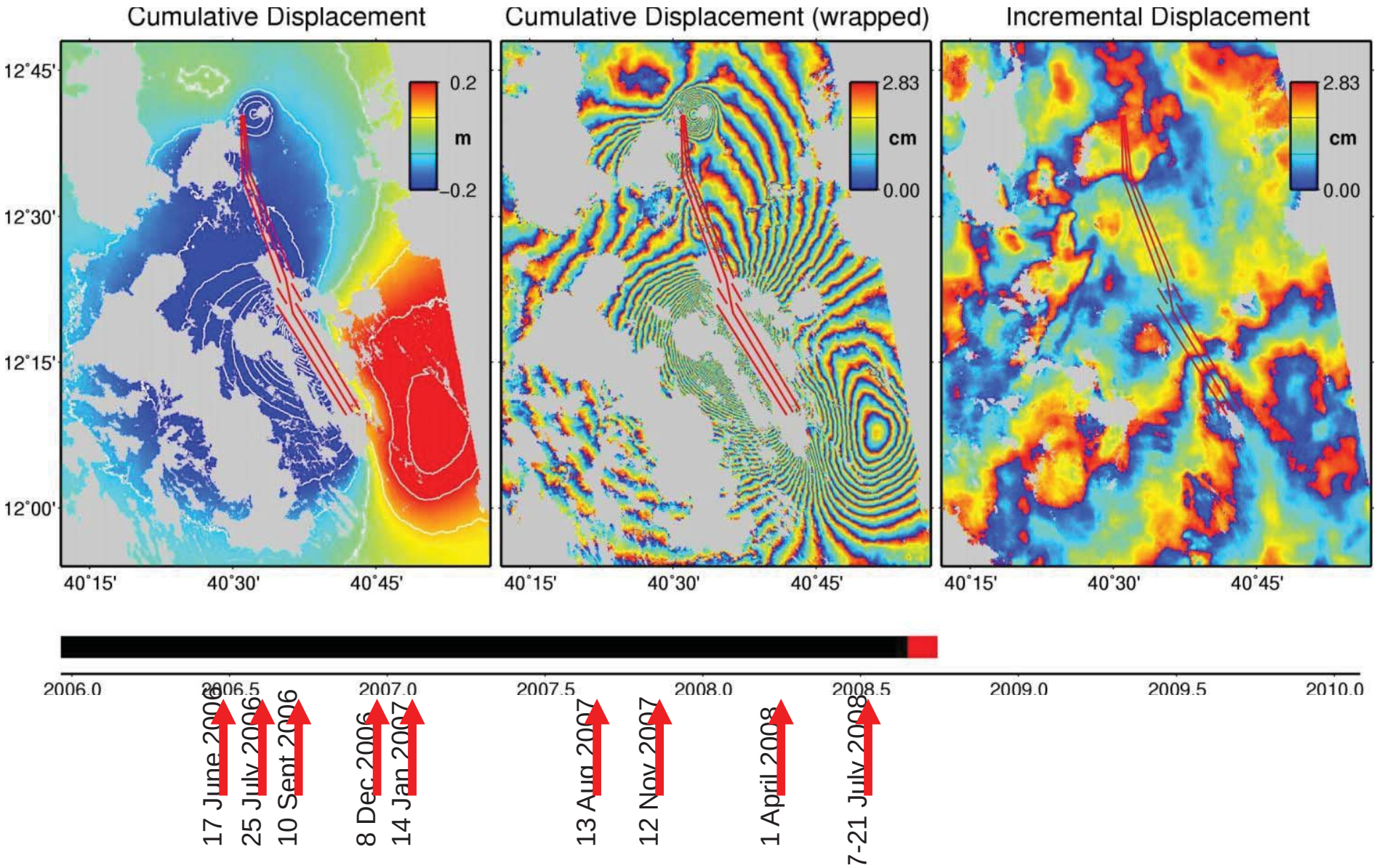
Post-intrusion deformation – Track 300



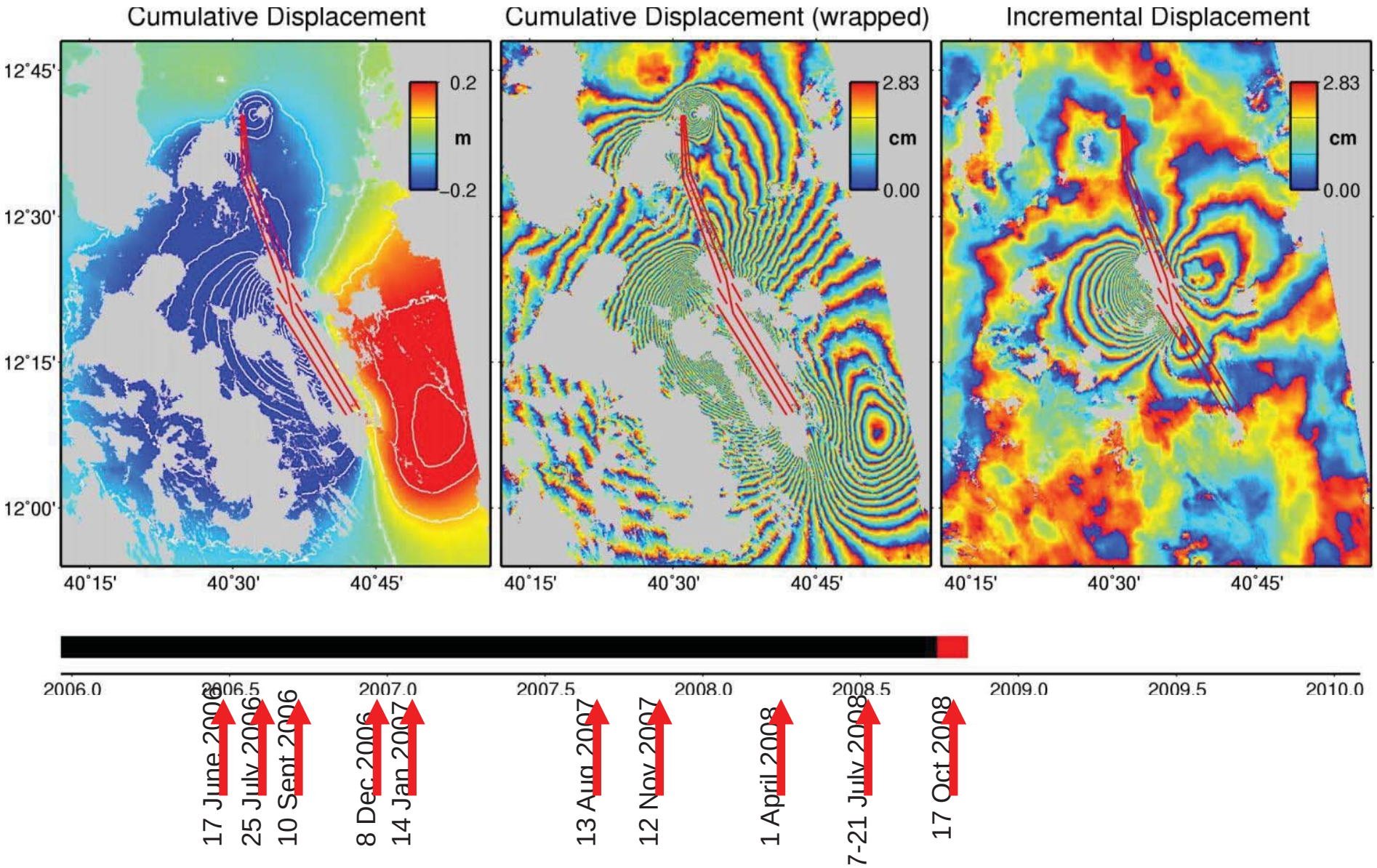
Post-intrusion deformation – Track 300



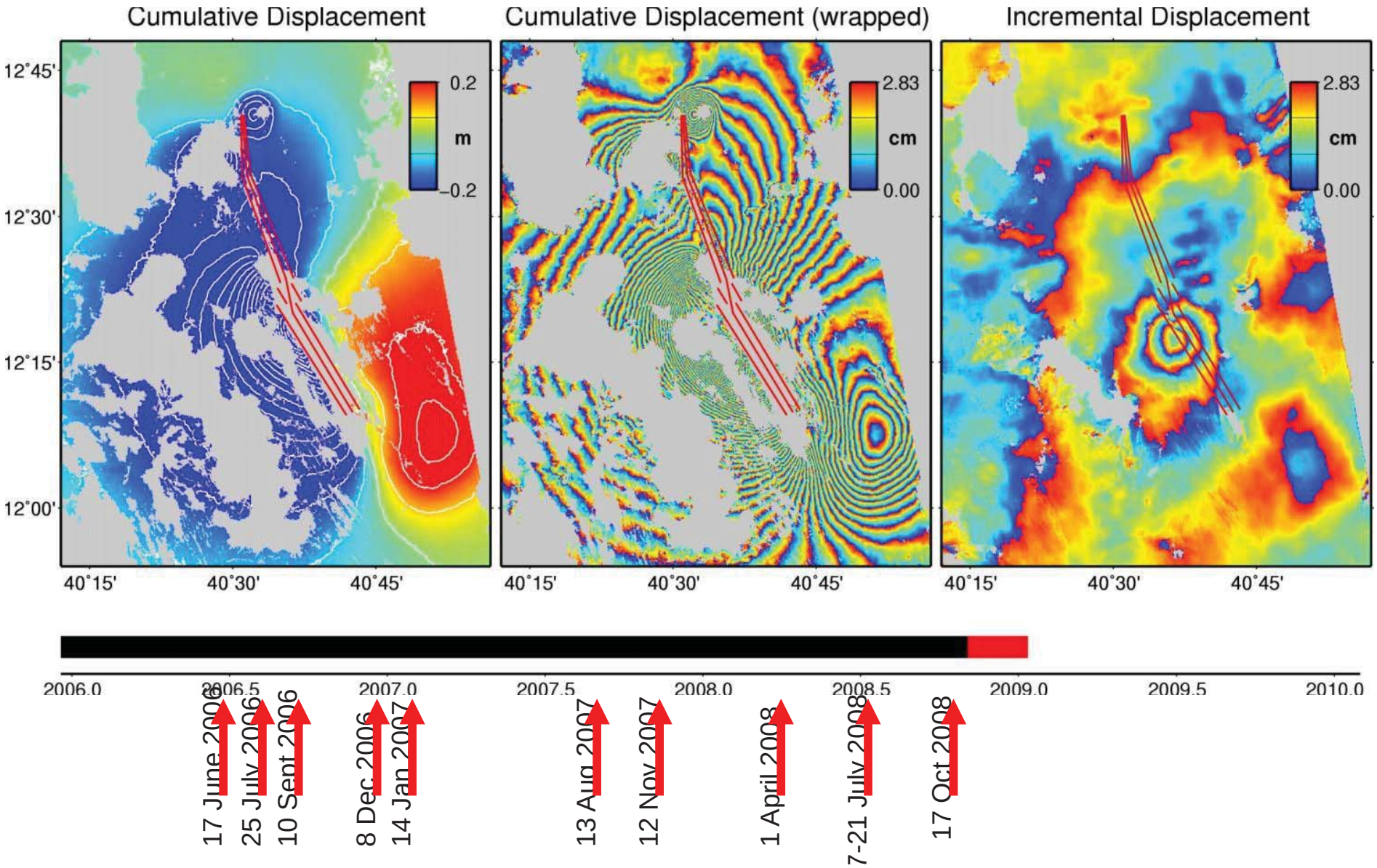
Post-intrusion deformation – Track 300



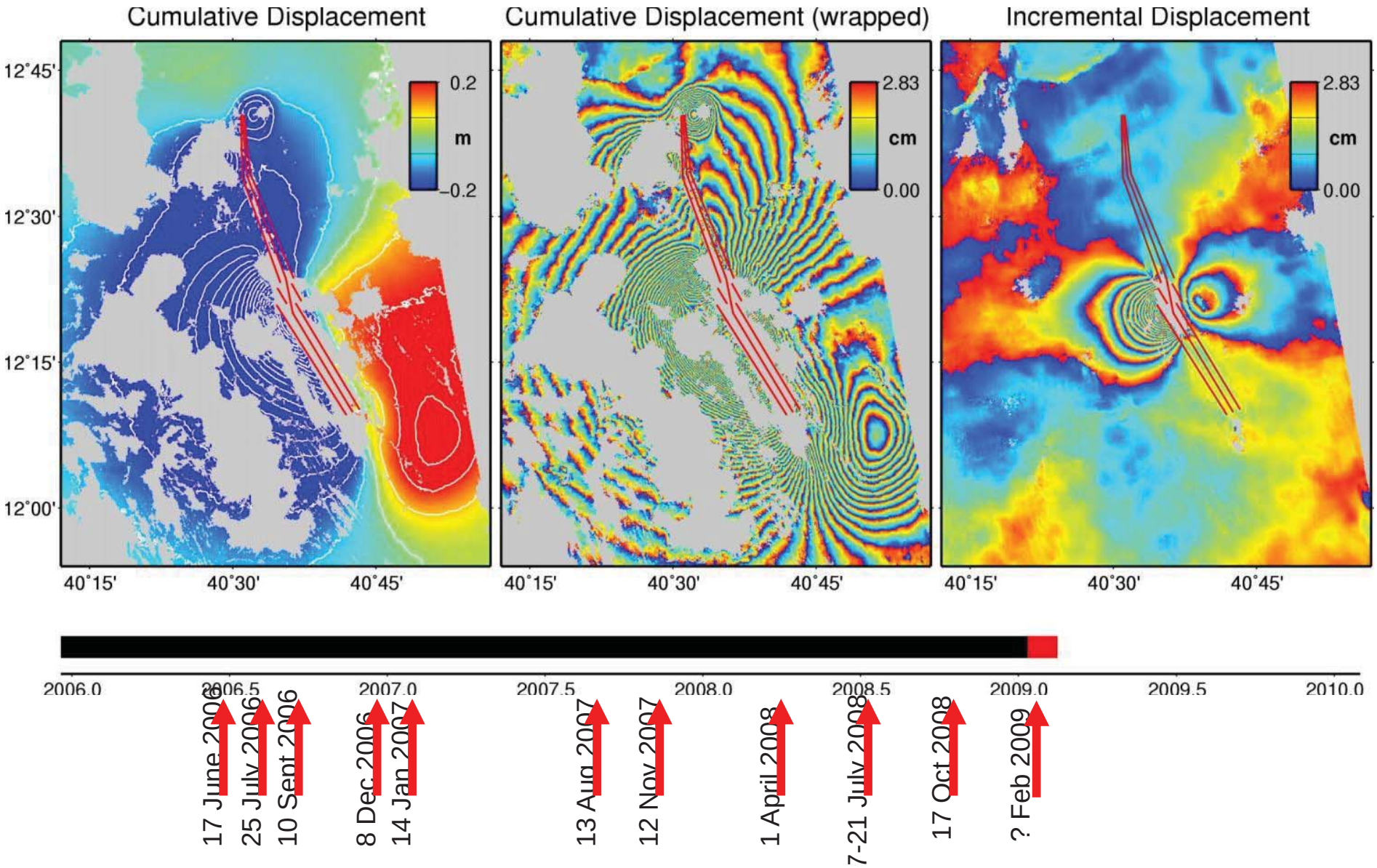
Post-intrusion deformation – Track 300



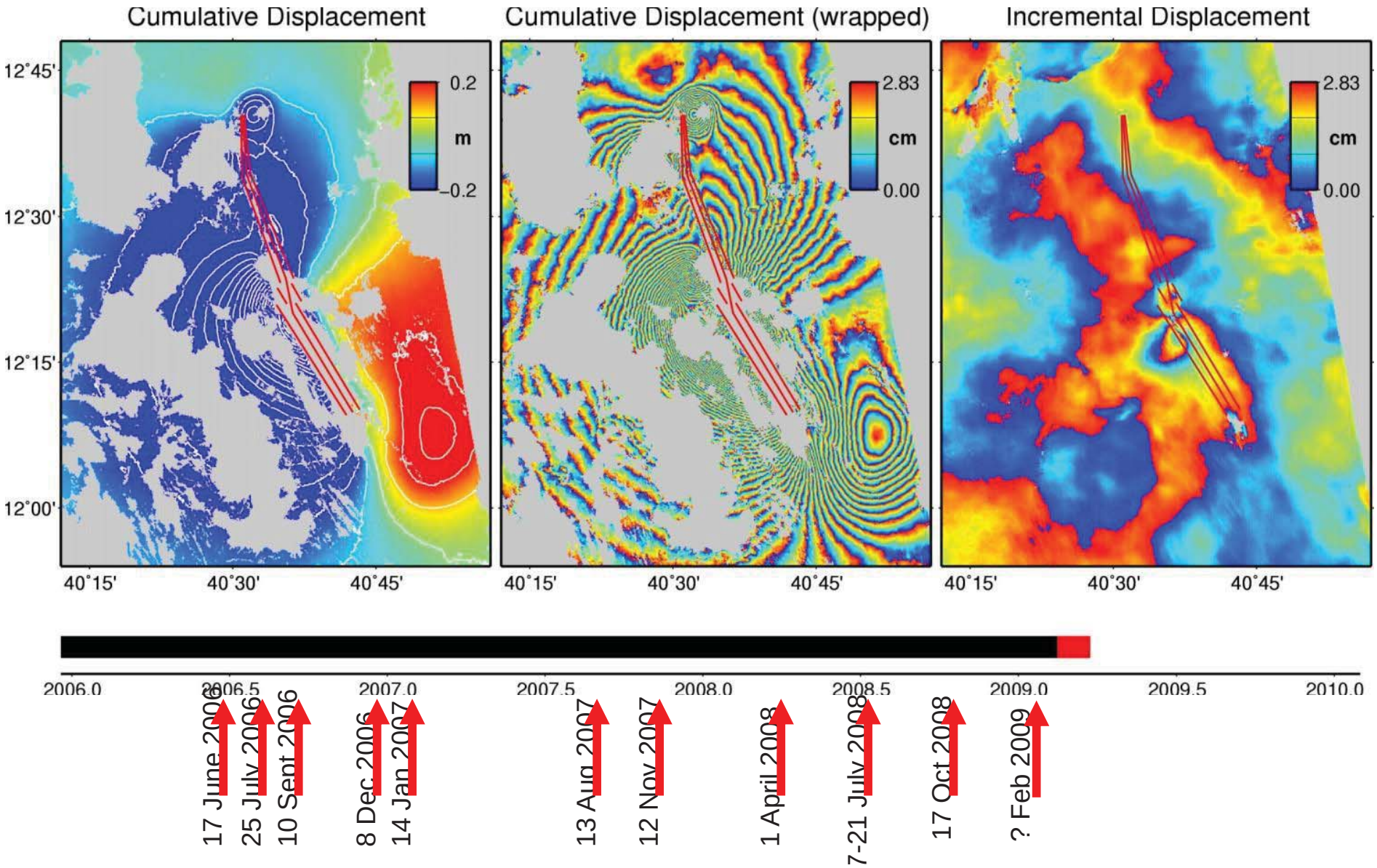
Post-intrusion deformation – Track 300



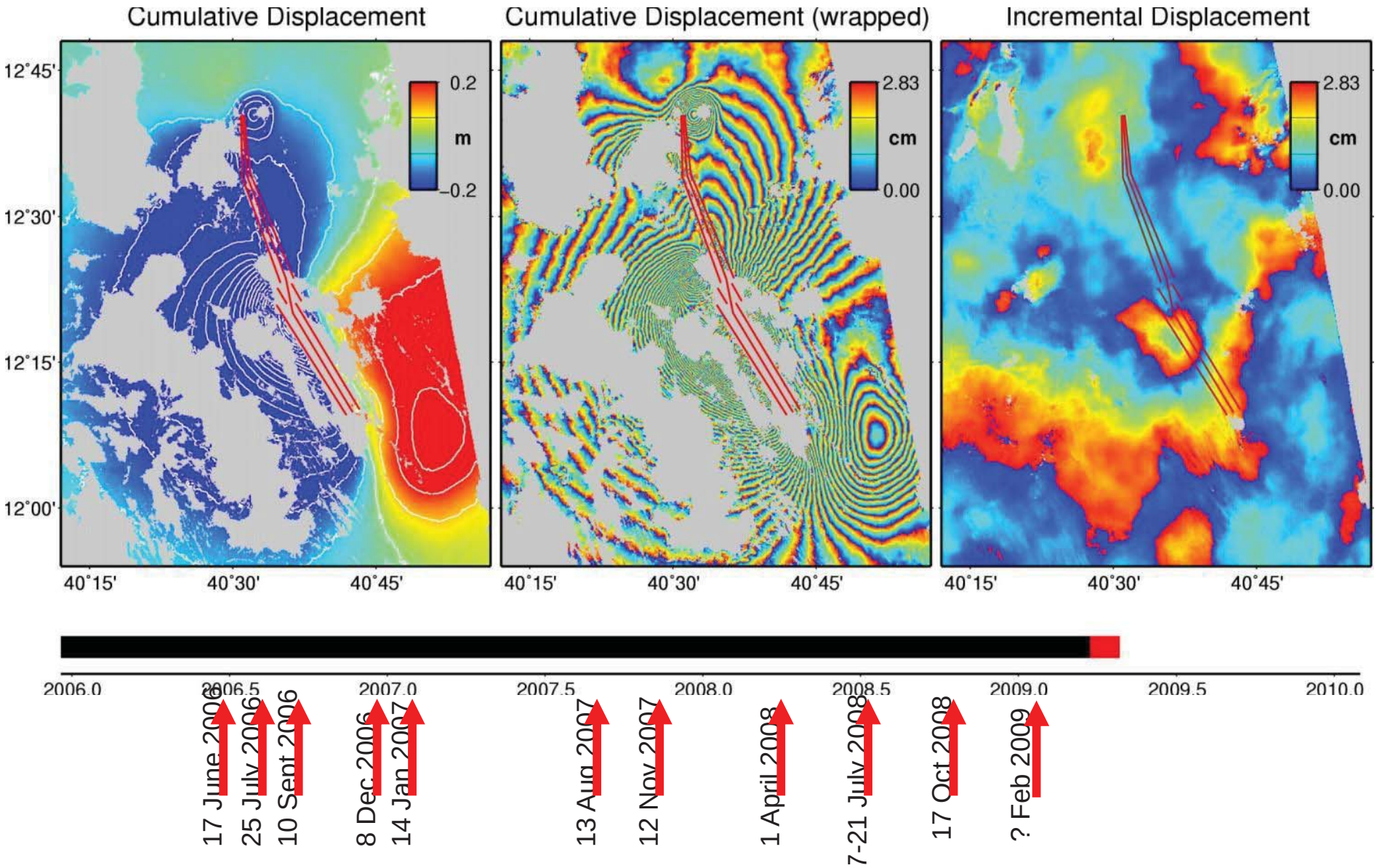
Post-intrusion deformation – Track 300



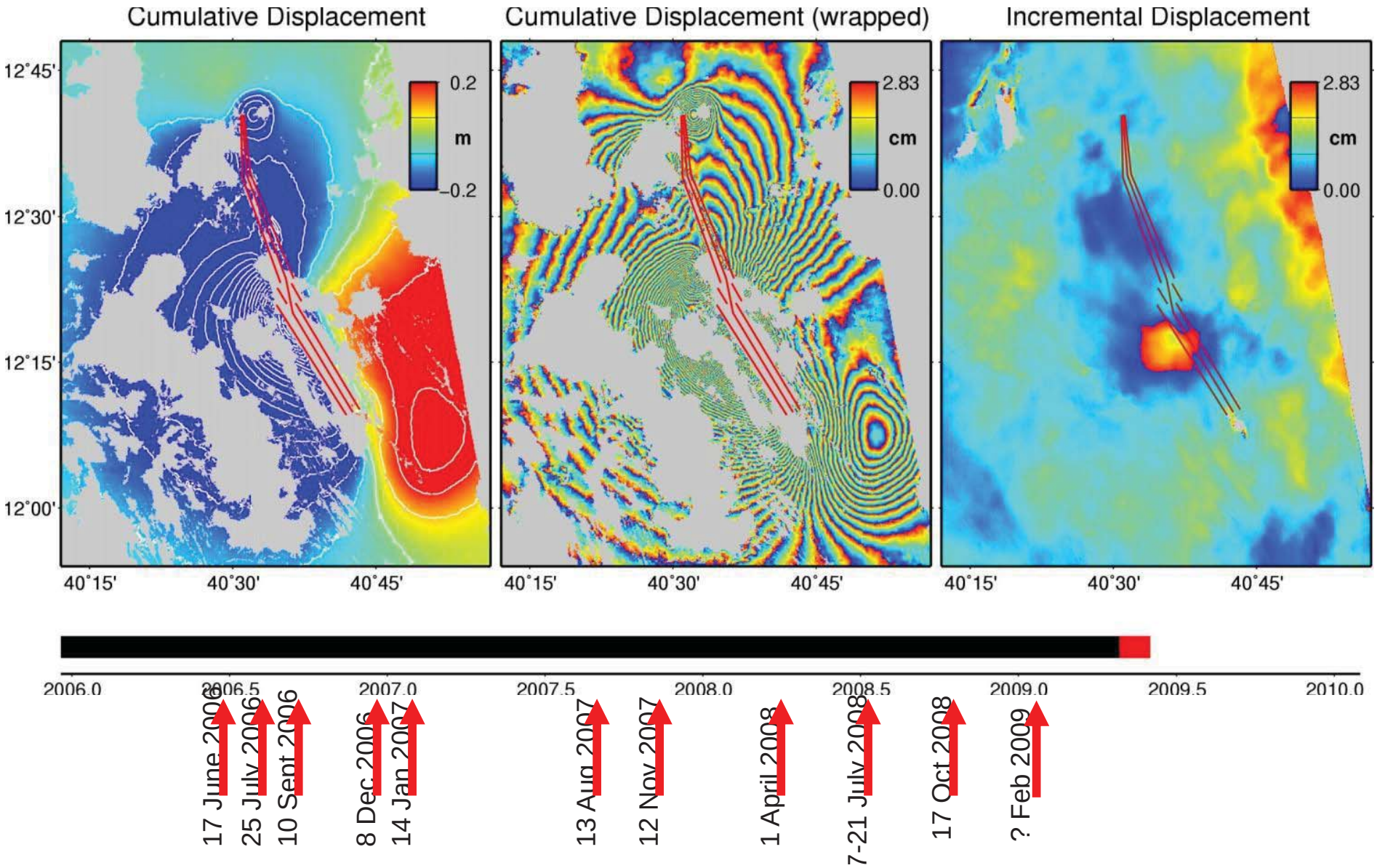
Post-intrusion deformation – Track 300



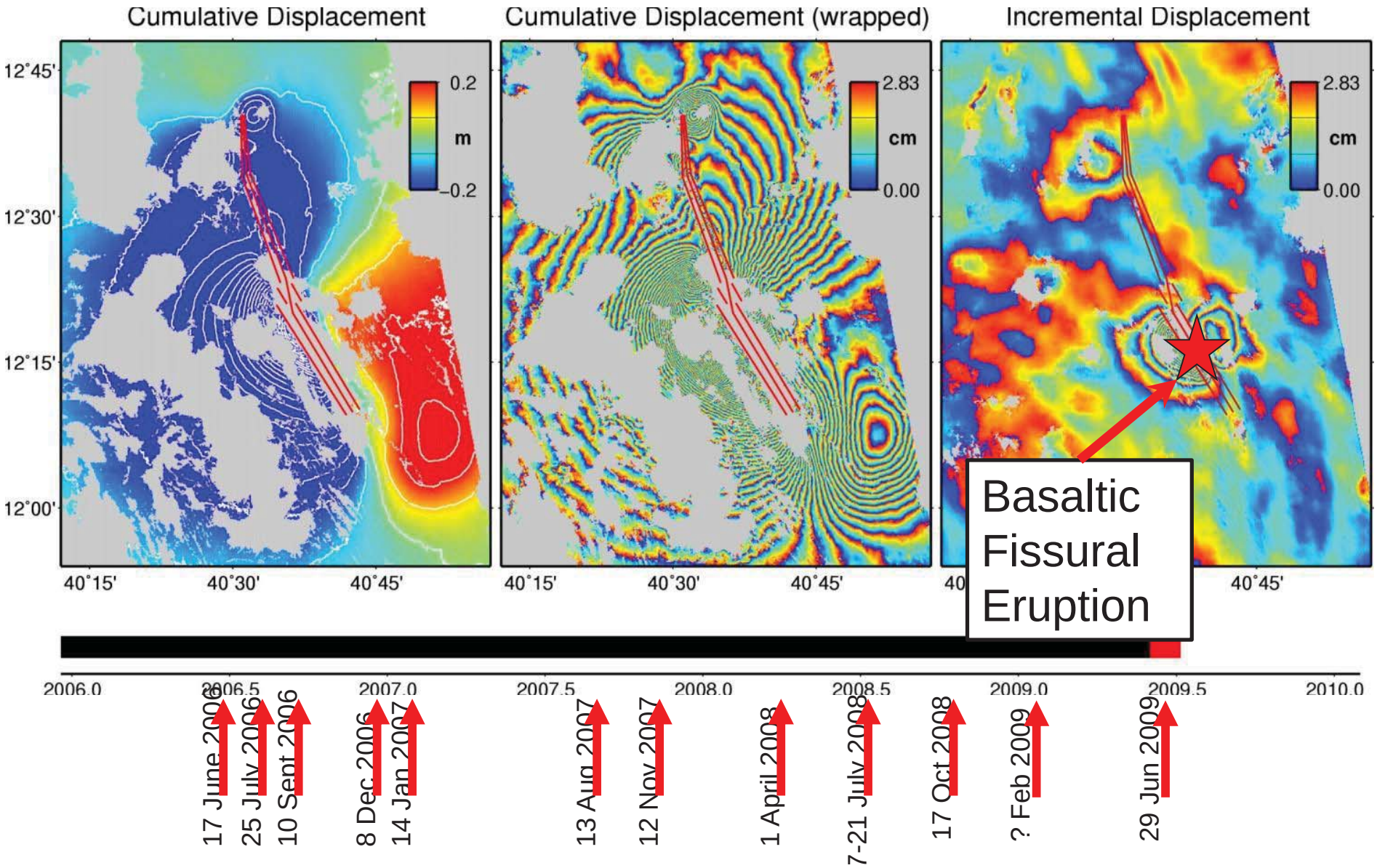
Post-intrusion deformation – Track 300



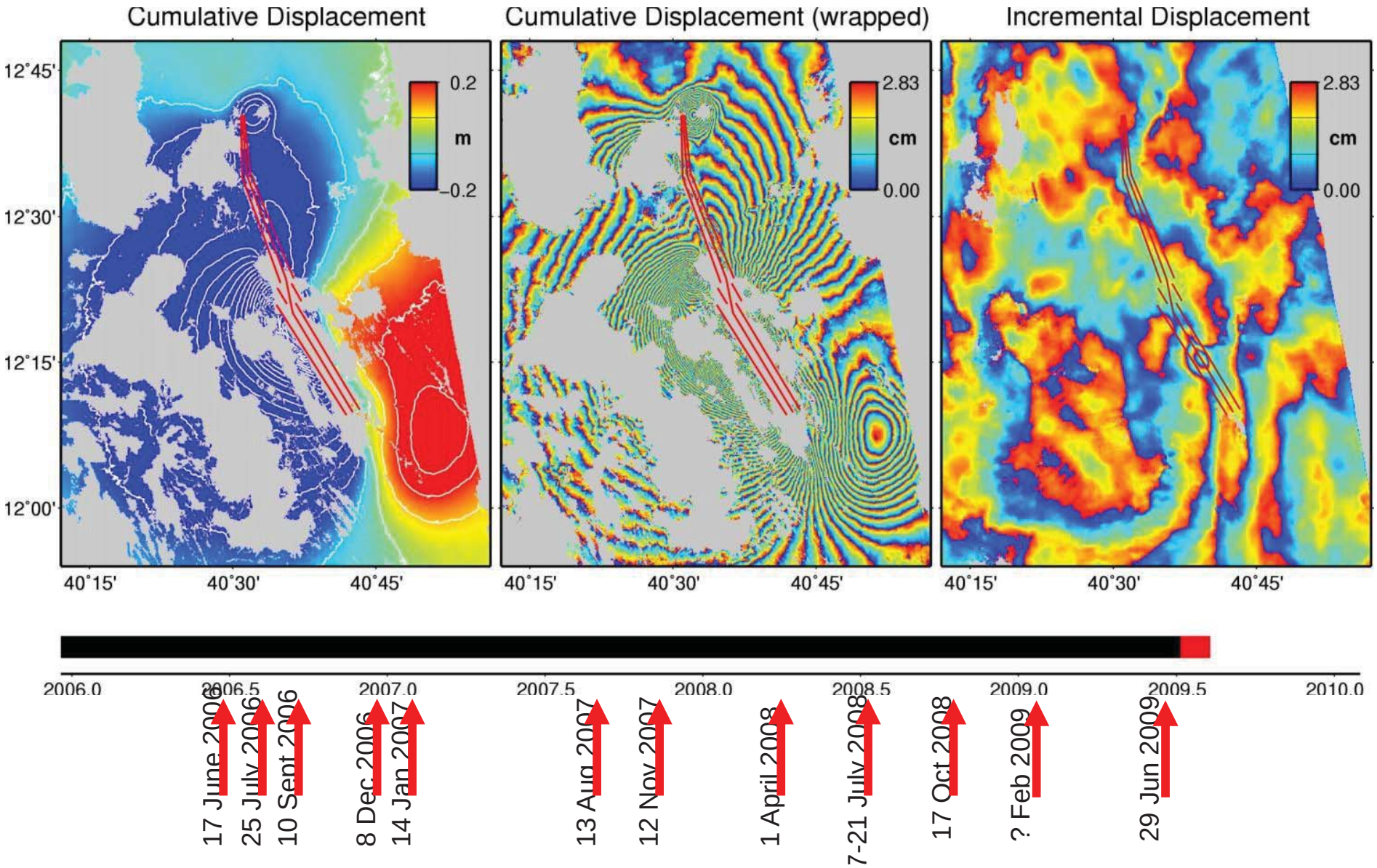
Post-intrusion deformation – Track 300



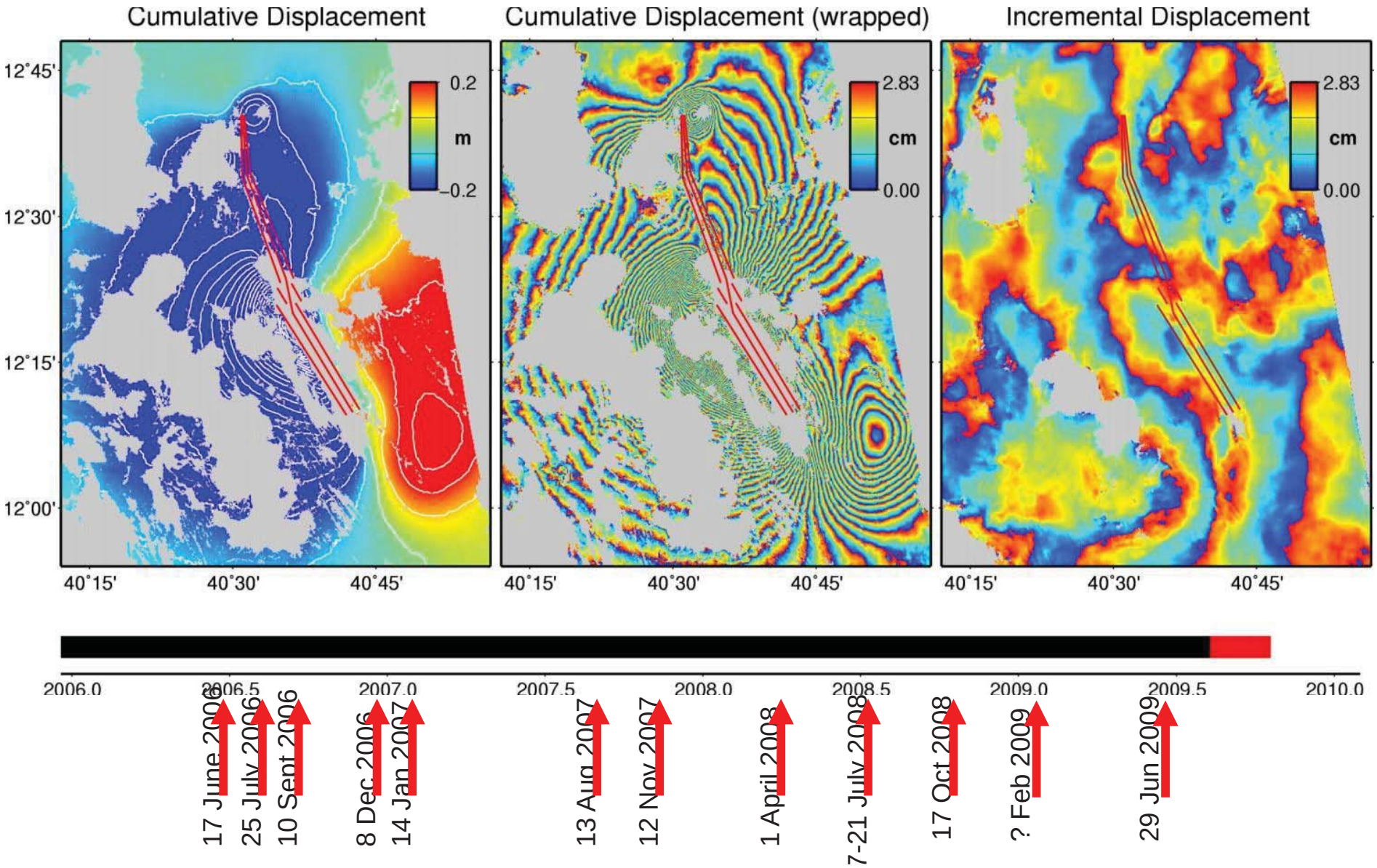
Post-intrusion deformation – Track 300



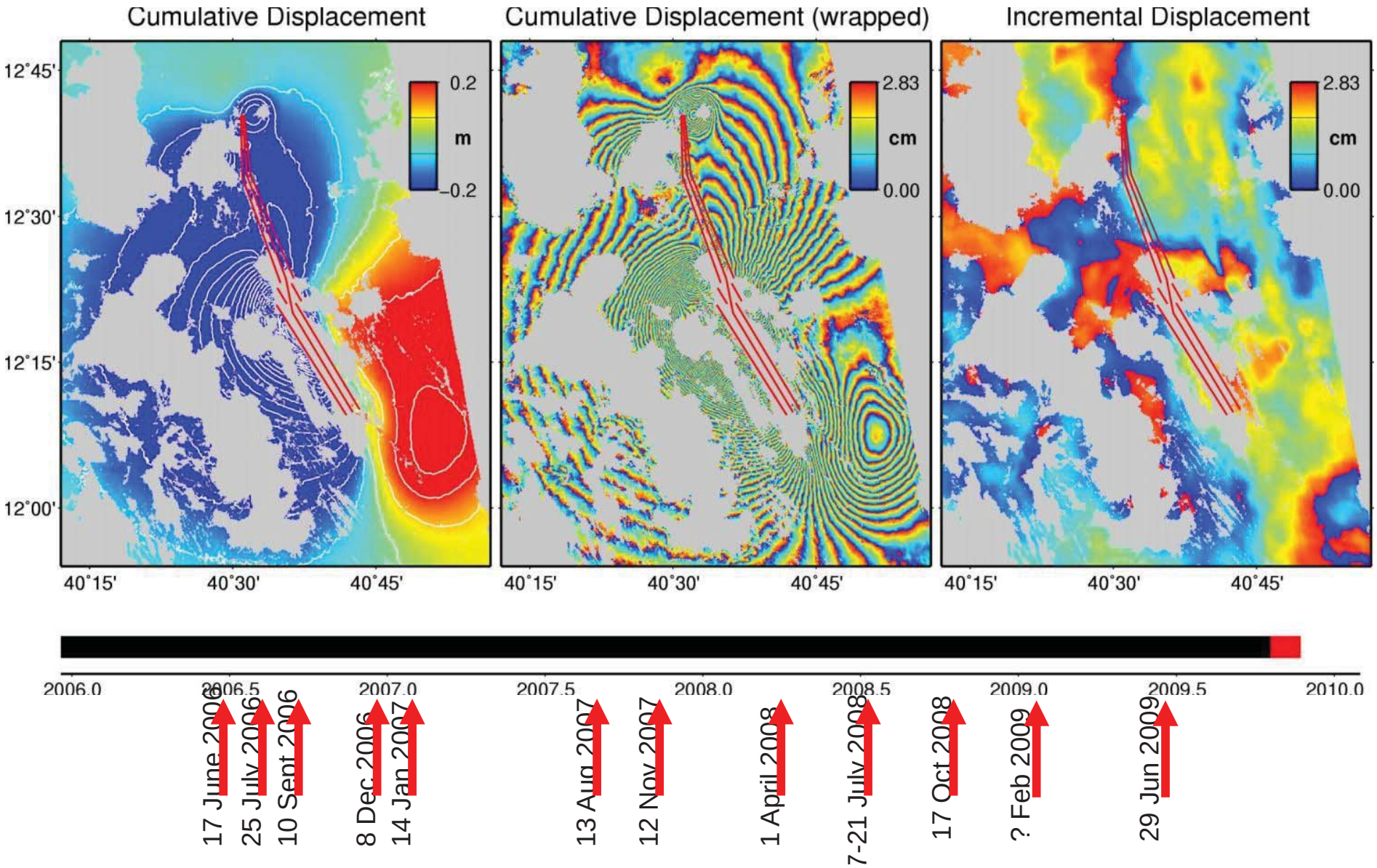
Post-intrusion deformation – Track 300



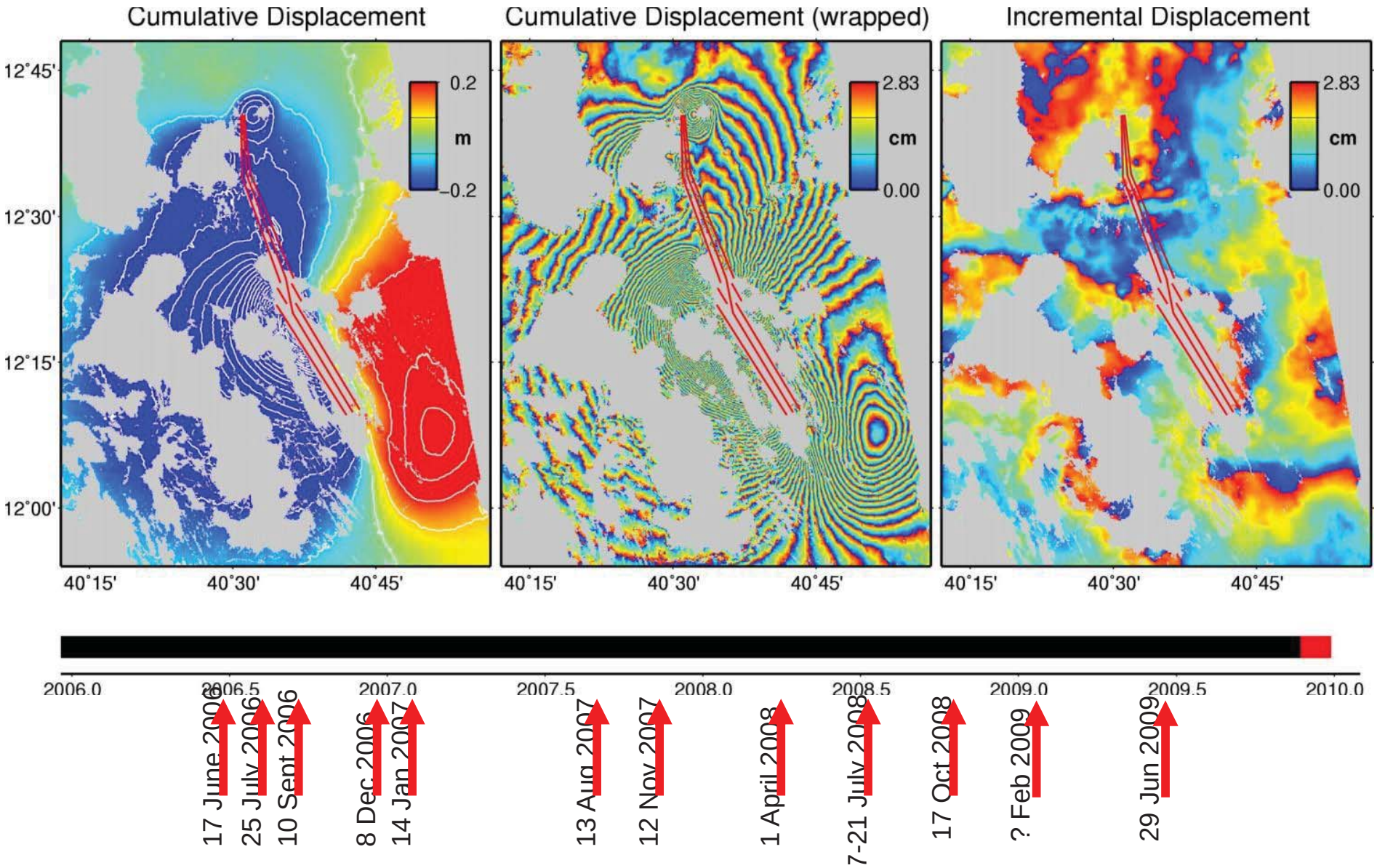
Post-intrusion deformation – Track 300



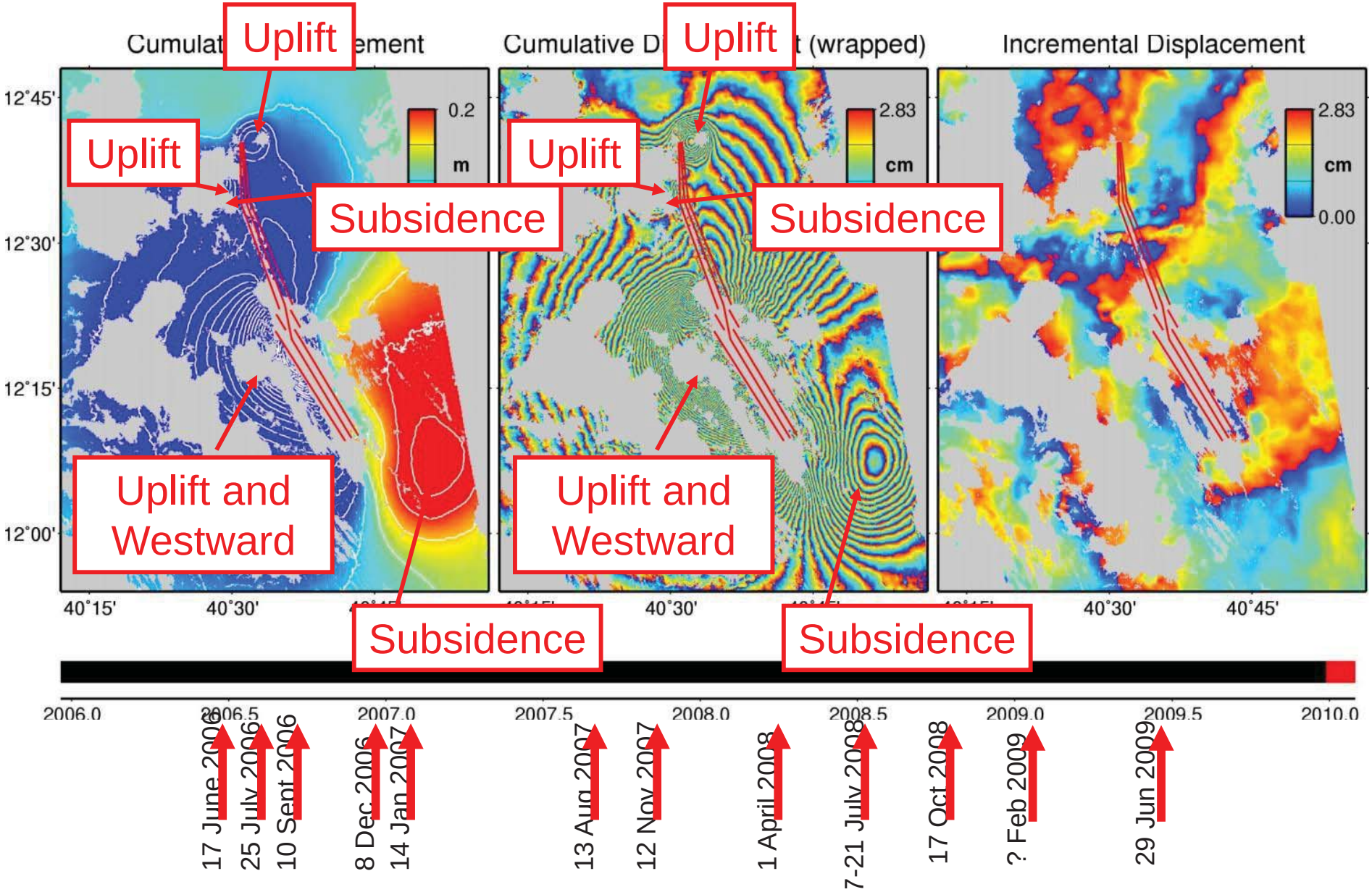
Post-intrusion deformation – Track 300



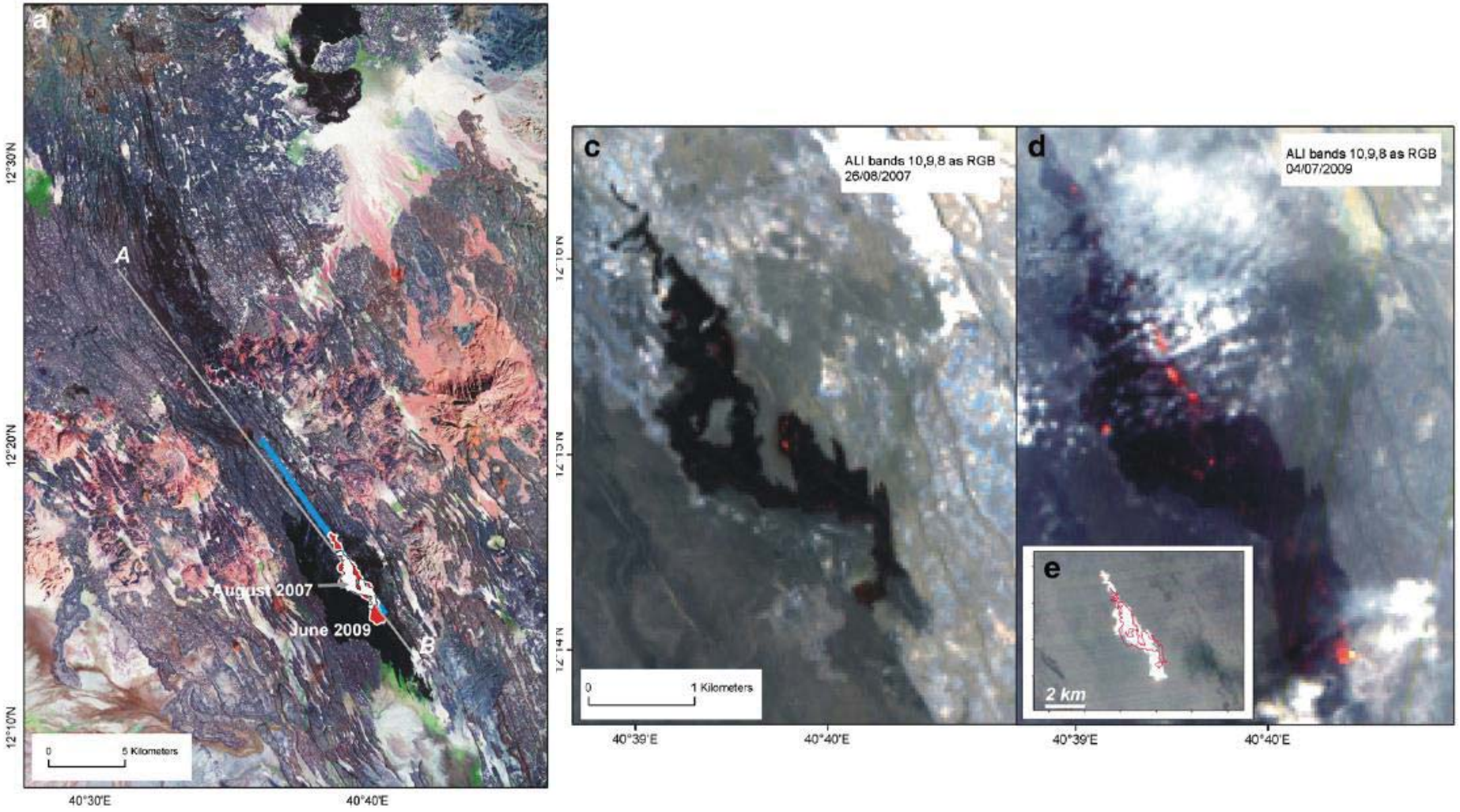
Post-intrusion deformation – Track 300



Post-intrusion deformation – Track 300

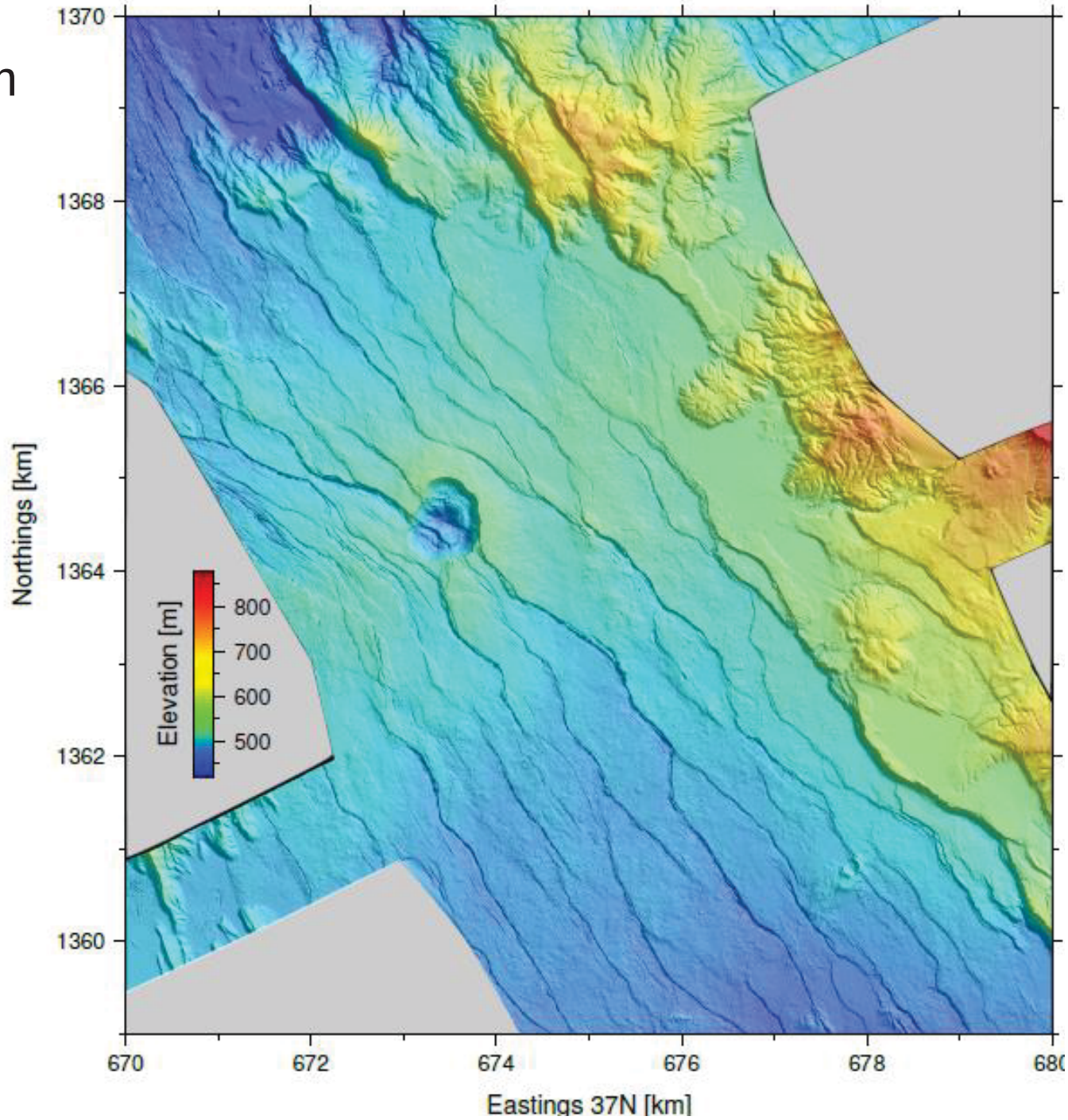


2007,2009 Basaltic Fissure Eruptions

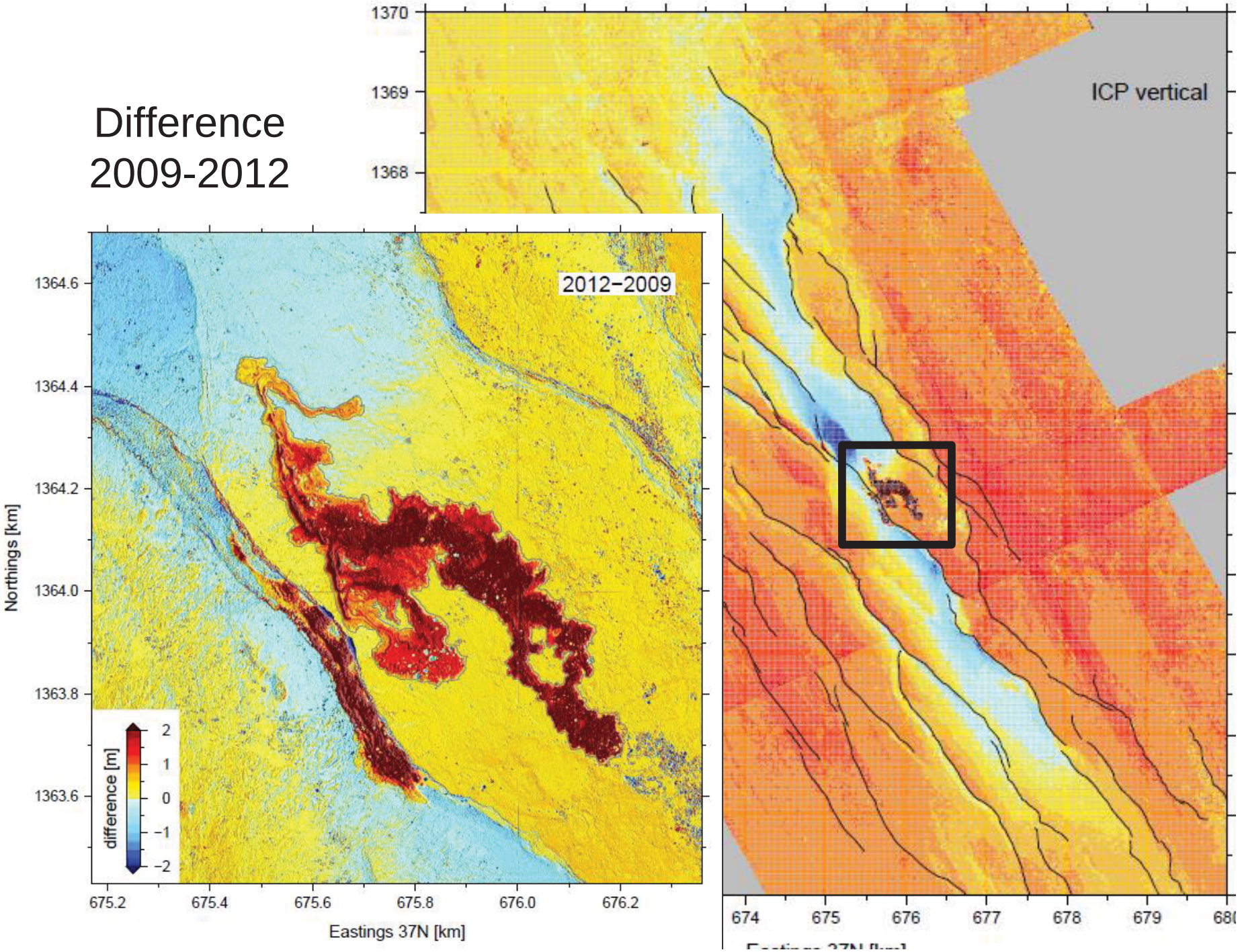


"Hypersthene normative" (intermediate) basalts:
SiO_2 48-49 wt%; MgO 5-6 wt%; Alkali 3.7-3.8 wt%
Ferguson et al., EPSL 2010

Topography from
LiDAR
~1 m resolution
October 2009

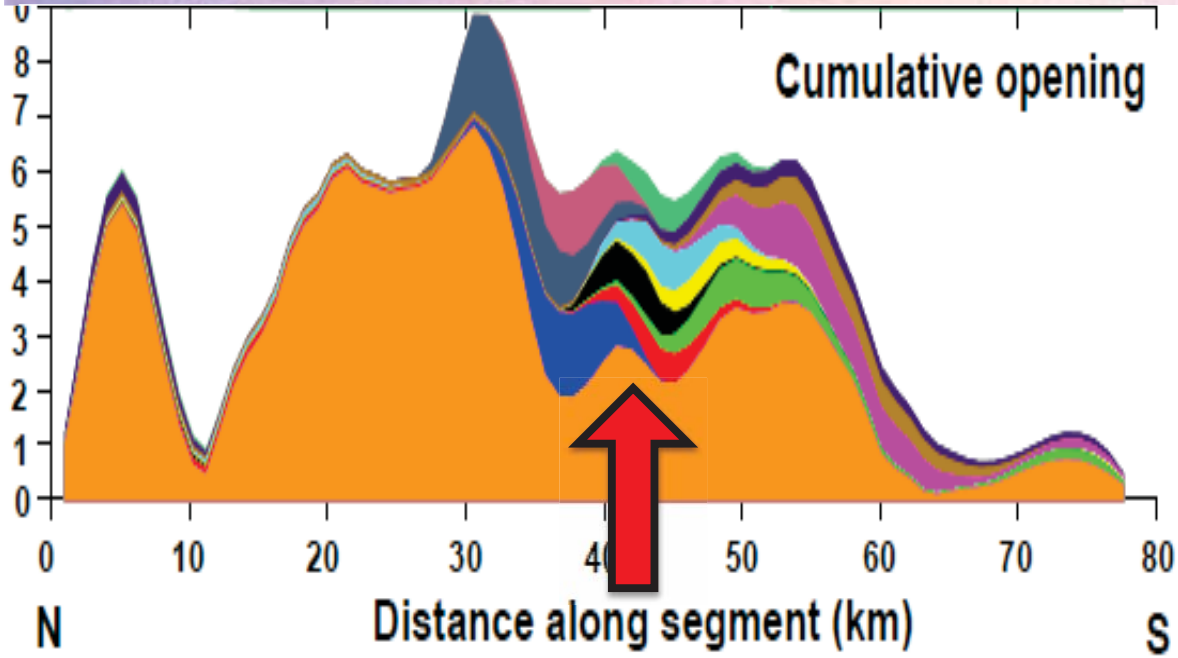


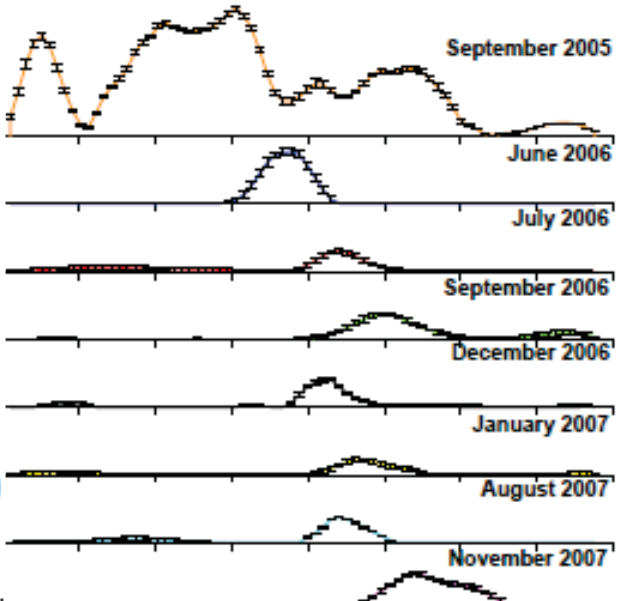
Difference 2009-2012

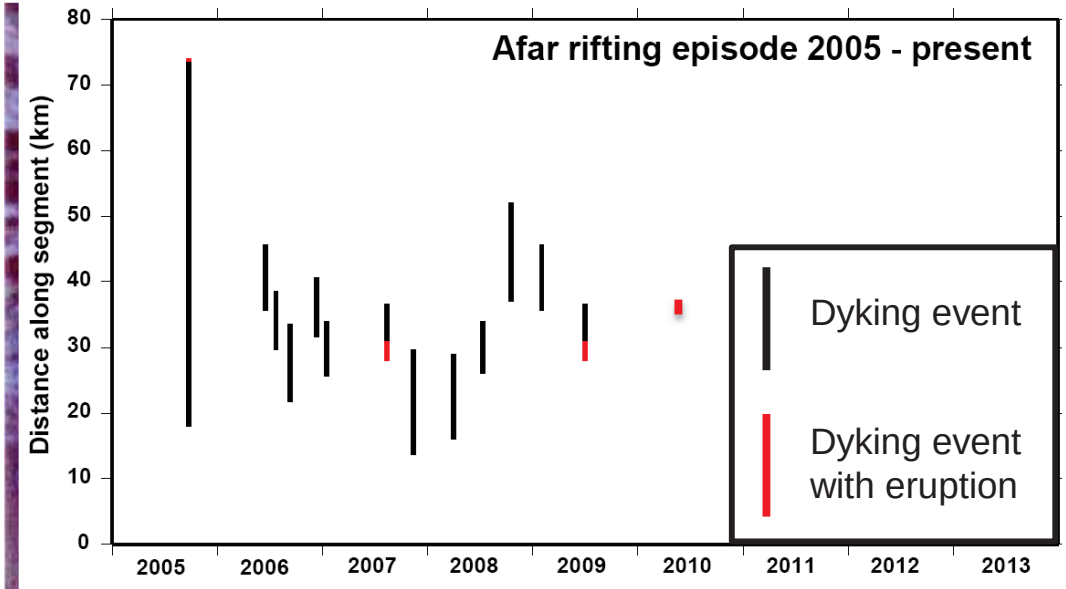


A Comparison with the Krafla rifting episode 1975-1984

A Comparison with the Krafla rifting episode 1975-1984



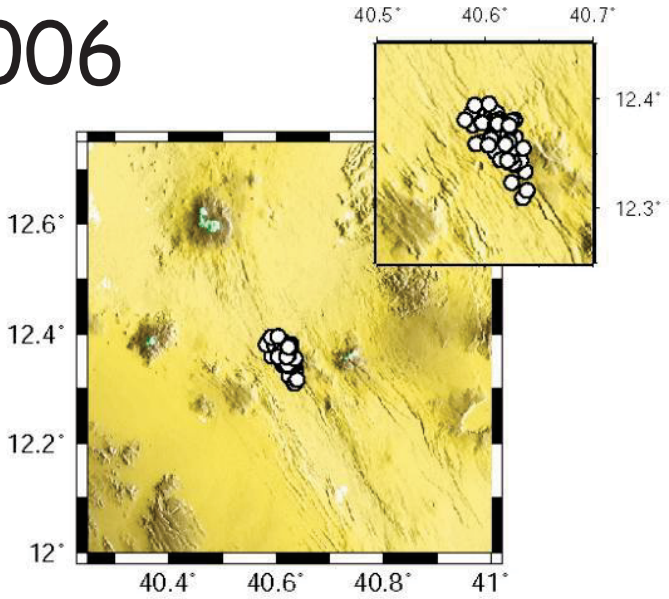


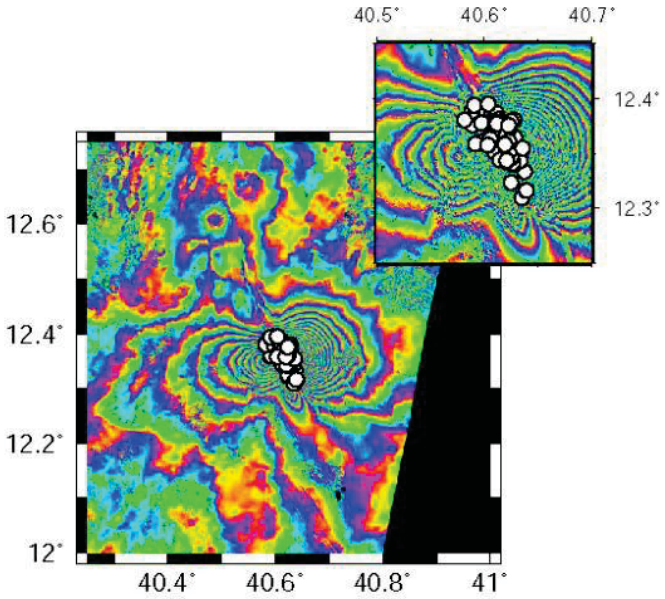


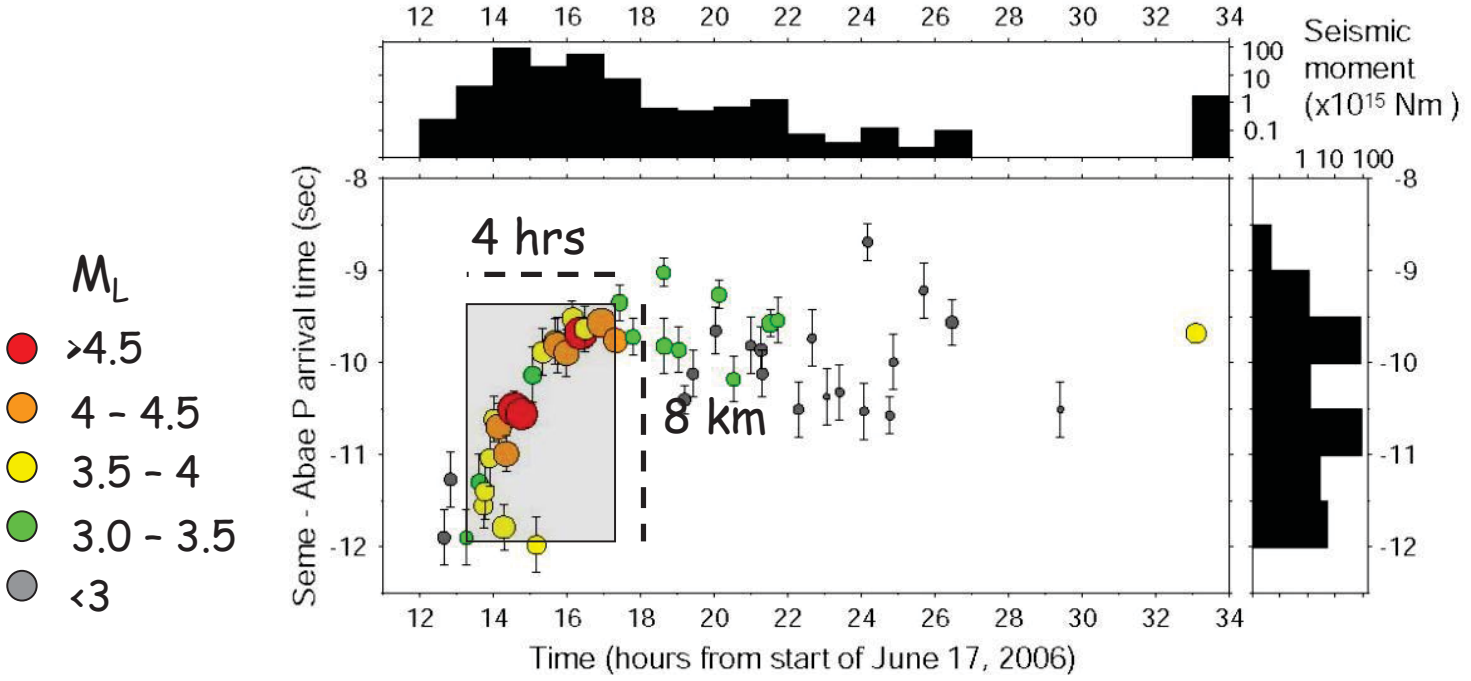
Hamling et al., GJI 2008; Hamling et al., Nat. Geo. 2010

17 June 2006

Dykes propagate laterally from central chamber. Keir et al, Geology 2009

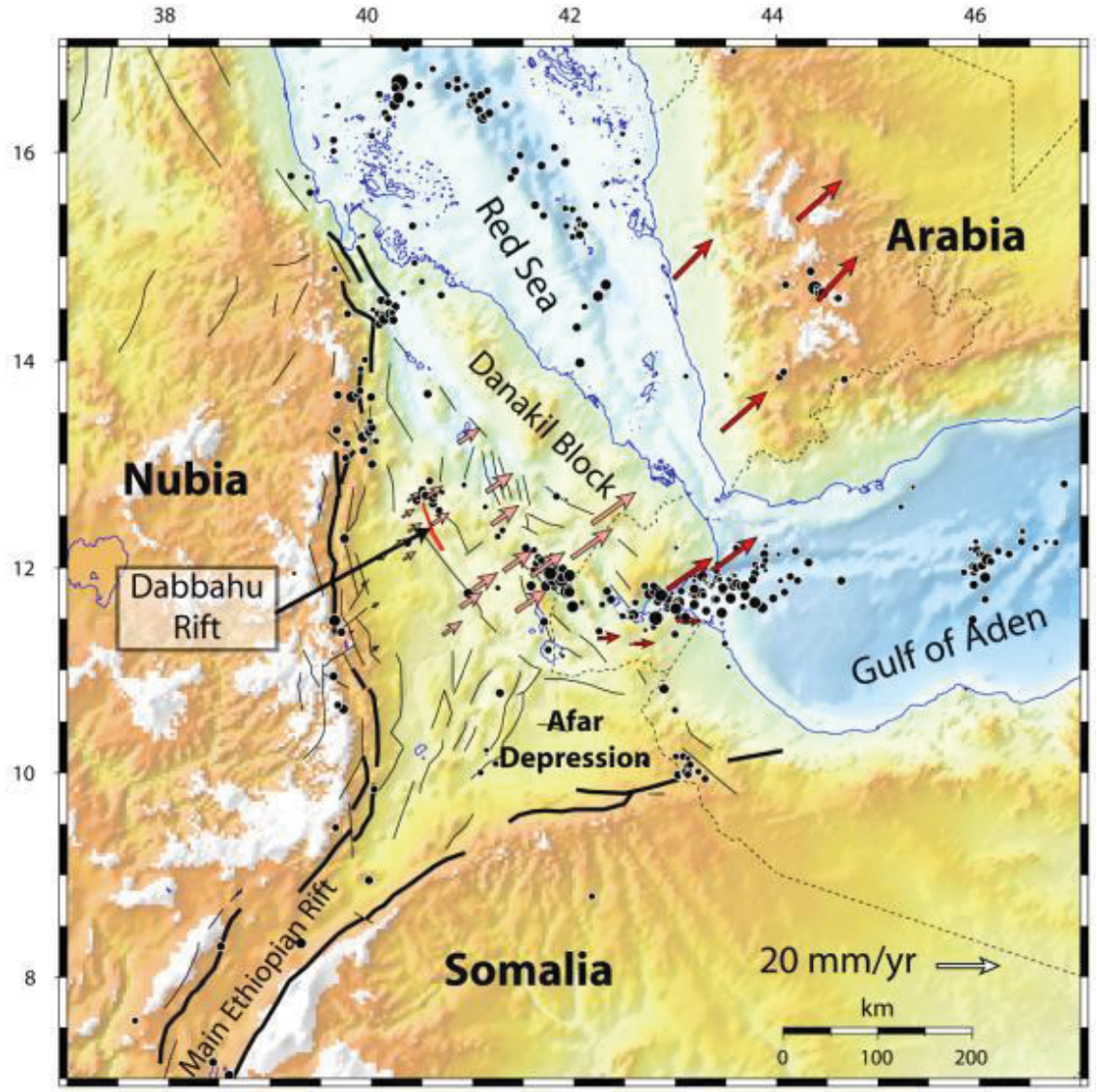






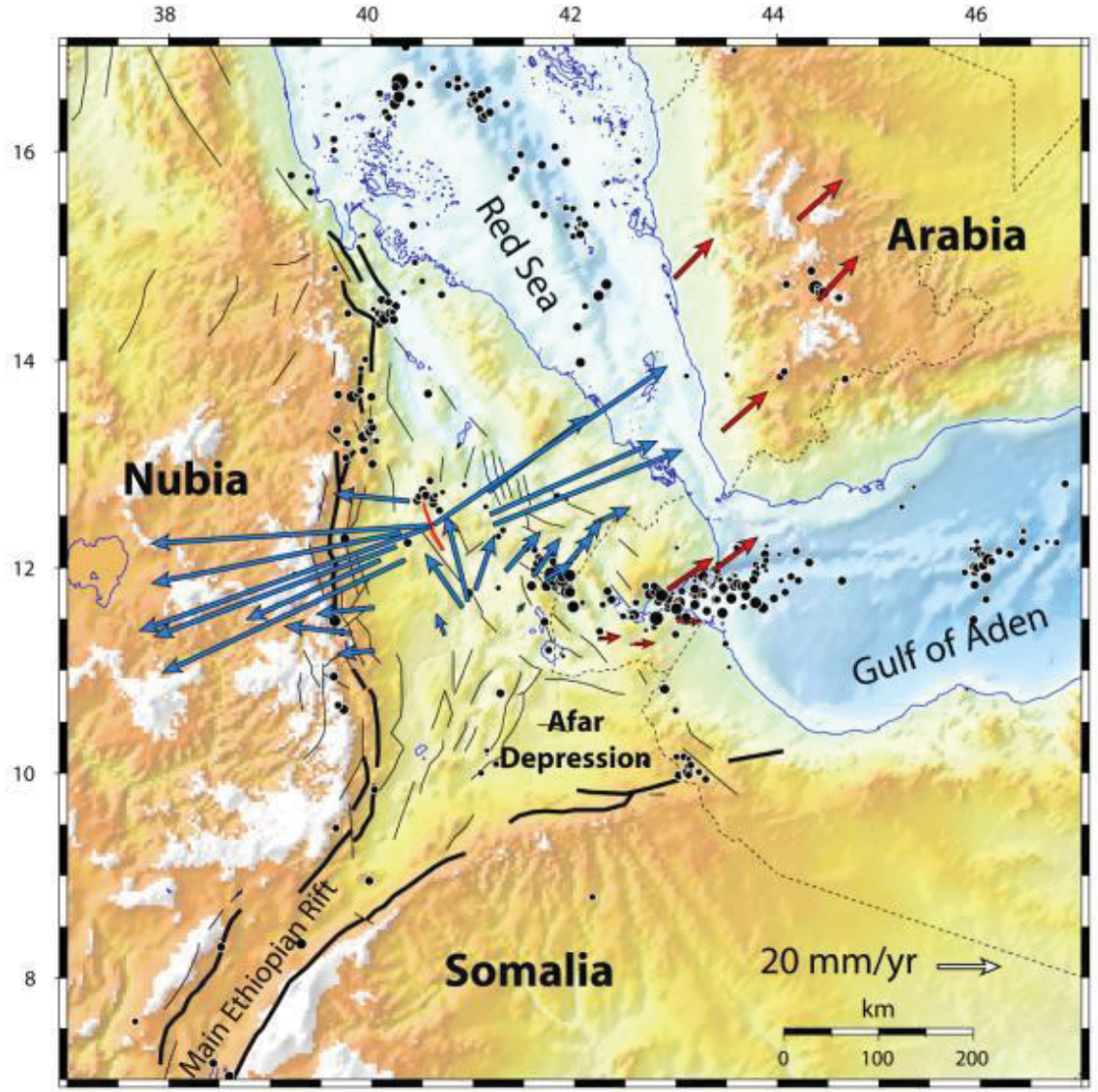
Courtesy, Eric Calais, Laura Bennati (Purdue)

Afar long-term kinematic framework



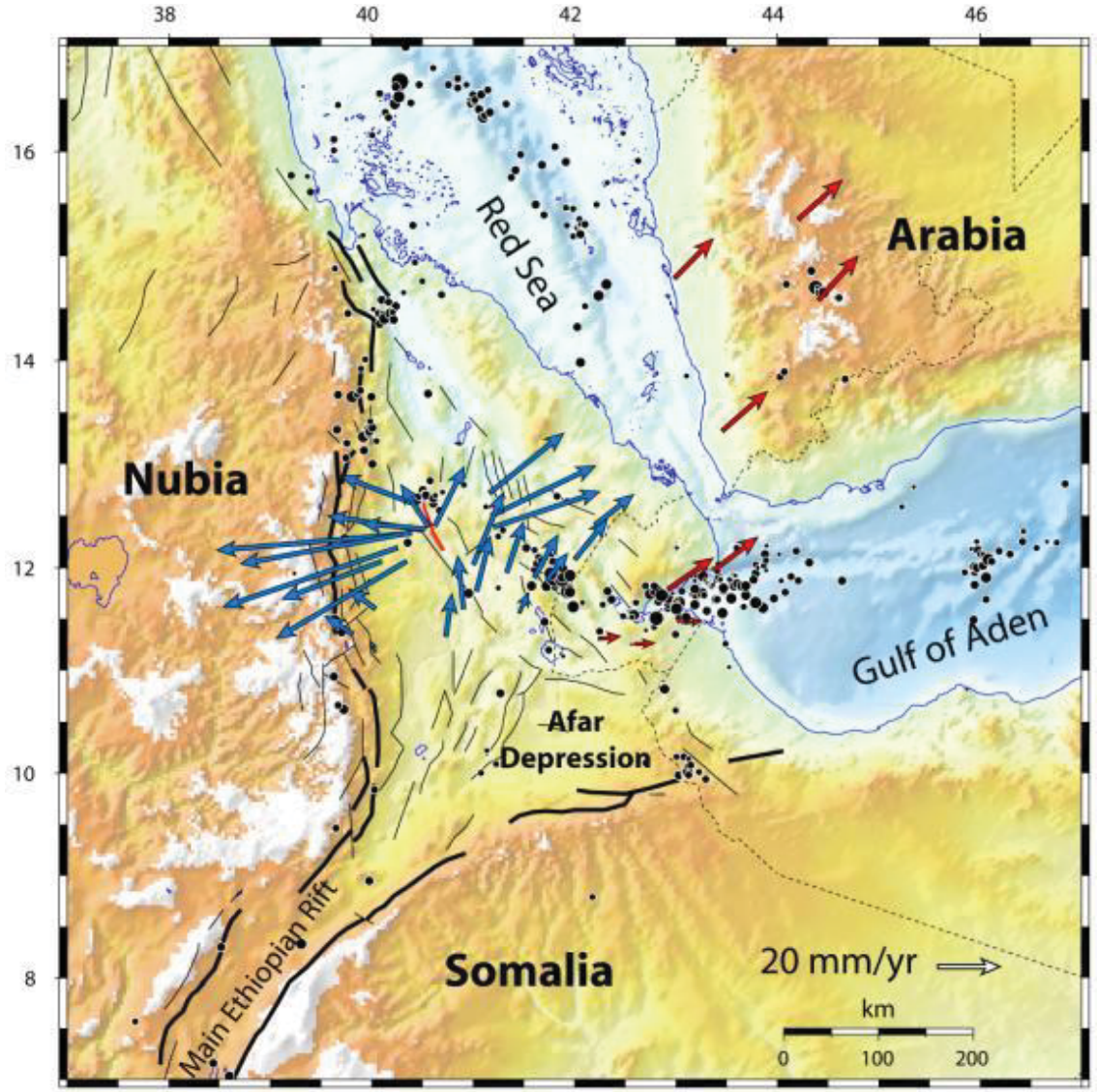
Courtesy, Eric Calais, Laura Bennati (Purdue)

GPS in Afar (01/08 to 03/09)

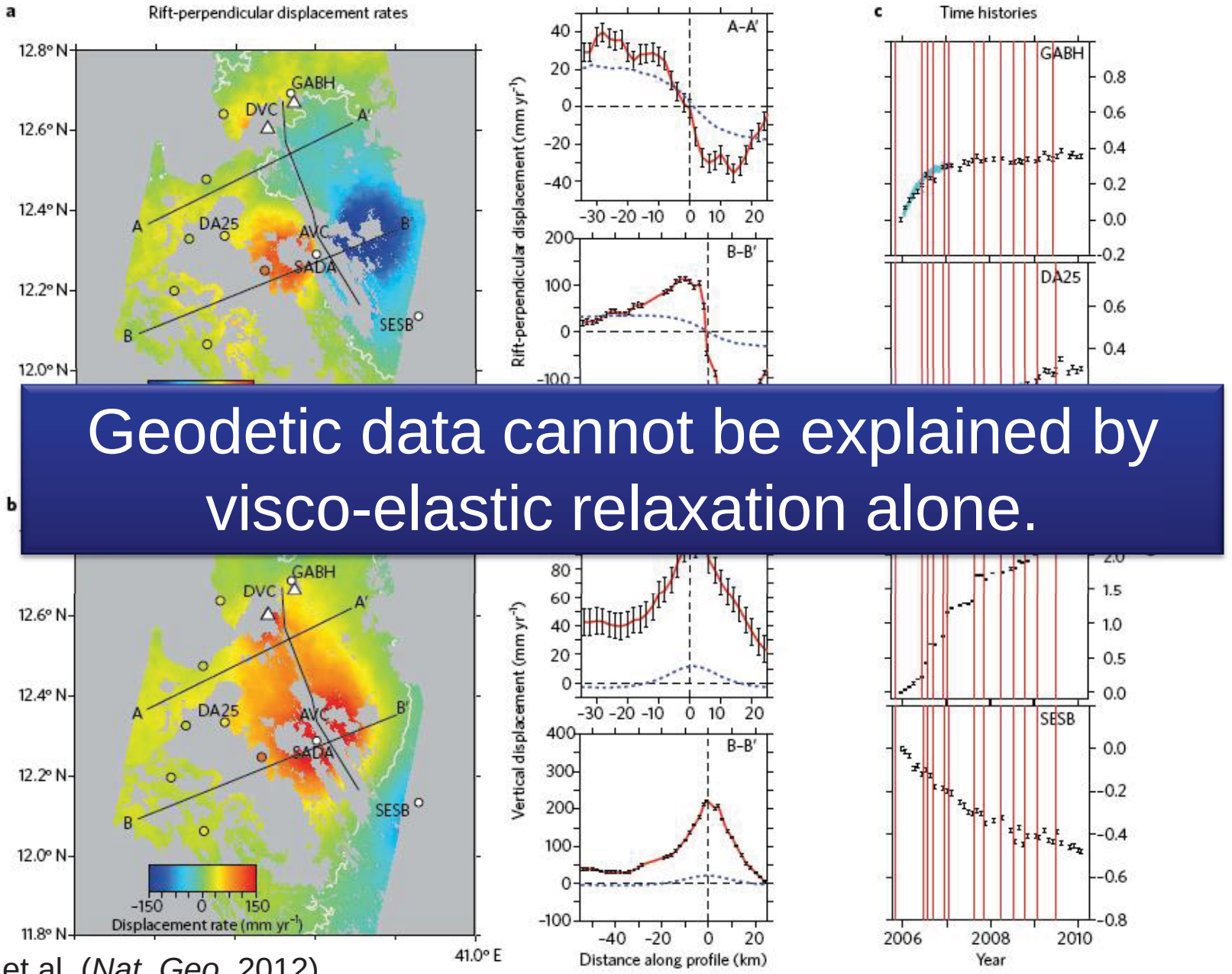


Courtesy, Eric Calais, Laura Bennati (Purdue)

GPS velocities – dykes removed

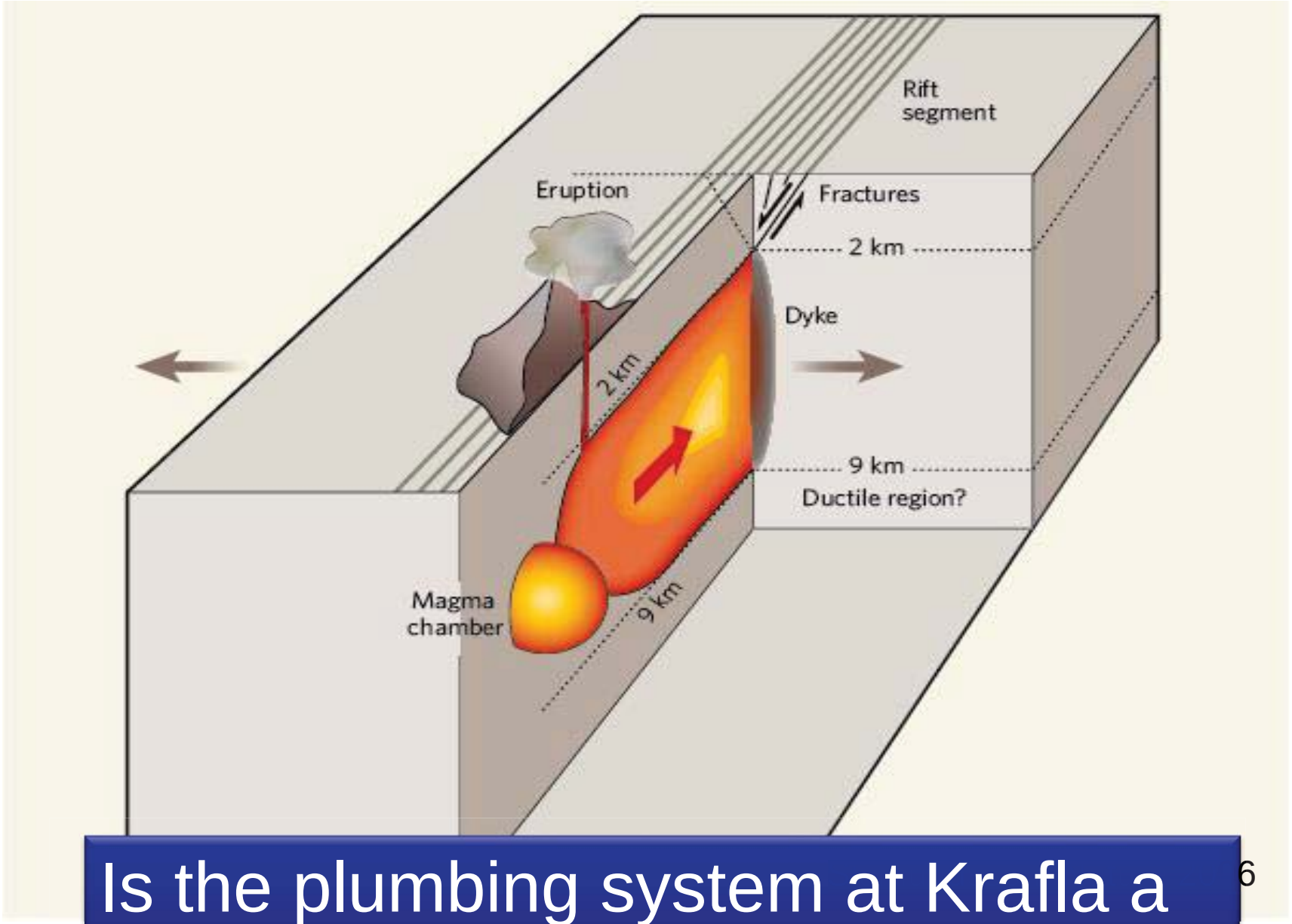


Combination of InSAR and GPS in Afar



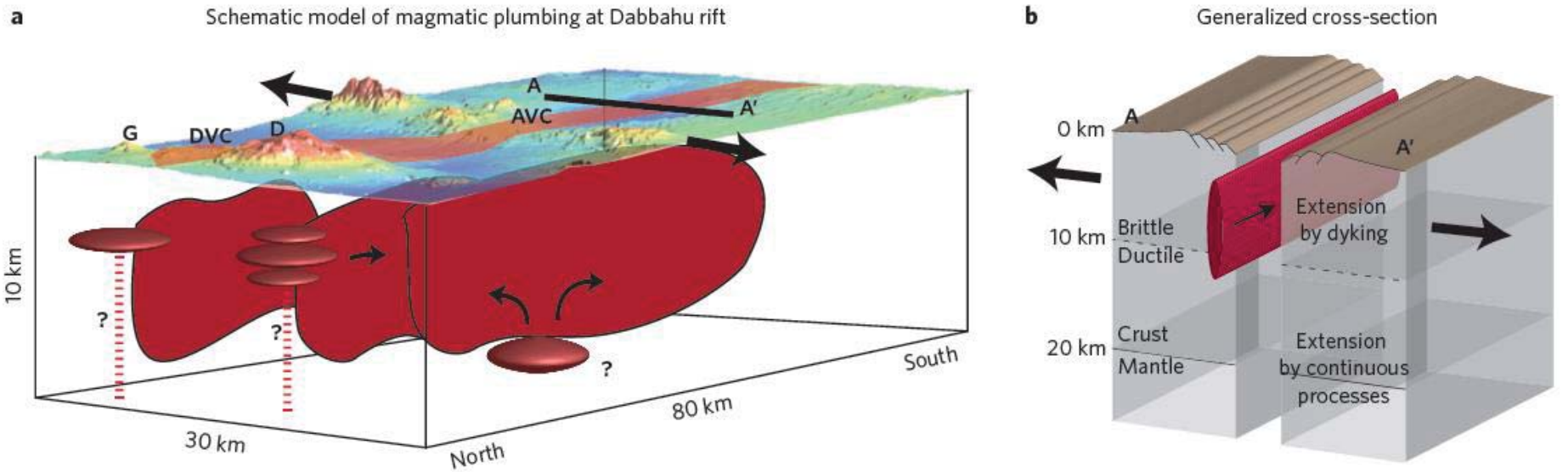
Geodetic data cannot be explained by visco-elastic relaxation alone.

Wright et al. (*Nat. Geo.* 2012)



Is the plumbing system at Krafla a good analogue for Afar?

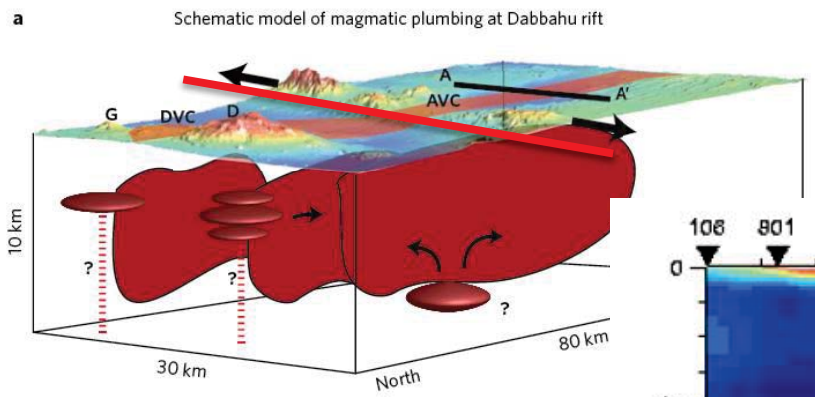
Conceptual Model for Rift Segment

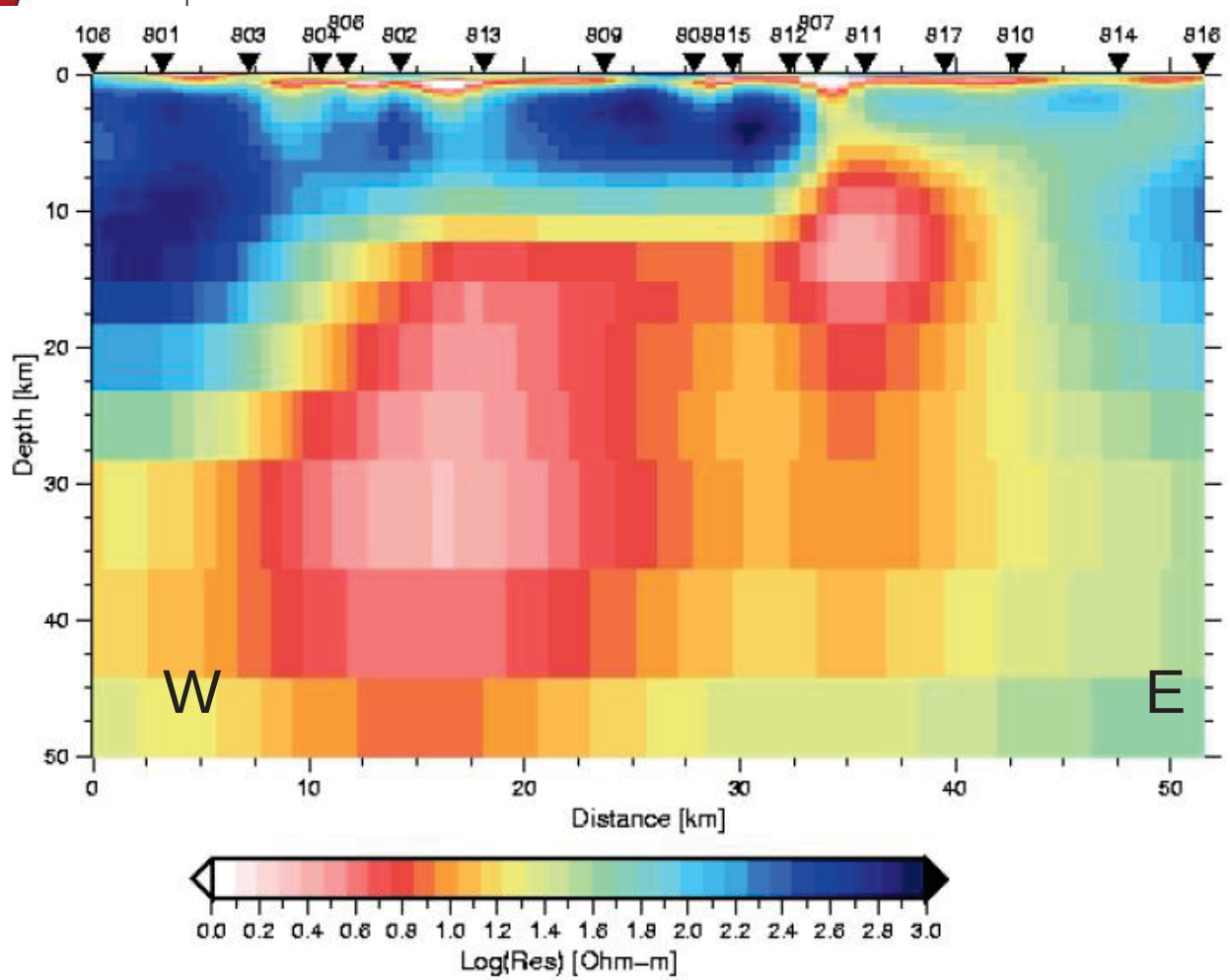


Wright et al. (*Nat. Geo.* 2012)

- Multiple interacting magma chambers
- Lateral flow of dykes in upper crust
- Continuous processes (magma + visco-elastic) in the lower crust

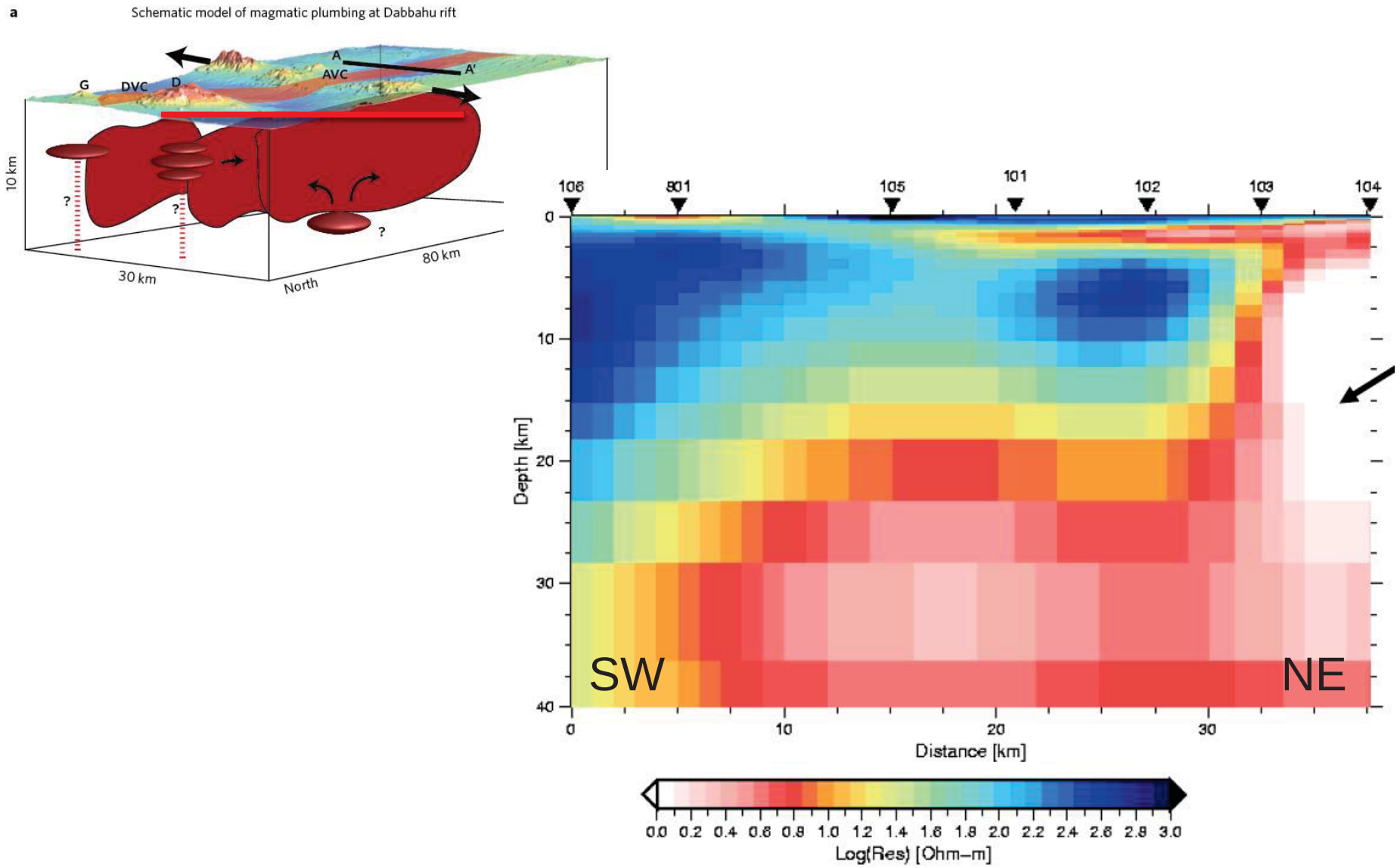
Additional evidence 1: Magnetotellurics





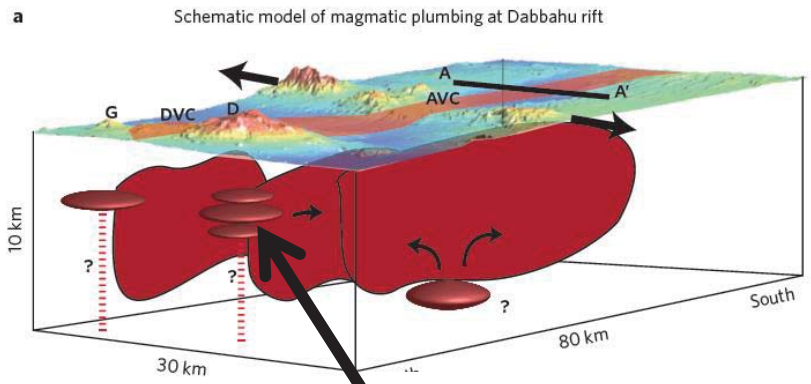
Whaler et al. (Addis Ababa, 2012)

Additional evidence 1: Magnetotellurics

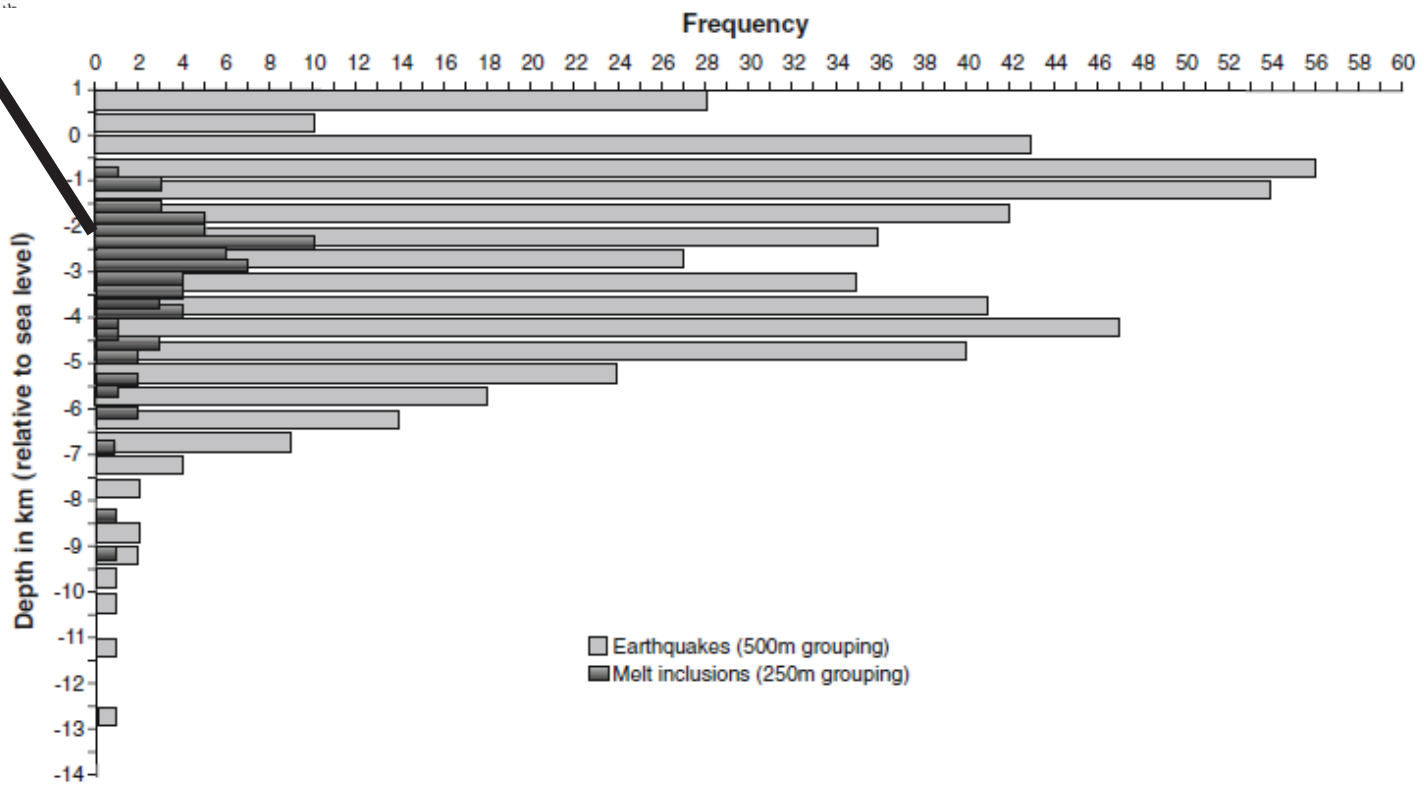


Whaler et al. (Addis Ababa, 2012)

Additional evidence 2: Petrology

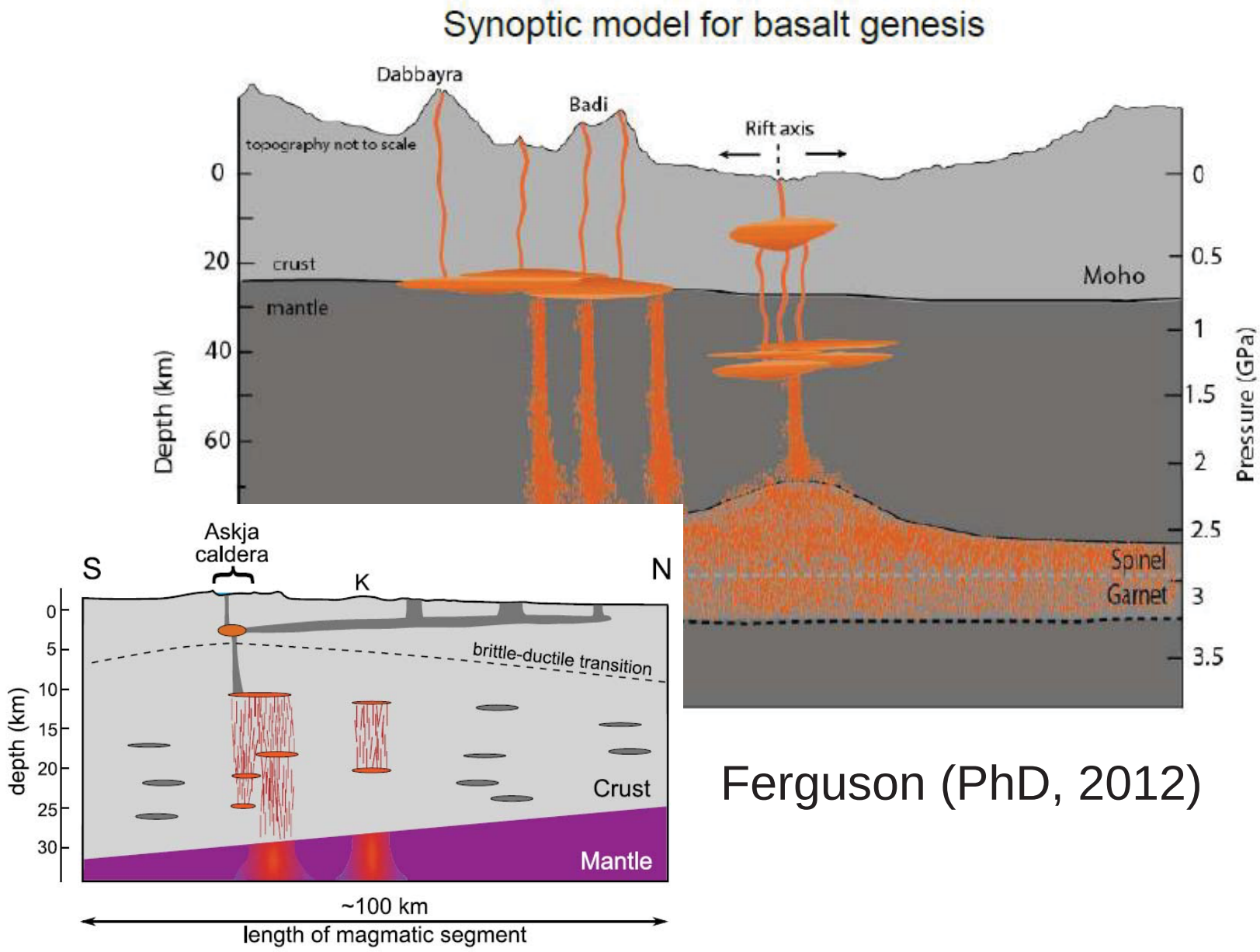


• To explain petrology, deformation and seismicity requires melt to be distributed in **stacked sills** in upper crust.



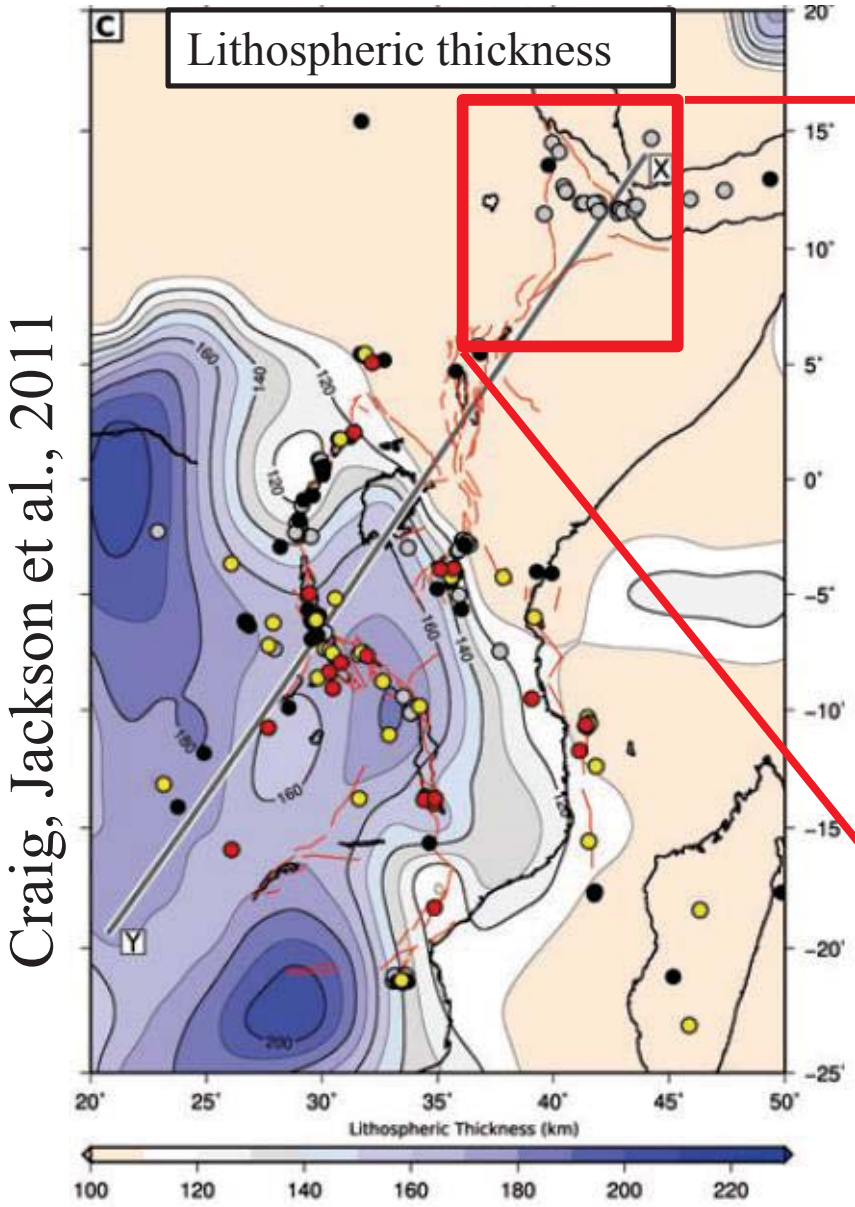
Field et al. (Bull Volc, 2012)

Additional evidence 2: Petrology



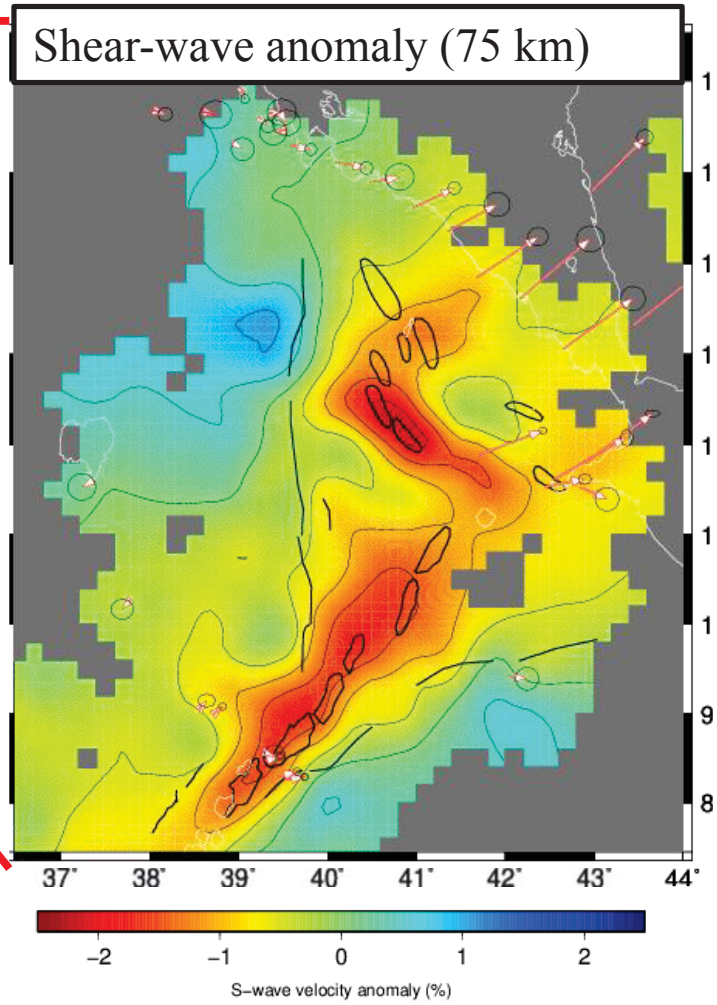
Ferguson (PhD, 2012)

Additional evidence 3: Seismic Imaging



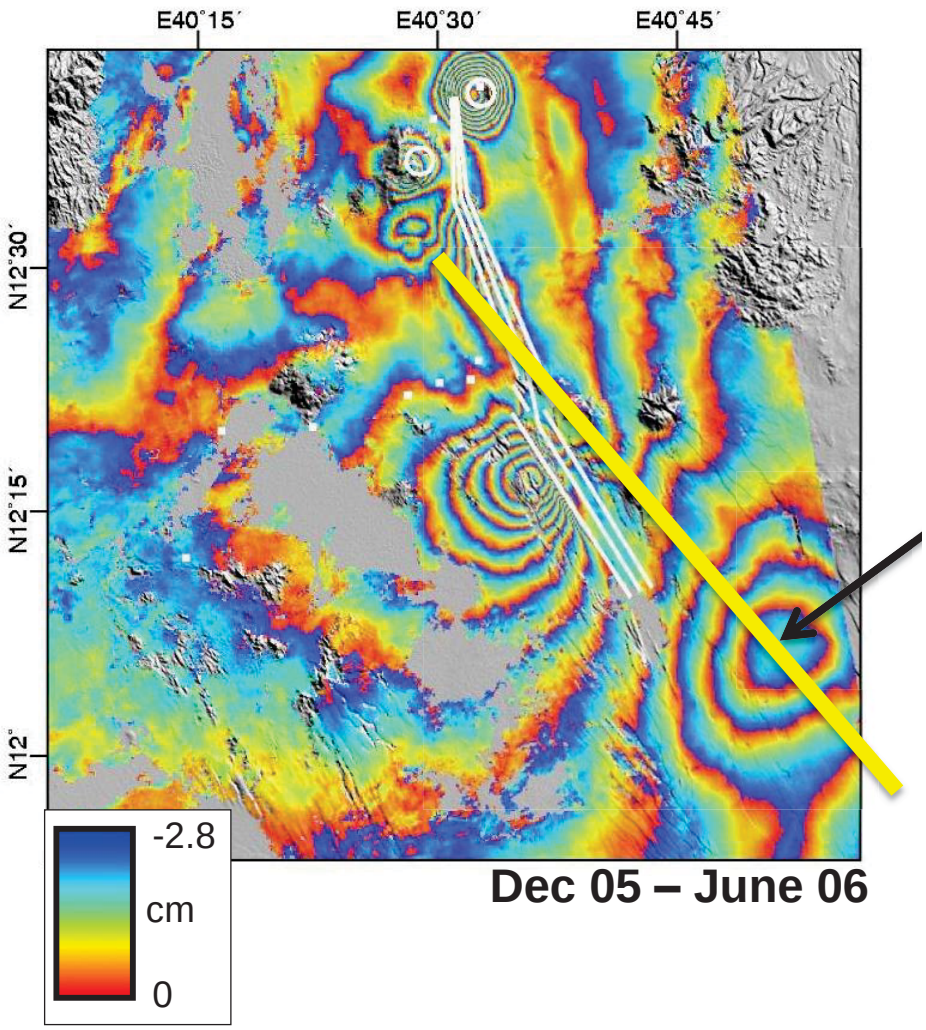
Craig, Jackson et al., 2011

Lithospheric thickness

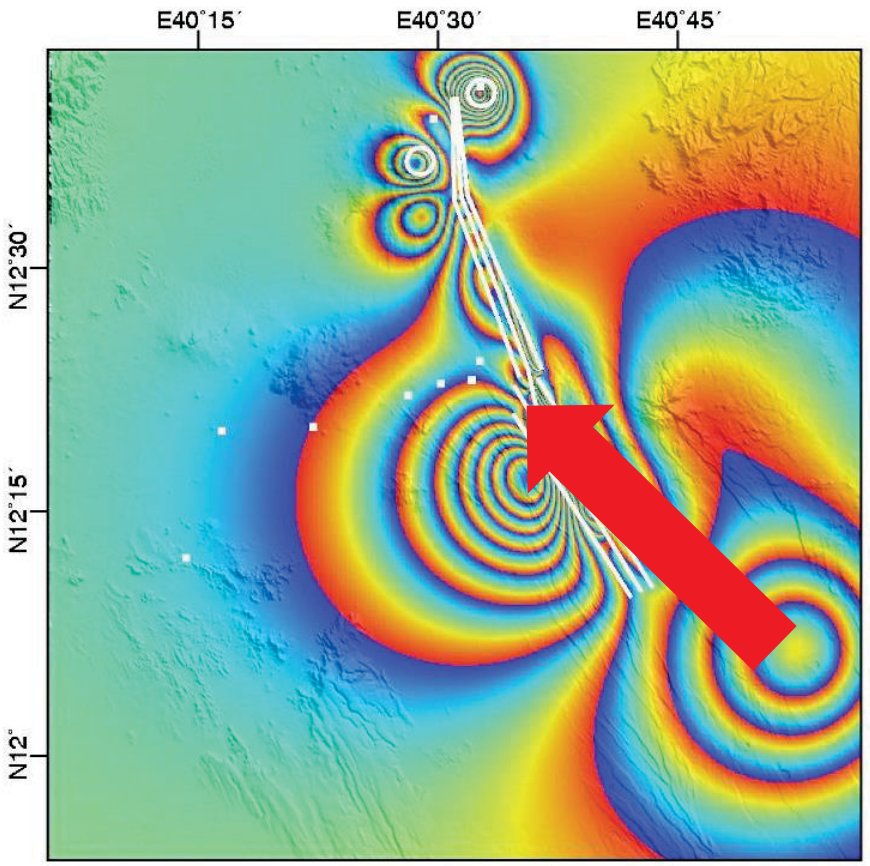


Hammond et al., 2013

Unresolved issues (1) – Lateral Flow in Lower Crust?

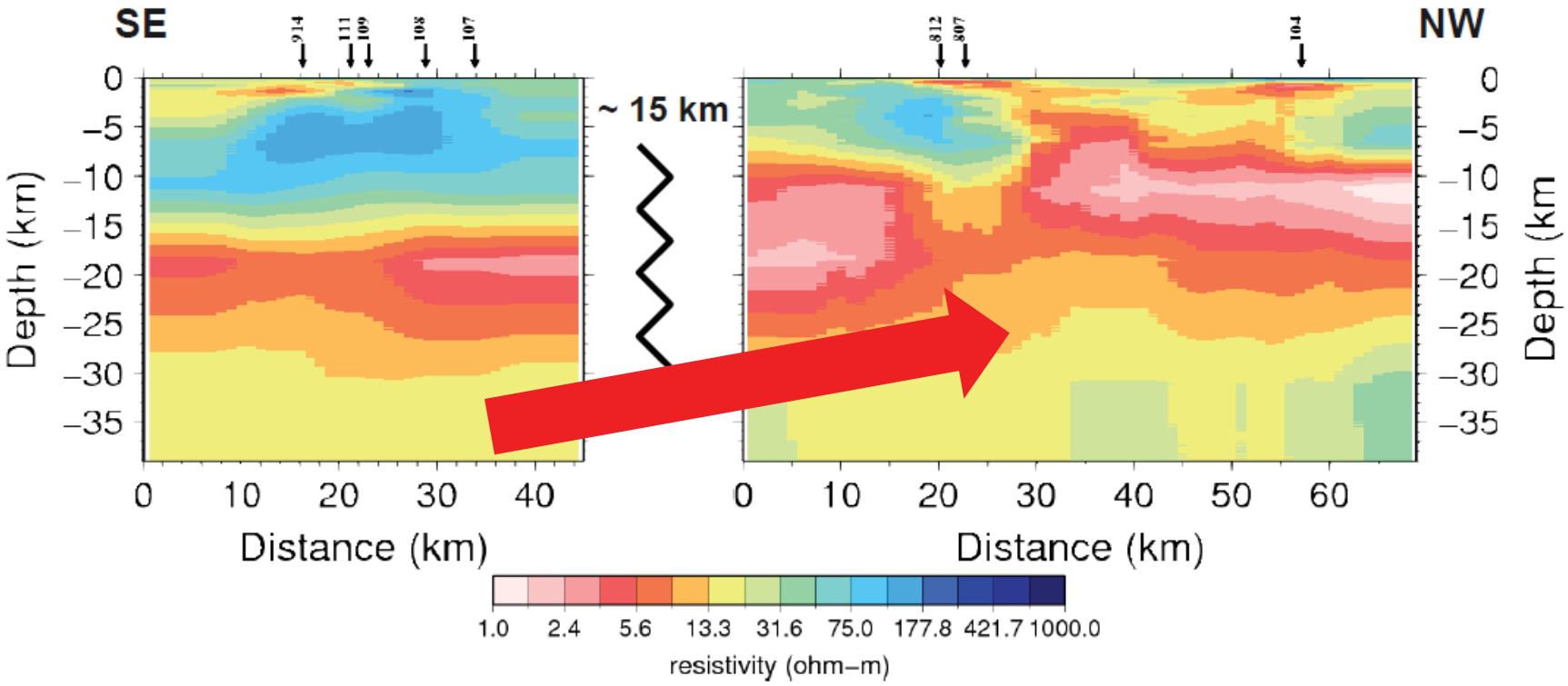


Dec 05 – June 06



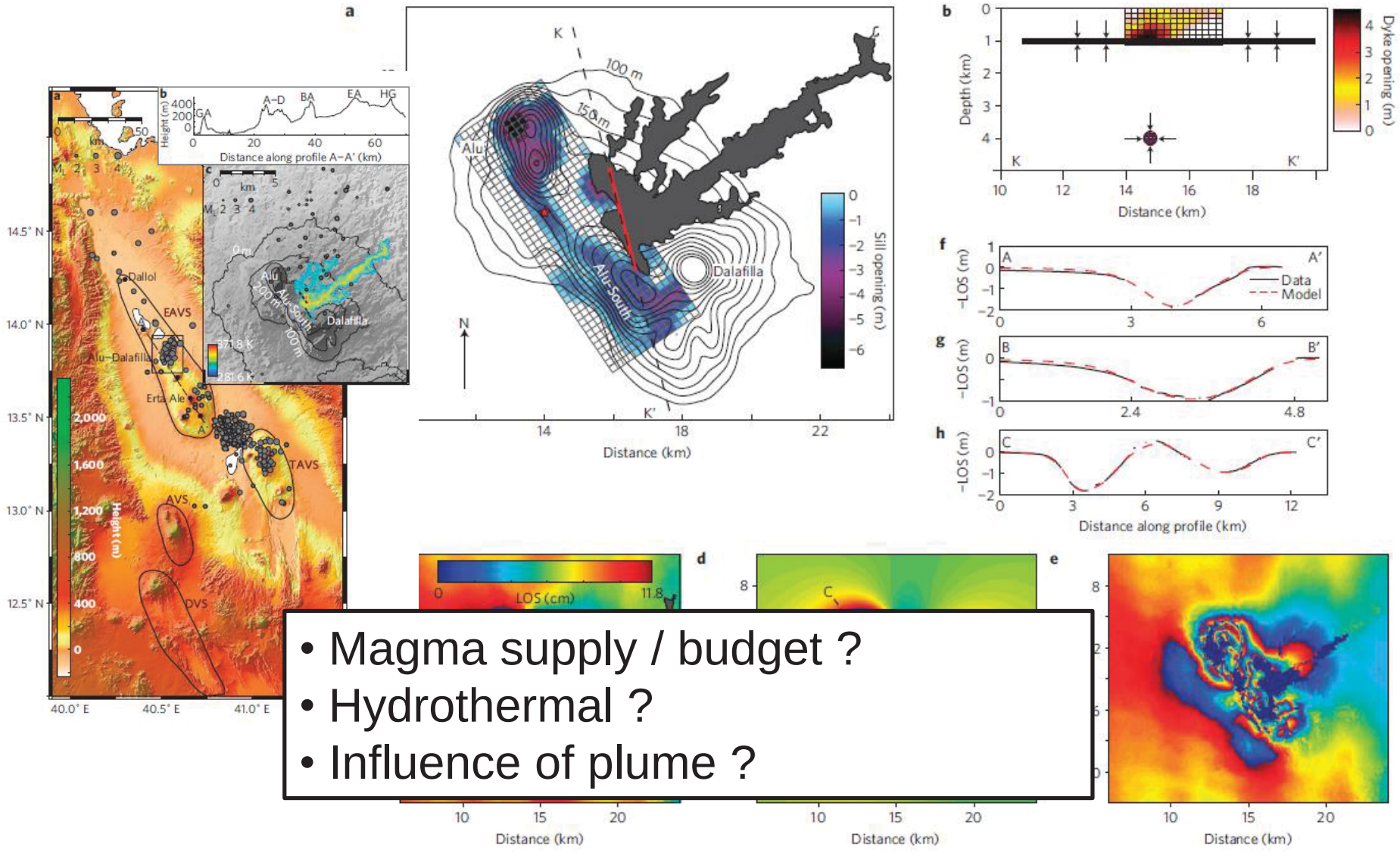
Deep deflation: 0.12 km^3, 15 km depth
[~0.4 km^3 for 2005-2009]

Unresolved issues (1) – Lateral Flow in Lower Crust?



3D MT inversion courtesy Sophie Hautot

Unresolved issues (2) – Controls on plumbing system / eruptive style?



- Magma supply / budget ?
- Hydrothermal ?
- Influence of plume ?

Pagli et al., (Nature Geoscience 2012)

Unresolved issues (3) – Long-range interactions?

Dallol dyke intrusion (2004)

Dabbahu (2005-2010): 14 dyke intrusions including 4 eruptions

Alu-Dalafilla Eruption (November 2008)

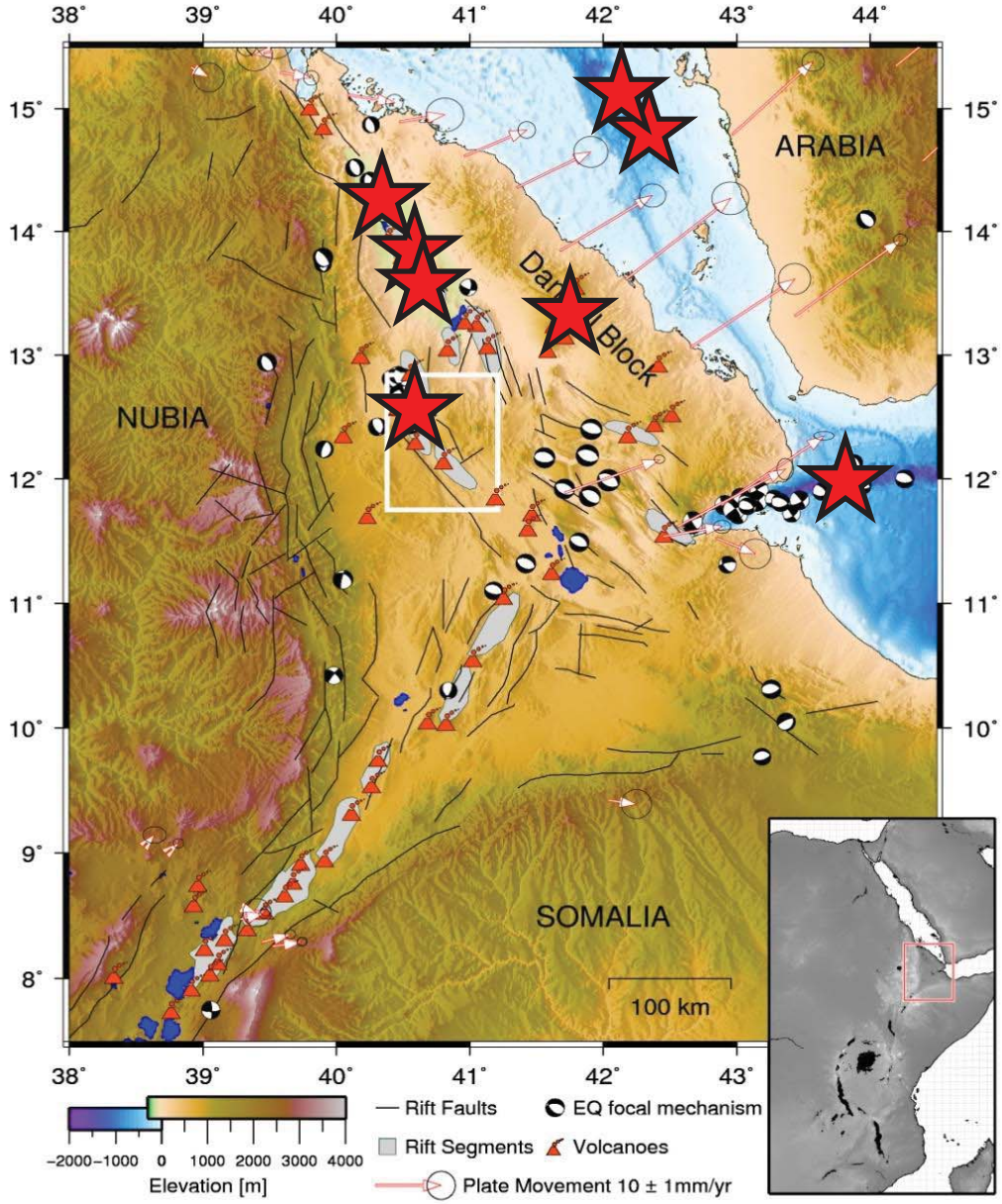
Erta Ale overflow (November 2010)

Nabro Eruption (June 2011)

Jebel al Tair (2007)

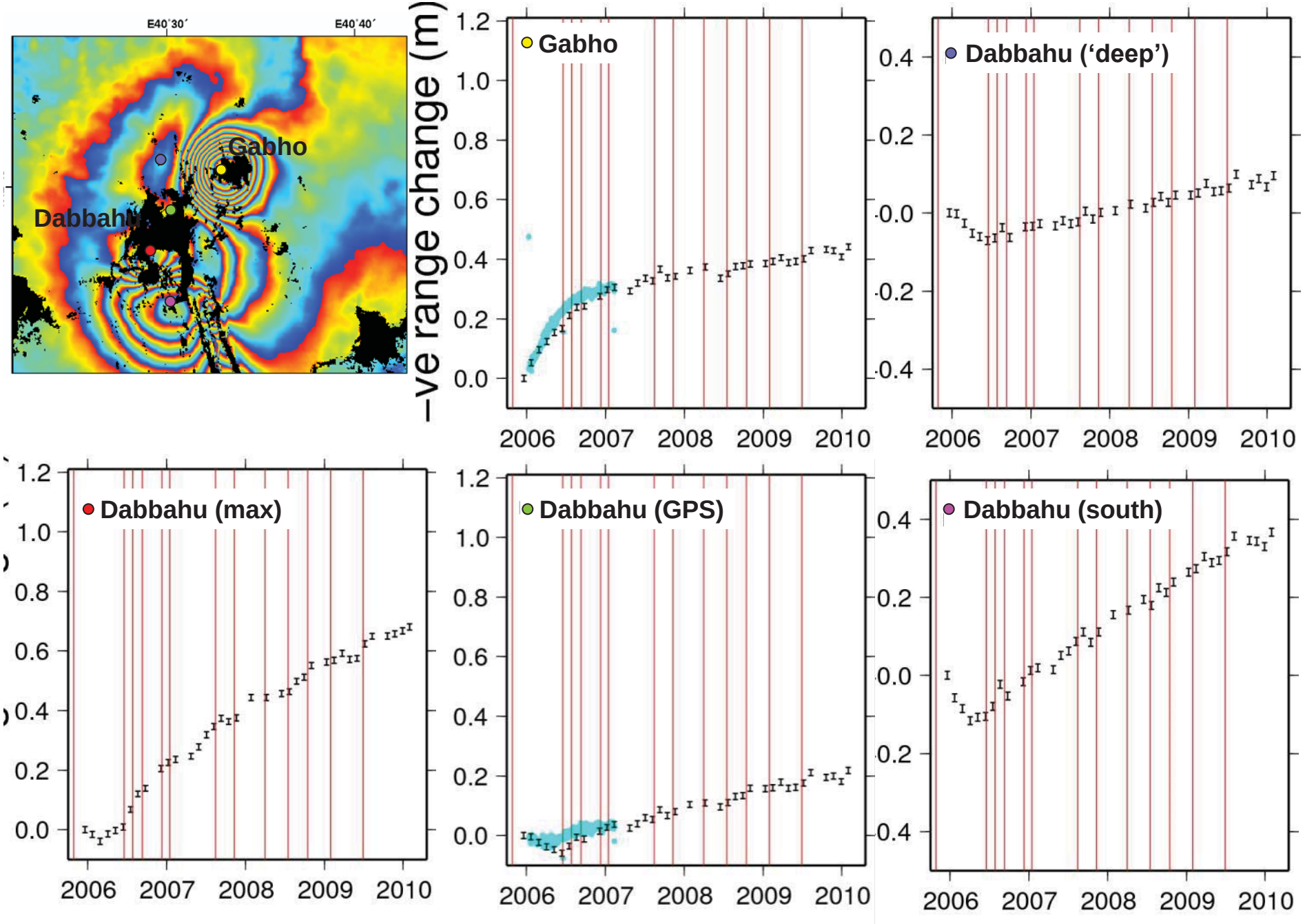
Gulf of Aden (2010-)

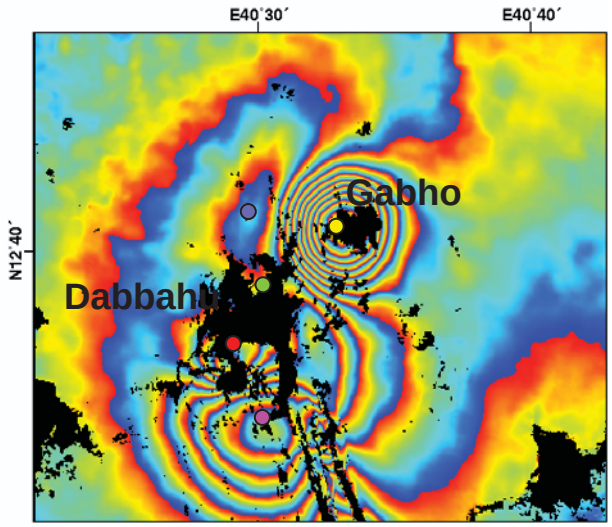
Zubair Group (2012)

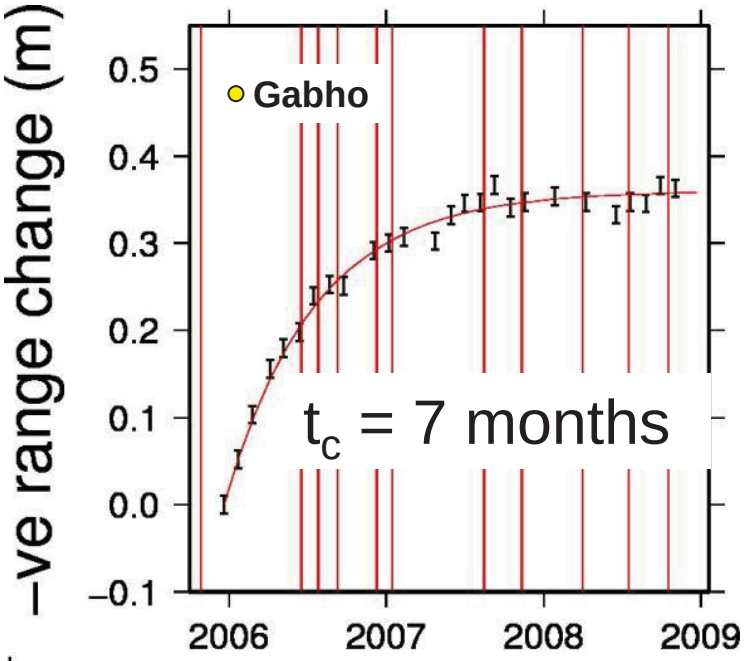


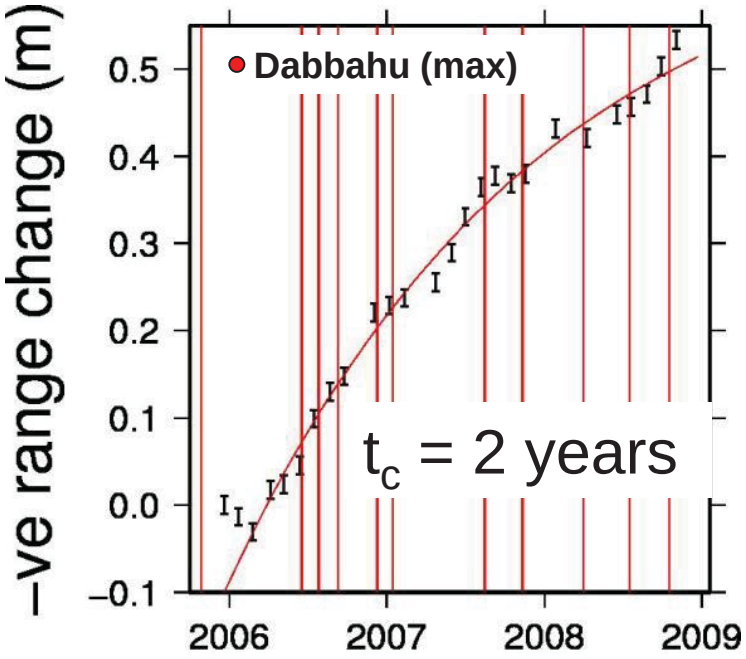
Conclusions

- The first observations of a modern subaerial rifting episode reveal a complex shallow magmatic system.
- A series of chambers in the upper crust are fed independently from below.
- Melt has migrated laterally in the lower crust / upper mantle for tens of kilometres.
- Our simple view of magma plumbing at slow-spreading ridges should be re-evaluated in light of these results.
- But behaviour of the rifting episode is remarkably similar to Krafla.
- “rules of the game” are different if magma is involved.


E40°30′
E40°40′
Gabho
Dabbahu
–ve range change (m)
Gabho
Dabbahu (‘deep’)
Dabbahu (max)
Dabbahu (GPS)
Dabbahu (south)
2006
2007
2008
2009
2010



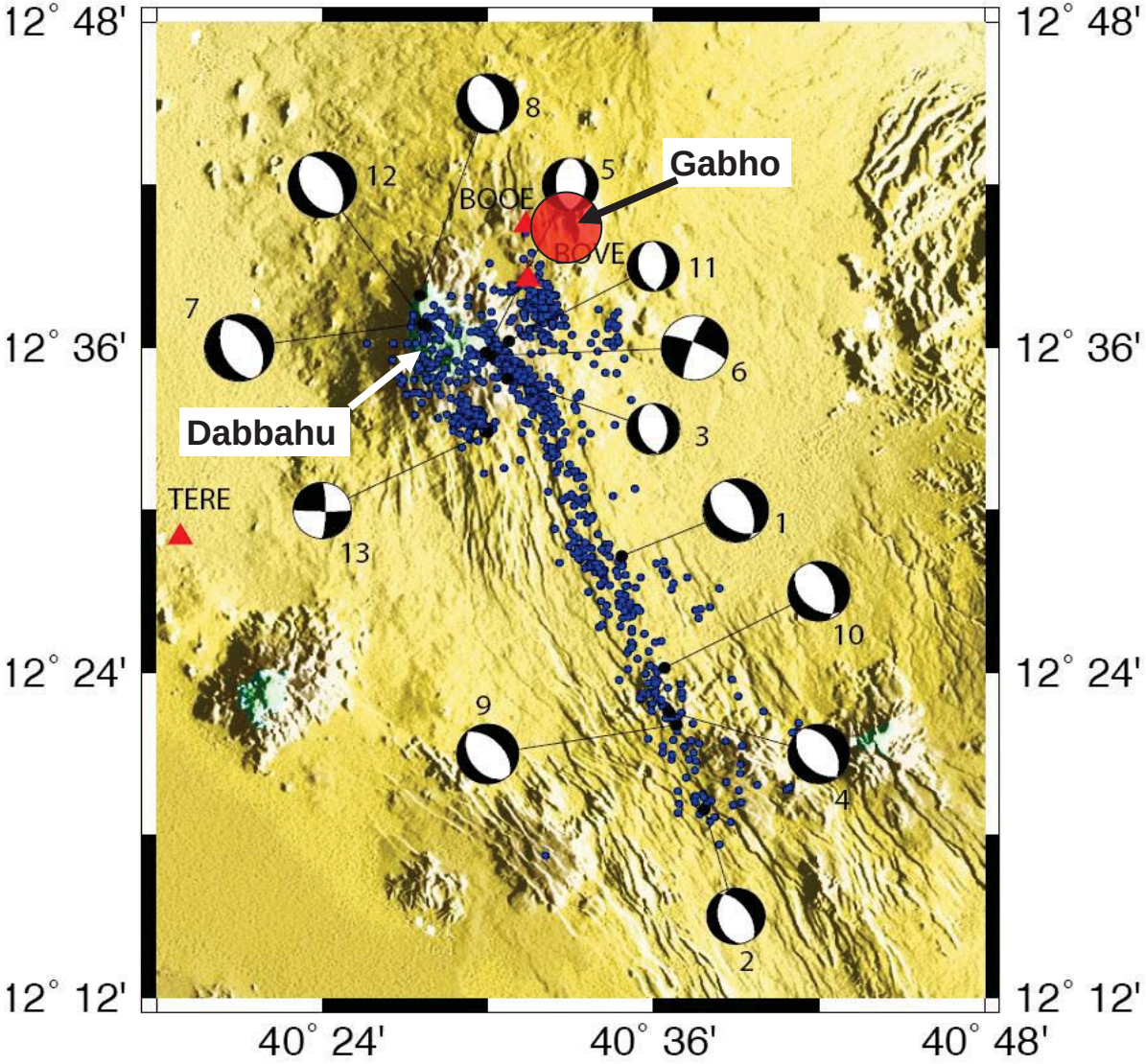


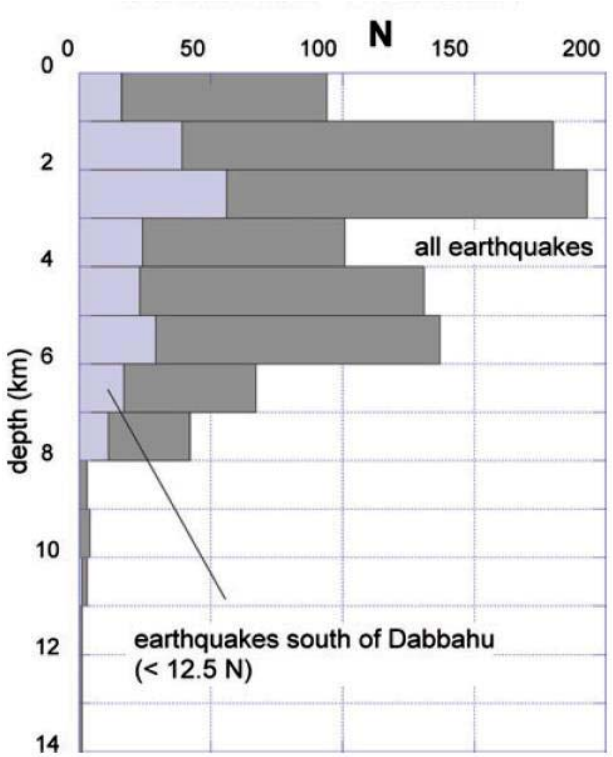


Exponentially decaying uplift with different time constants (fits simple repressurisation model)

Suggests separate links to deep source

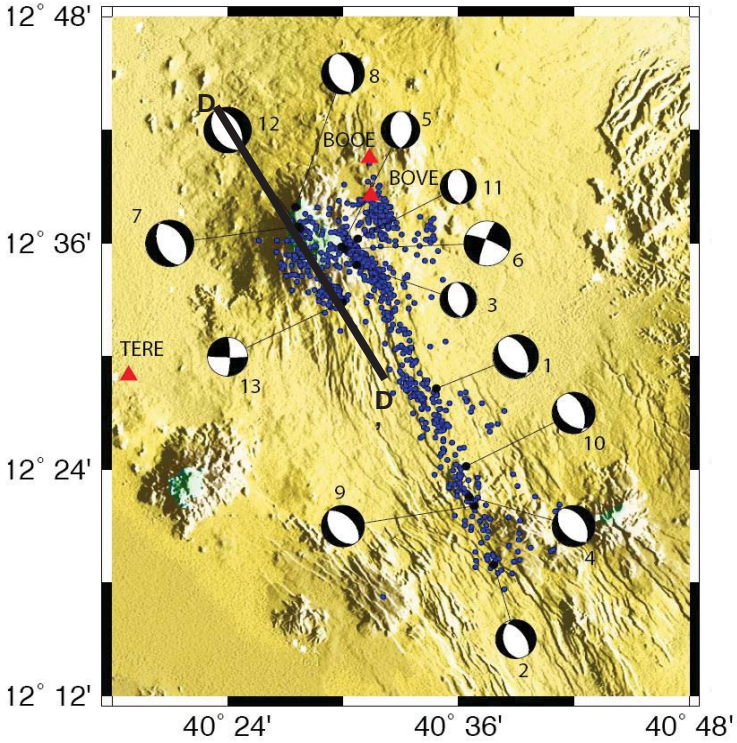
Seismicity from urgency array – 19 Oct 2005 – 31 March 2006

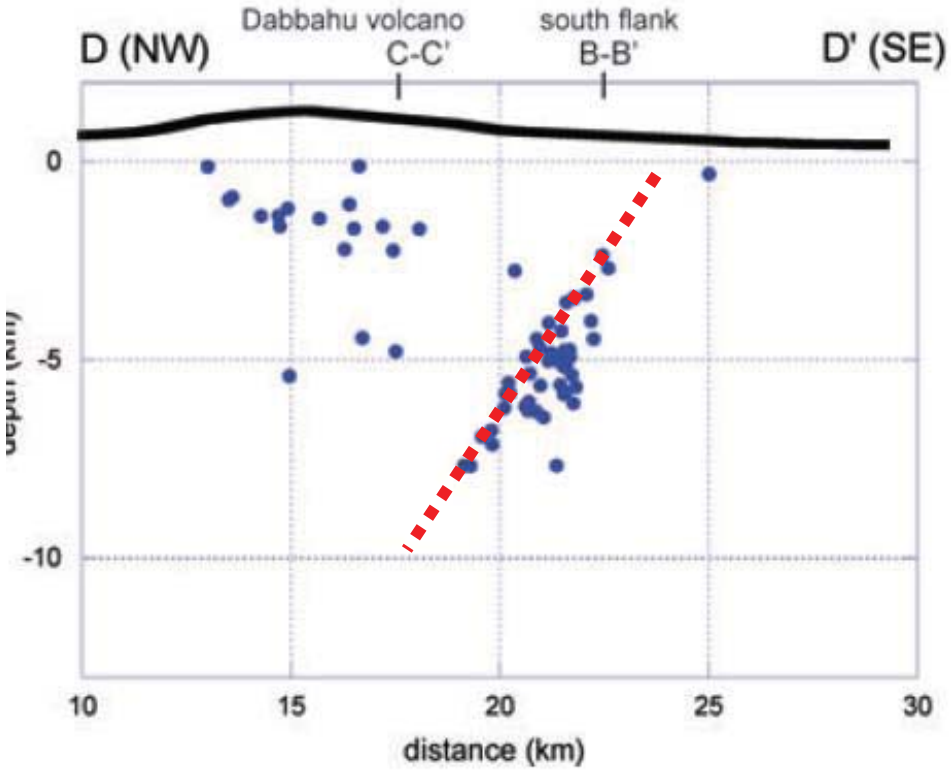




From Ebinger et al., GJI 2008. Best ~1000 events after double difference relocation

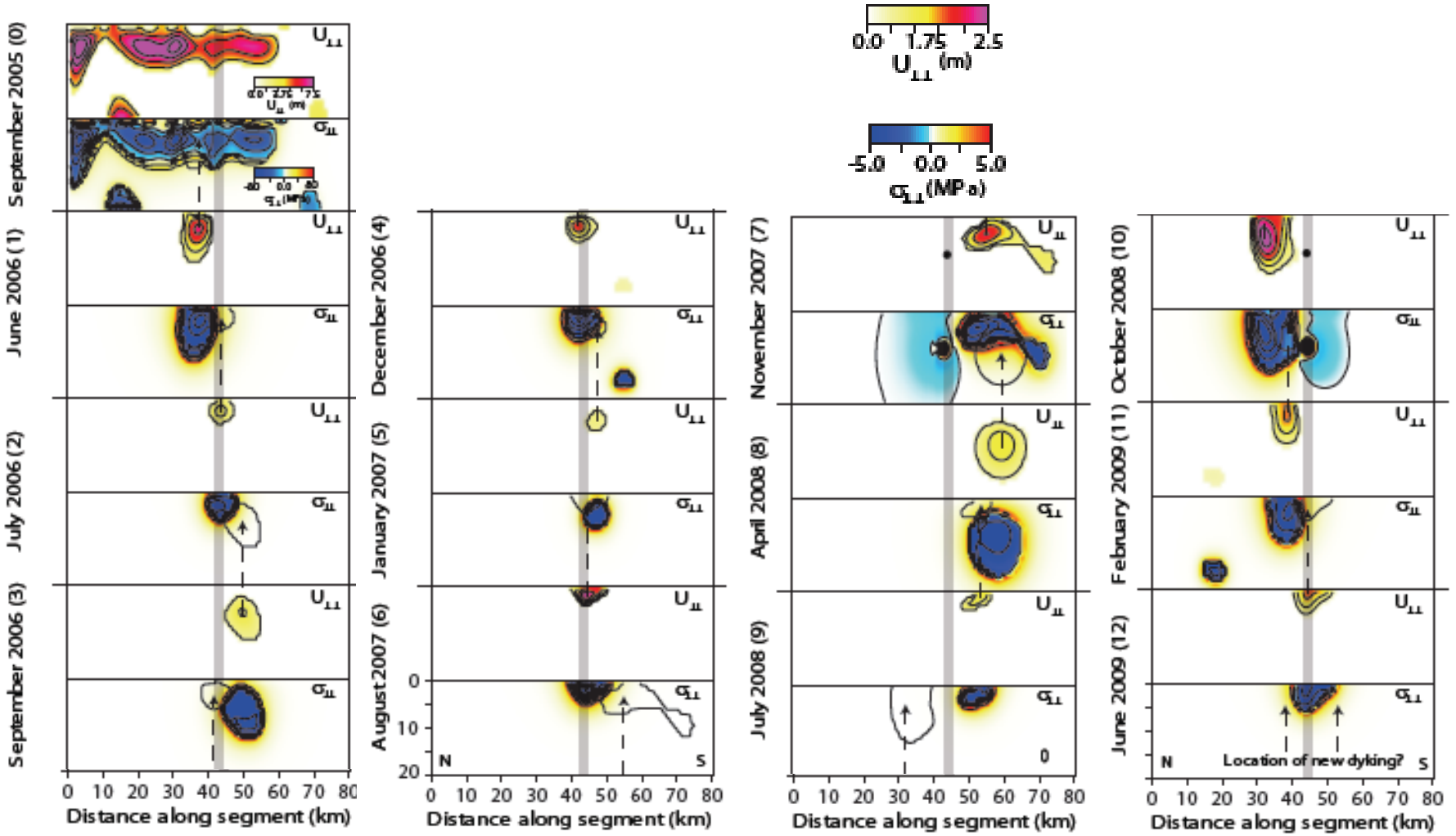
Seismicity from urgency array – 19 Oct 2005 – 31 March 2006



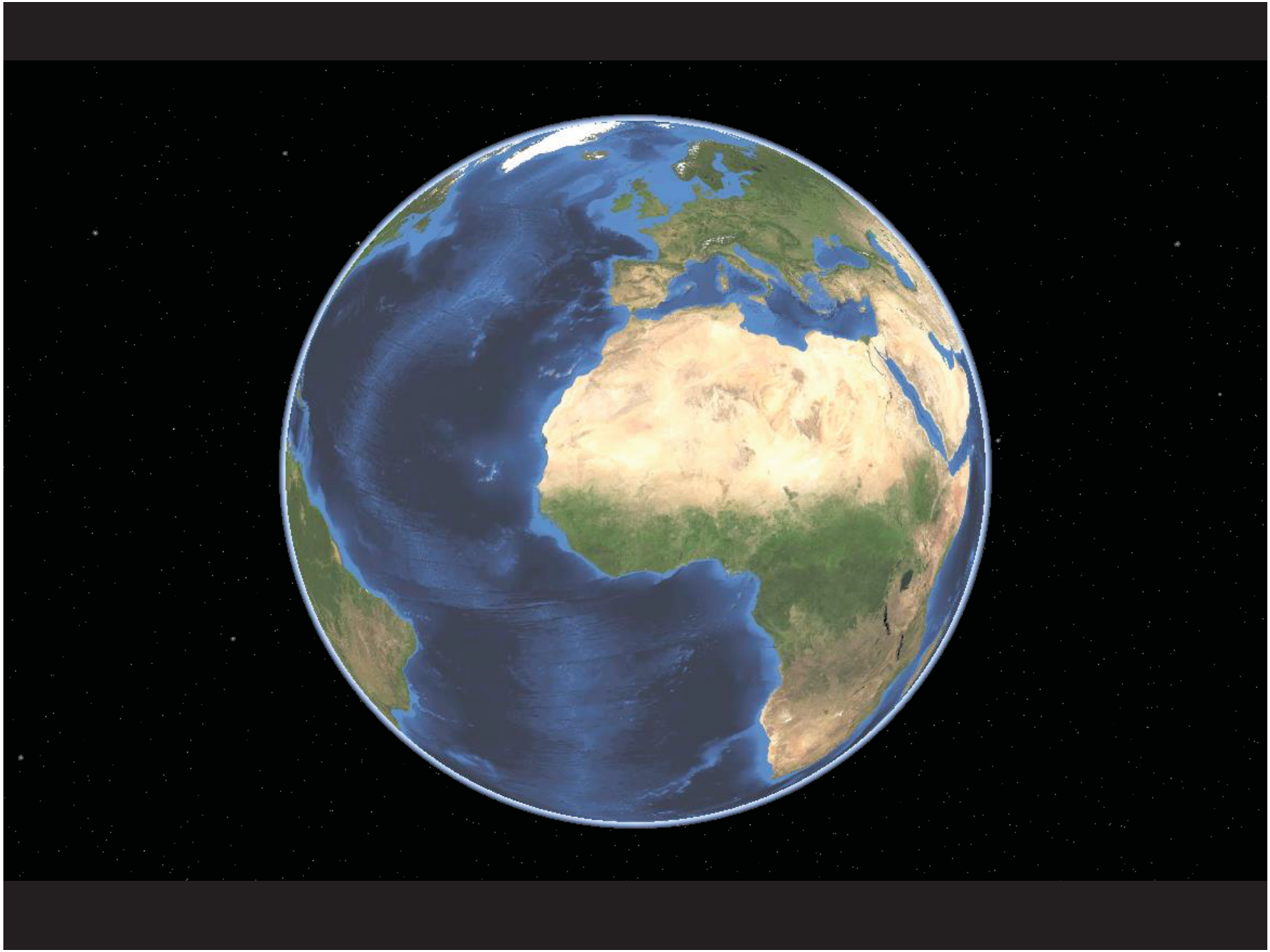


From Ebinger et al., GJI 2008

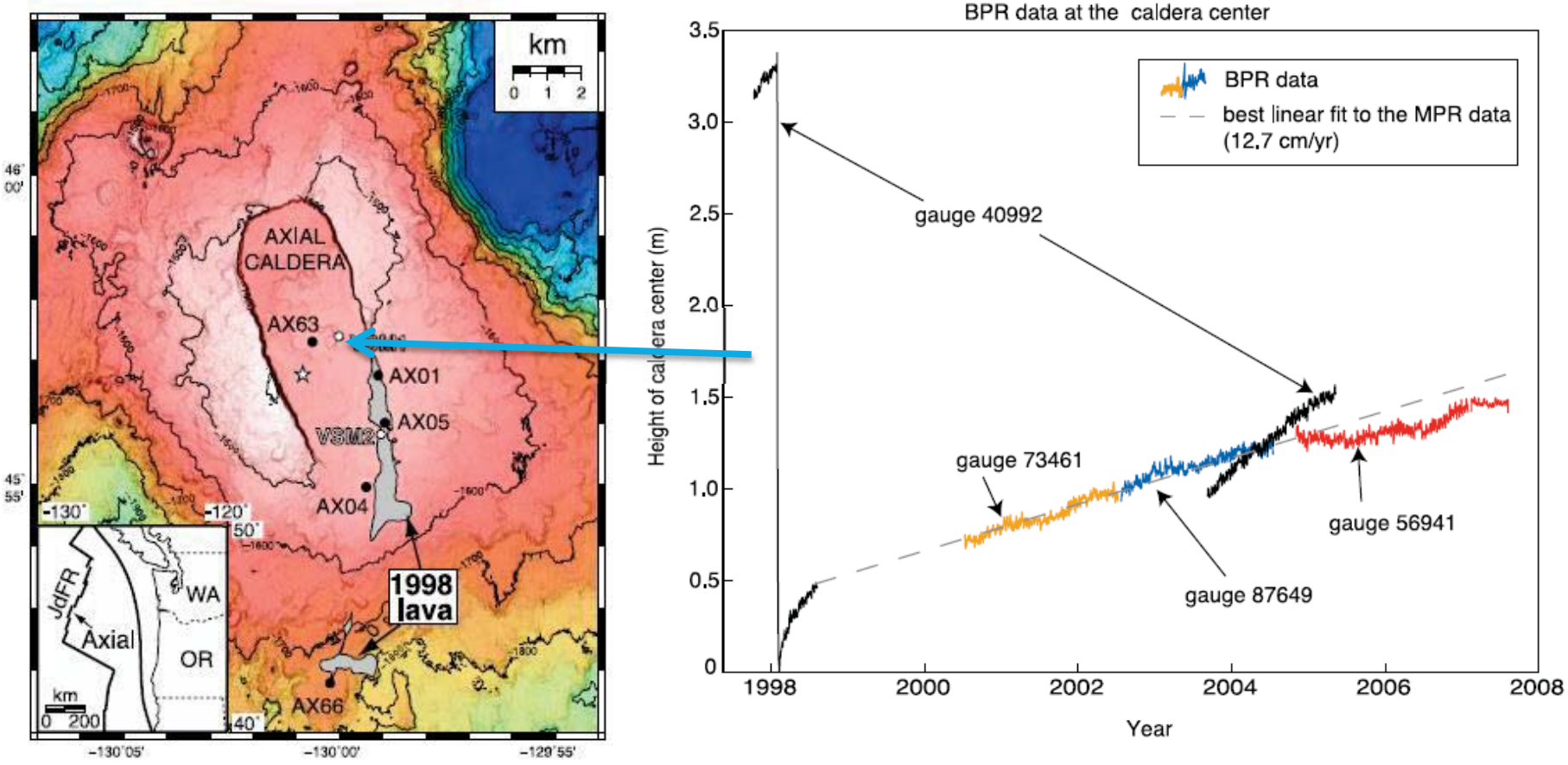
Stress changes control location of dykes



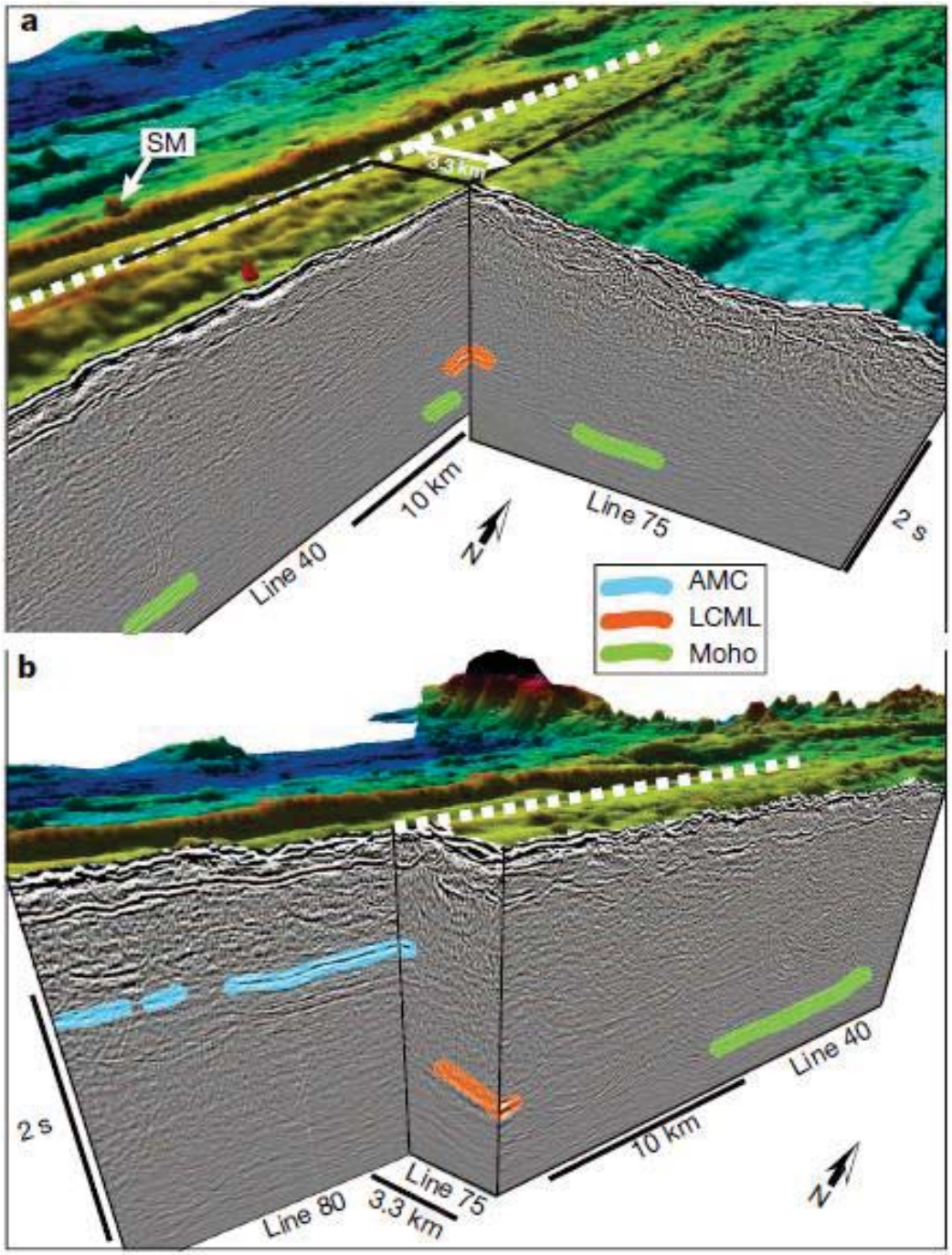
Hamling et al, Nature Geoscience 2010



Volcano Geodesy at a submarine Mid-Ocean Ridge (Nooner and Chadwick, G-cubed 2010)



Extremely rare and difficult to observe a transient, dynamic event on a MOR. This is the ONLY example from 60,000 km of submerged Mid-Ocean Ridge.



Juan de Fuca Ridge
- intermediate spreading rate
(Canales et al., *Nature* 2009)

Usually make dynamic inferences from structure