Rifting Events studied using InSAR

Sigurjón Jónsson

with contributions from Wenbin Xu[1], Joël Ruch and Teng Wang[2]

King Abdullah University of Science and Technology (KAUST)

[1]Now Hong Kong Polytechnic Univ. [2]Now at EOS, Singapore

Crustal Deformation & InSAR (CDI) group at KAUST

http://cdi.kaust.edu.sa

King Abdullah University of Science and Technology

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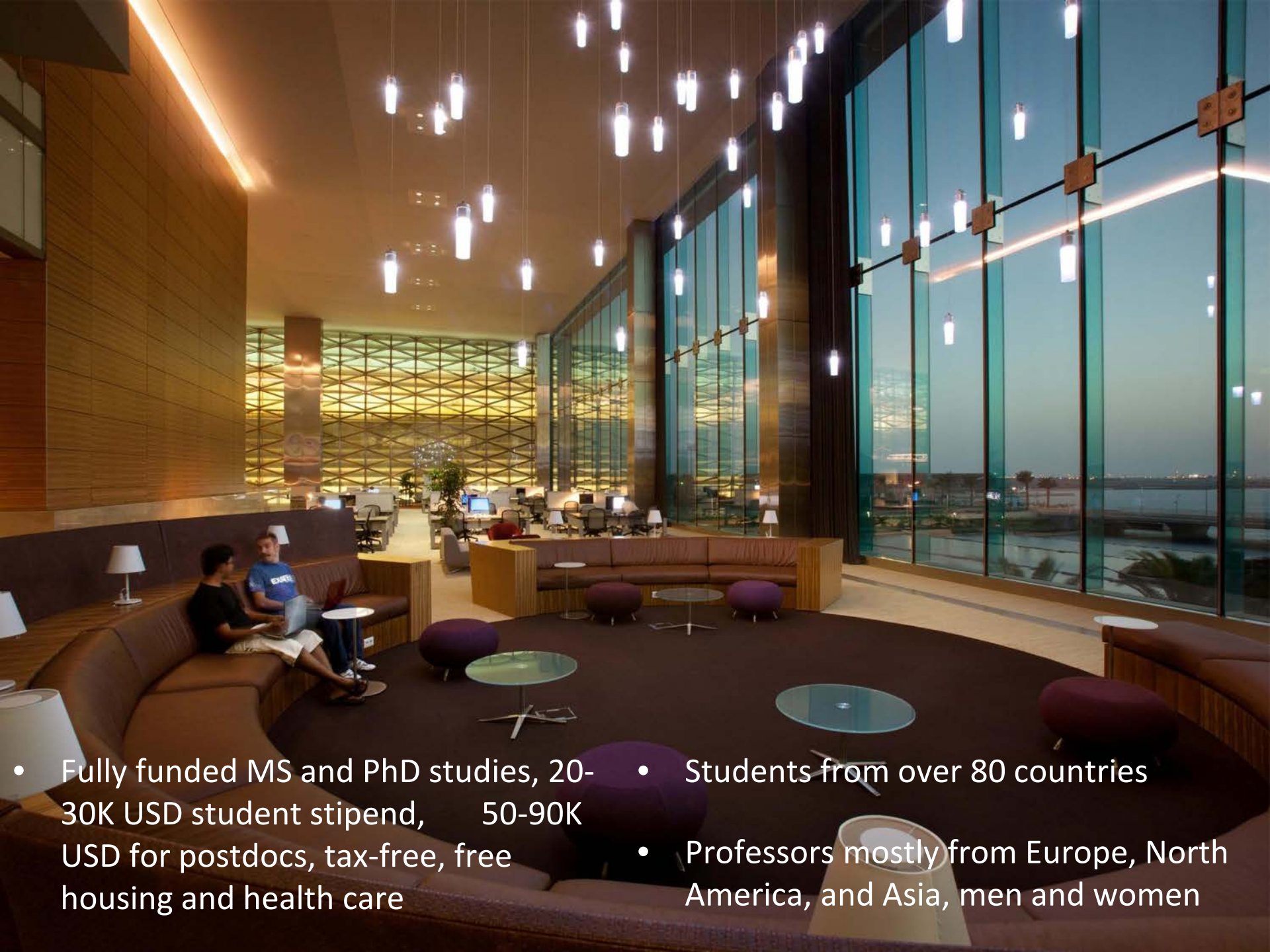
What is KAUST?

Where is KAUST?

Built on the Red Sea coast in Thuwal, 80 km north of Jeddah, opened in 2009

KAUST is a graduate level research university

- Founded in 2009, now an international community of over 7000 people
- Special focus on four areas of global significance: Food, Water, Energy and the Environment



- Fully funded MS and PhD studies, 20-30K USD student stipend, 50-90K USD for postdocs, tax-free, free housing and health care
- Students from over 80 countries
- Professors mostly from Europe, North America, and Asia, men and women

KAUST: Fast Facts – a growing university

KAUST has **~1000** students (400 M.S. and 600 Ph.D.), will grow to about 2000 students in the next several years

Now there are **150** faculty members (12 in Earth Sci.), but at maturity they will be around 225 (20-25 Earth Sci.)

About 450 postdocs and 250 research scientists (this will double)

KAUST is already making impact, **ranked #1 in the world in "citations per faculty"** (*QS University ranking 2015-2016*)

We are always looking for excellent students and postdocs!

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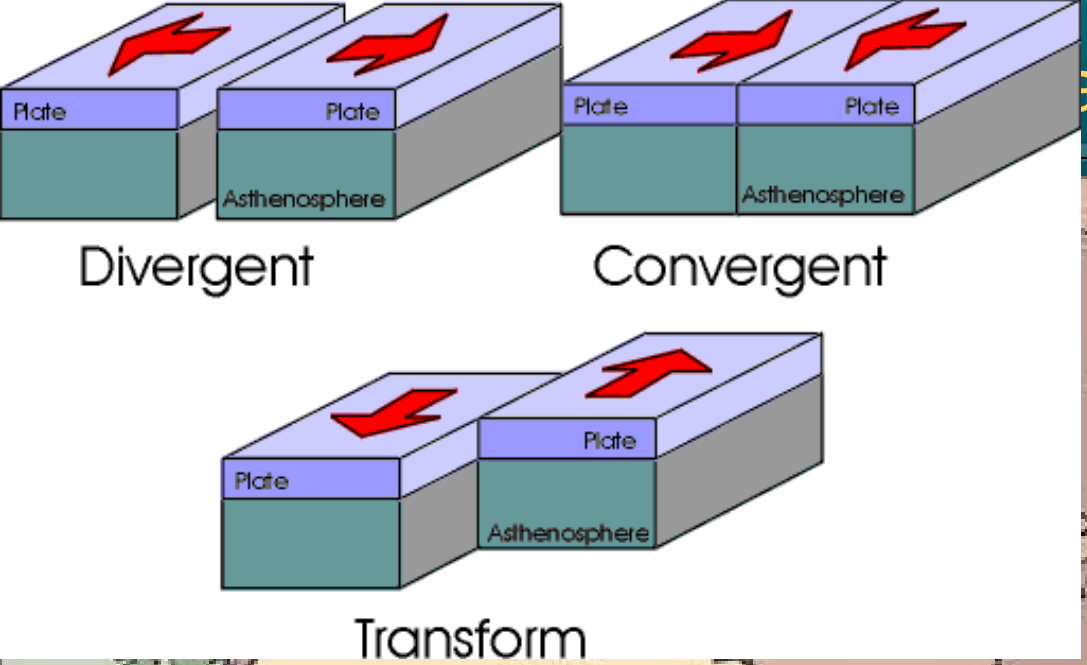
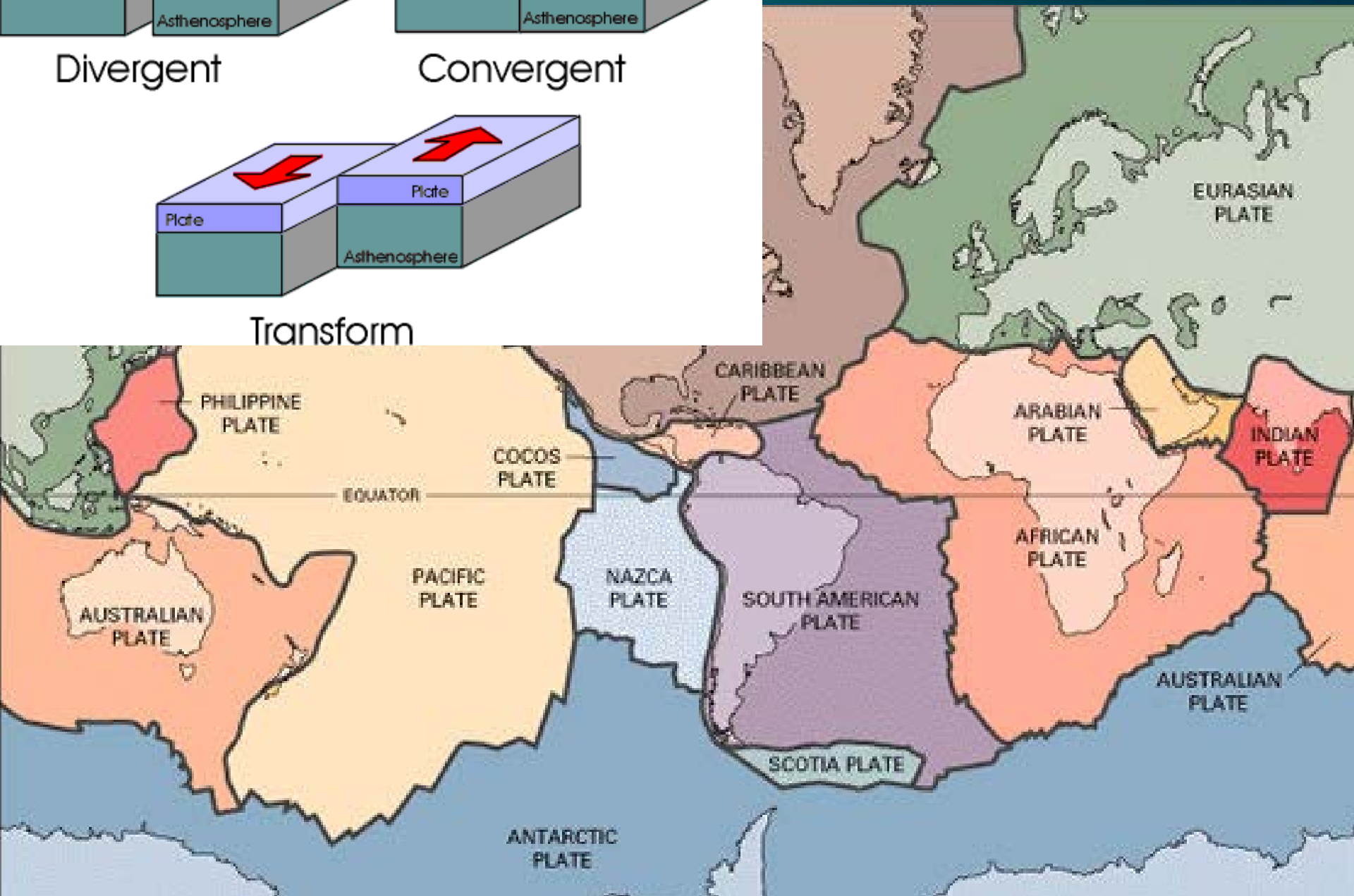
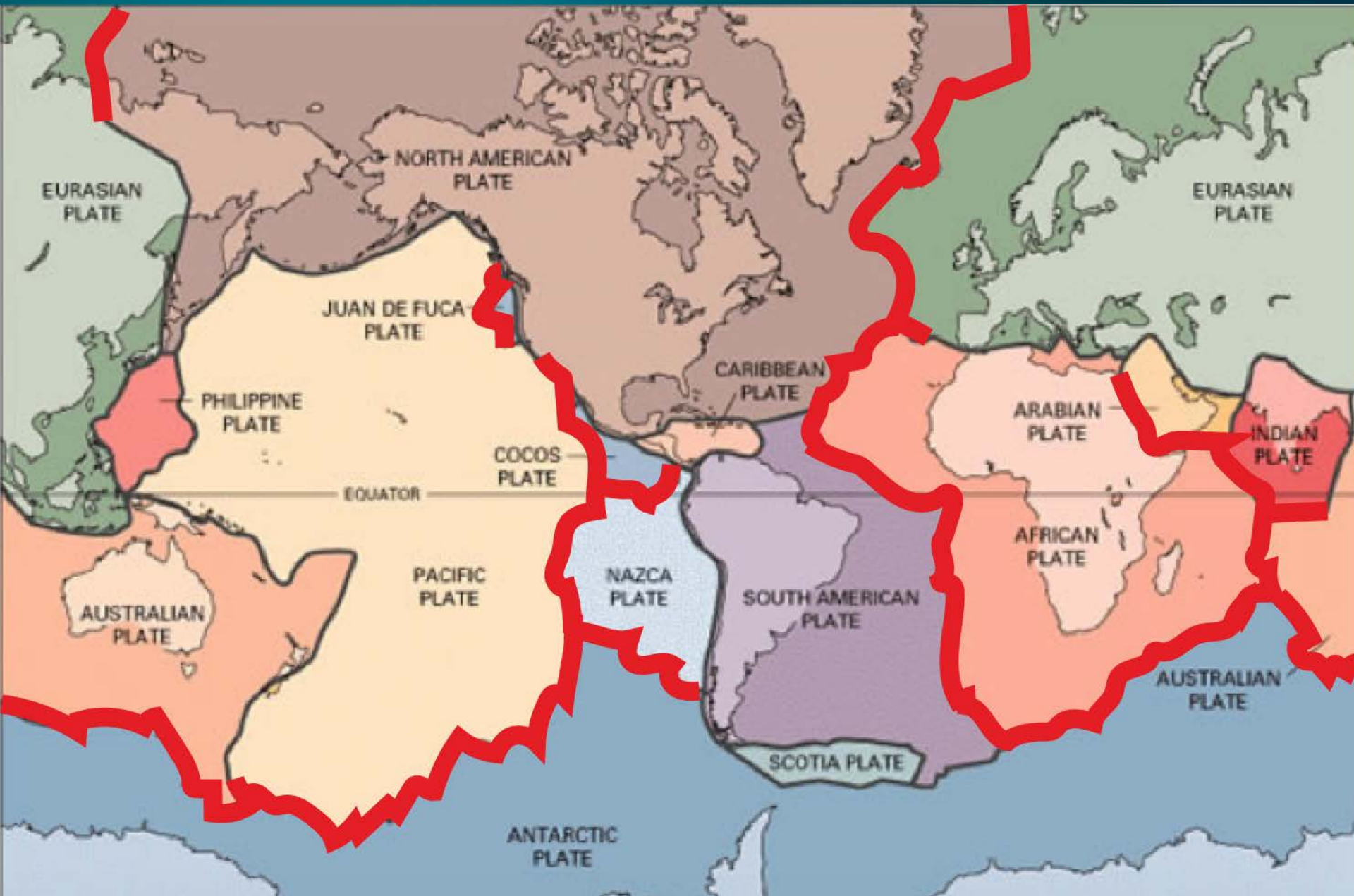
What is a Rifting Event?

ate Boundaries

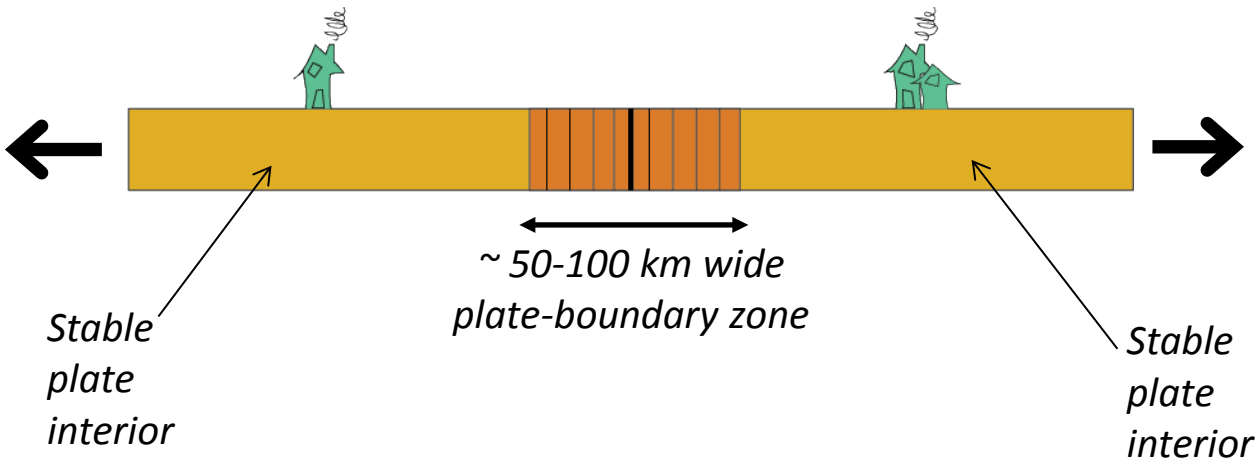




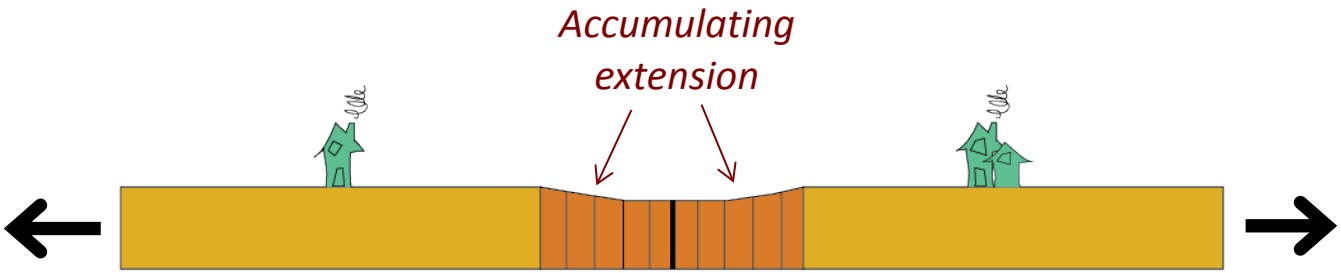
Divergent Plate Boundaries



Rifting Cycle at Divergent Plate Boundaries

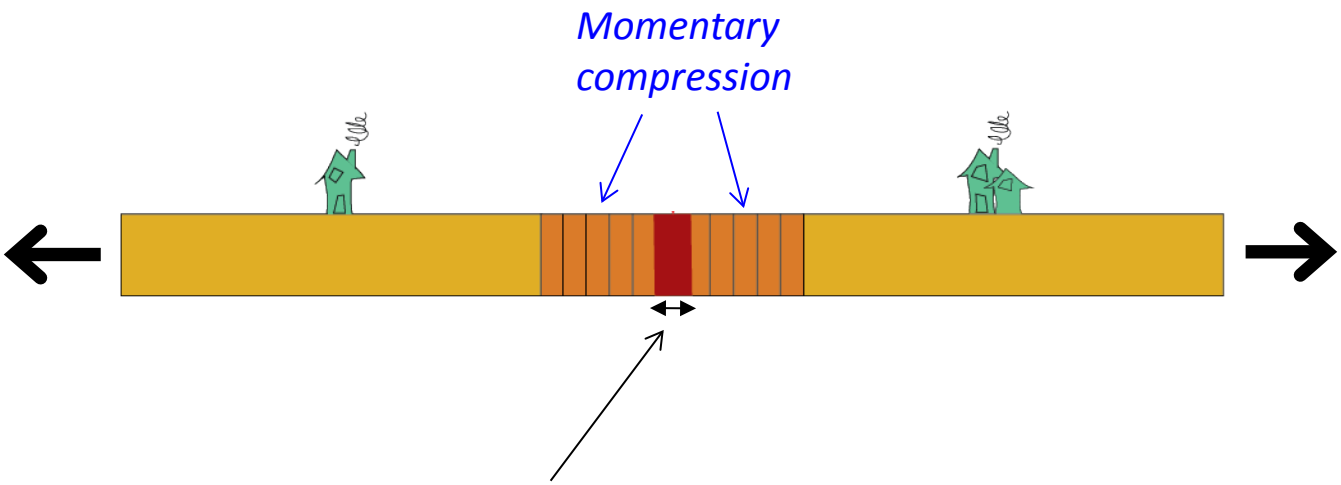


Rifting Cycle at Divergent Plate Boundaries



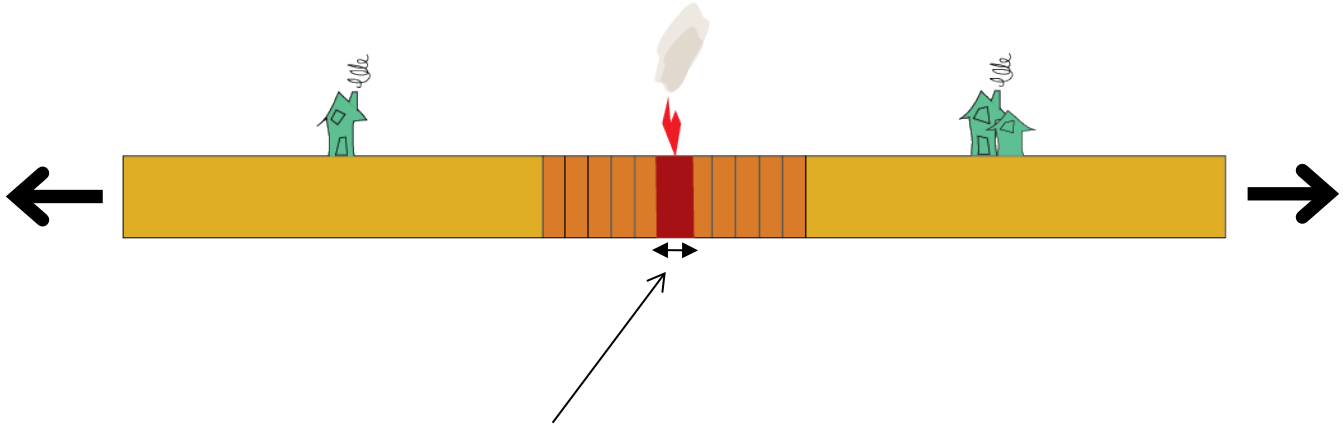
Stretching at 1-8 cm per year for ~100-200 years

Rifting Cycle at Divergent Plate Boundaries



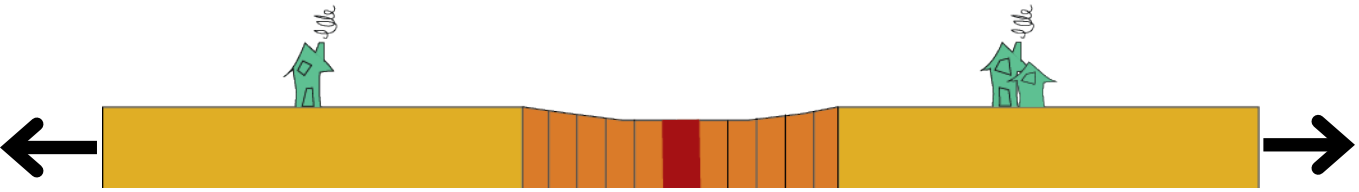
Rifting dike intrusion, ~1-10 m wide

Rifting Cycle at Divergent Plate Boundaries



Rifting dike intrusion, ~1-10 m wide

Rifting Cycle at Divergent Plate Boundaries



Continued stretching at 1-8 cm per year for ~100-200 years

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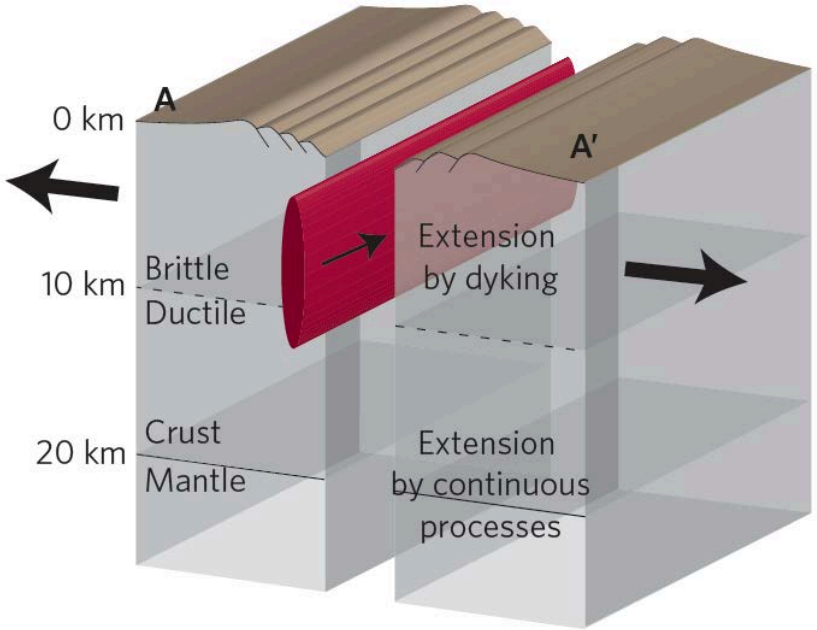
Why are Rifting Events important?

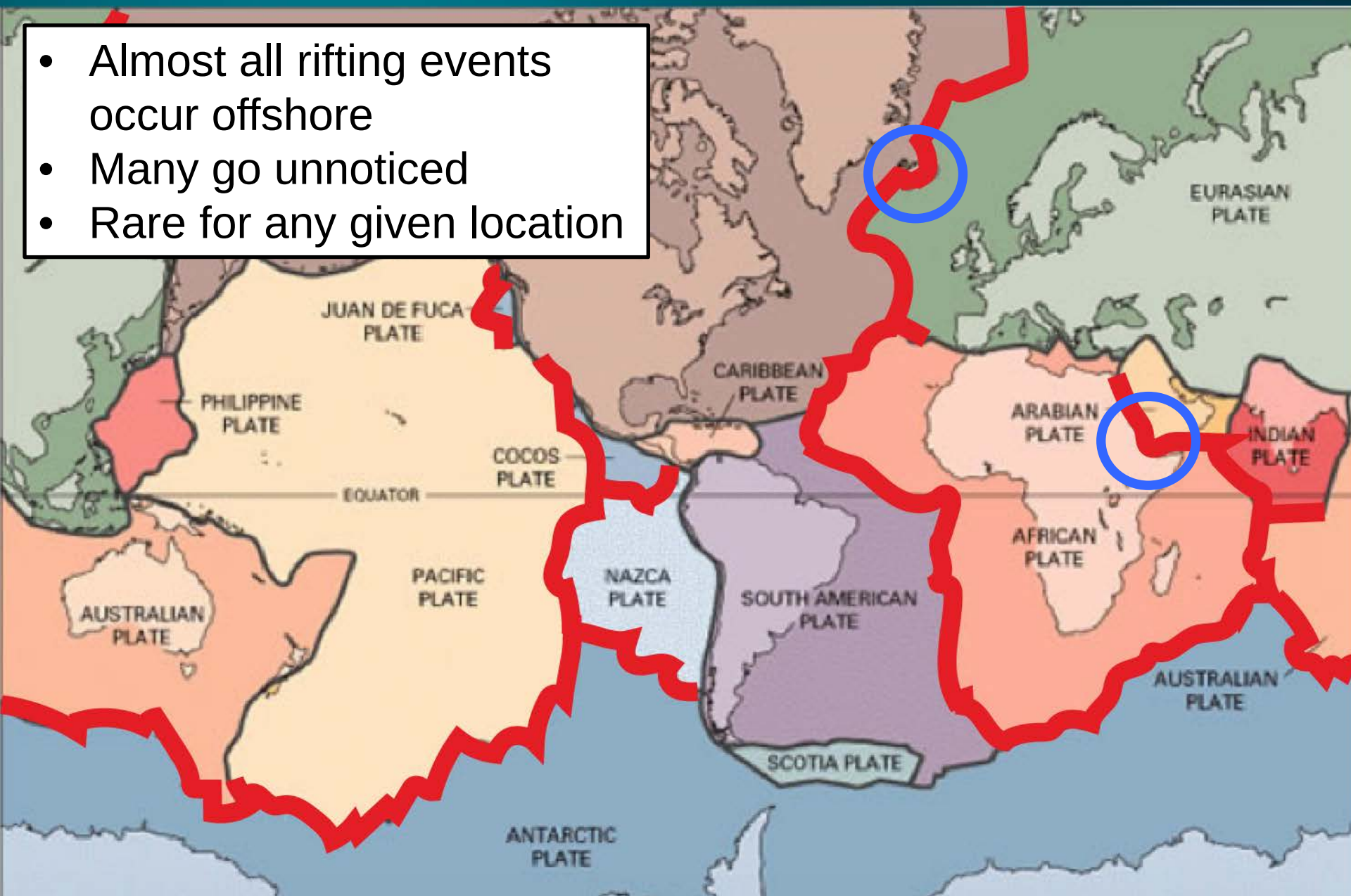
Importance of Rifting Events

- Do they kill people?
- Laki eruption 1783-84
- Cause multi-meter transient deformation -> large stress changes
- Can provide rich information about structure and dynamics
- My parents live on top of a rift!



Wright et al., 2012

Problem: Rifting events are hard to capture



- Almost all rifting events occur offshore
- Many go unnoticed
- Rare for any given location

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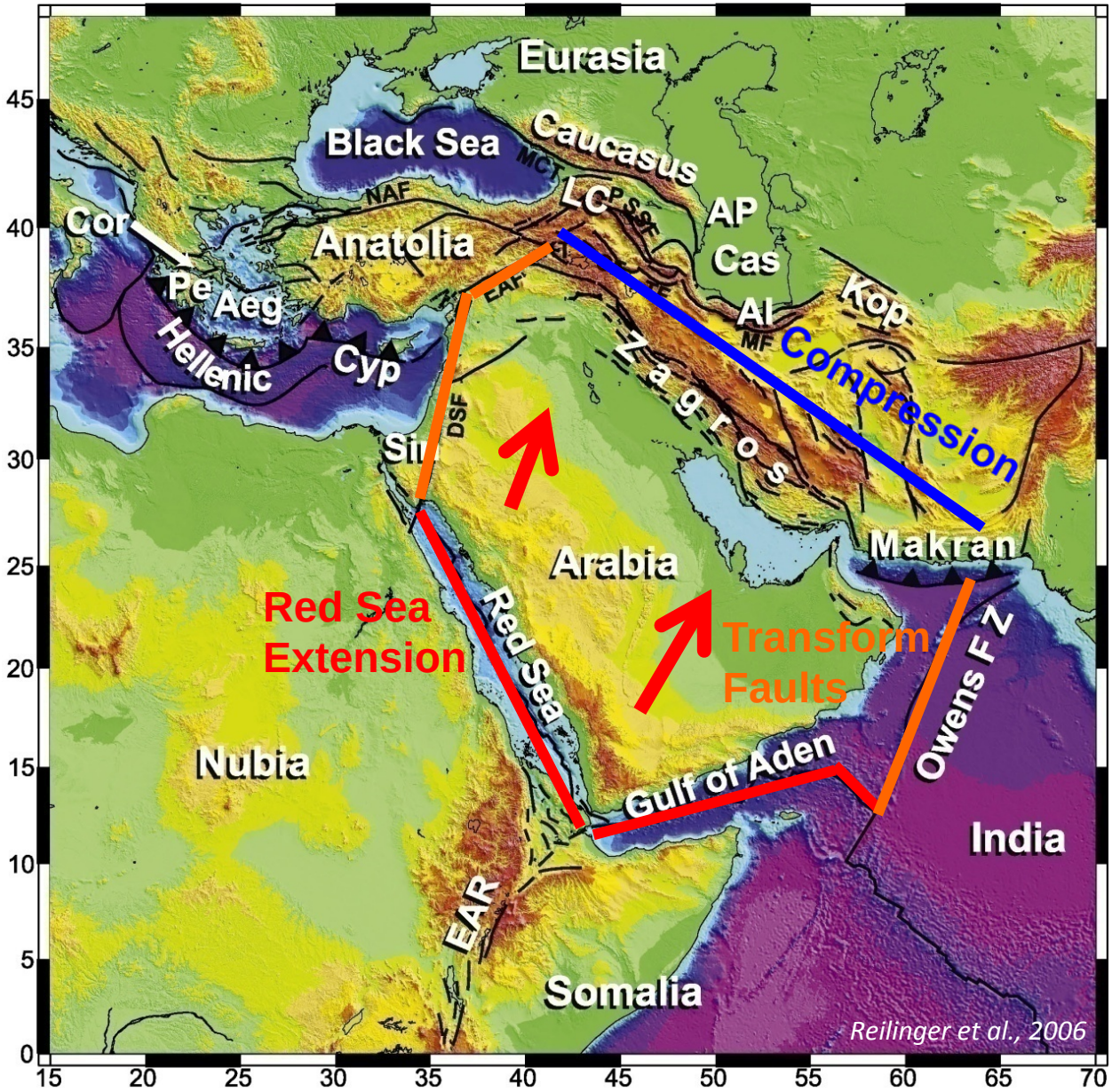
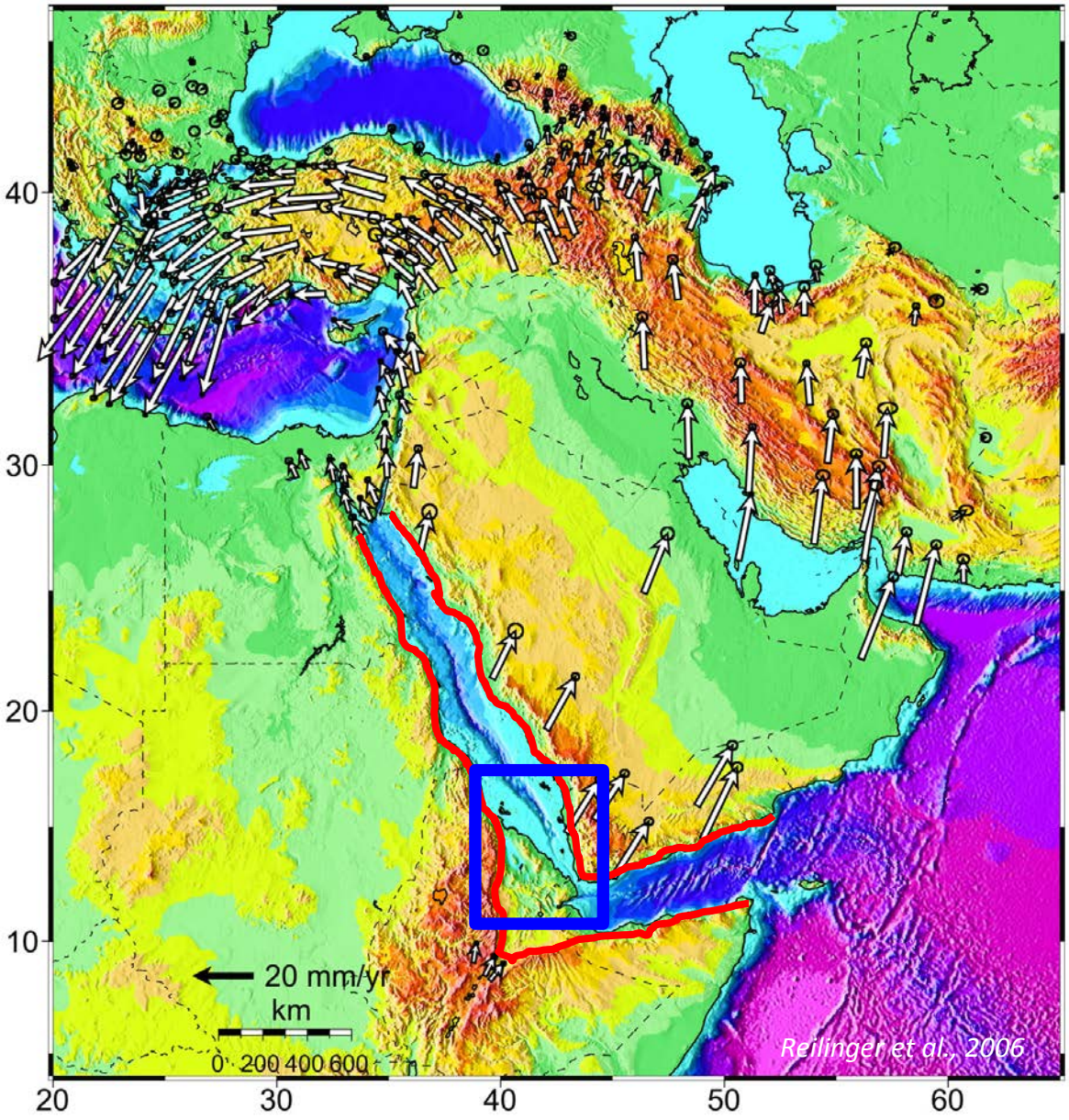
Southern Red Sea

Tectonics of the Arabian Plate



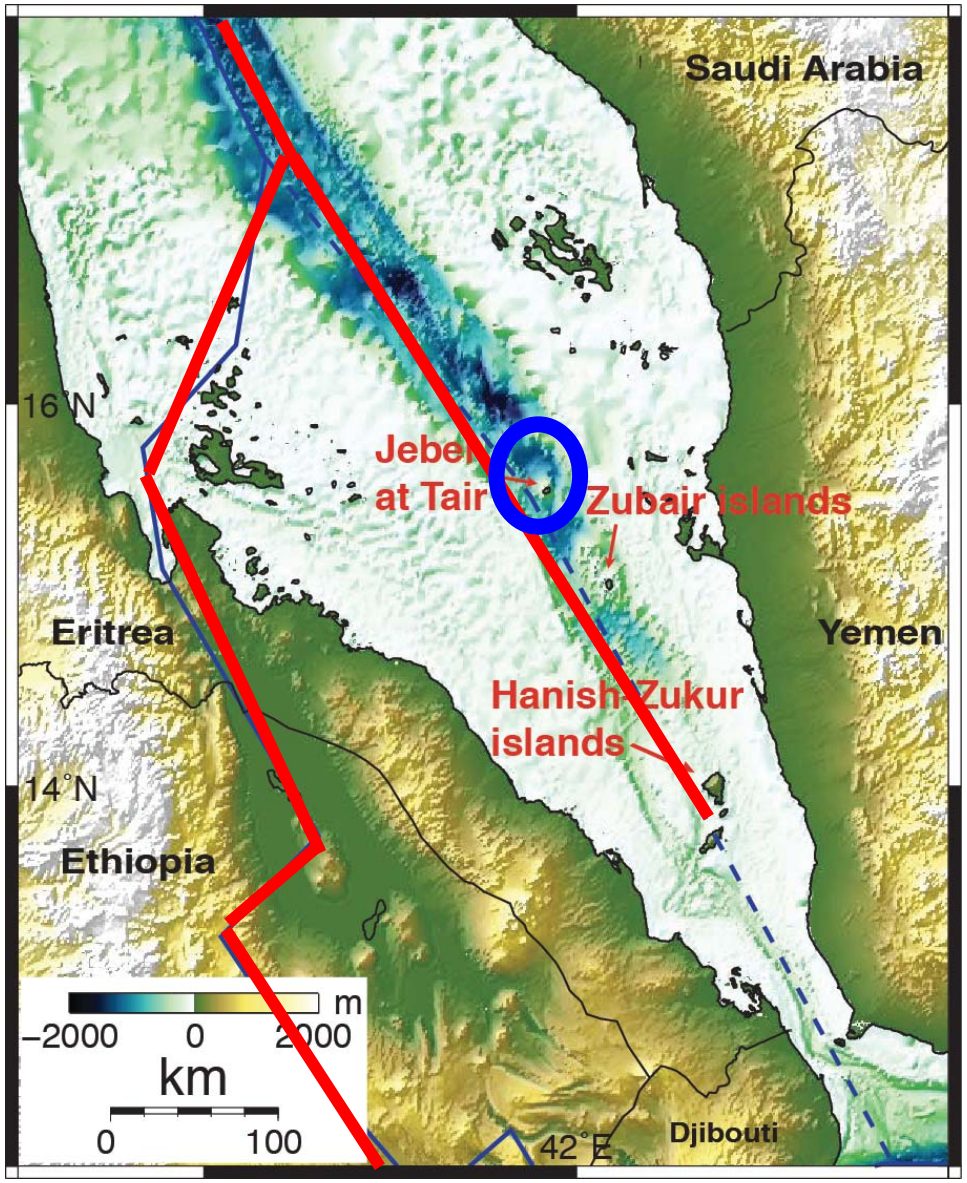
- Arabia is moving northward w.r.t. Eurasia
- The plate is bounded by a variety of plate boundaries
- Extension in the south
- Transform faulting in the west and east
- Compression in the north

Tectonics of the Arabian Plate



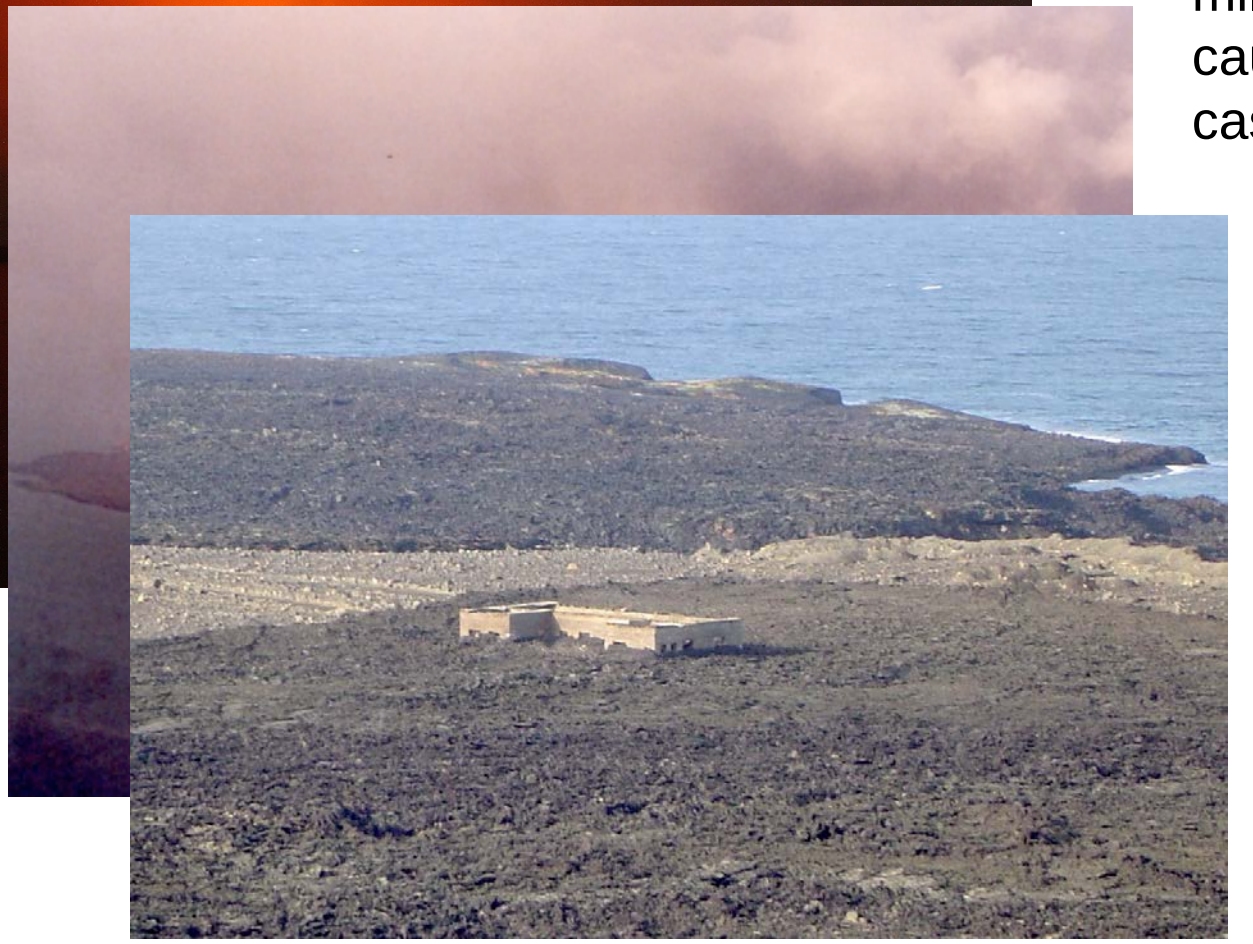
- GPS velocities with respect to Eurasia
- Arabian plate internally stable
- Opening rate in the Red Sea increases from about 7 mm/yr in the north, to 16 mm/yr in the south

Southern Red Sea



- Two parallel rift systems
- Three recent eruptions
- Jebel at Tair (2007-8) and within Zubair islands in 2011-12 and 2013
- First known volcanic activity in the southern Red Sea in over a century

The 2007-8 Tair Island eruption

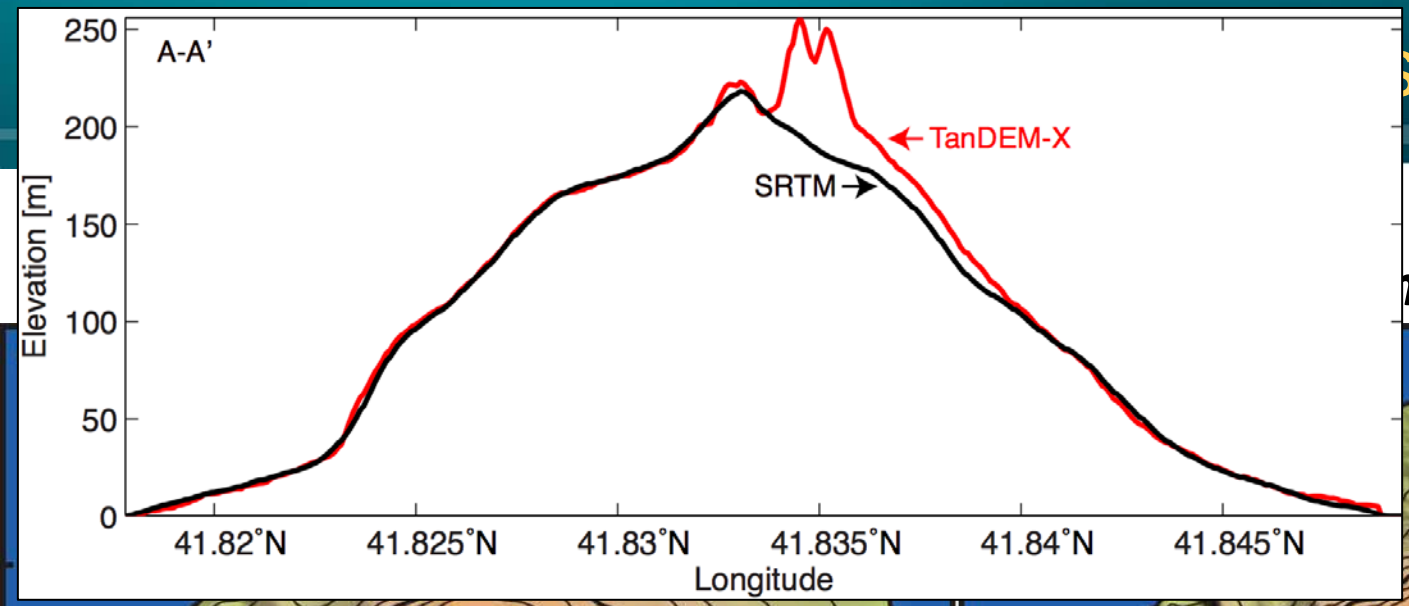


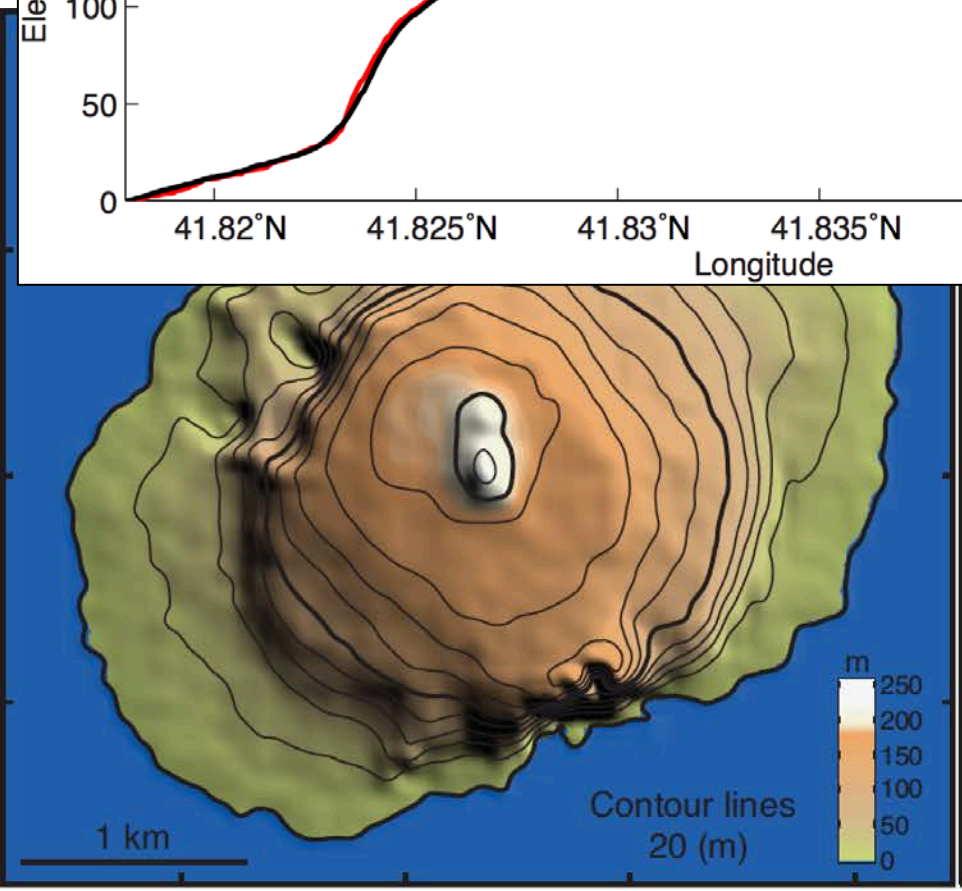
- Eruption destroyed the military outpost and caused several casualties

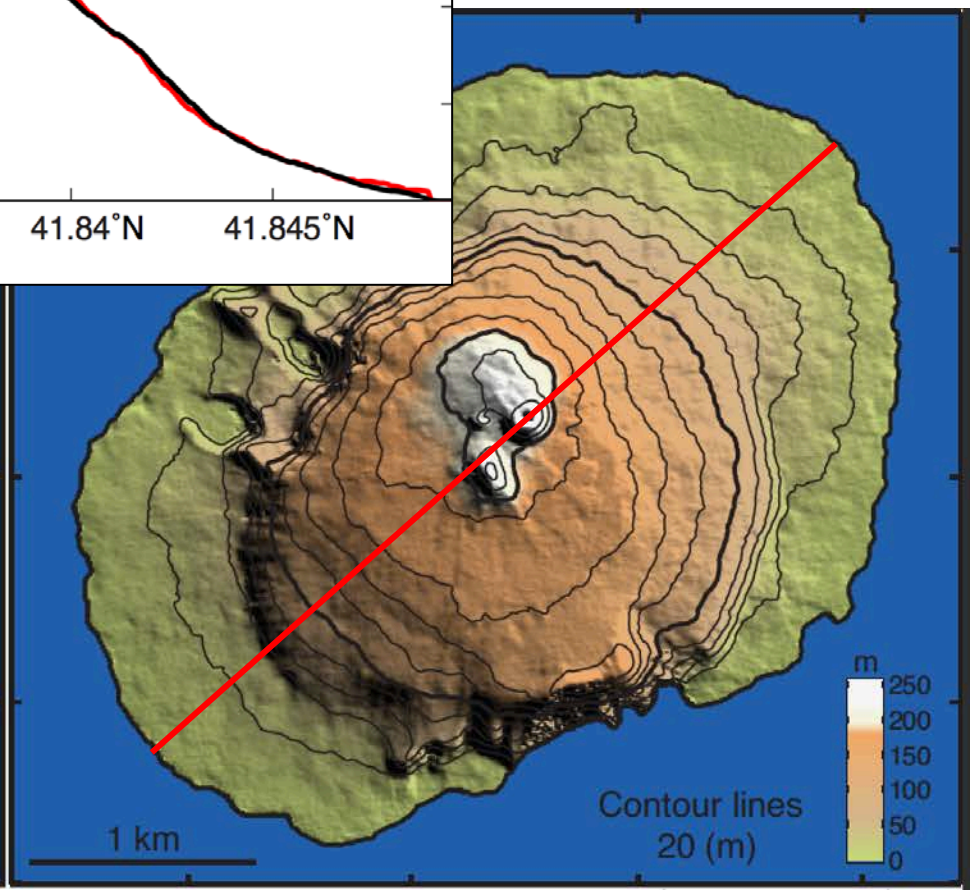
Photos from Jamal Sholan, Seismological and Volcano observatory, Yemen

sland

n DEM

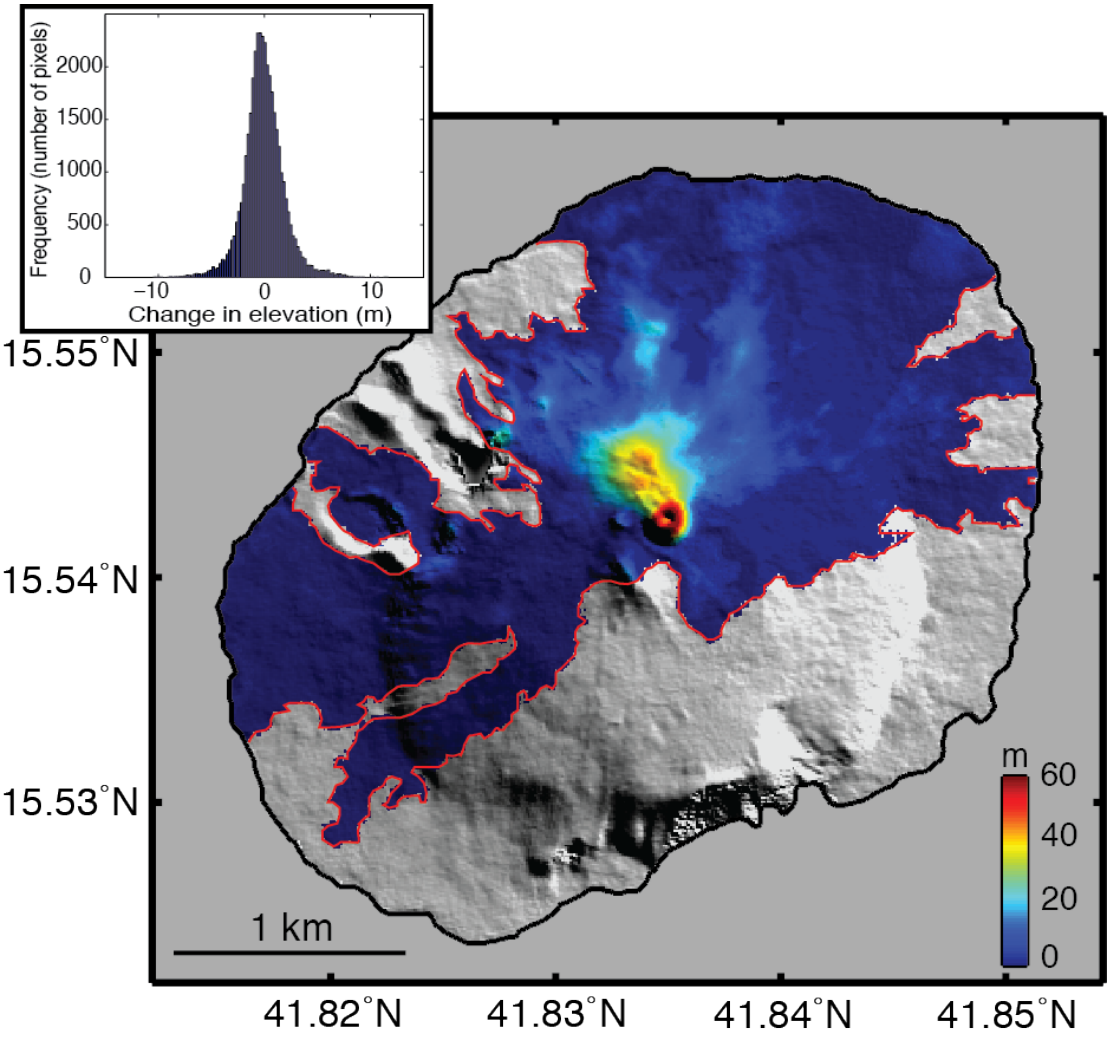

A-A'
Elevation [m]
250
200
150
100
50
0
TanDEM-X
SRTM
41.82°N
41.825°N
41.83°N
41.835°N
41.84°N
41.845°N
Longitude


m
250
200
150
100
50
0
Contour lines
20 (m)
1 km


m
250
200
150
100
50
0
Contour lines
20 (m)
1 km

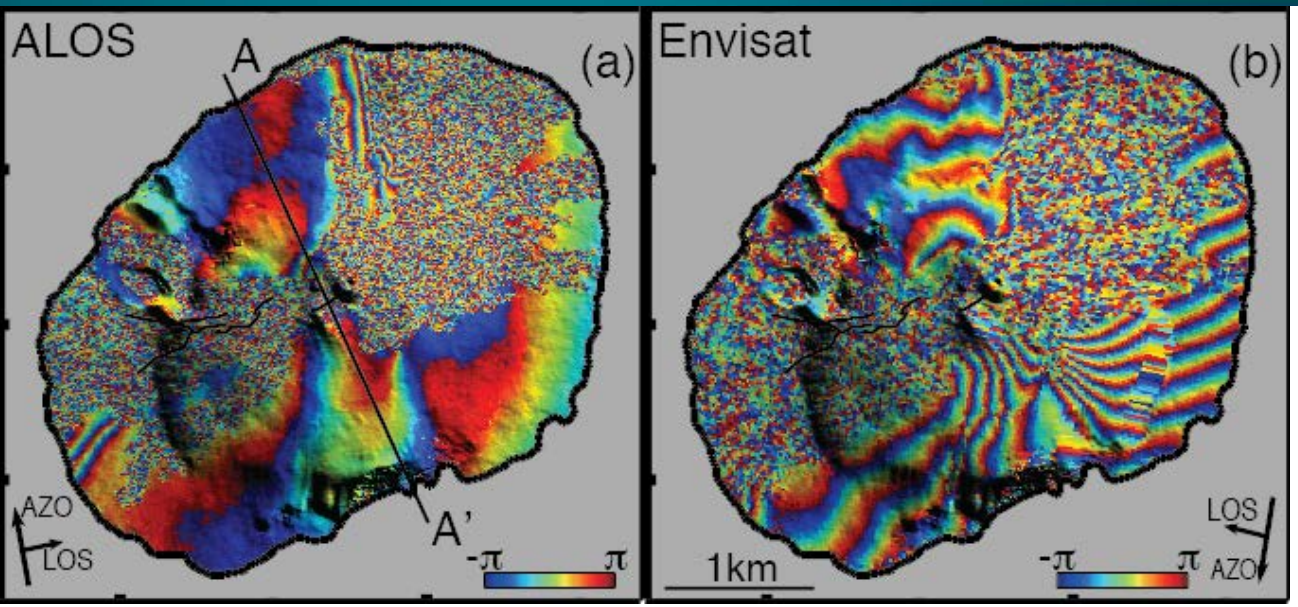
Lava Flow Volume from DEM differencing

- DEM differencing between a post-eruption TanDEM-X DEM and an ALOS-corrected SRTM DEM.

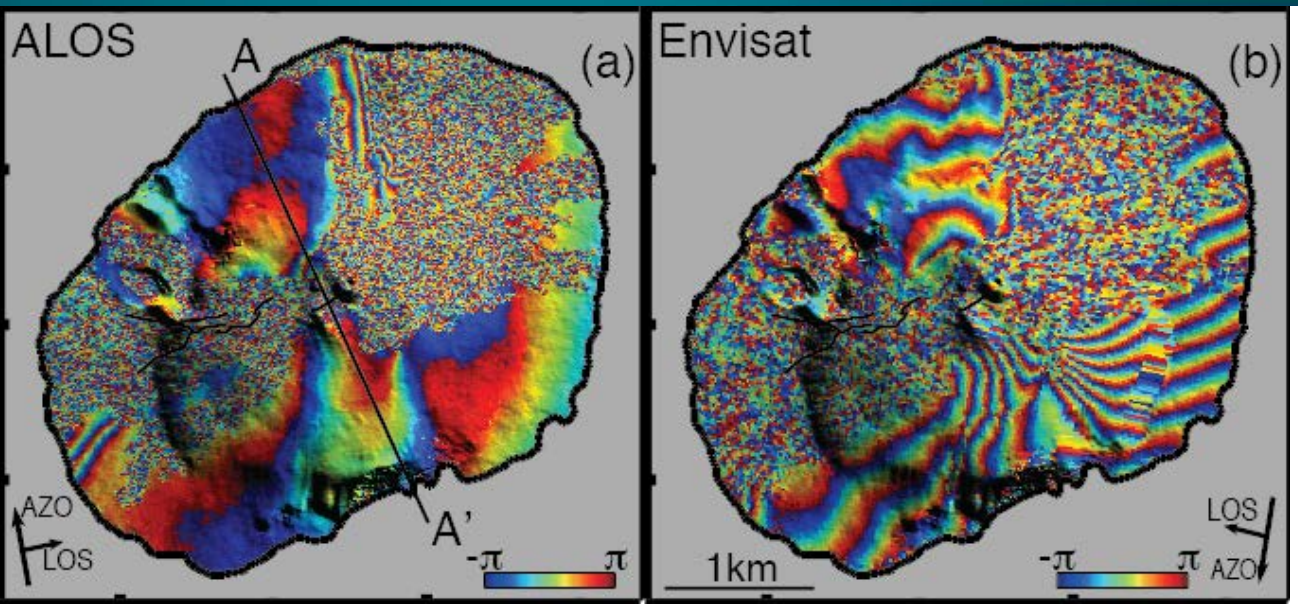


- Average thickness 3.8 m, volume ~0.02 km^3

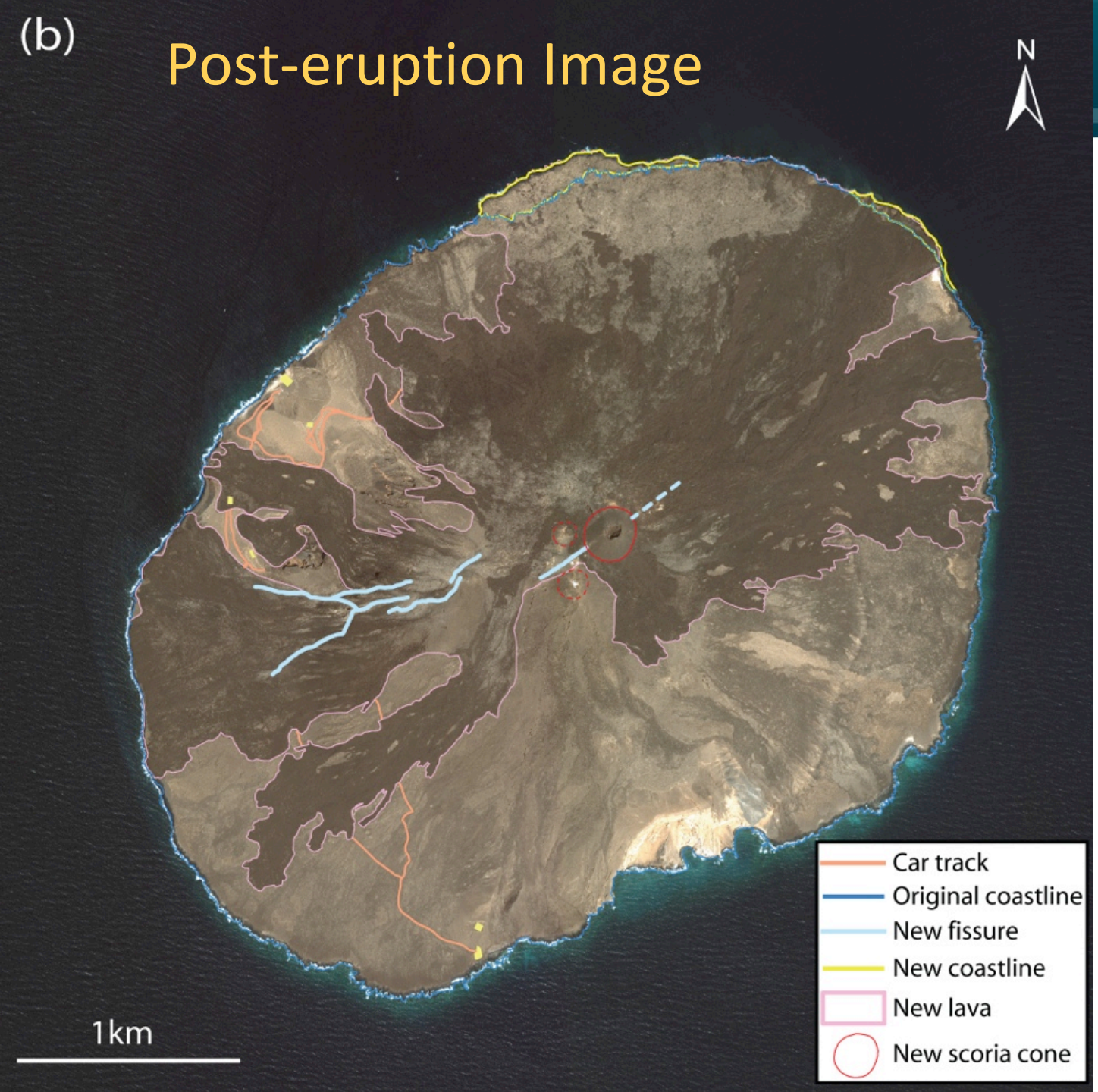
Co-eruption Ground Deformation



Co-eruption Ground Deformation

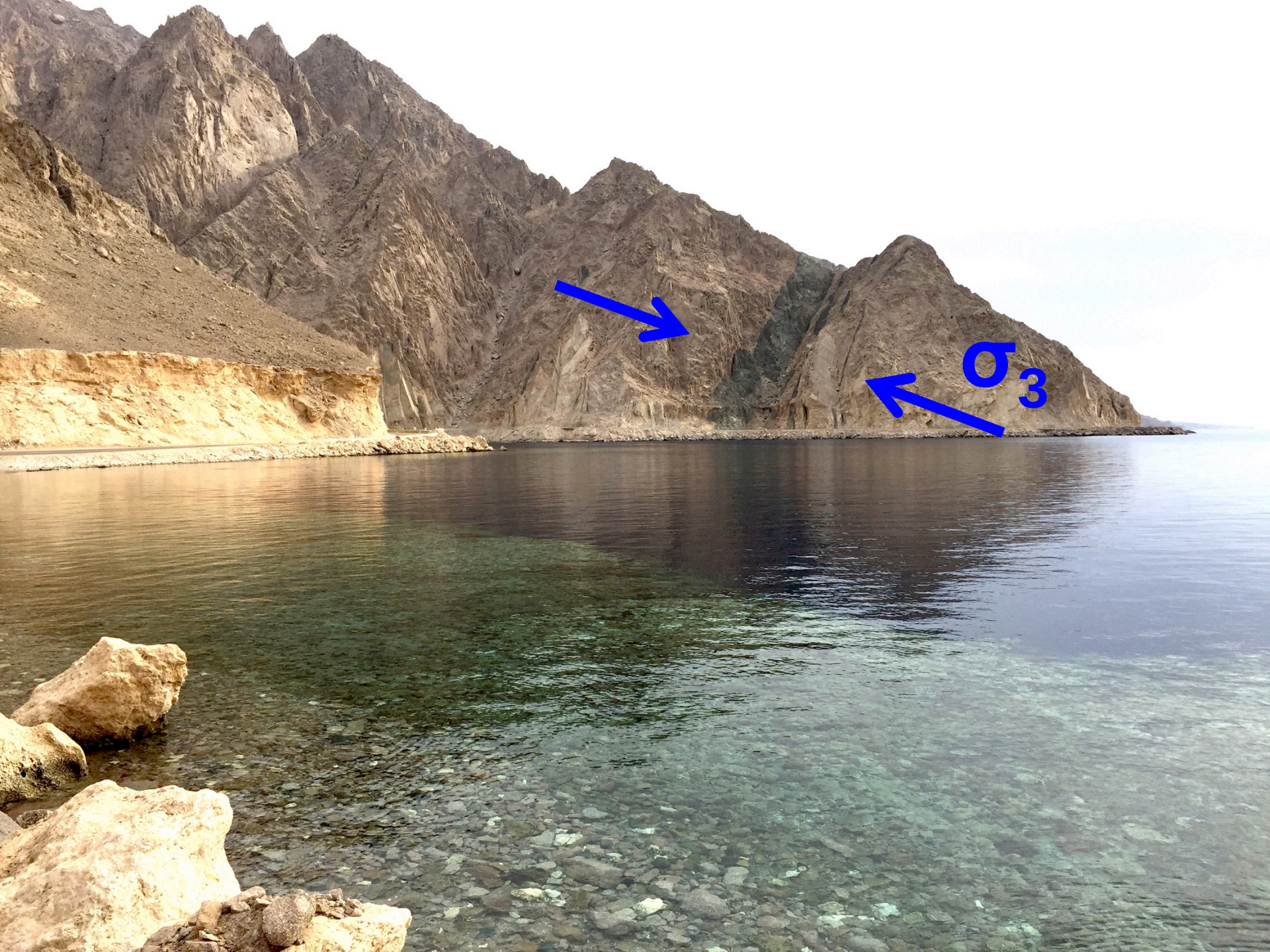


- The co-eruption deformation is complex
- Ascending ALOS, Descending Envisat, and ALOS azimuth offsets, signal partly lost due to the new lava



- Worldview-2, resol.: 50 cm
- New lava covers half of the island
- Fissures with NE strike

Xu and Jónsson, Bull. Volcanol. 2014

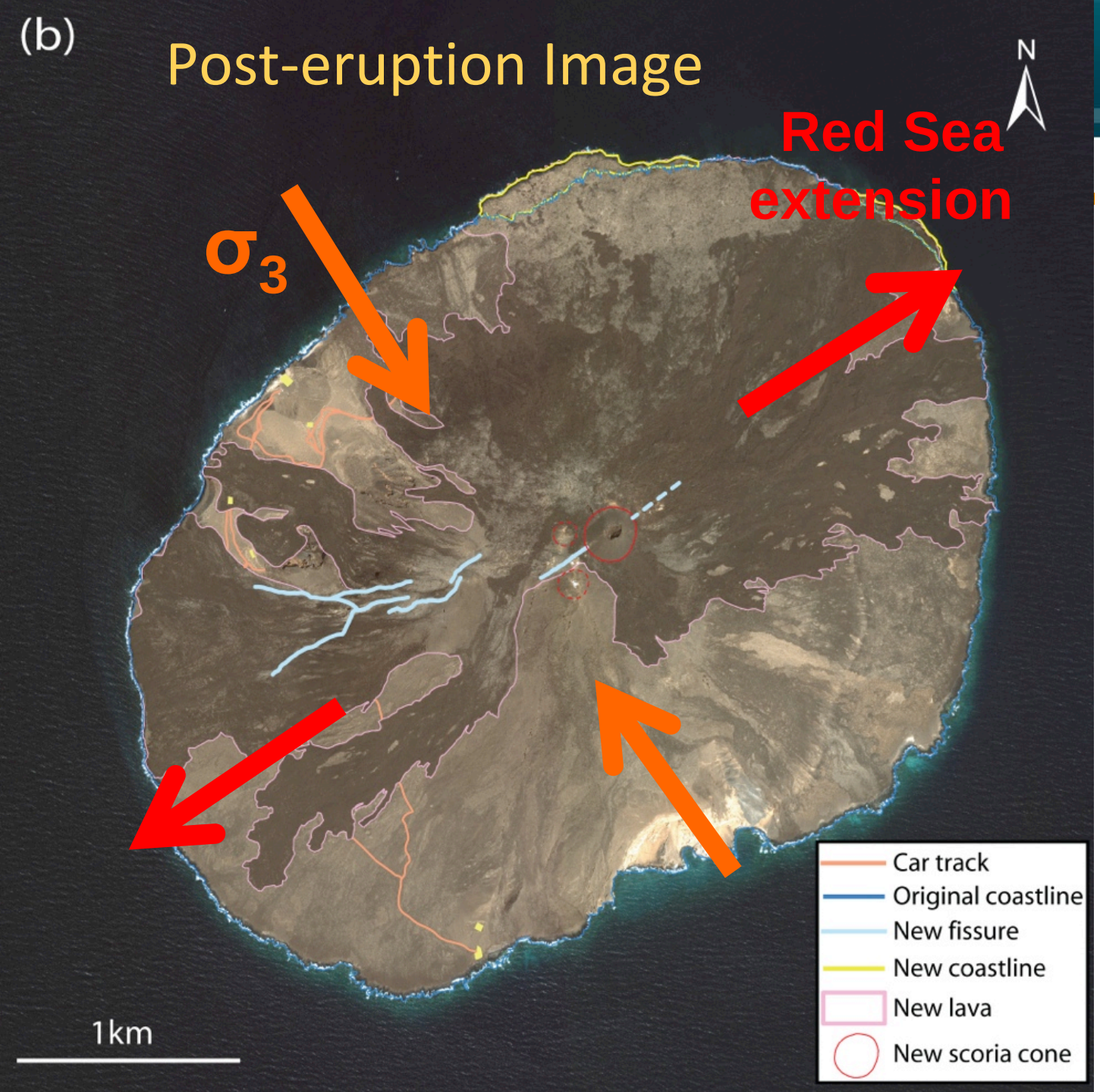

σ_3


~6-7 m

Dike Intrusions

Dikes indicate stress directions

- Fluid filled cracks
- Choose path of minimum resistance
- Perpendicular to minimum compressional stress σ_3

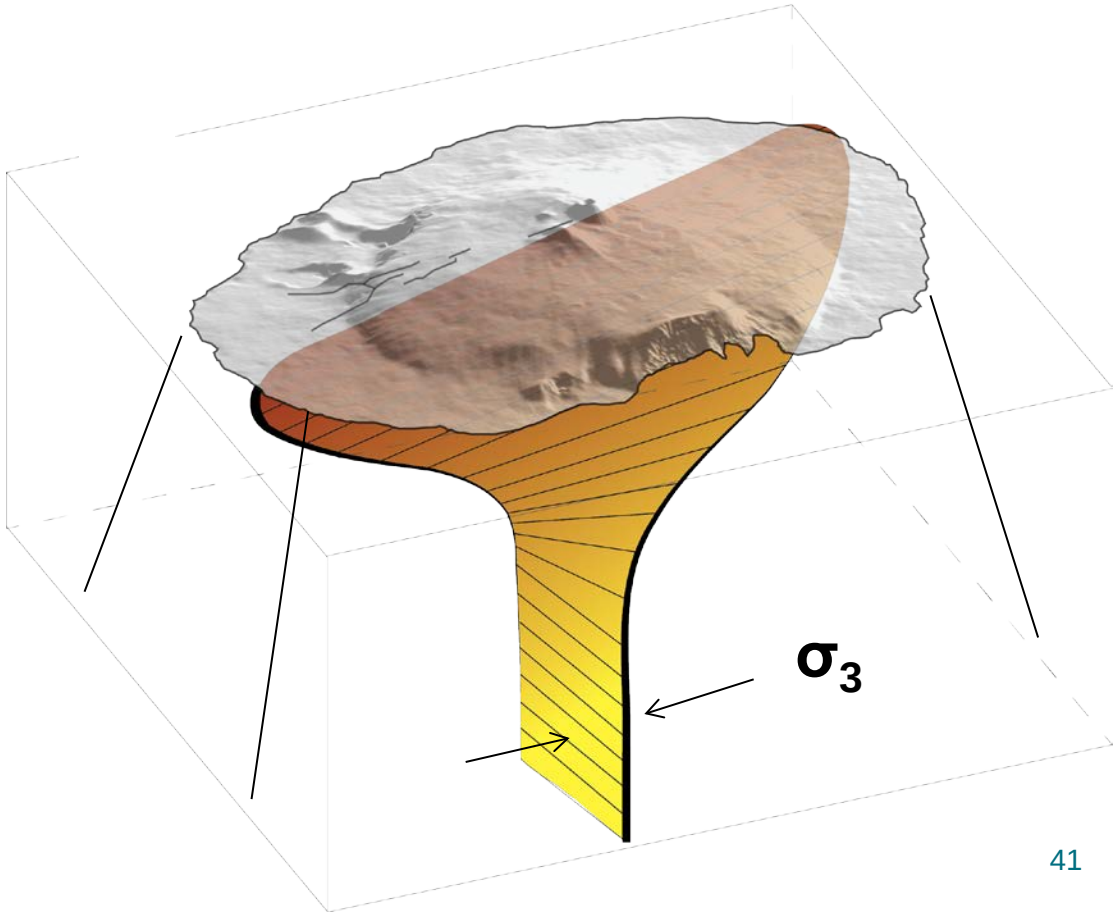


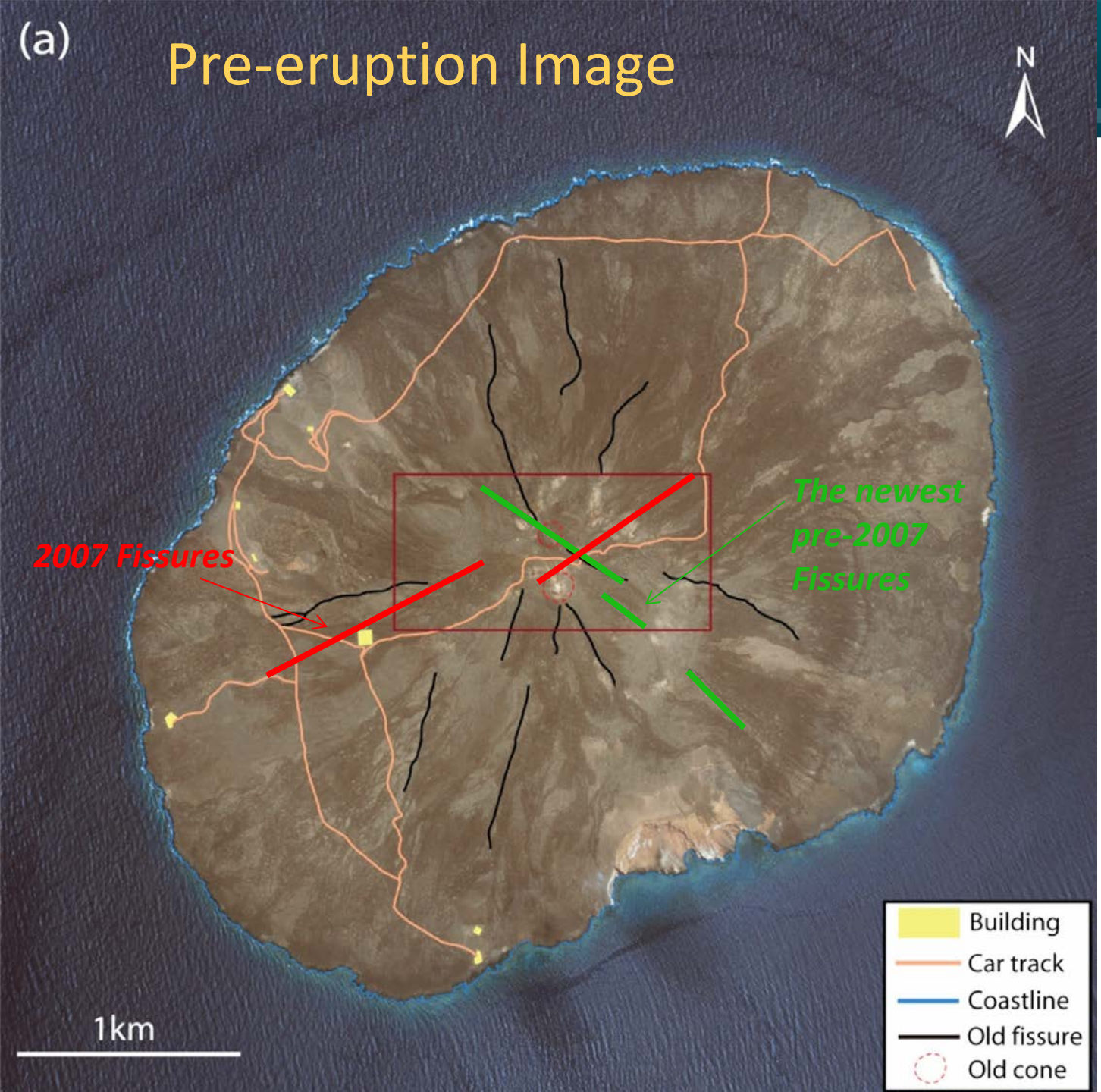
Minimum compressional stress NW orientated along Red Sea!

Xu and Jónsson, Bull. Volcanol. 2014

Dike Rotation in a Local Stress Field

- The dike likely started propagating with a trend parallel to the Red Sea
- After it entered the ~1400 m high volcanic edifice it rotated, controlled by the local stress field, which appears to be isolated from the regional stress field

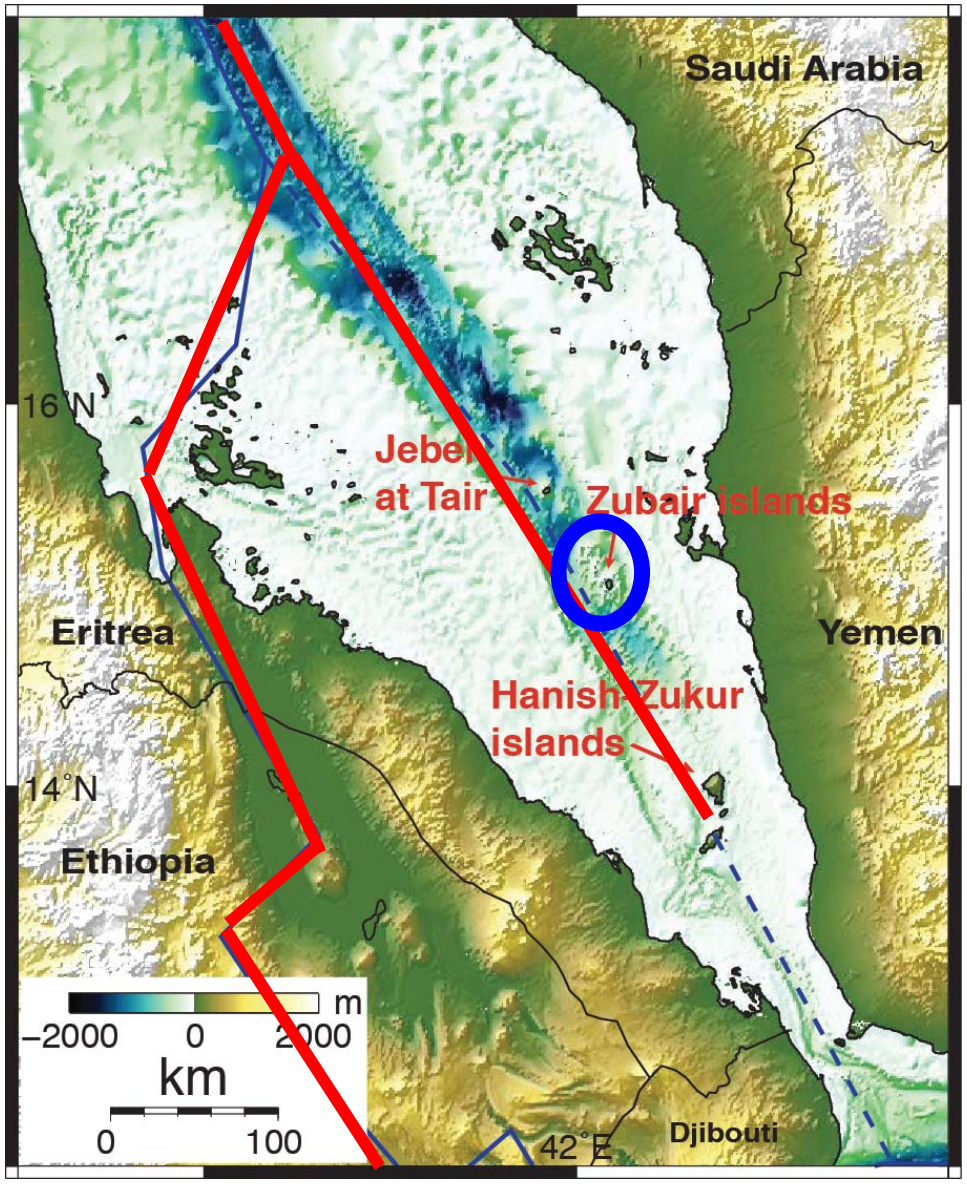




- Old surface fissures with different orientations

Xu and Jónsson, Bull. Volcanol. 2014

Southern Red Sea



- Two parallel rift systems
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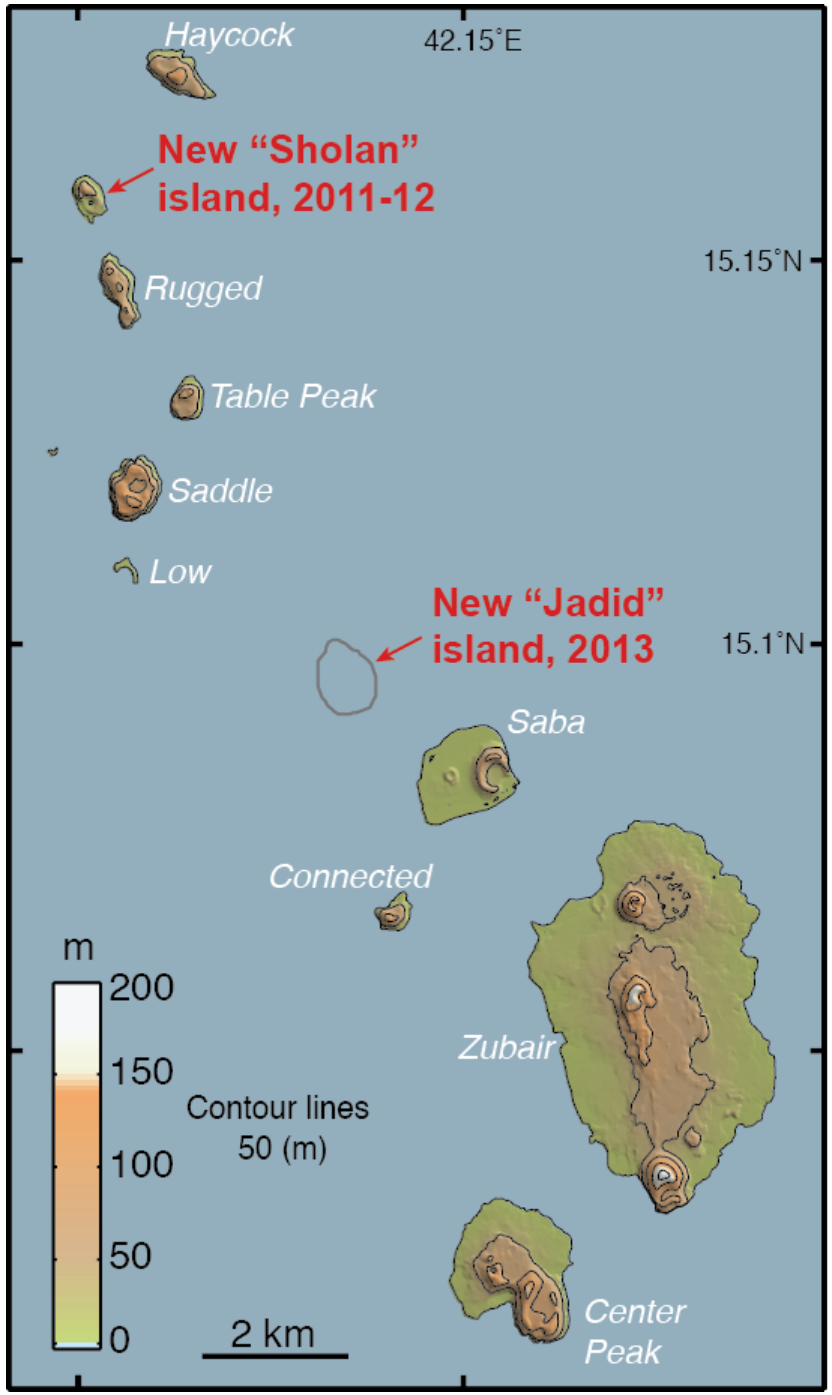
- First known volcanic activity in the southern Red Sea in over a century

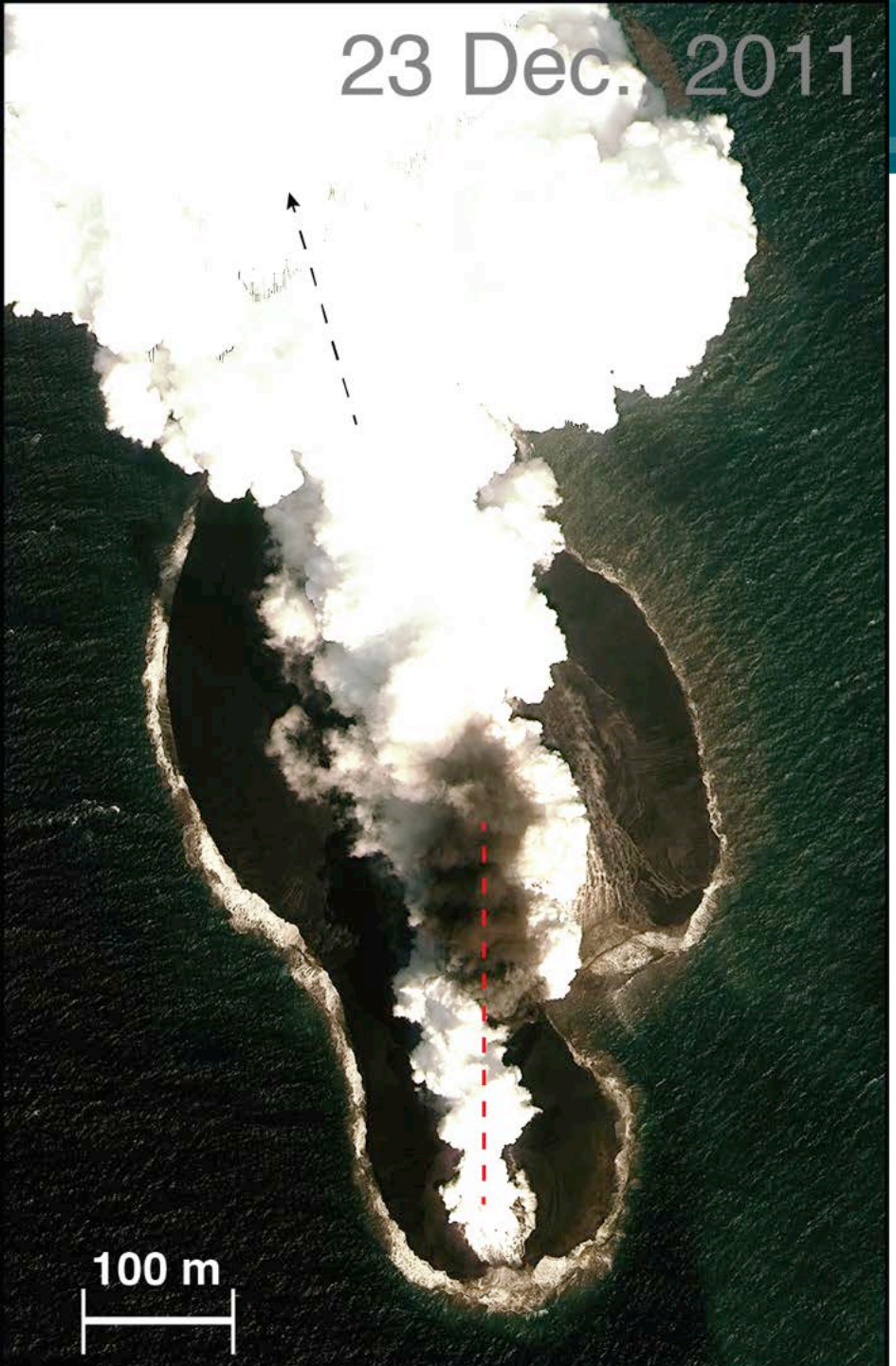
Zubair Islands



Jónsson and Xu, 2015

Two new islands!

TanDEM-X DEM

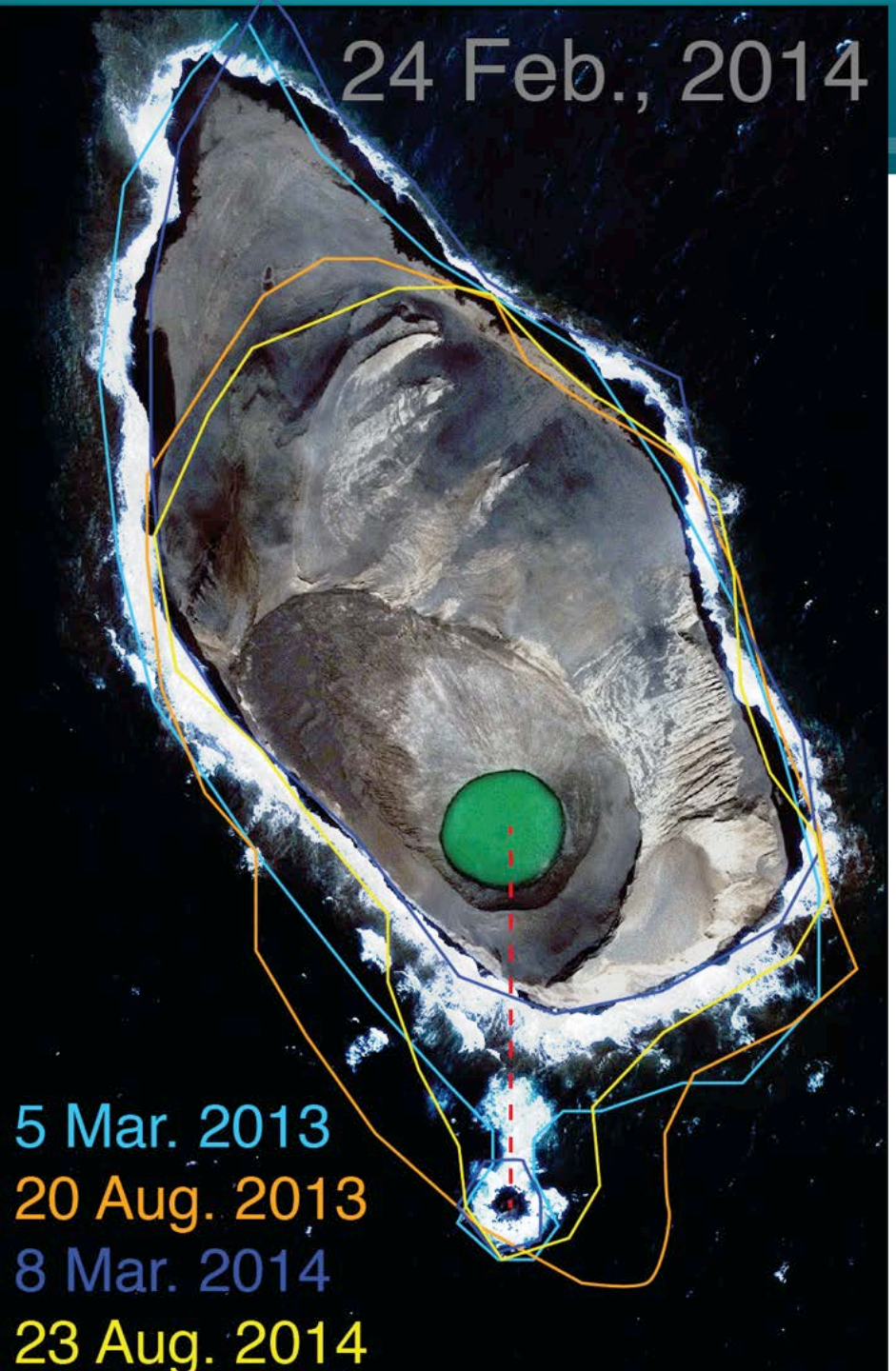


- Island already formed after only 5-day eruption
- N-S lineation indicates possible fissure eruption

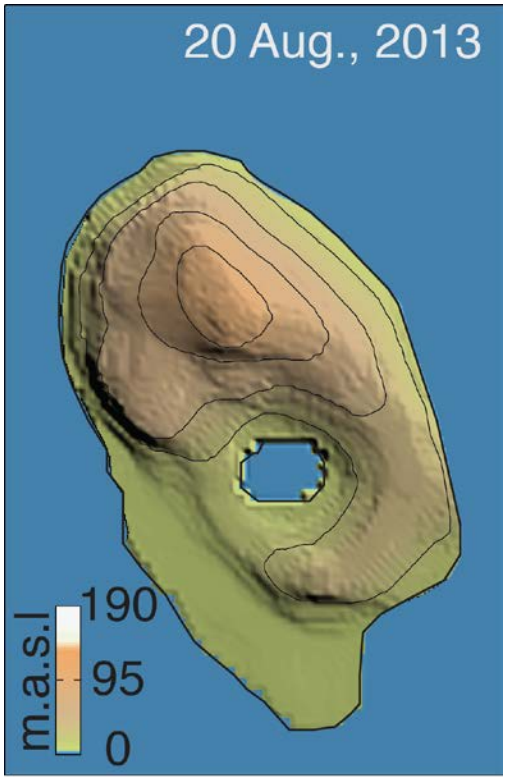
- Eruption still ongoing
- Island grown larger
- Only a central crater active

- Eruption has ended
- Must have stopped between 9 Jan and 12 Jan

- A lake has formed in the crater
- Some coastal erosion visible



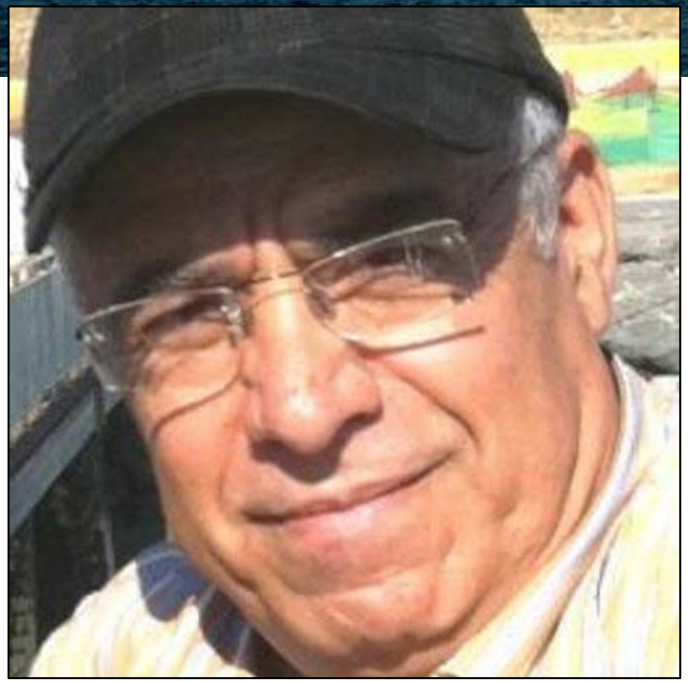
- More coastal erosion and landslides
- Seasonal mass movements



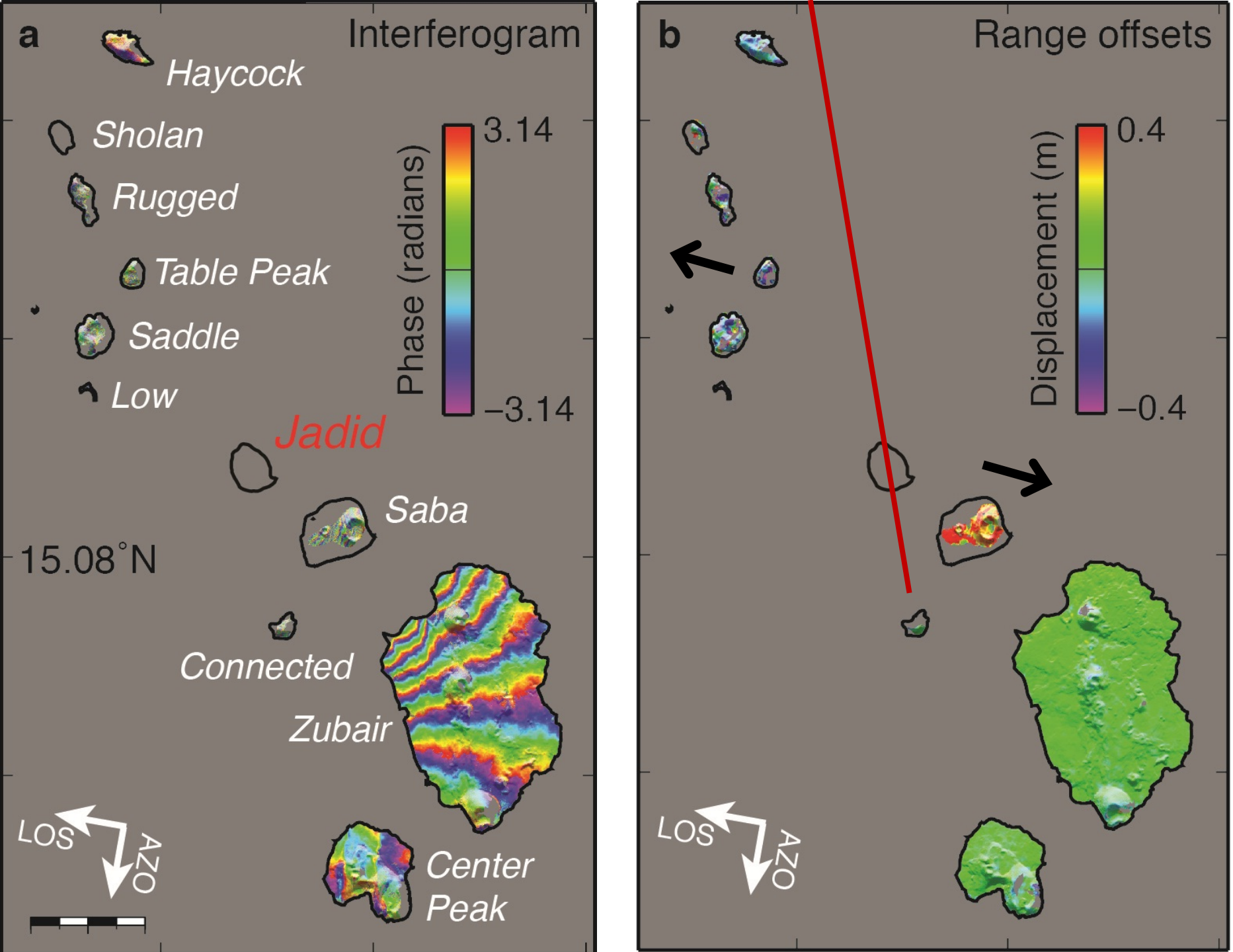
TanDEM-X DEM

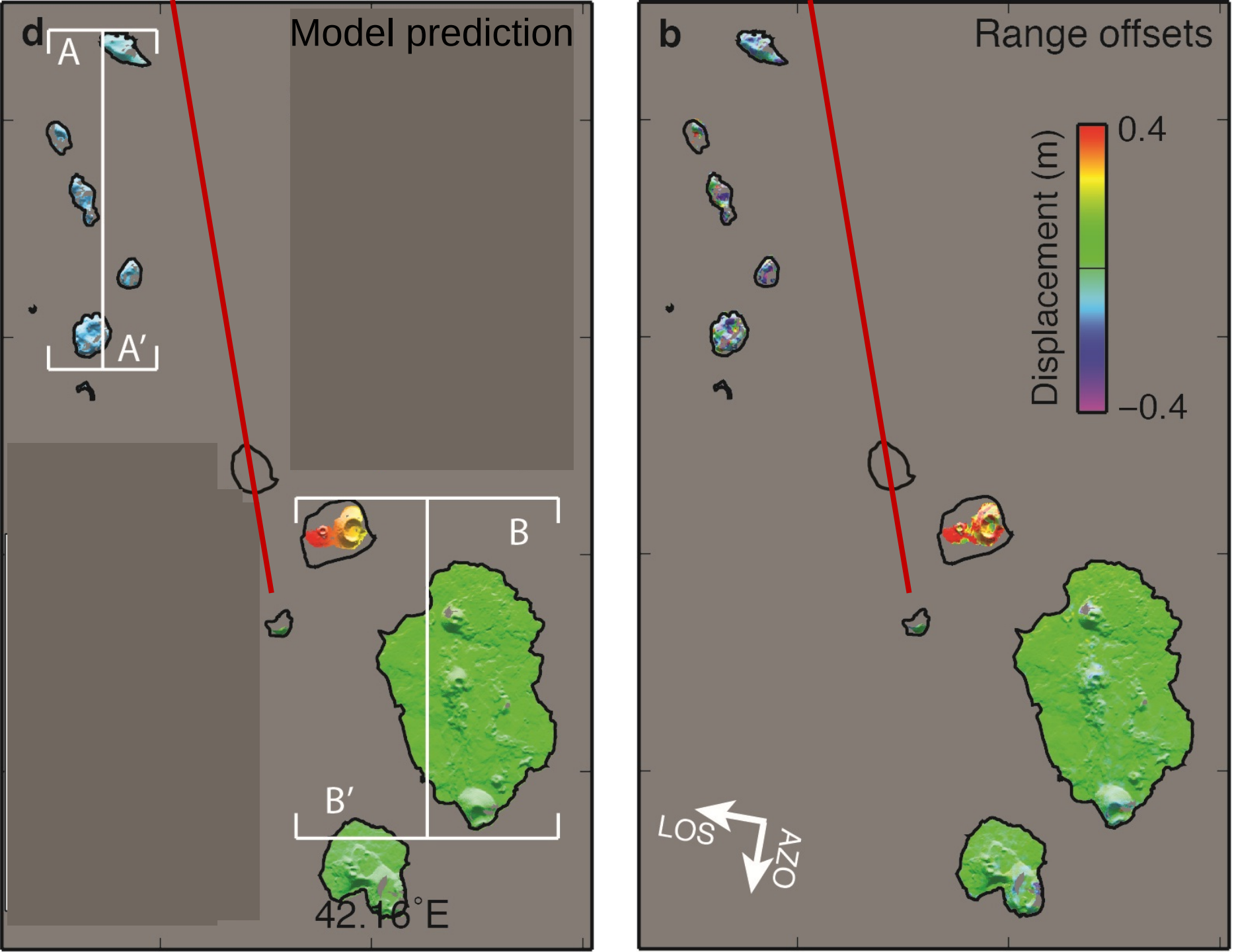
Sholan Island

Photo: Jamal Sholan

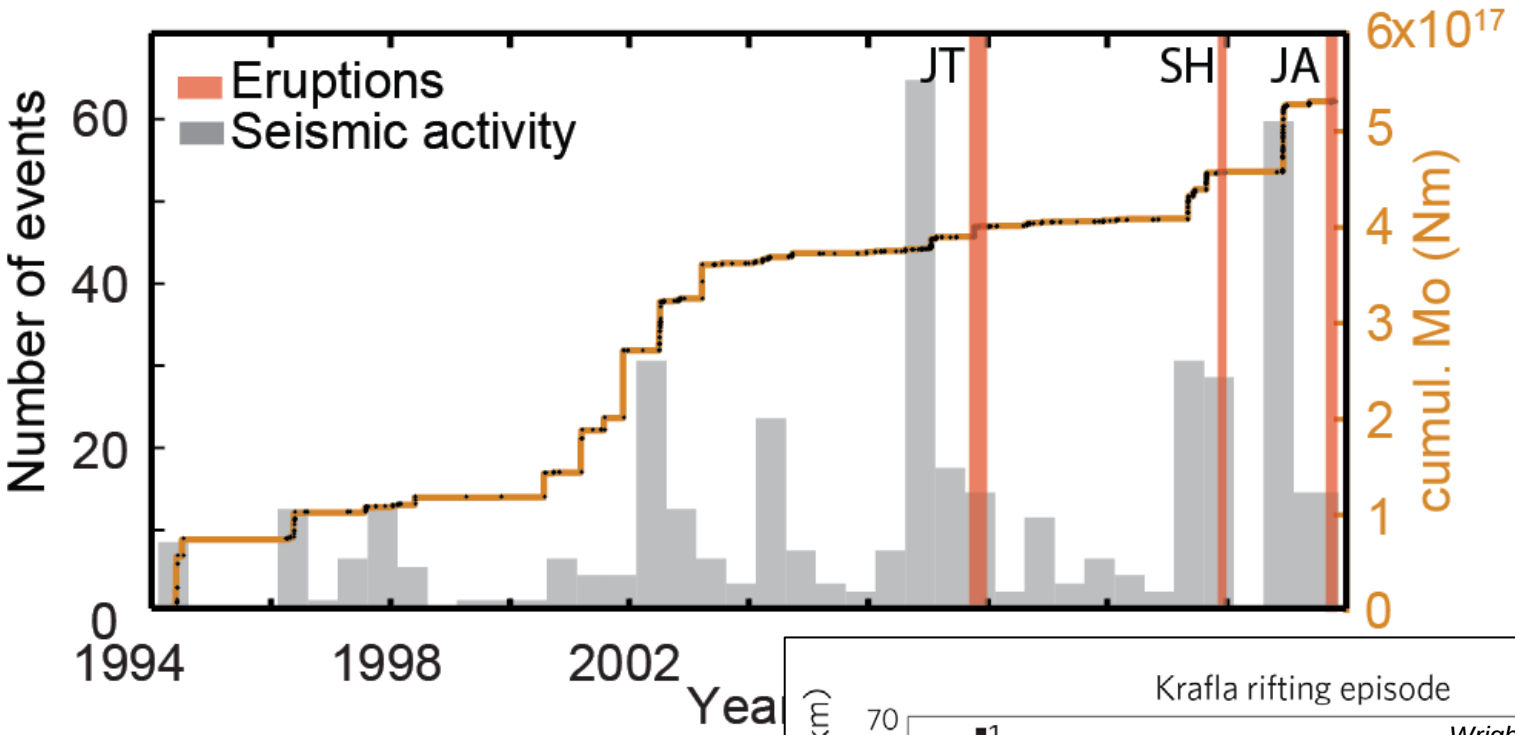


- Jamal Sholan, the first Yemeni scientist to visit the island

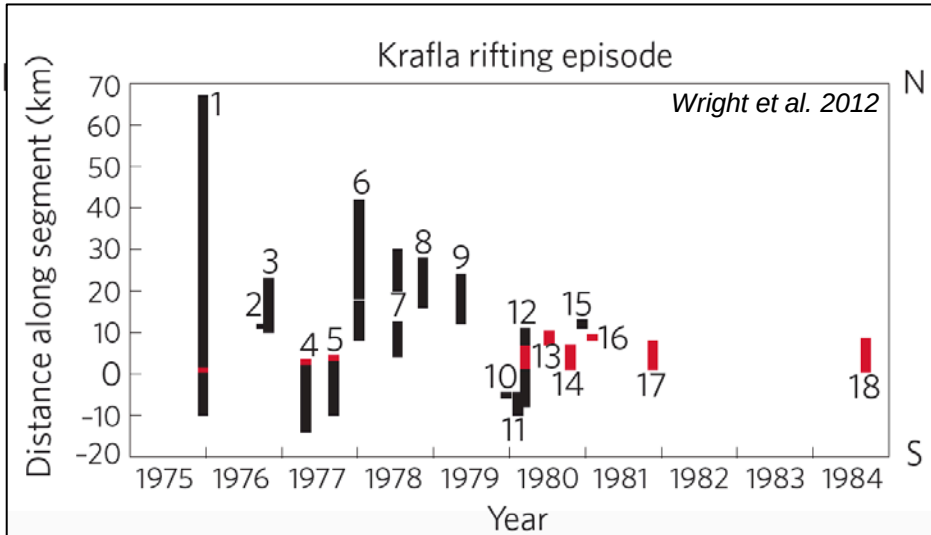

a
Interferogram
Haycock
Sholan
Rugged
Table Peak
Saddle
Low
Jadid
Saba
15.08°N
Connected
Zubair
Center
Peak
Phase (radians)
3.14
−3.14
LOS
AZO
b
Range offsets
Displacement (m)
0.4
−0.4
LOS
AZO

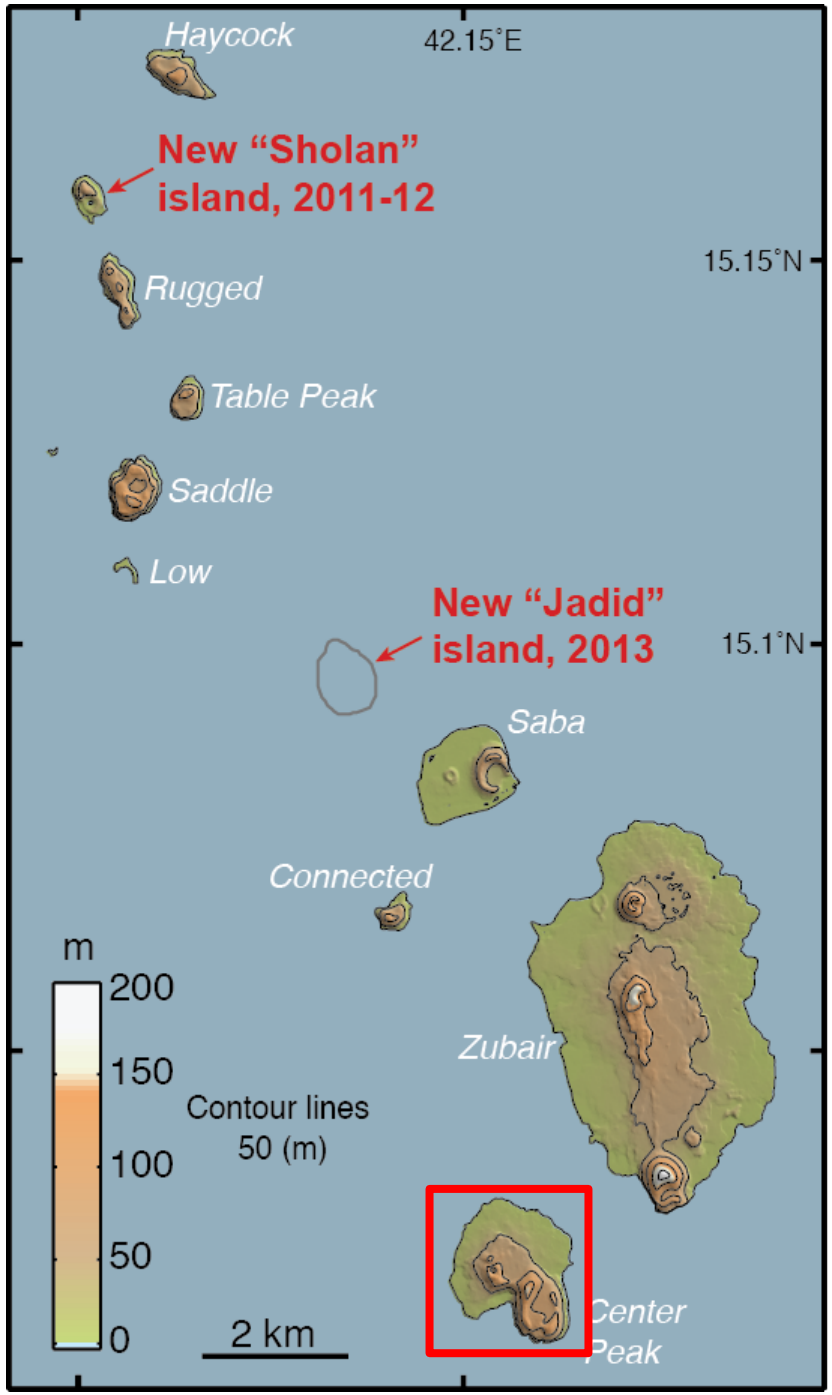

d
Model prediction
A
A′
B
B′
42.16°E
b
Range offsets
Displacement (m)
0.4
−0.4
LOS
AZO

Southern Red Sea Earthquake Swarms

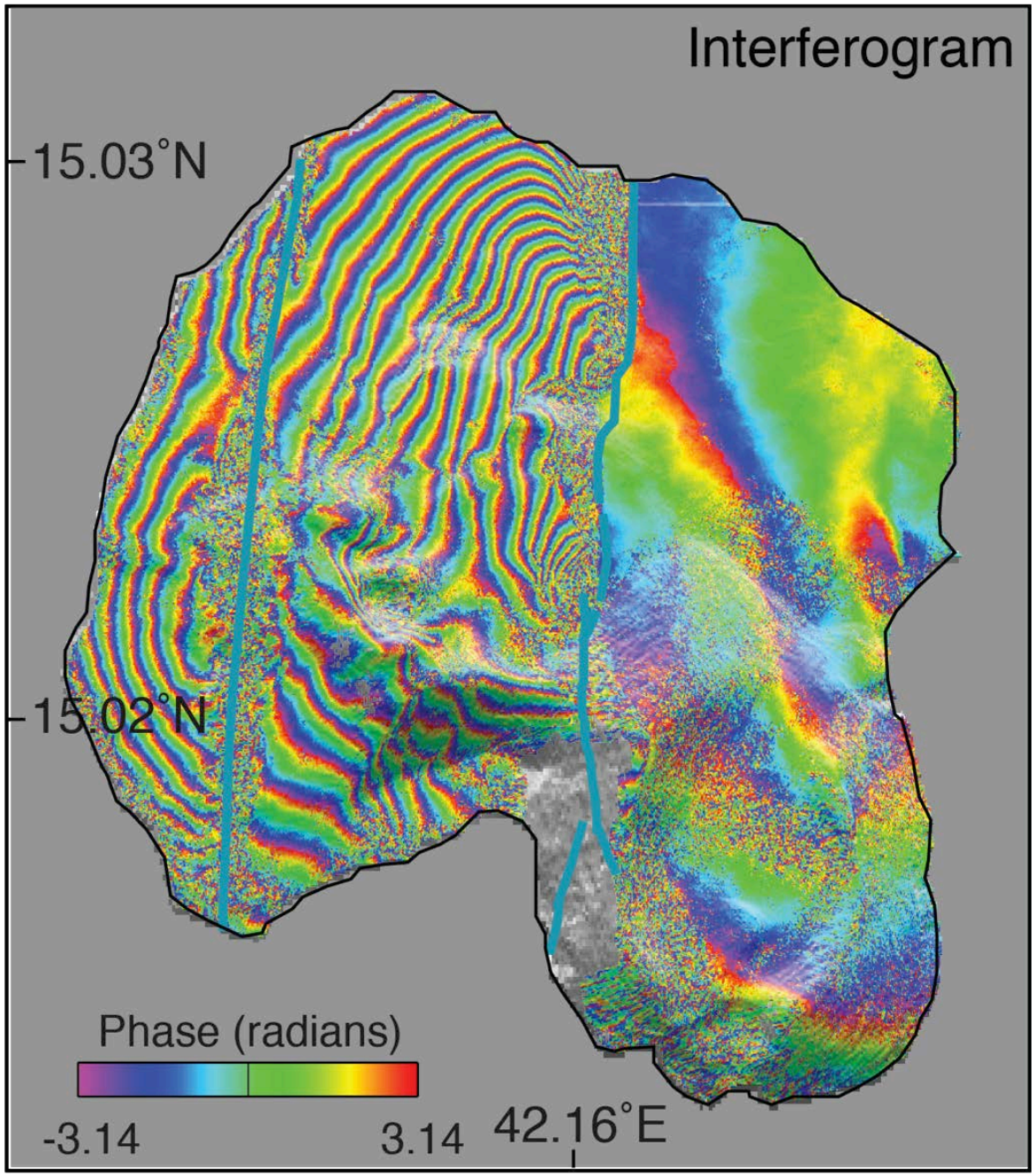


Rifting episode?



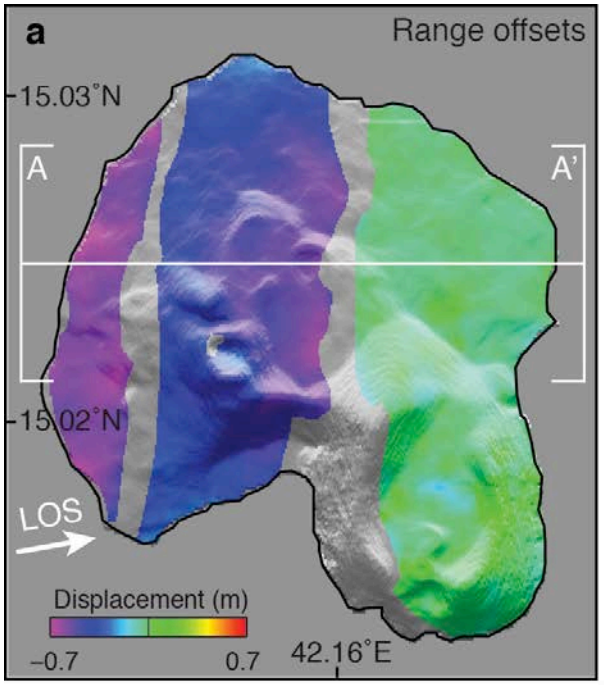


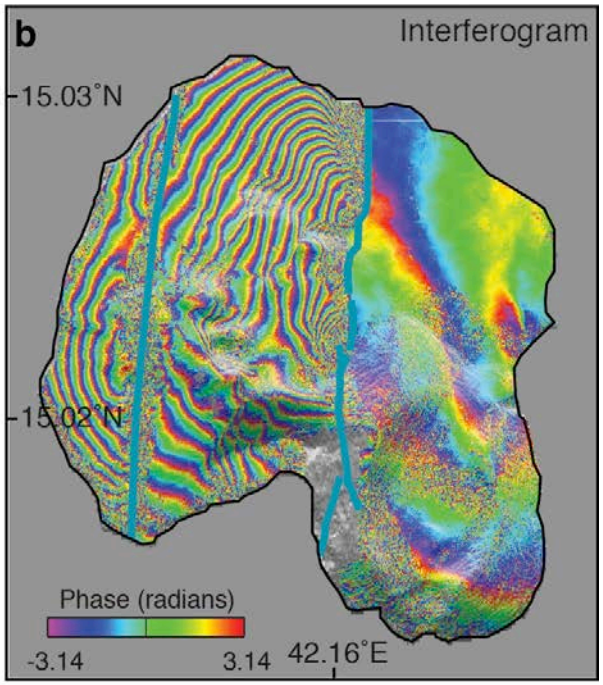
Jónsson and Xu, 2015



Centre Peak Island

- Dec. 2012 – Dec. 2013 Interferogram
- Another one indicates deformation occurred before Aug. 2013, but not during the Jadid eruption
- Likely coinciding with the January 2013 earthquake swarm



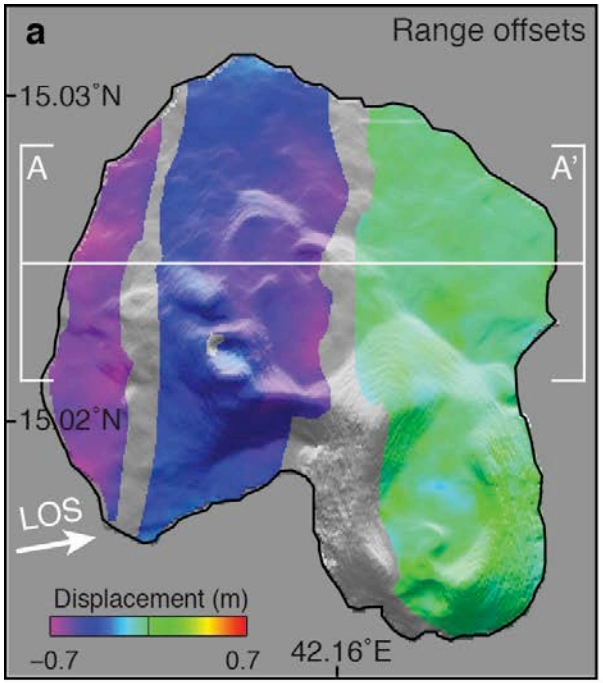


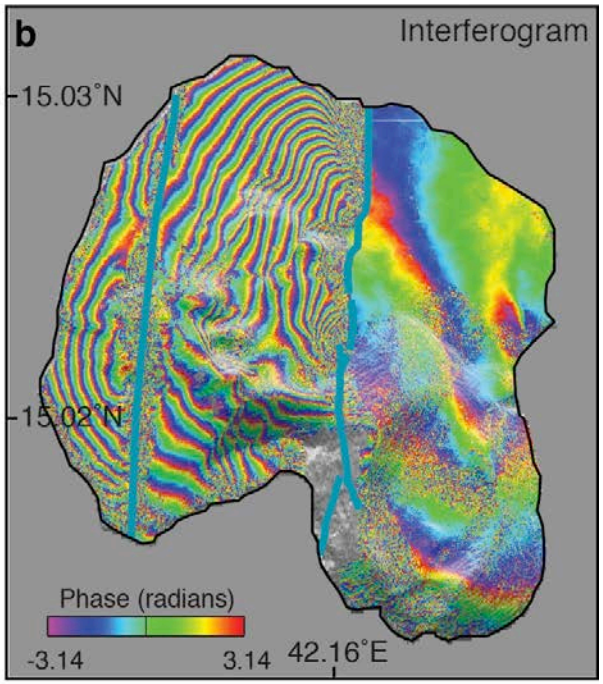
Centre Peak Island

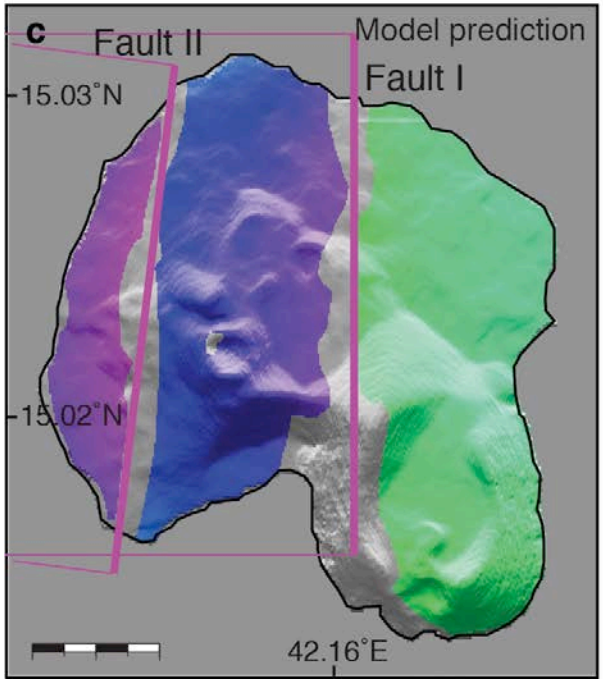
- SAR offsets help again

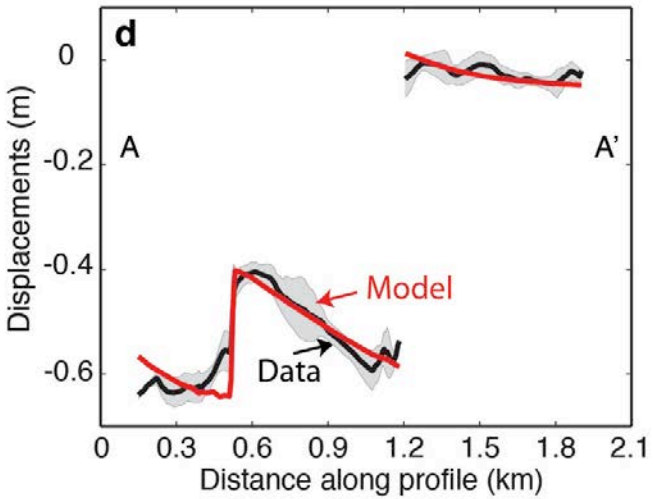
Centre Peak Island

- SAR offsets help again

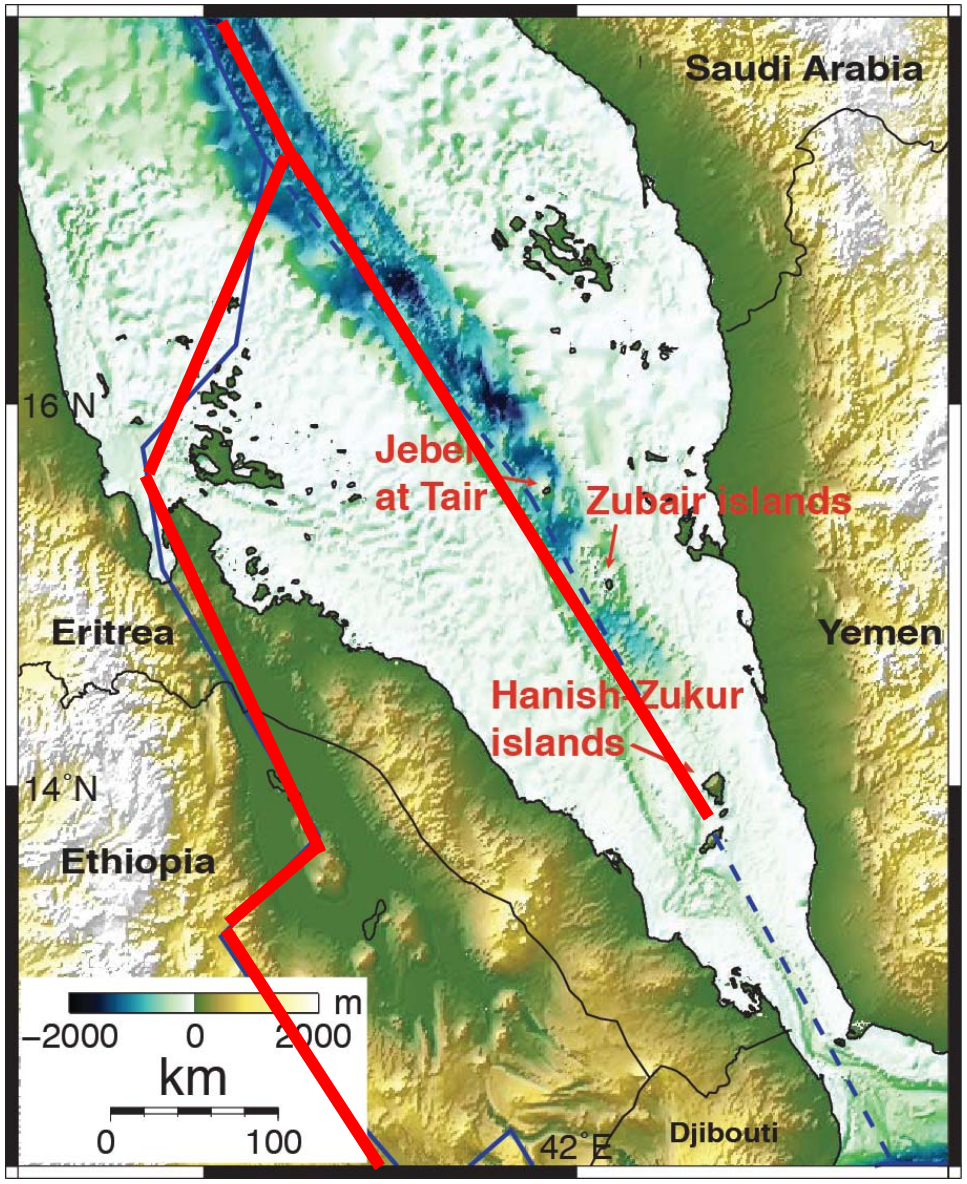


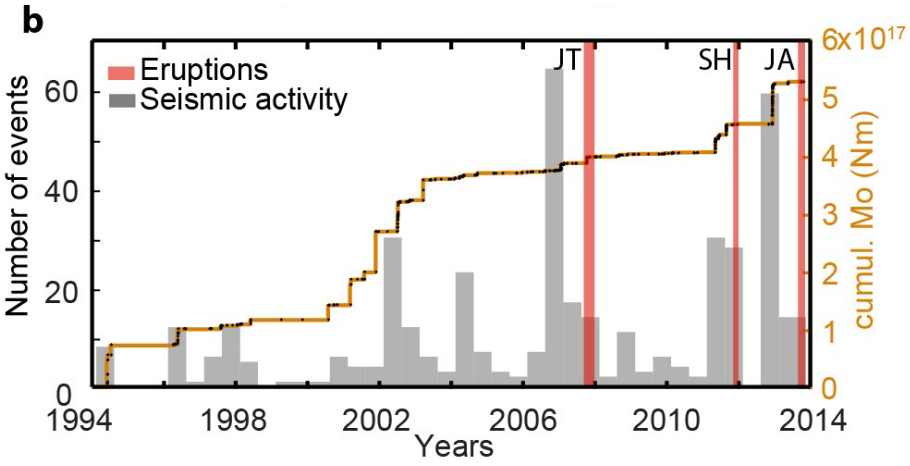






Rifting Episode? Yes, probably





Xu, Ruch & Jónsson, Nature Communications, 2015

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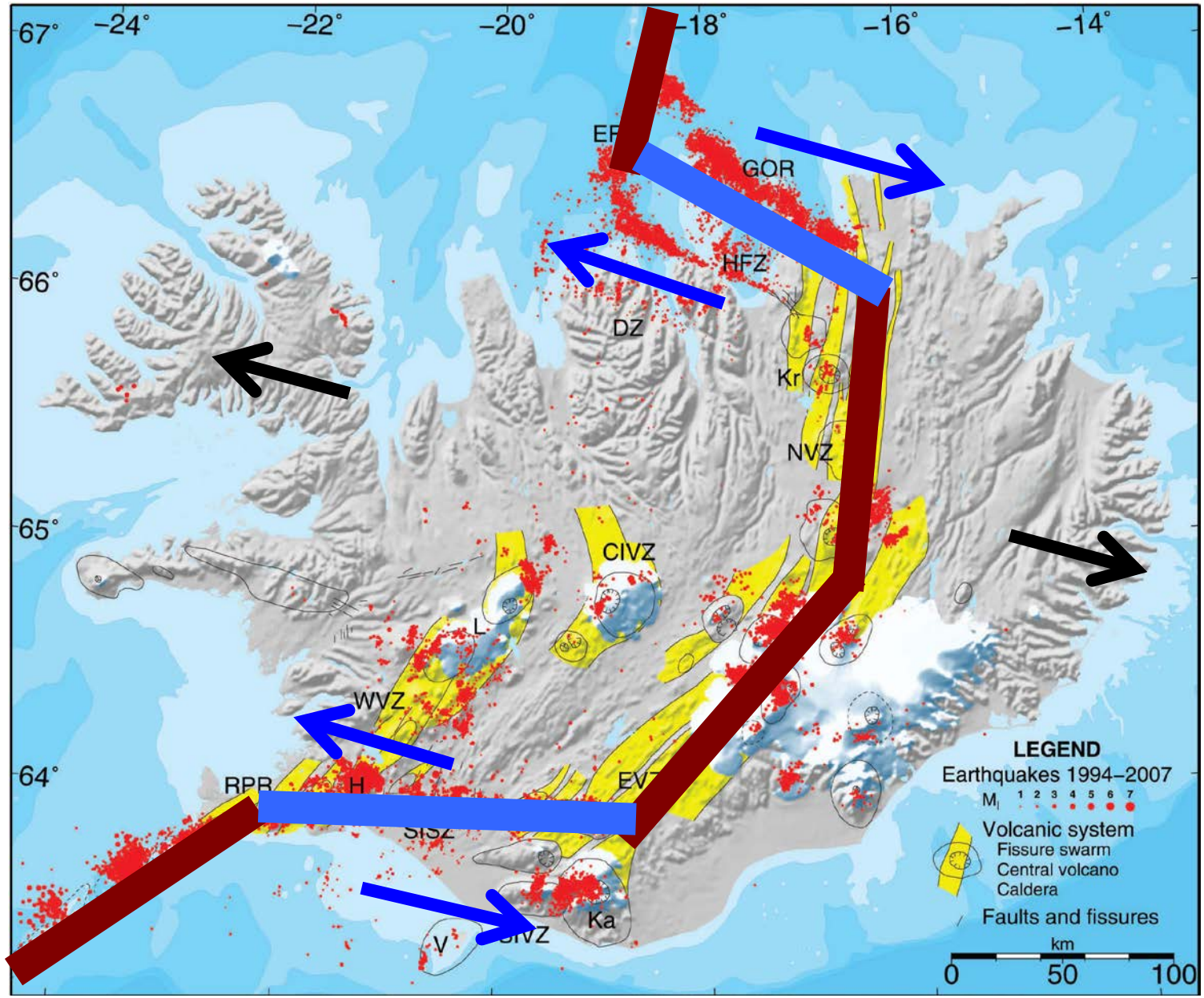
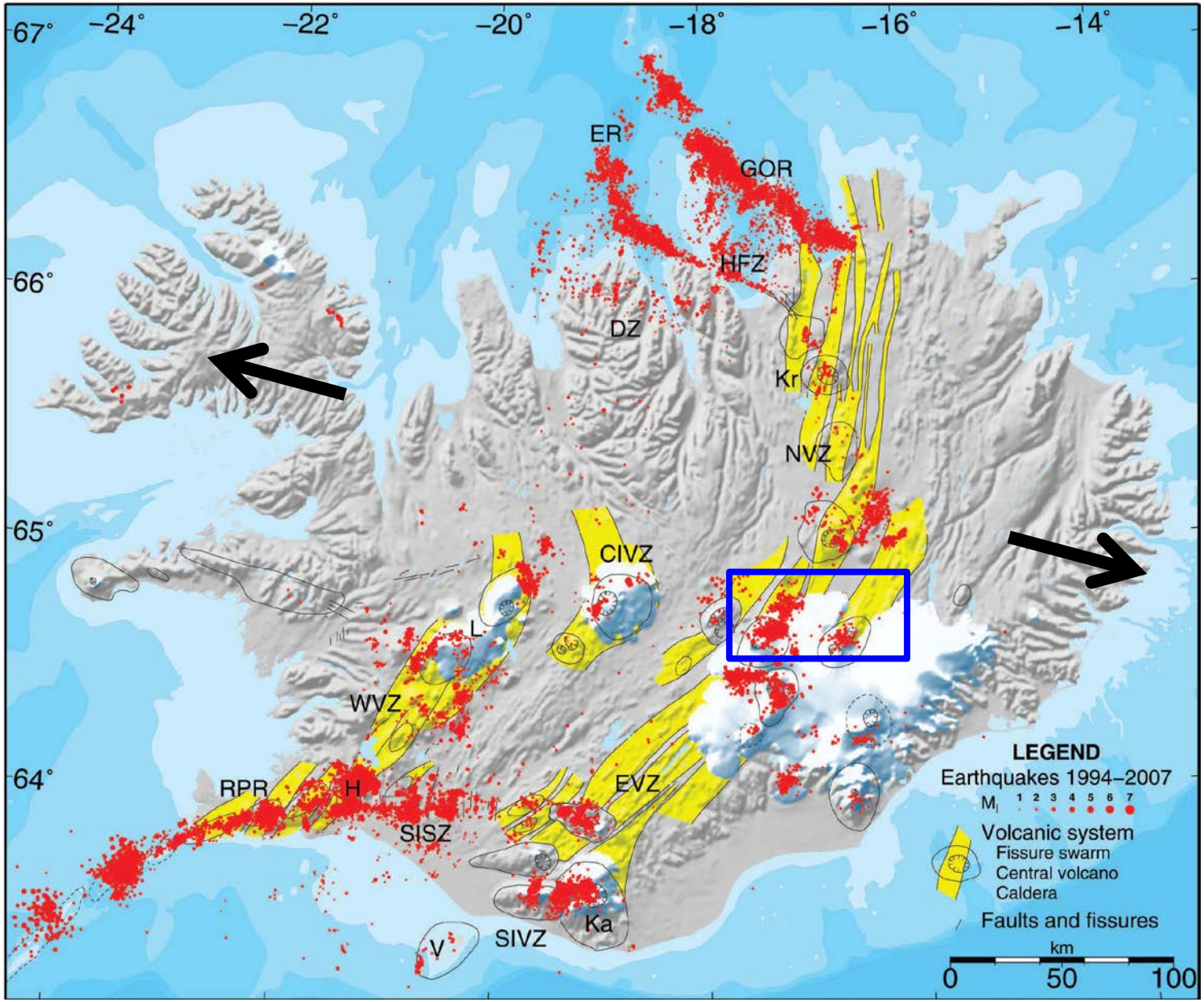
Iceland

Earthquakes and Volcanic Systems in Iceland



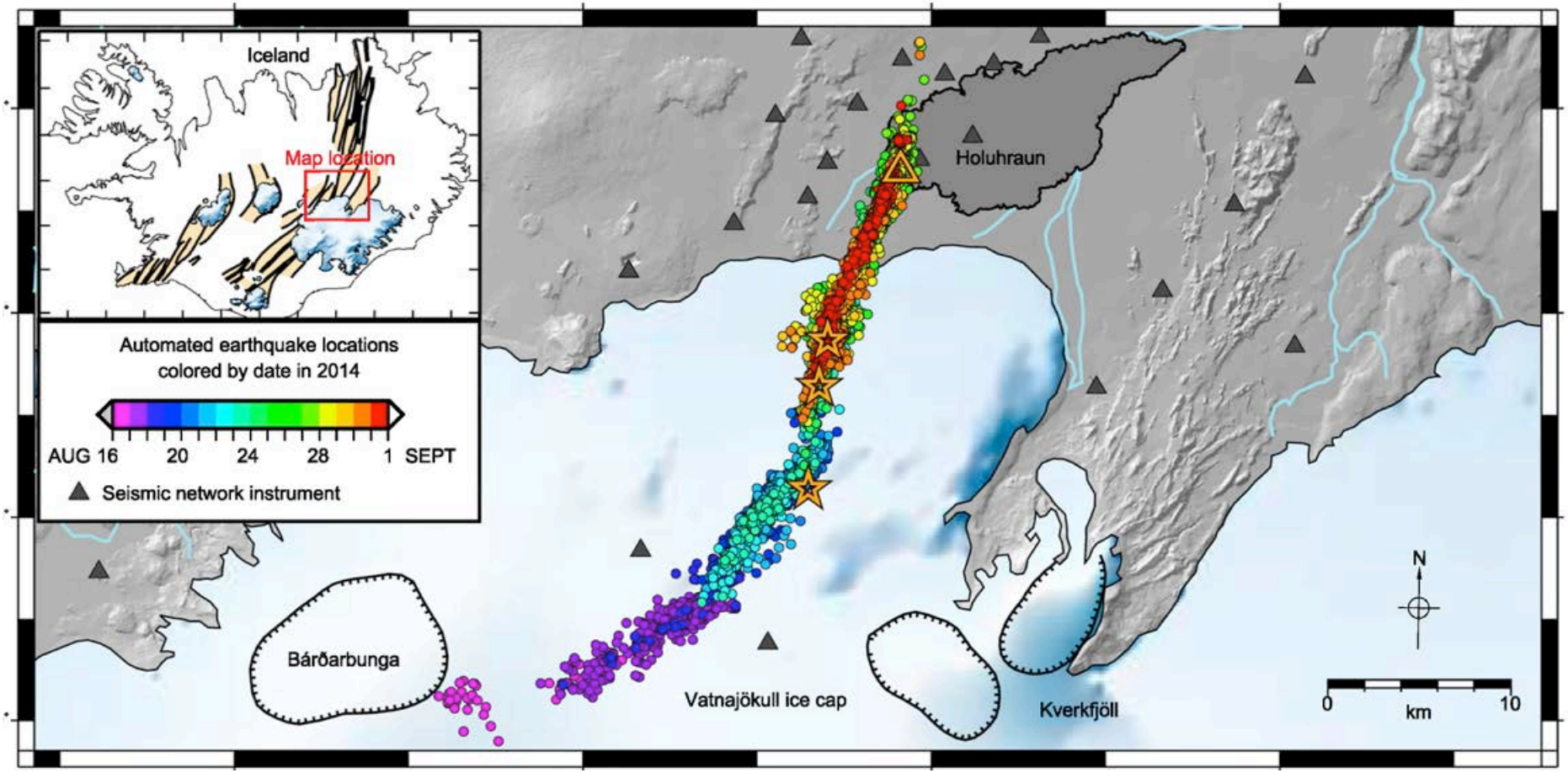
IMO and Einarsson et al., 2008

Earthquakes and Volcanic Systems in Iceland



IMO and Einarsson et al., 2008

Earthquake activity during the intrusion



Ágústsdóttir et al., GRL, 2016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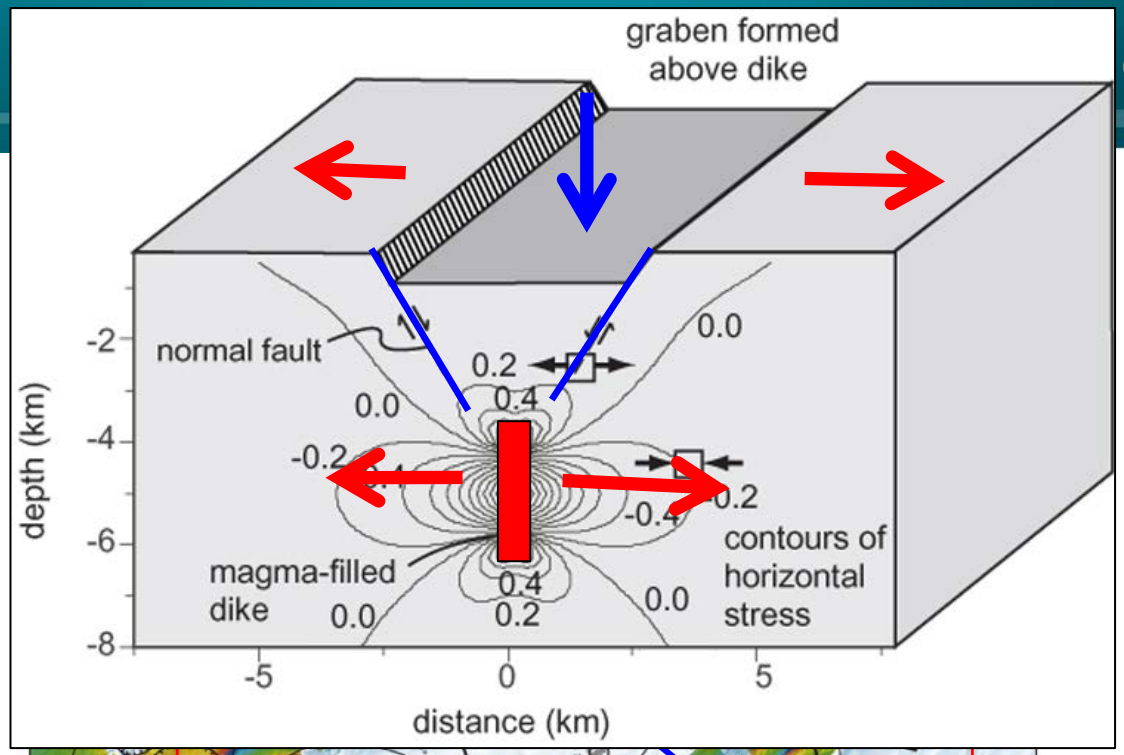
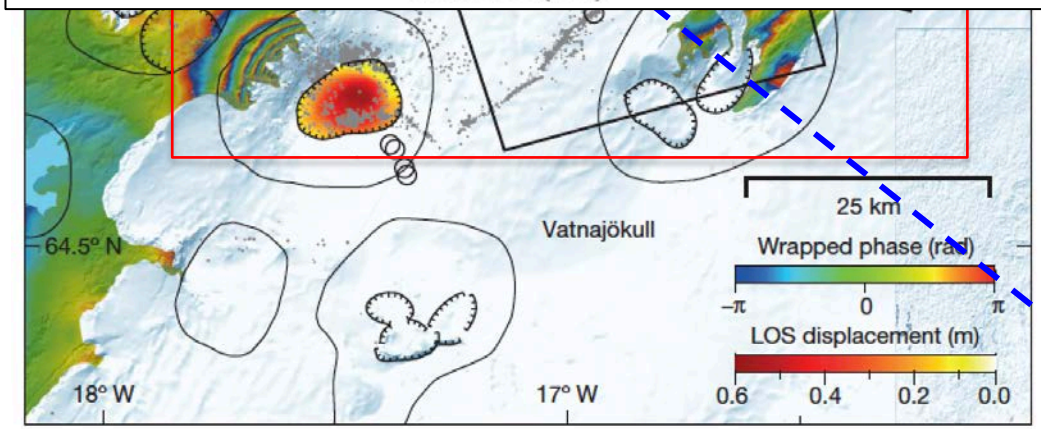
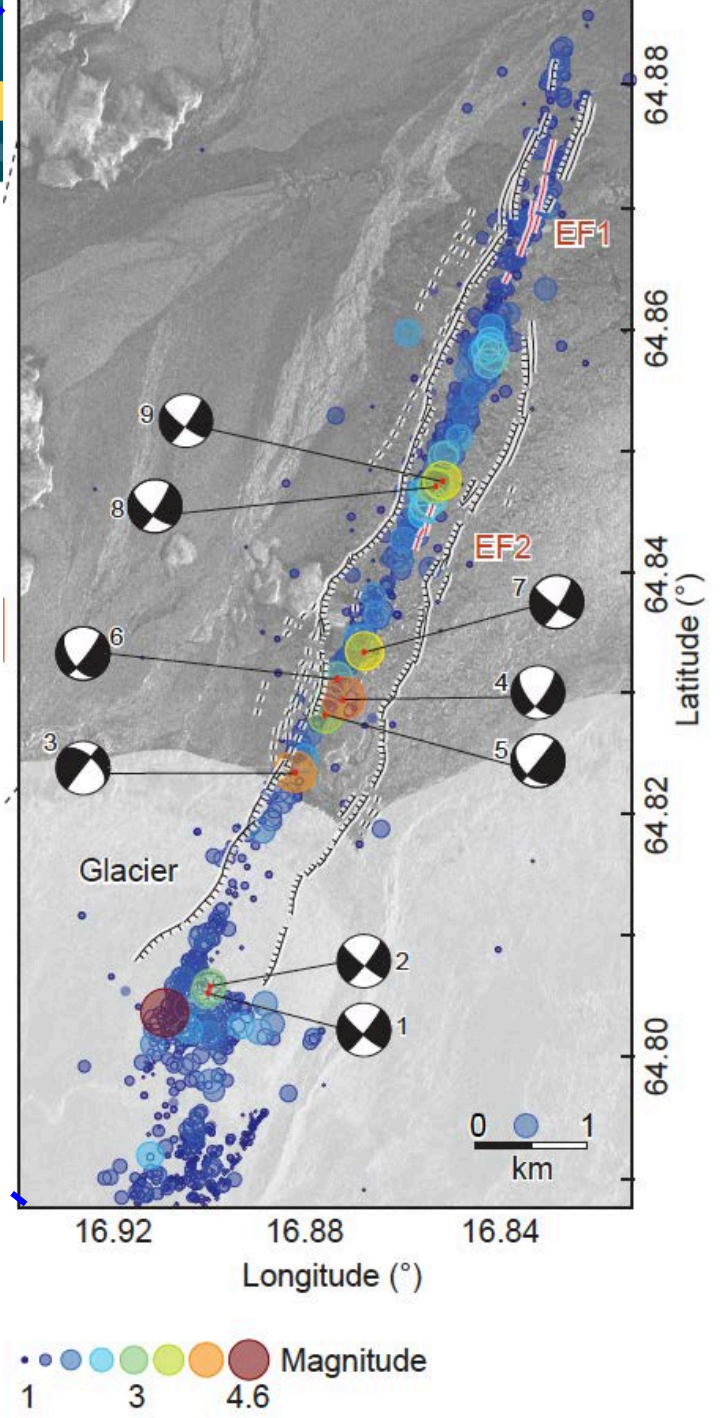
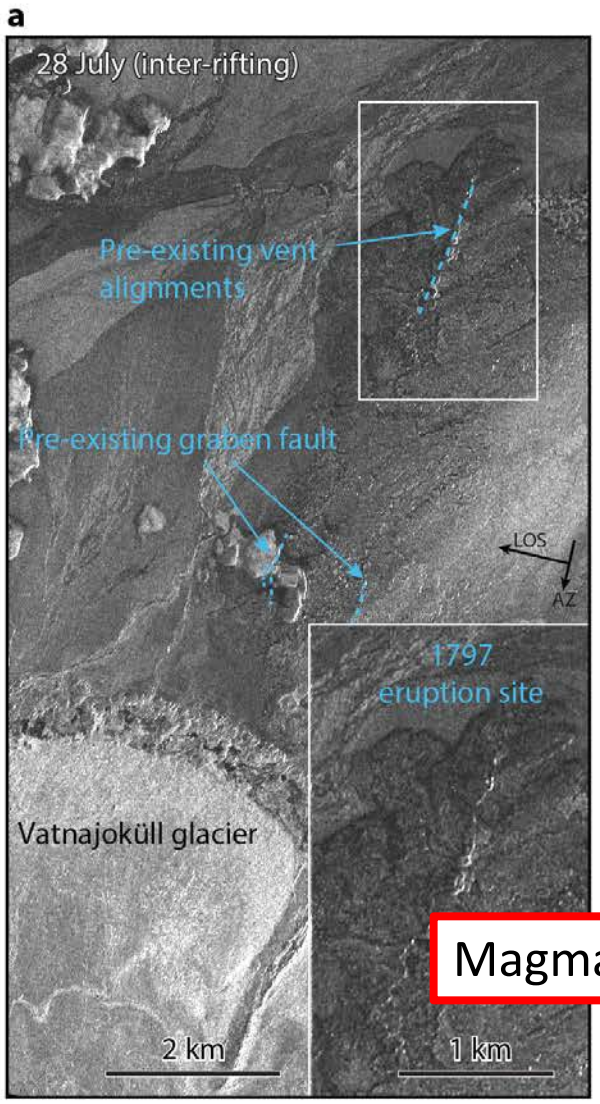




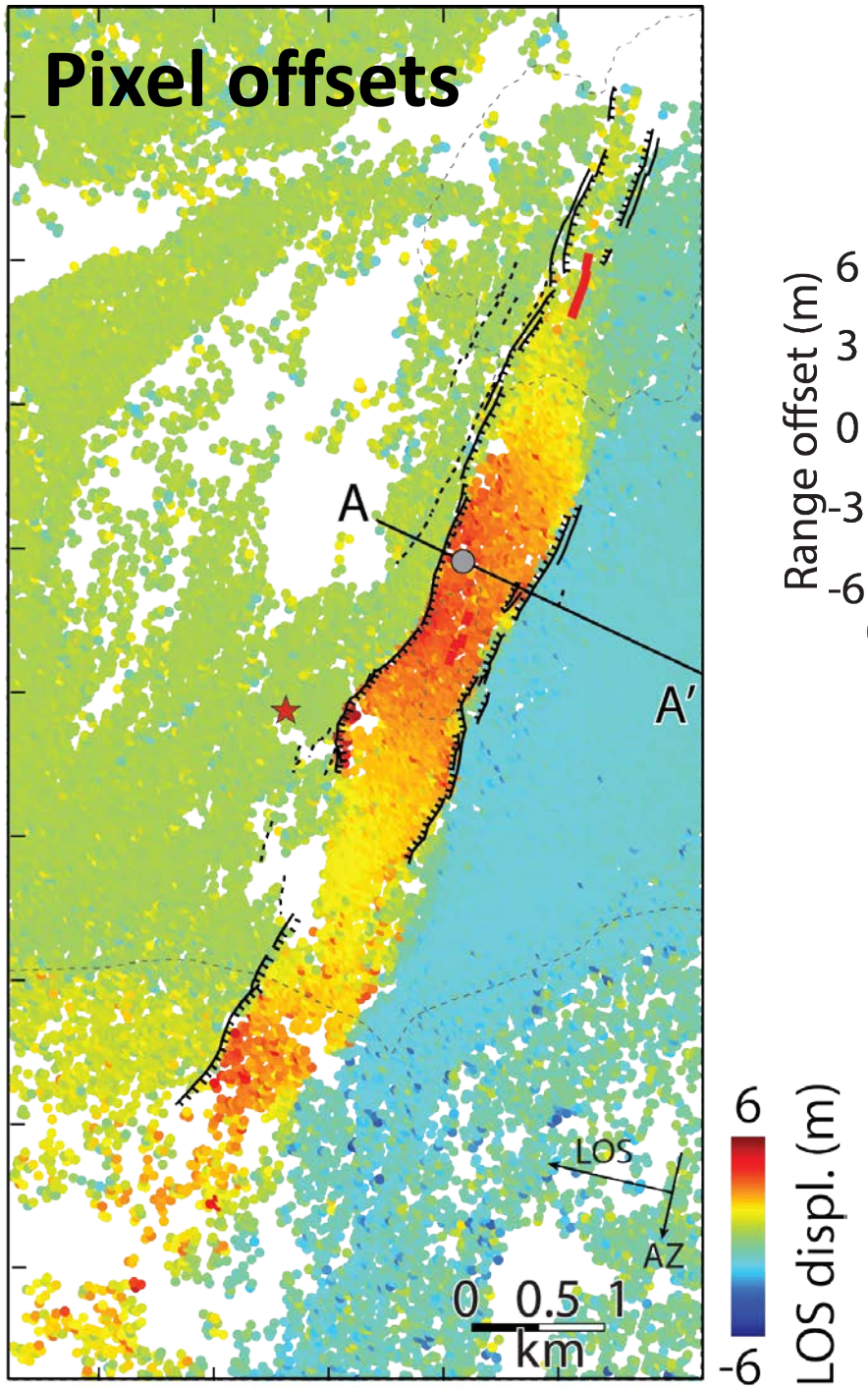


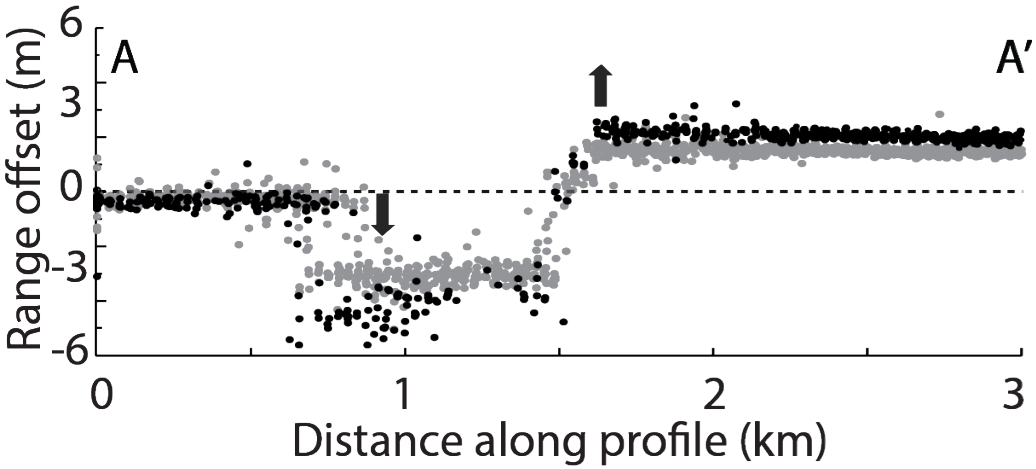
Sigmundsson et al., Nature, 2015

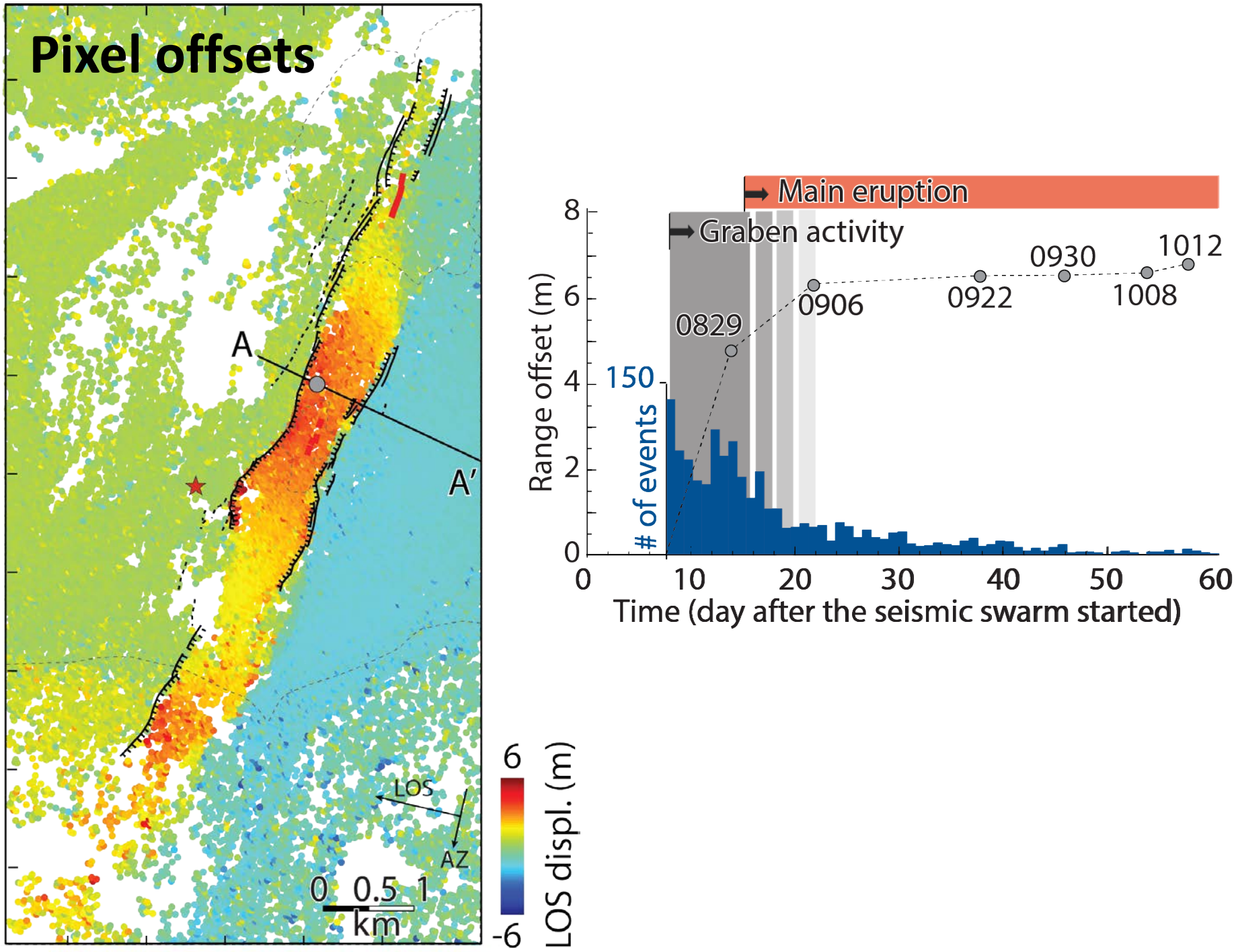
Graben fault reactivation in SAR images



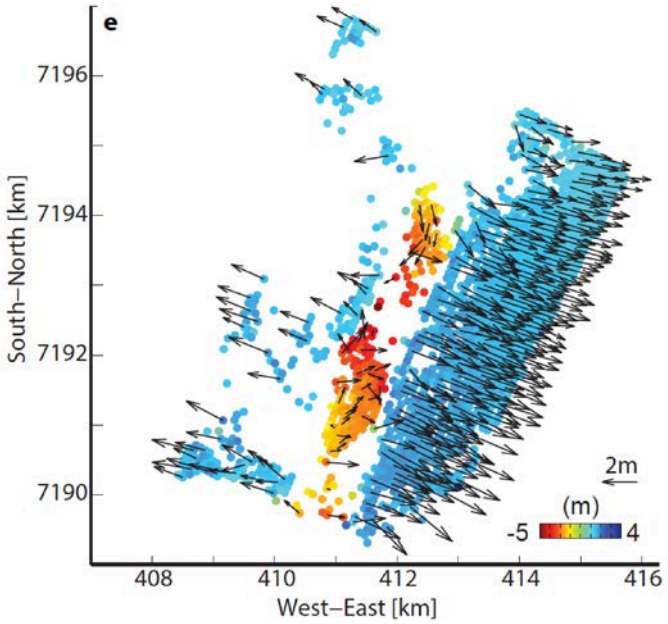
Magma used the same pathway as for the 1797 eruption!


Pixel offsets
A
A′
LOS
AZ
0 0.5 1
km
6
-6
LOS displ. (m)

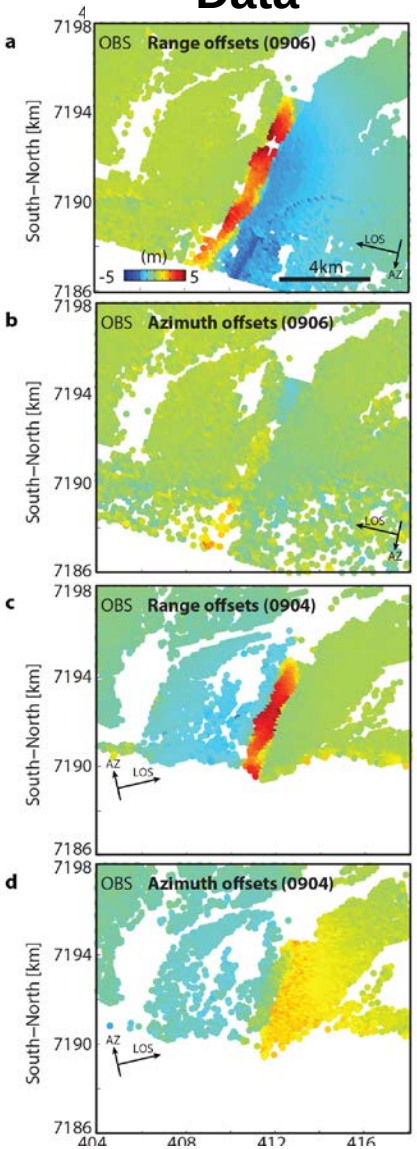

A
A′
6
3
0
-3
-6
Range offset (m)
0
1
2
3
Distance along profile (km)


Pixel offsets
A
A′
LOS
AZ
0 0.5 1
km
6
-6
LOS displ. (m)
Main eruption
Graben activity
0829
0906
0922
0930
1008
1012
150
# of events
Range offset (m)
0
2
4
6
8
0
10
20
30
40
50
60
Time (day after the seismic swarm started)

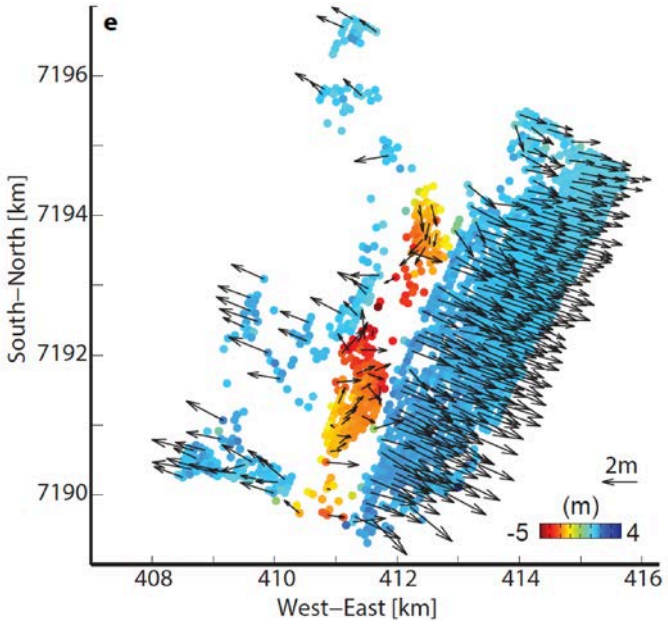
3D Displacement and modeling

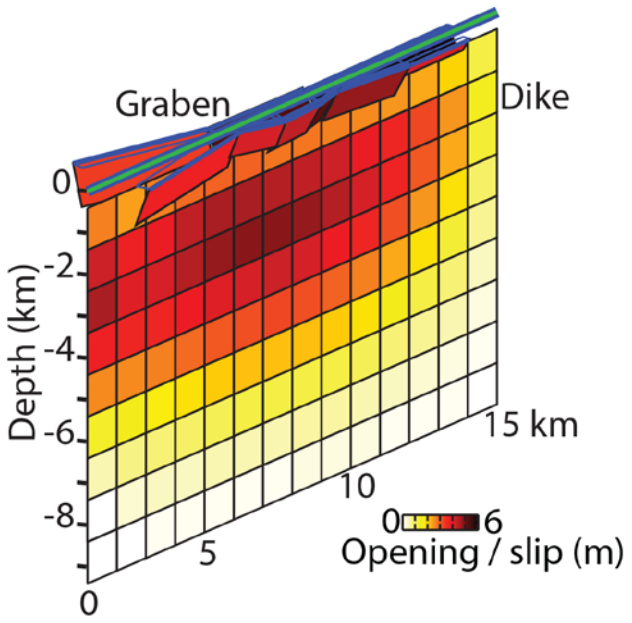


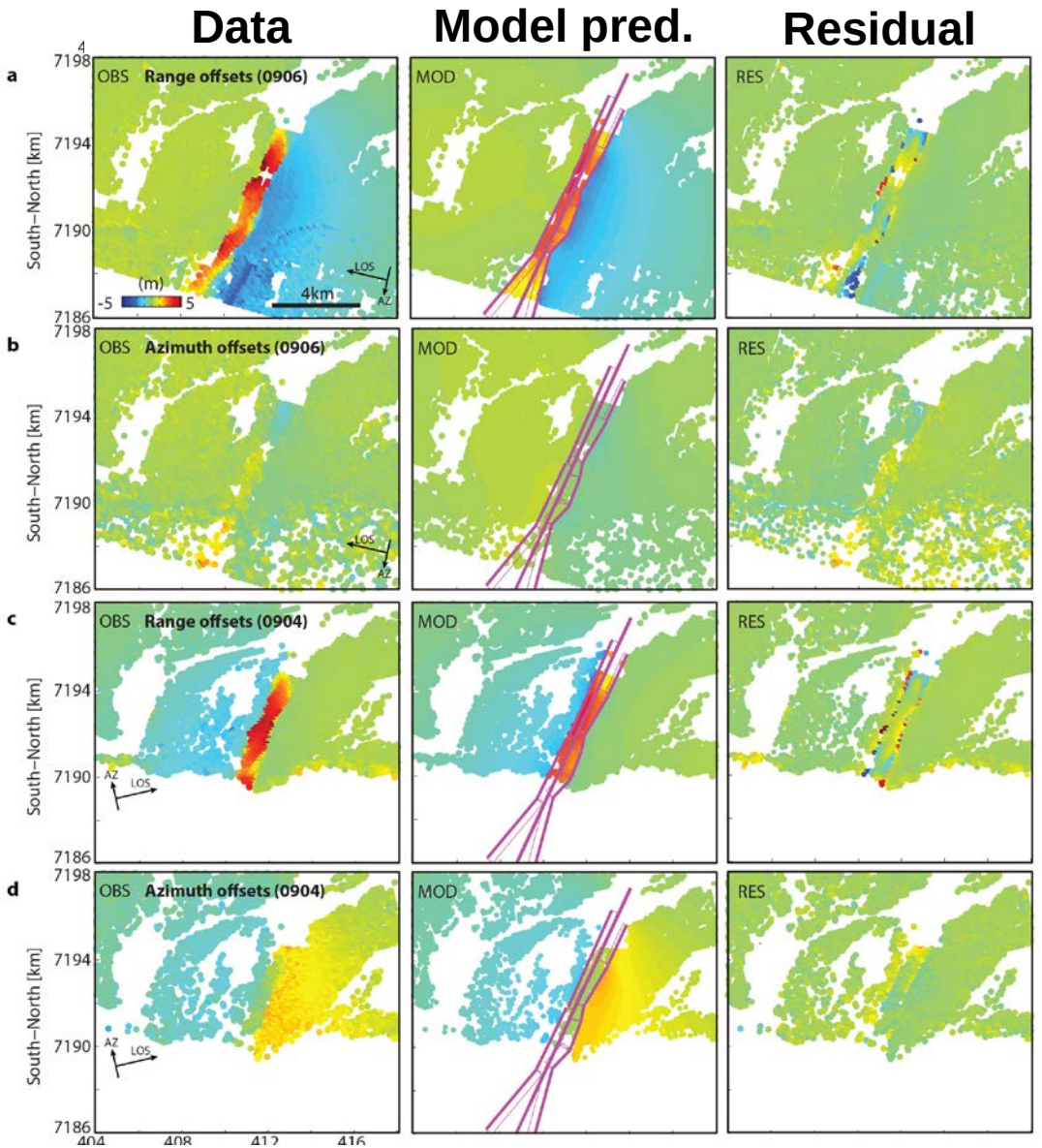
Data



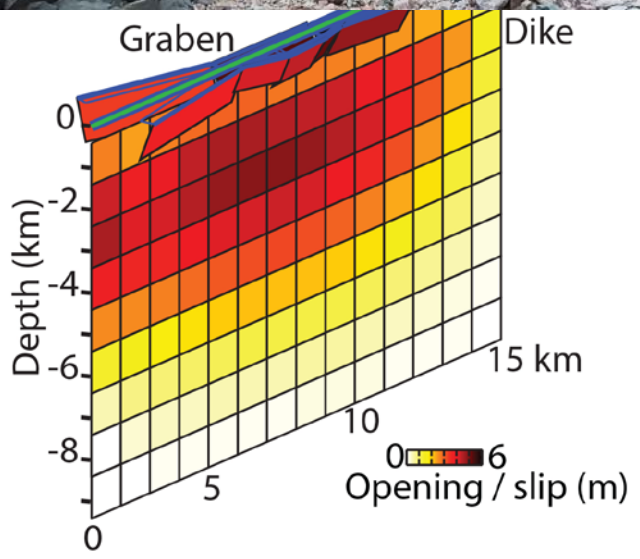
3D Displacements and modeling

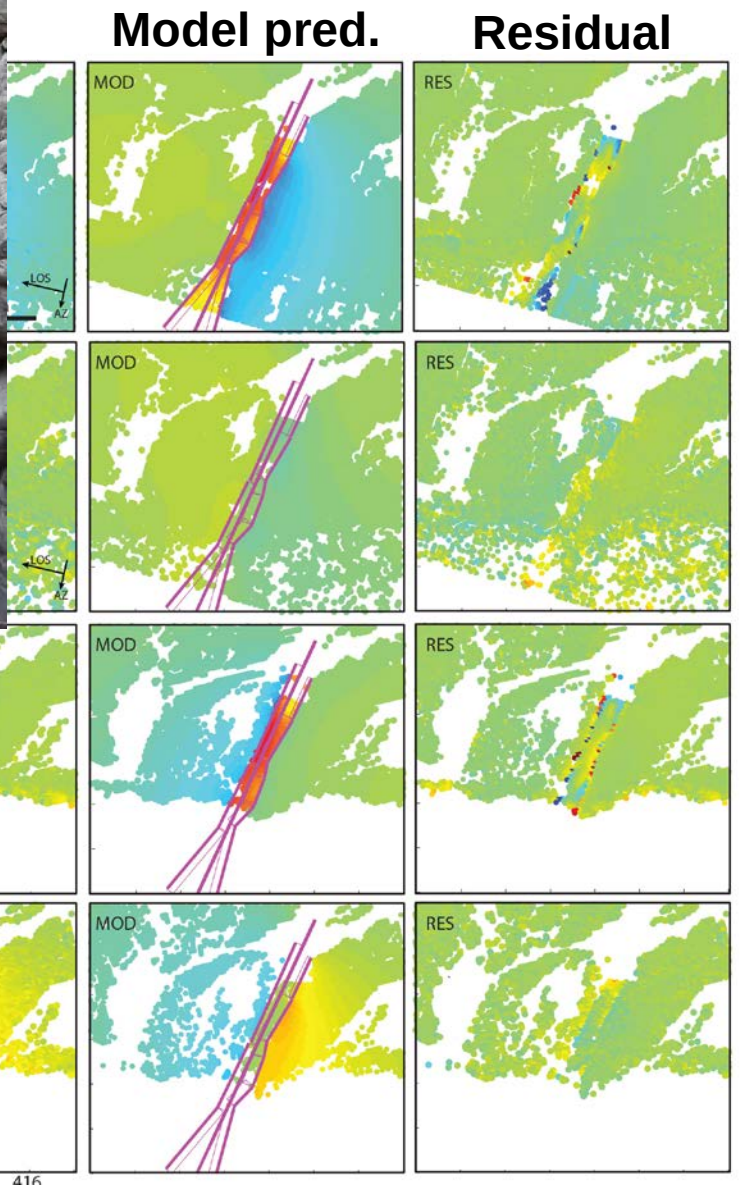




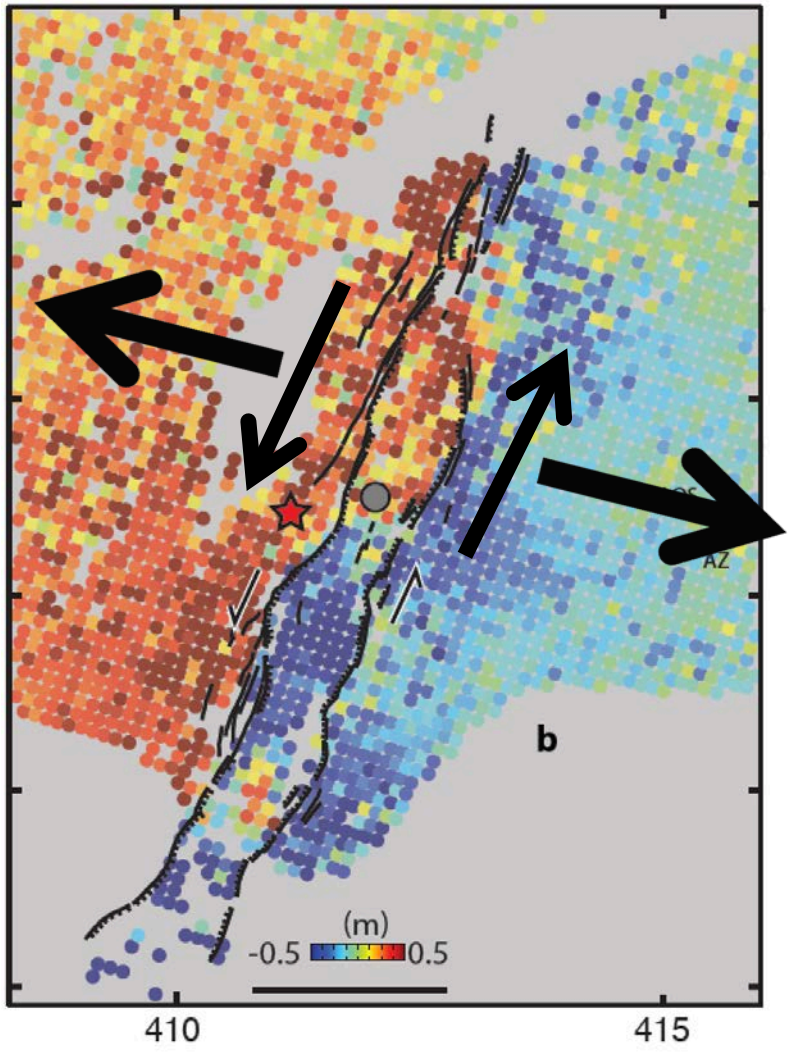


lacements and modeling





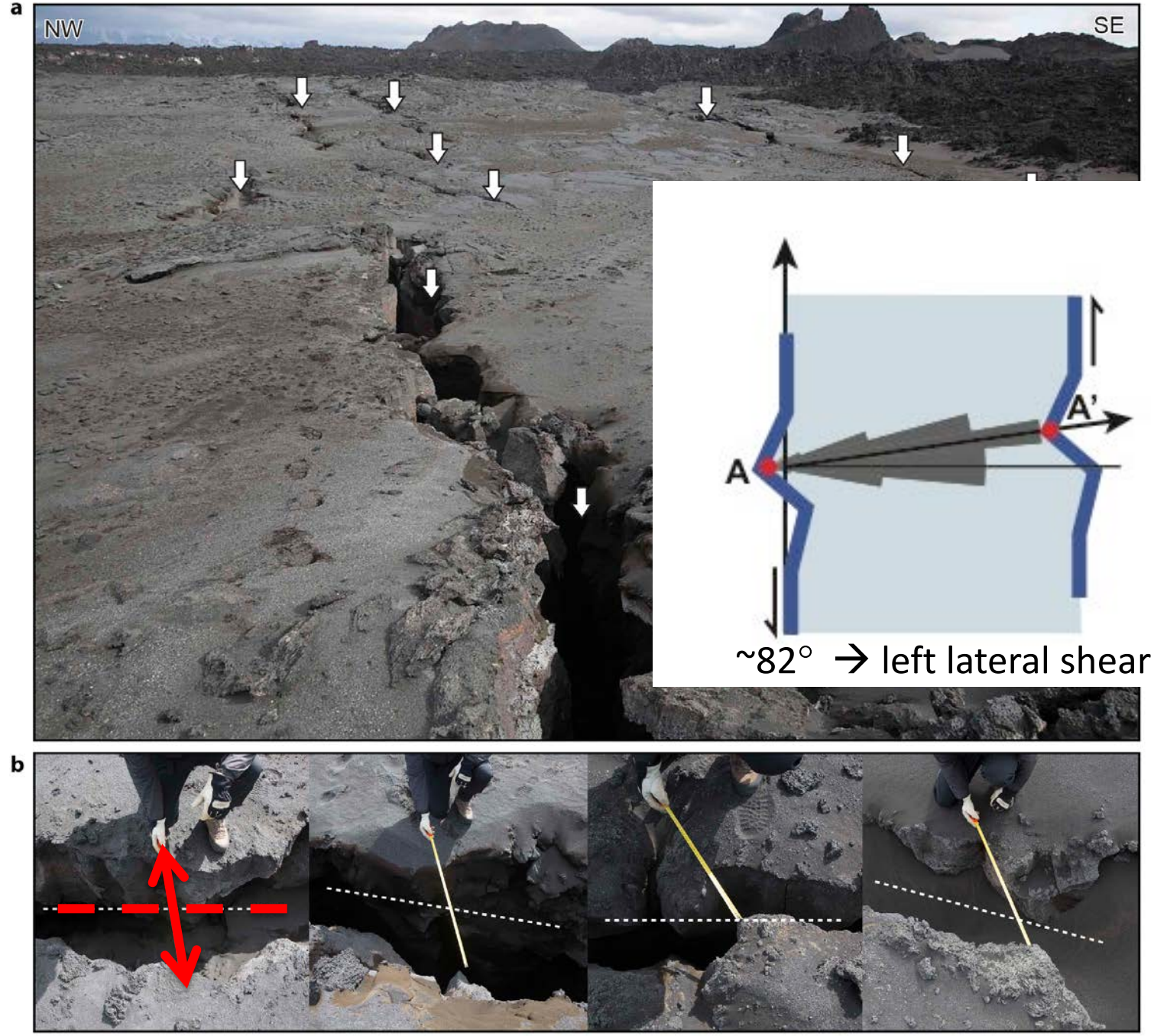
Azimuth offset residuals reveal >0.5 m shear



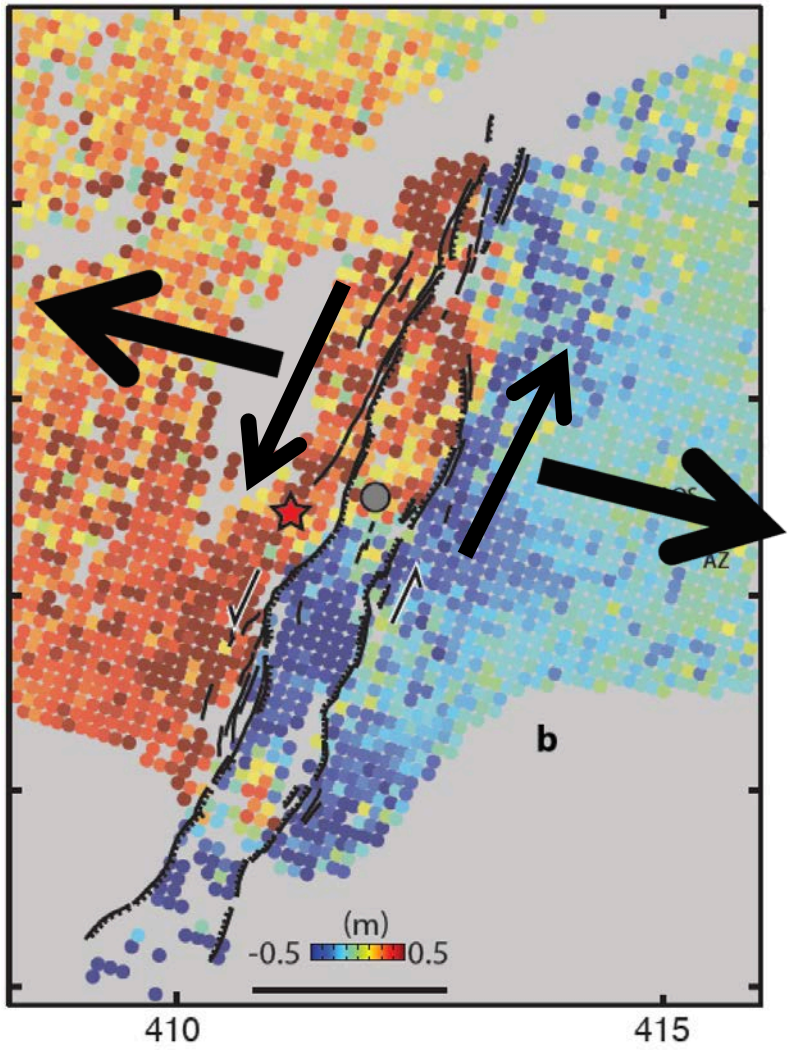
Graben not orthogonal to the plate motion, difference ~10°

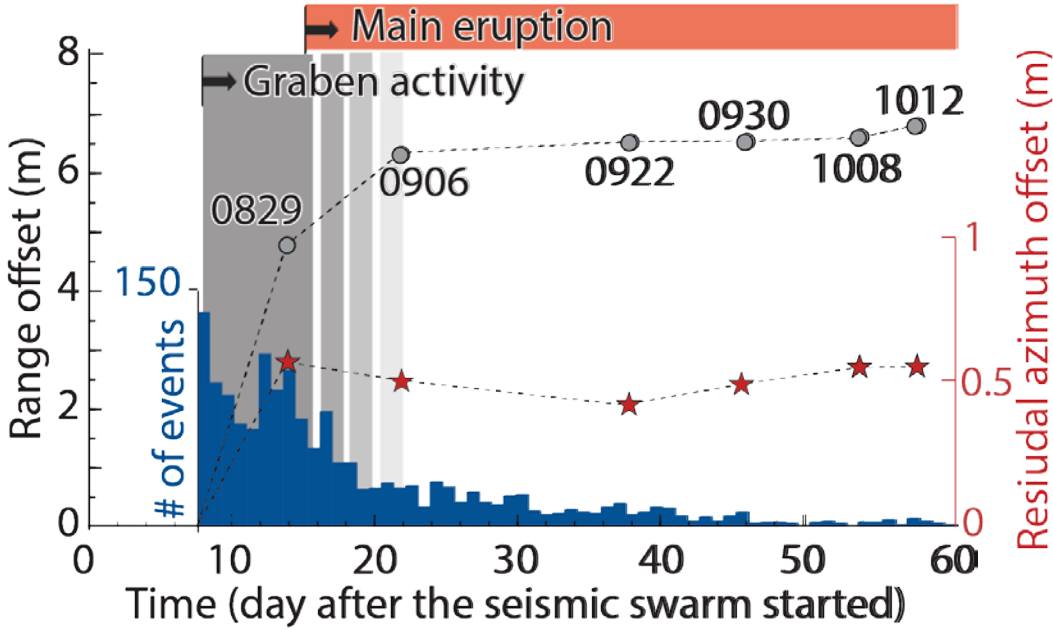
Why is the intrusion not perpendicular to σ_3?

Graben fractures in the field


a
NW
SE
A
A'
~82° → left lateral shear
b

The shear occurred in the beginning!



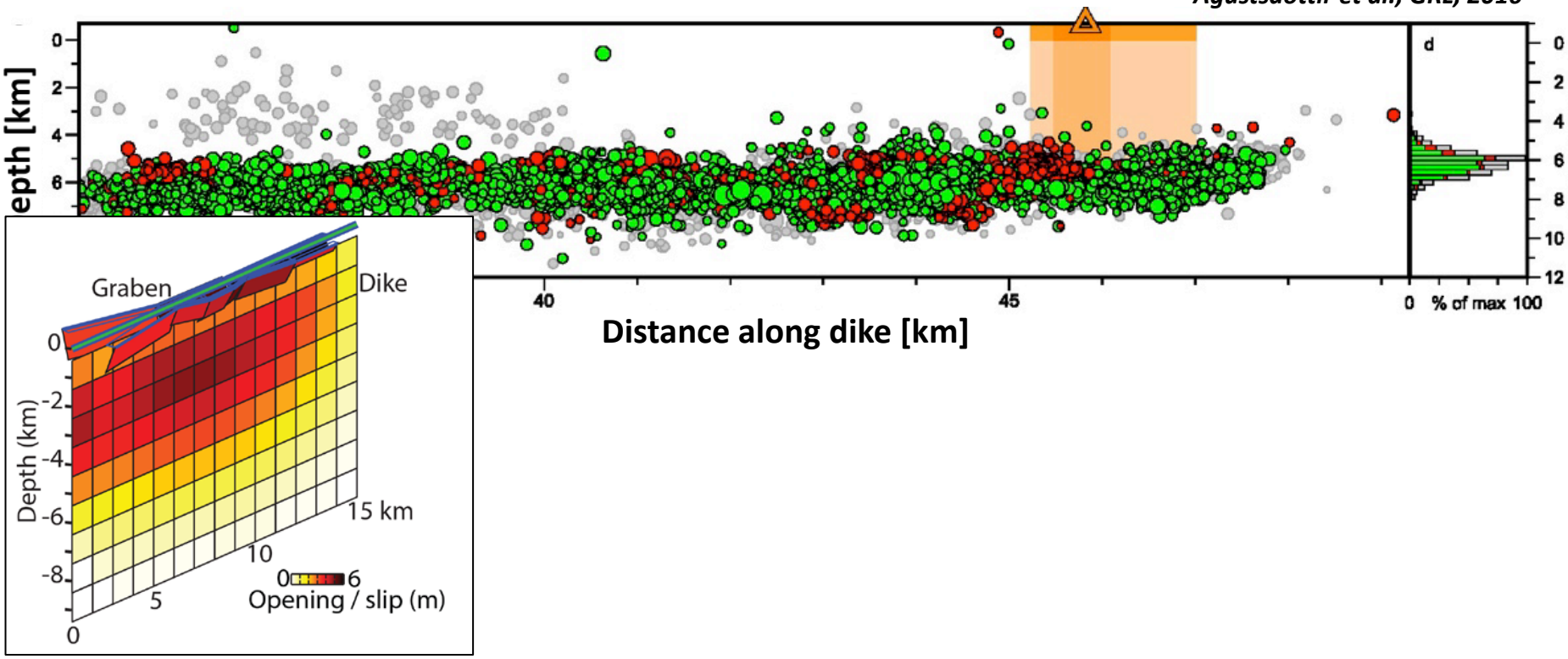


Opening and shear followed by additional opening

Earthquakes occurred below the dike

- All the earthquakes are below 6 km depth
- Occur below the dike intrusion
- Graben faulting and opening of the fissure is aseismic
- Indicates magma moved along pre-existing fractures

Ágústsdóttir et al., GRL, 2016



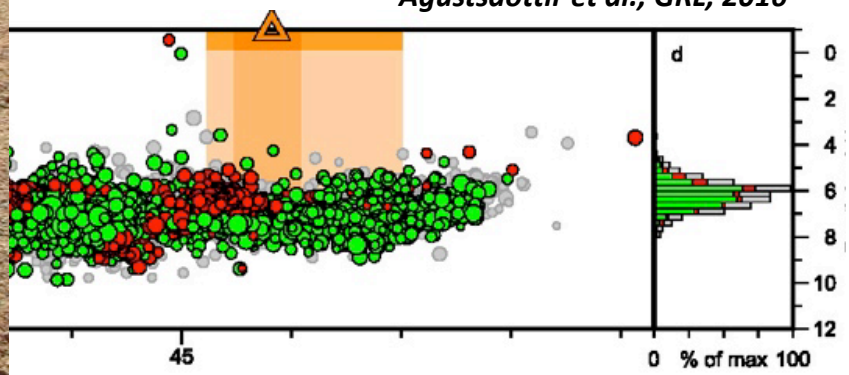
the dike

n depth

fissure is aseismic

-existing fractures

Ágústsdóttir et al., GRL, 2016

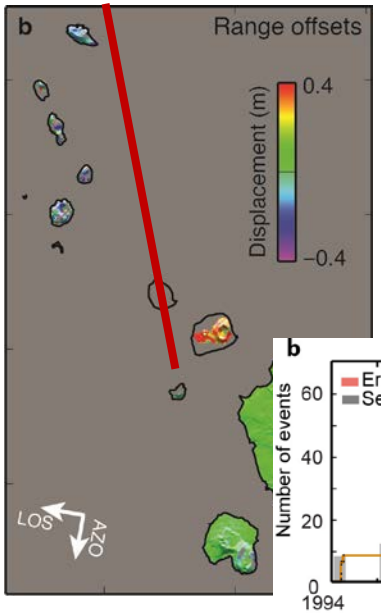


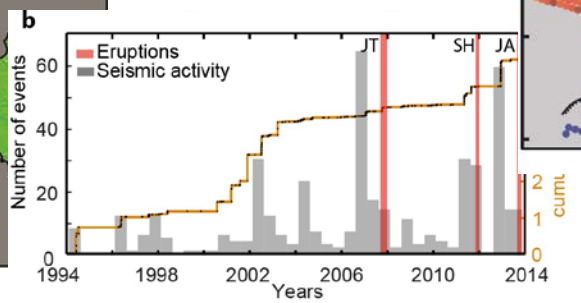
ke [km]

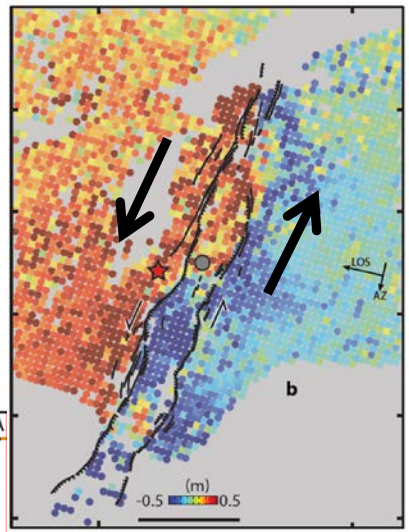
Ruch, Wang, Xu, Hensch & Jónsson, Nature Communications 2016

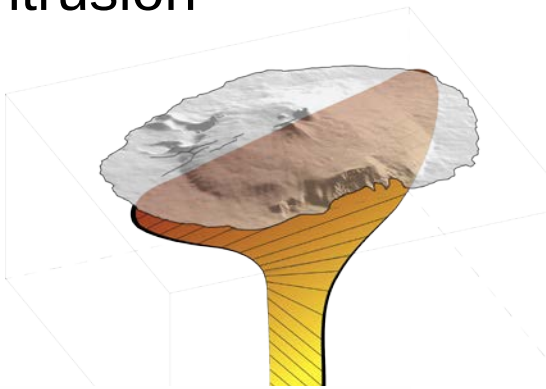
Conclusions

- At Tair Island, isolated edifice stress field, temporarily varying
- SAR obs. show **multiple rifting events** in southern Red Sea
- With seismicity/eruptions suggest a **rifting episode**
- In Iceland, we observe **graben shear**, confirmed in the field
- Graben faulting and fissure opening aseismic, intrusion influenced by **pre-existing fractures**
- **What next?**



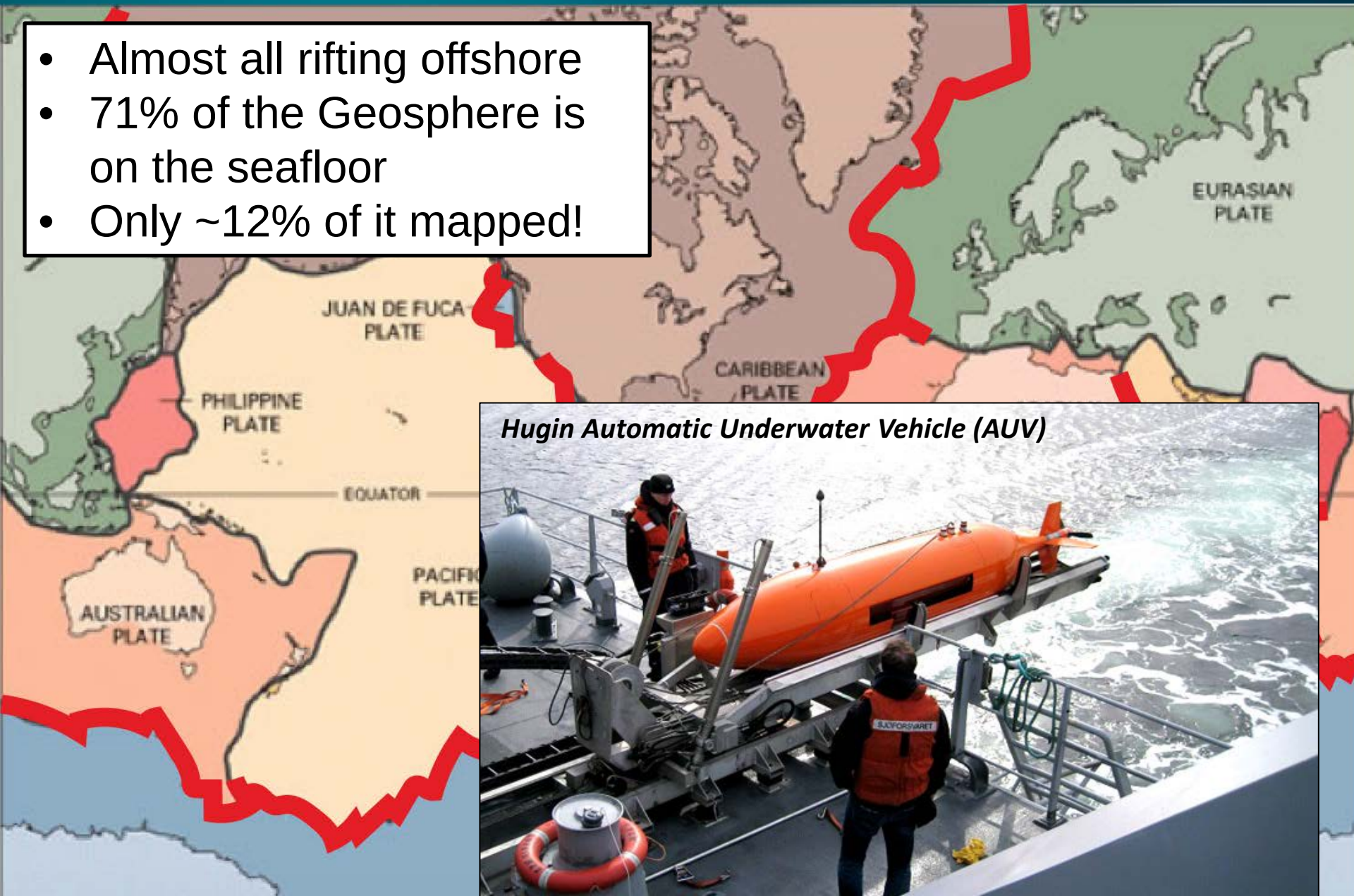






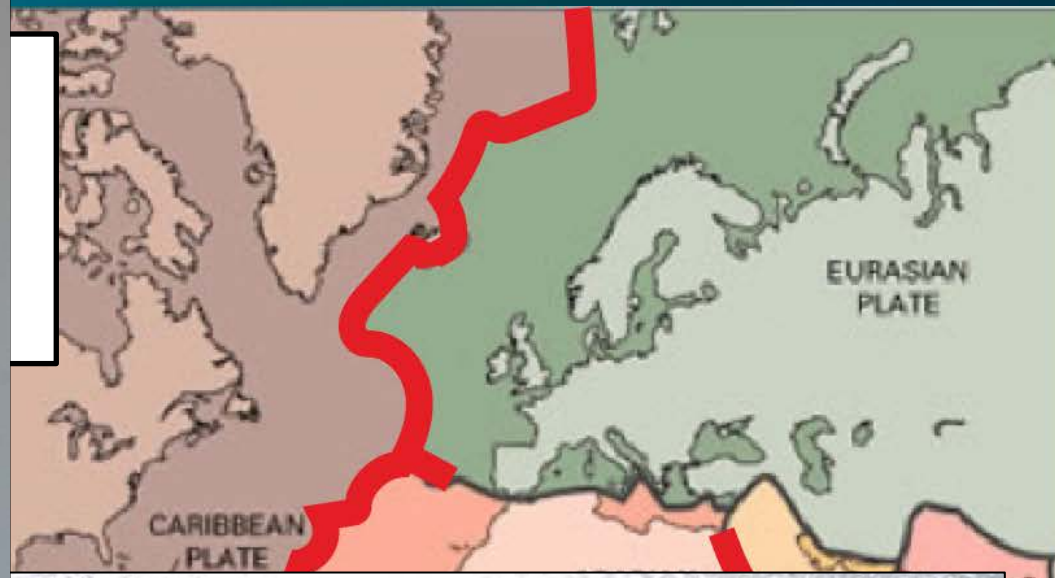
Problem: Rifting events are hard to capture

- Almost all rifting offshore
- 71% of the Geosphere is on the seafloor
- Only ~12% of it mapped!



Hugin Automatic Underwater Vehicle (AUV)

s are hard to capture



tomatic Underwater Vehicle (AUV)

Wenbin Xu

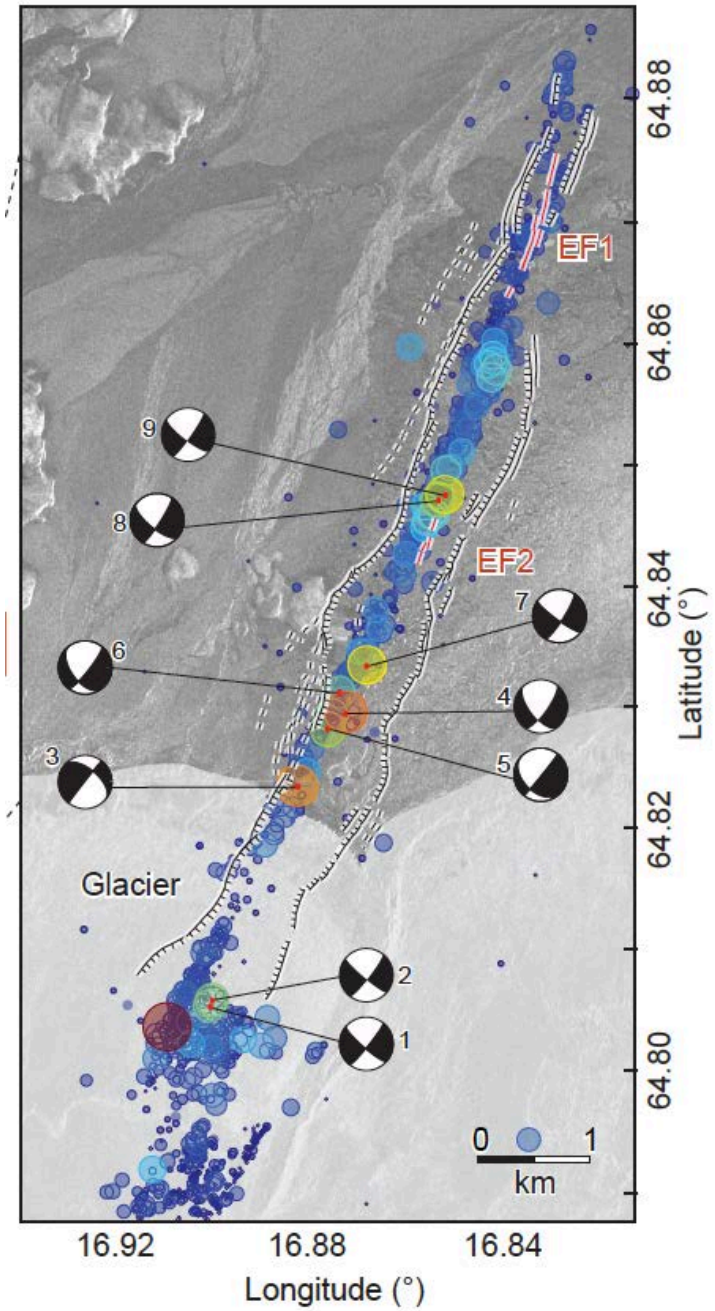
Joel Ruch

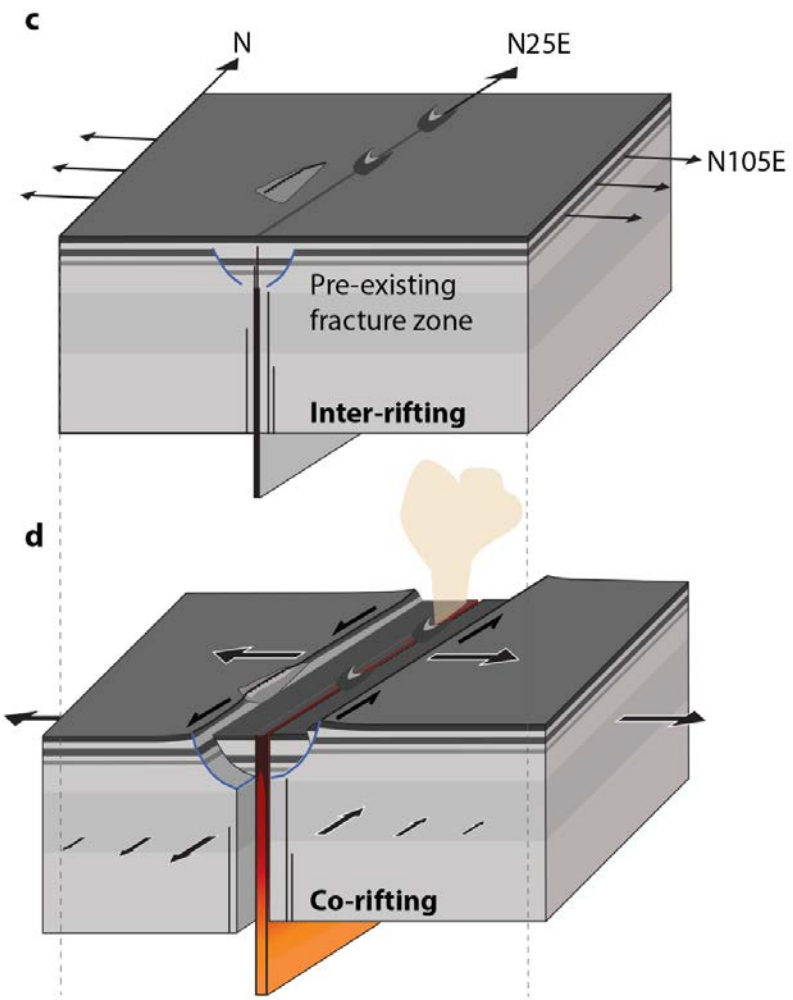
Thanks!

Xu, Ruch & Jónsson, Red Sea rifting episode, Nature Communications, 2015

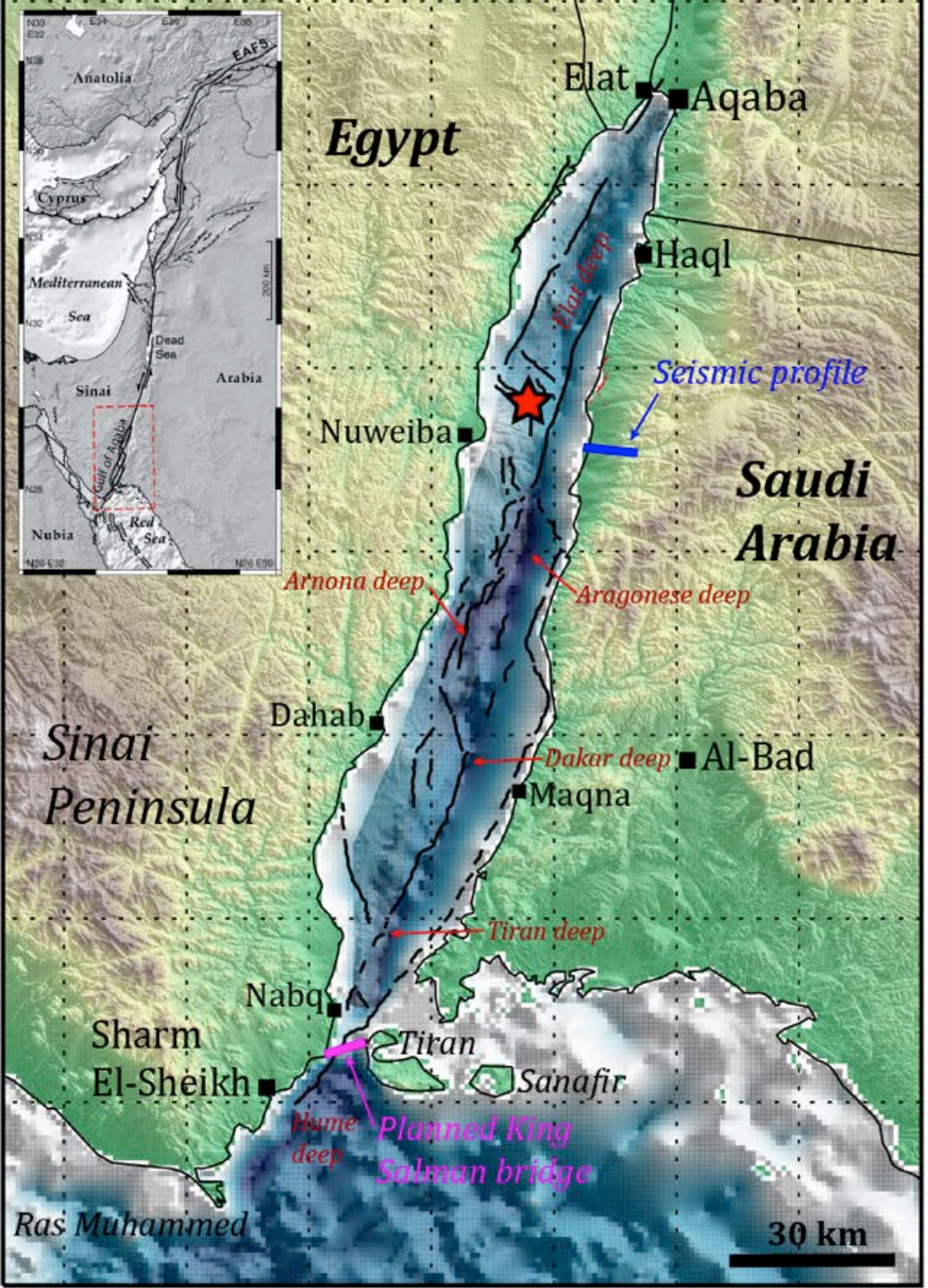
Ruch, Wang, Xu, Hensch & Jónsson, Oblique rifting in Iceland, Nature Communications, 2016

Earthquakes show left-lateral strike slip mechanisms





A New Project

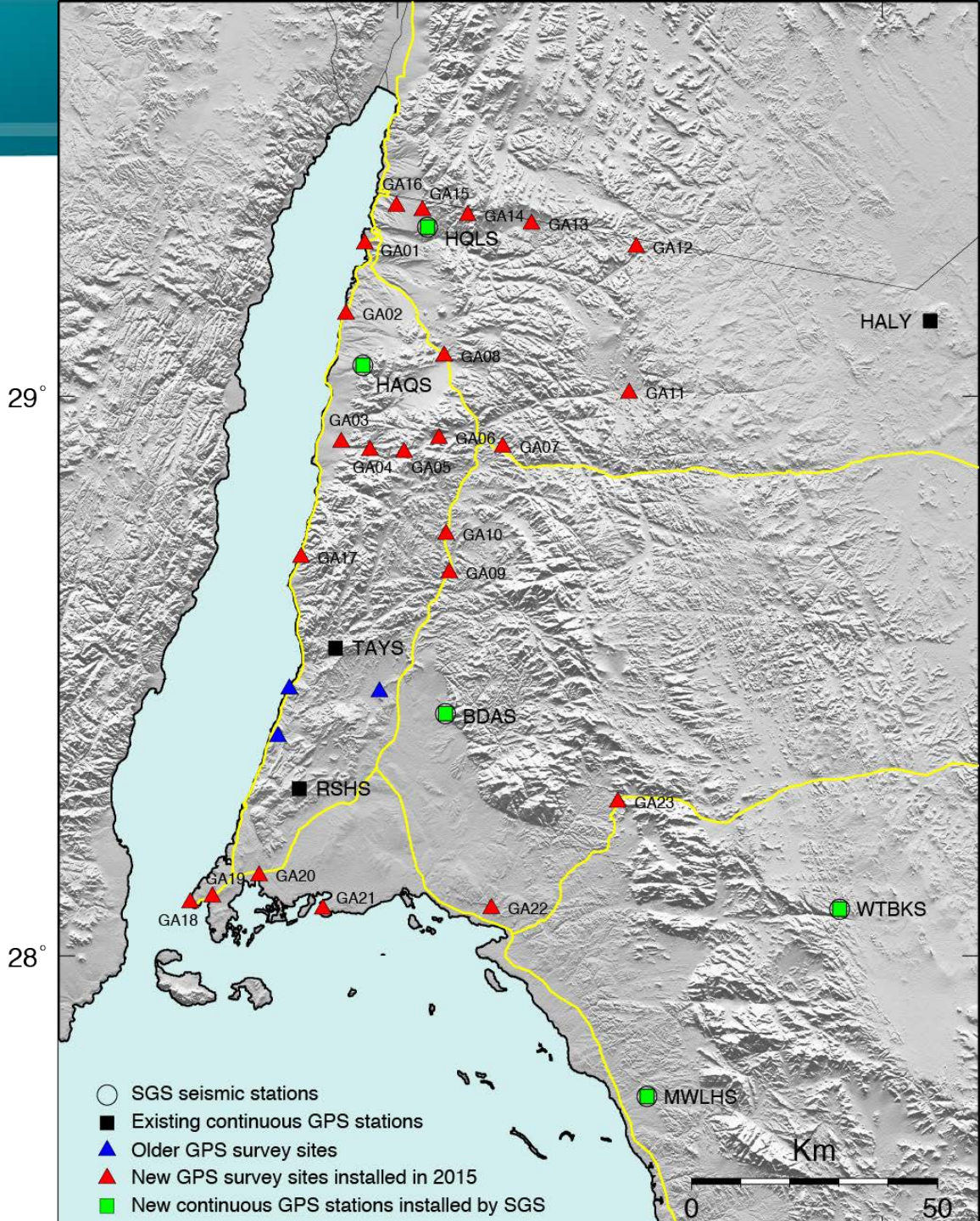


- On earthquake hazard reseach in Gulf of Aqaba and Strait of Tiran (GAST)
- Transtensional fault system
- Saudi Arabia plans to build a bridge to Egypt
- Cruise, fault mapping, sediment coring, uplifted corals, GPS/InSAR, etc.
- With Yann Klinger (Paris), Fred. Masson (Strasbourg), Ulas Avsar (METU-Ankara), Martin Mai (KAUST)

Uplifted corals

GPS measurements

- Network from 2015



A lot of difficut fieldwork ahead…