Ground deformation in active unexploited high-temperature geothermal area (Krísuvík)

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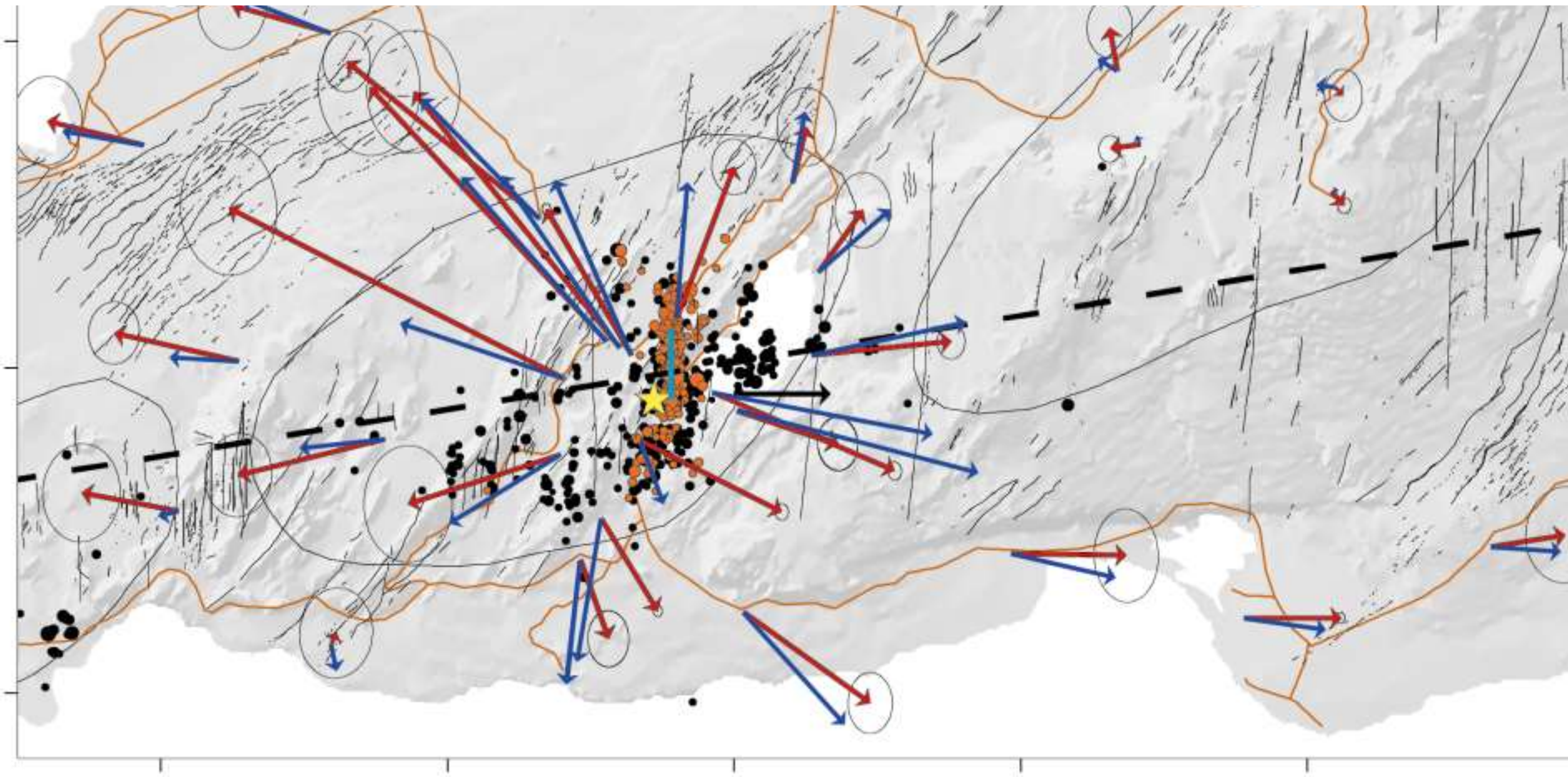
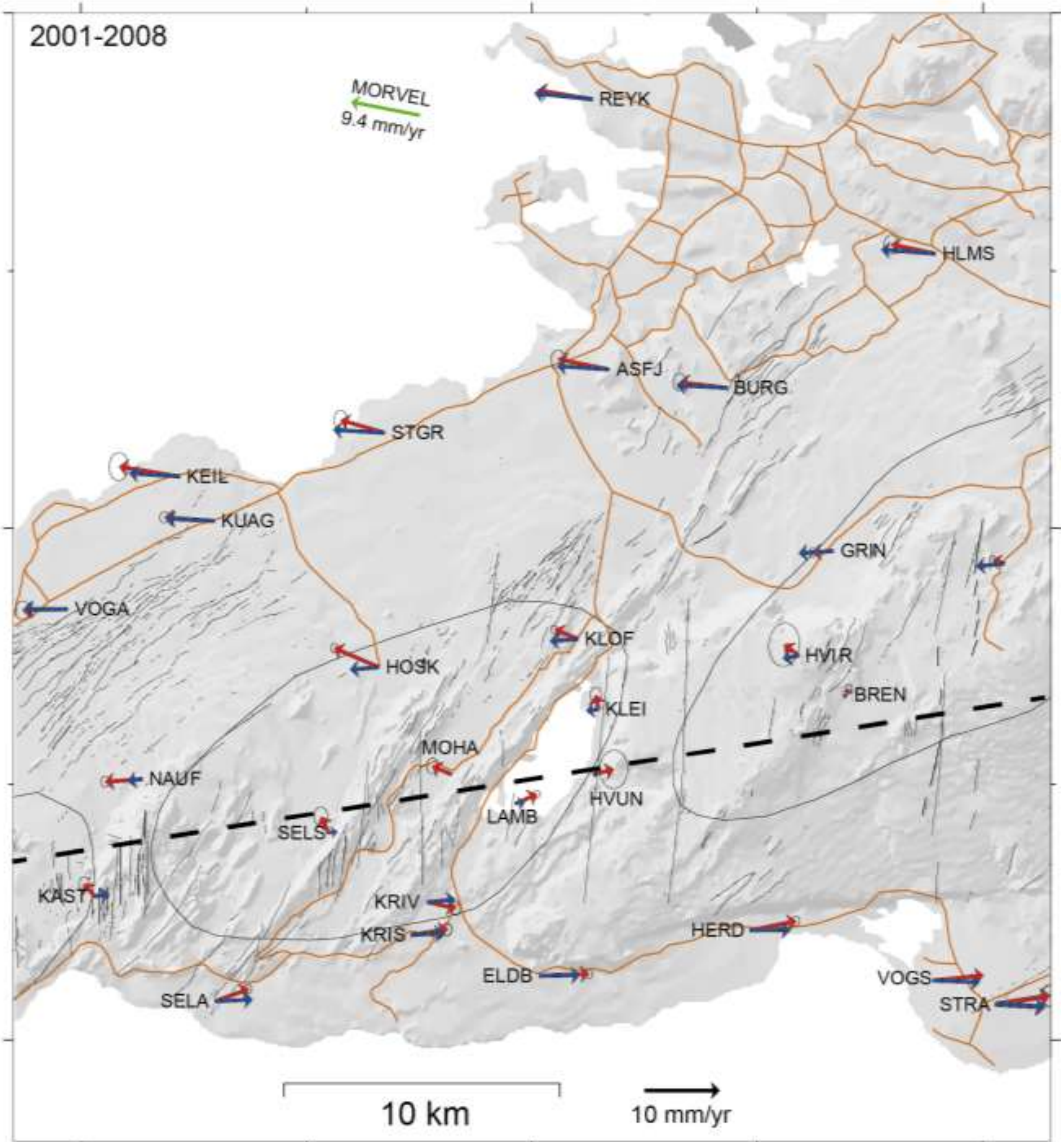
[1]GNS Science, New Zealand, [2]Nordic Volcanological Center, Institute of Earth Sciences, Univ. Iceland, [3]Icelandic Meteorological Office





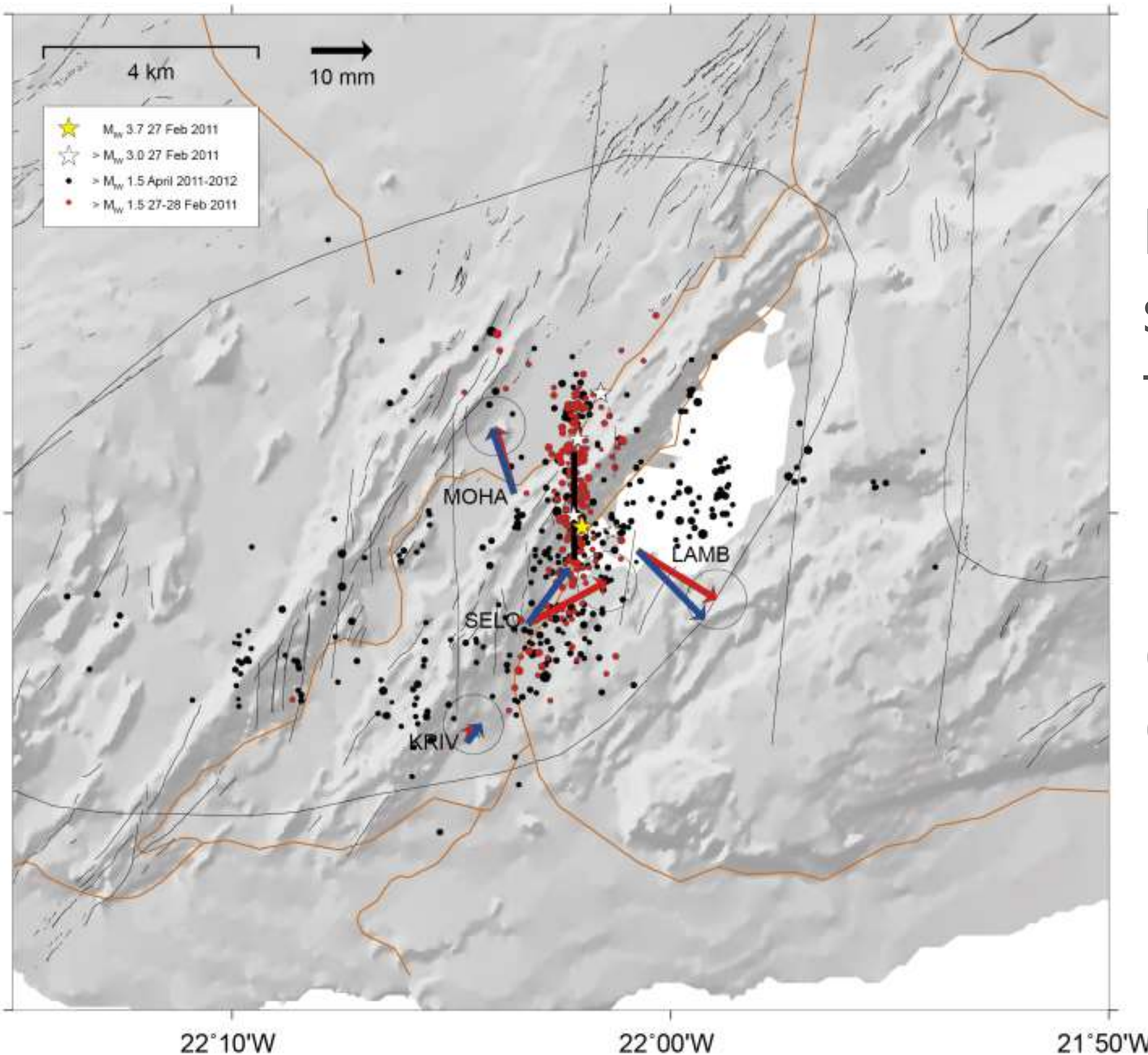
Reykjanes Peninsula oblique rifting plate boundary

Volcanic systems
Strike-slip faults

Red-GPS
Blue-model

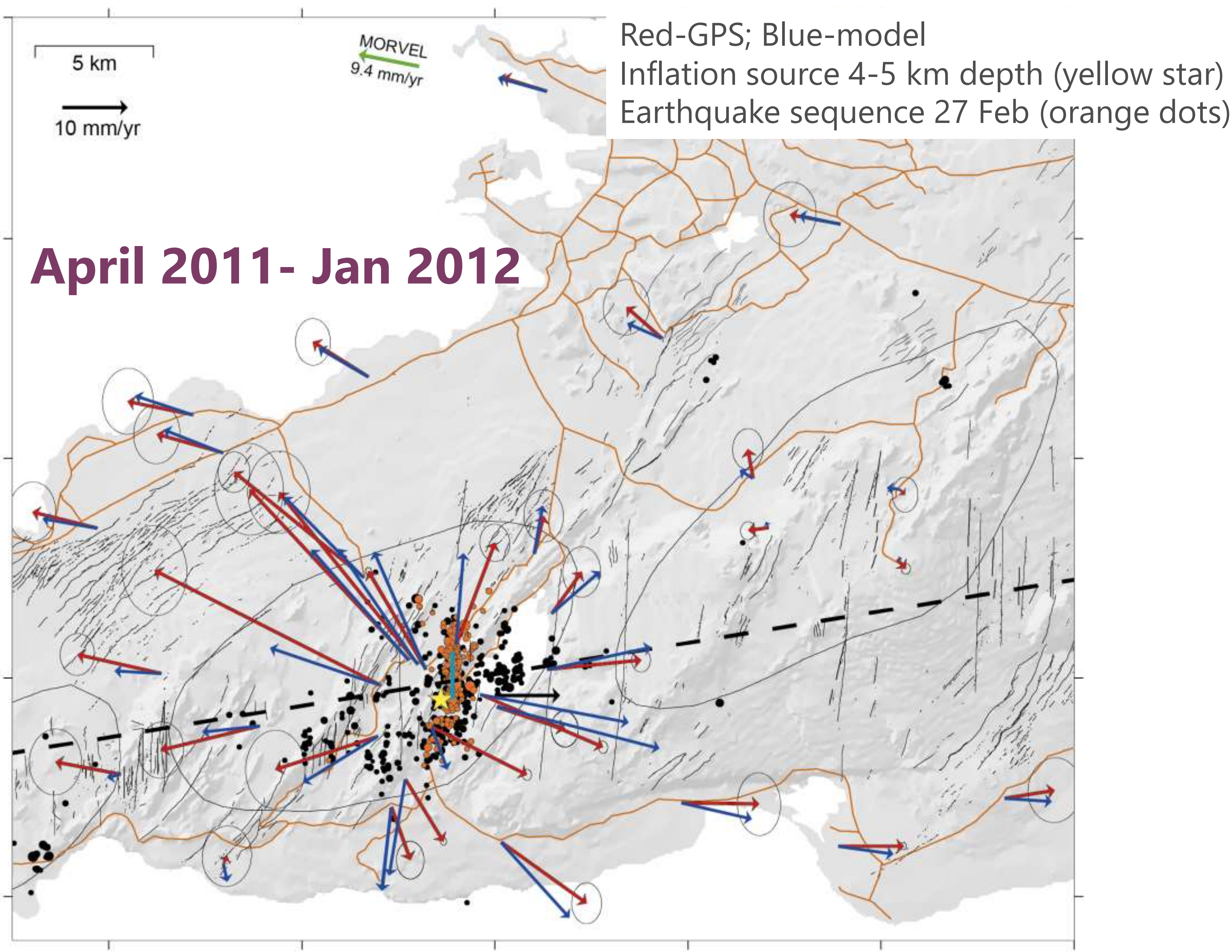
19 mm/yr transform motion
6.5 mm/yr extension
6 km locking depth

27 February 2011 M_{lW}3.7



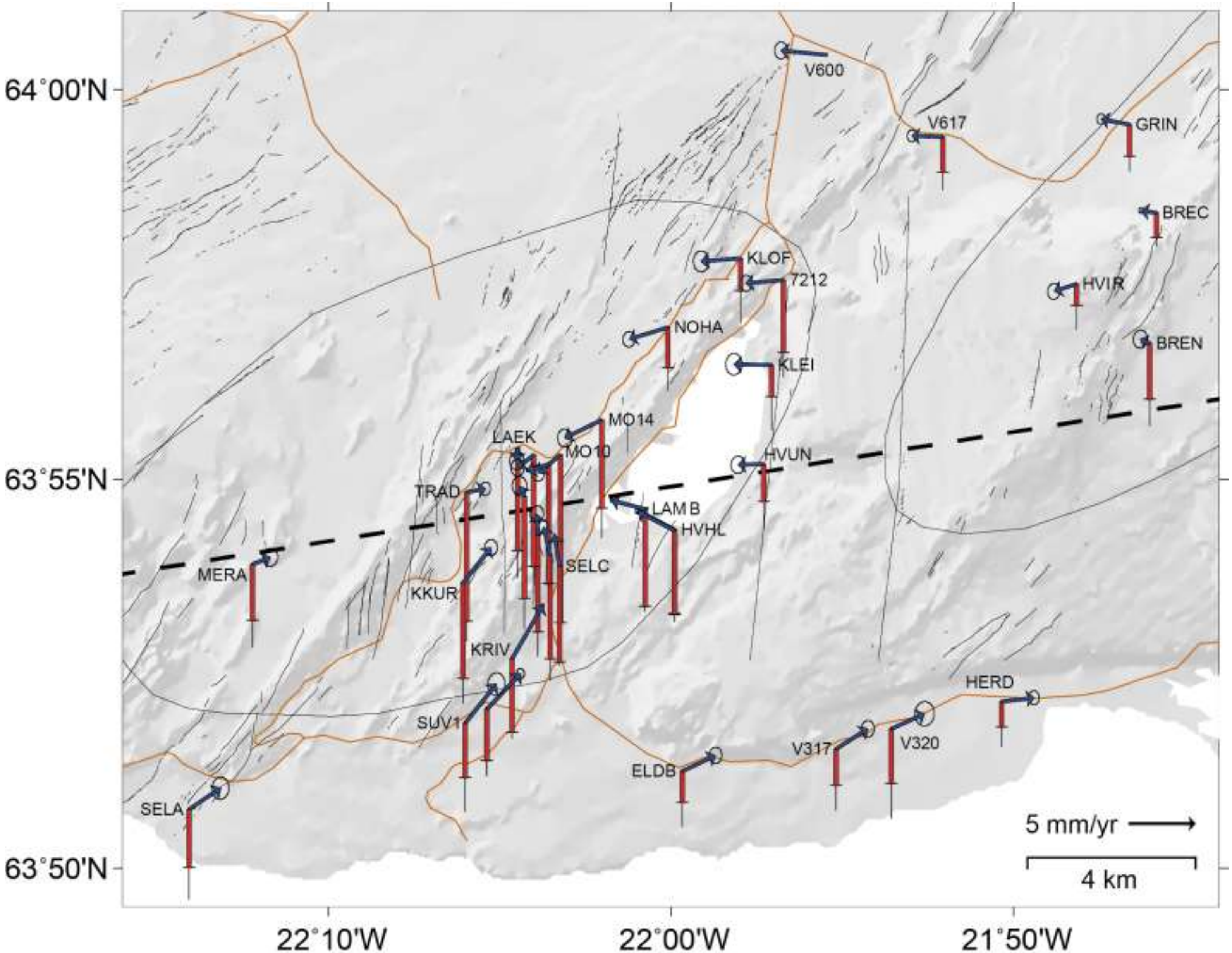
Right-lateral strike slip fault

M_W 4.7:
0.2 m slip
0.4-2 km deep
2 km long

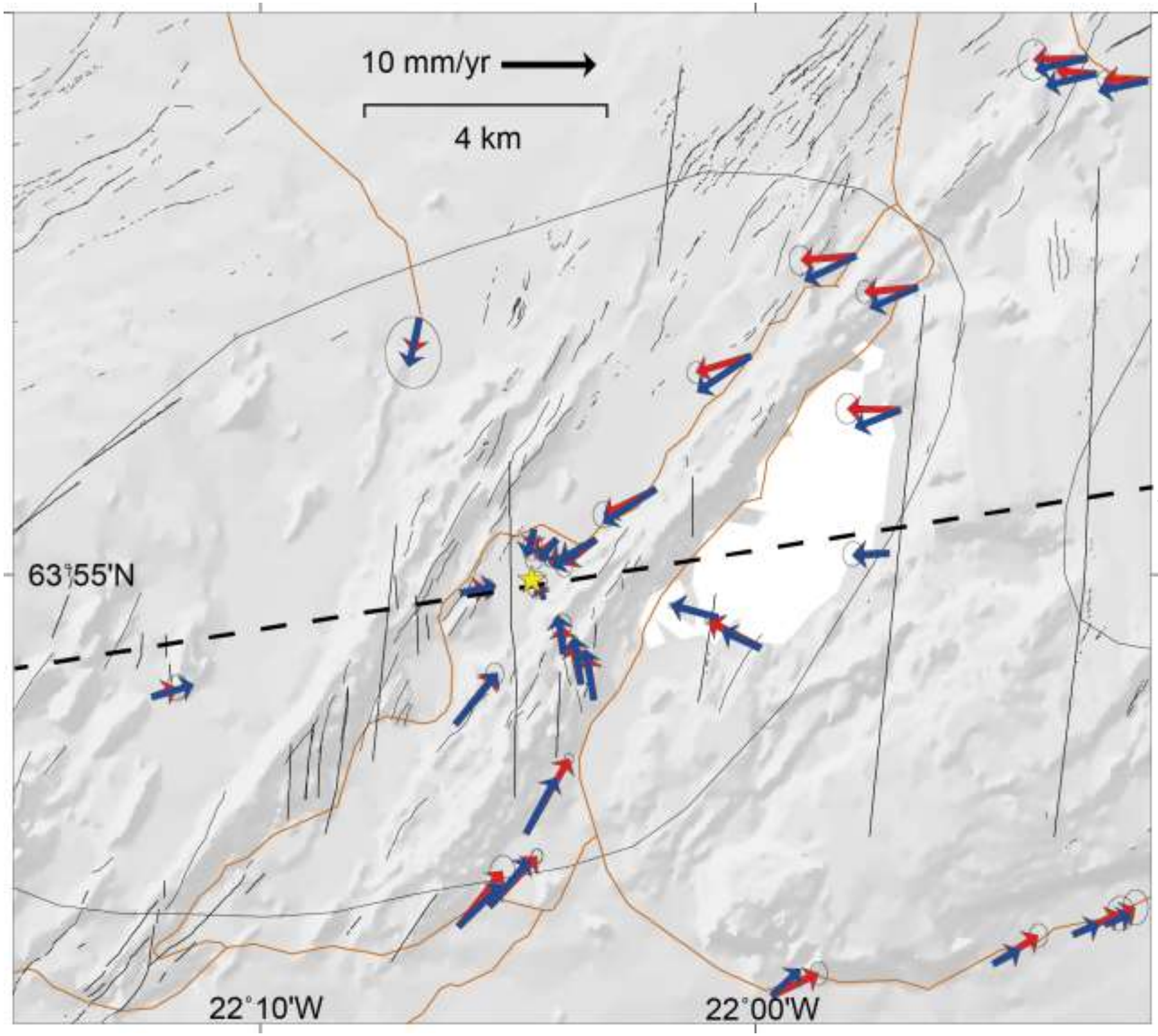


5 km
10 mm/yr
MORVEL
9.4 mm/yr
Red-GPS; Blue-model
Inflation source 4-5 km depth (yellow star)
Earthquake sequence 27 Feb (orange dots)
April 2011- Jan 2012

2012 – 2015: Horizontal and vertical

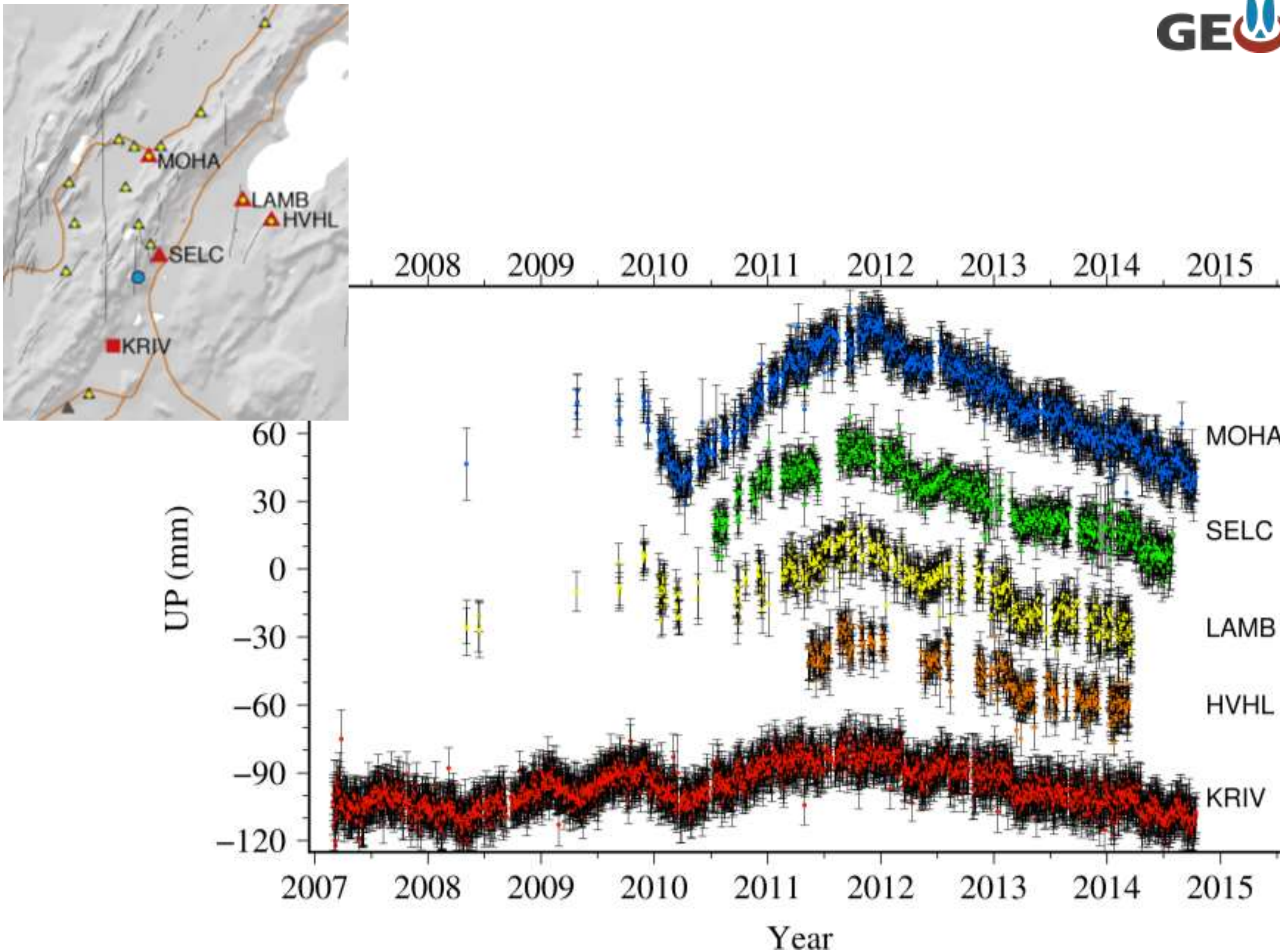


Deflation source 2012-2015

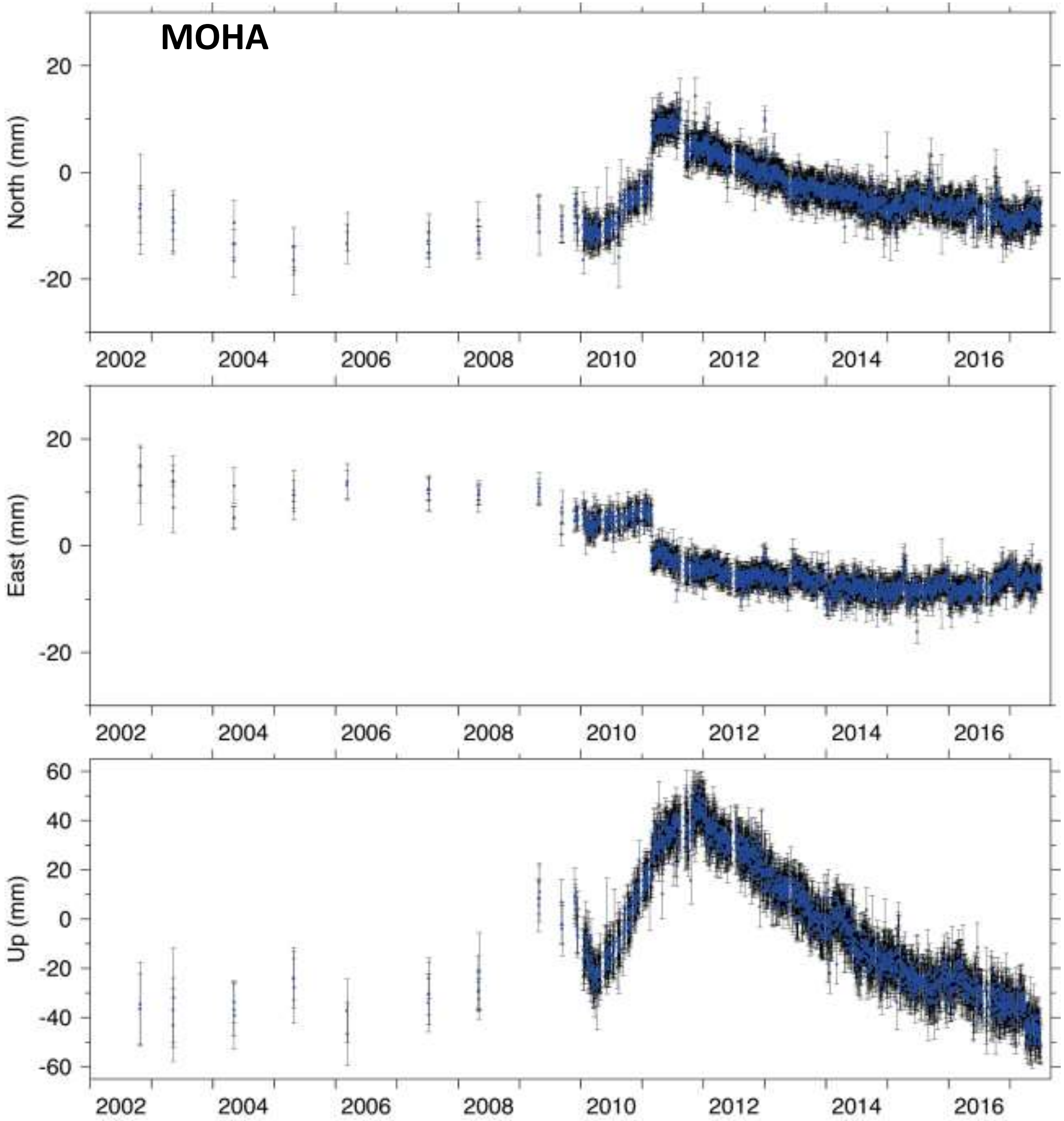


Depth = 3-4 km

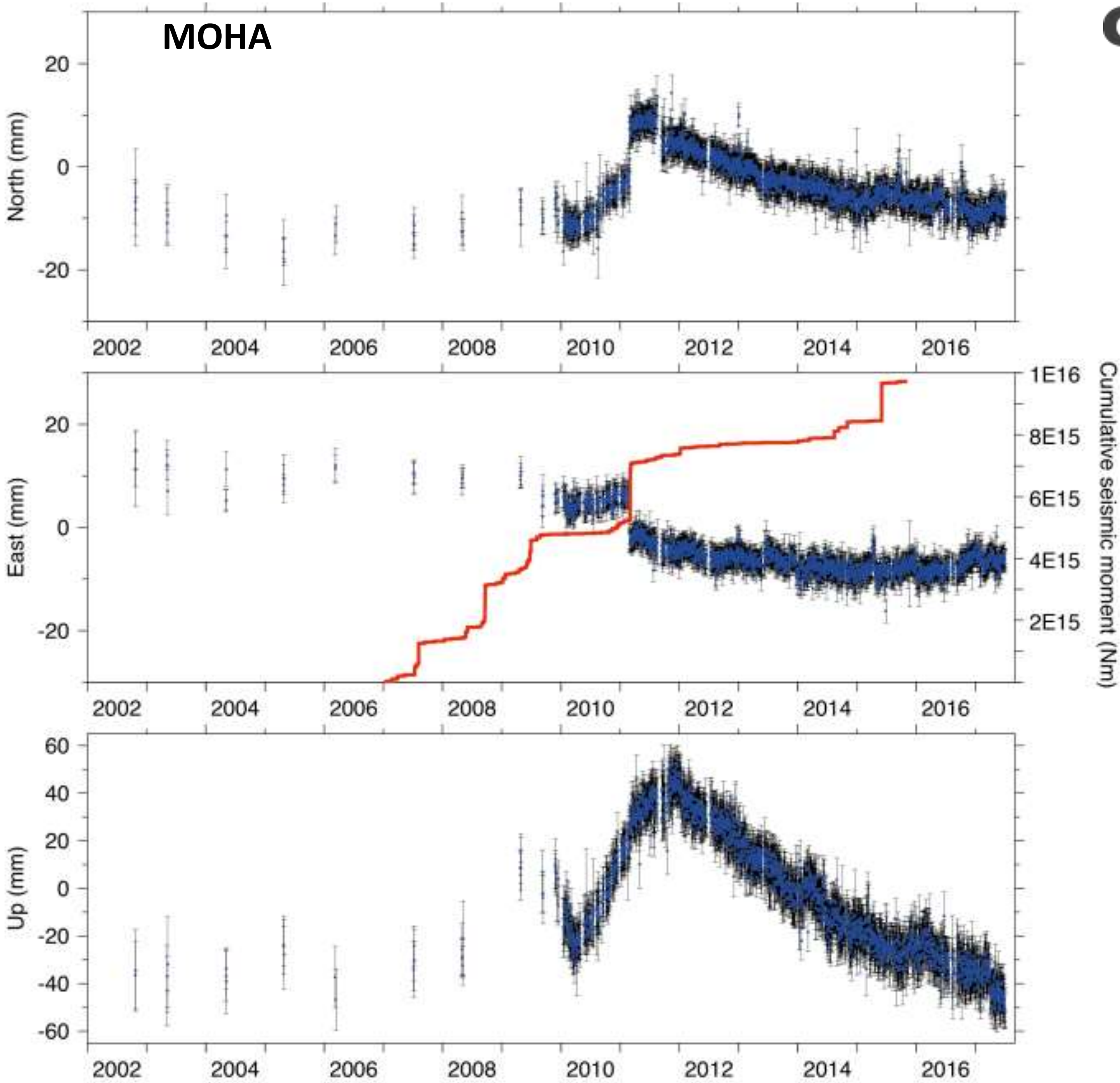
ΔV = -0.001 km^3/yr



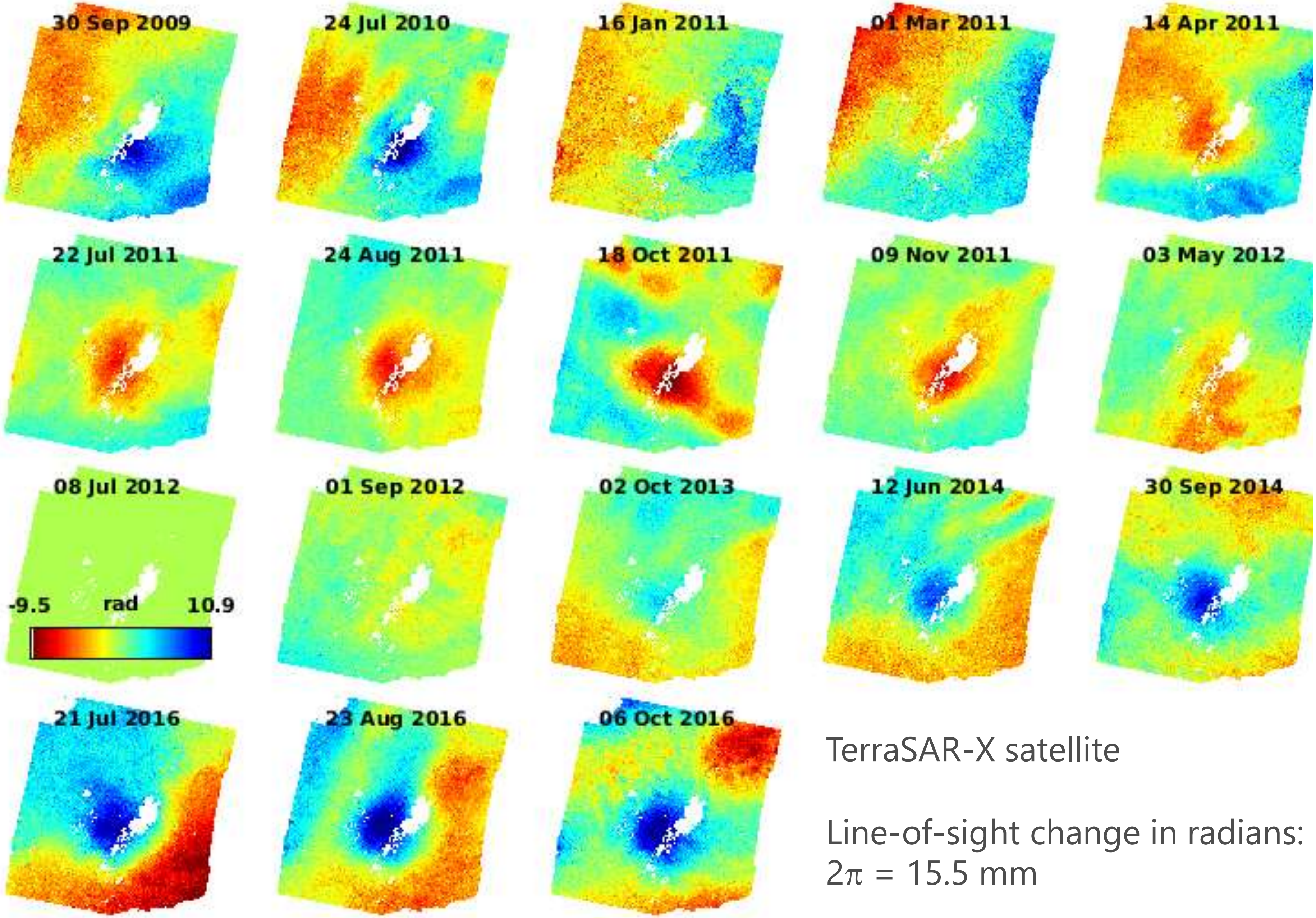
MOHA
LAMB
HVHL
SELC
KRIV
2008 2009 2010 2011 2012 2013 2014 2015
60
30
0
−30
−60
−90
−120
UP (mm)
MOHA
SELC
LAMB
HVHL
KRIV
2007 2008 2009 2010 2011 2012 2013 2014 2015
Year



MOHA
North (mm)
East (mm)
Up (mm)
20
0
-20
60
40
-40
-60
2002
2004
2006
2008
2010
2012
2014
2016


MOHA
North (mm)
20
0
-20
2002
2004
2006
2008
2010
2012
2014
2016
East (mm)
-20
Cumulative seismic moment (Nm)
1E16
8E15
6E15
4E15
2E15
Up (mm)
60
40
-40
-60

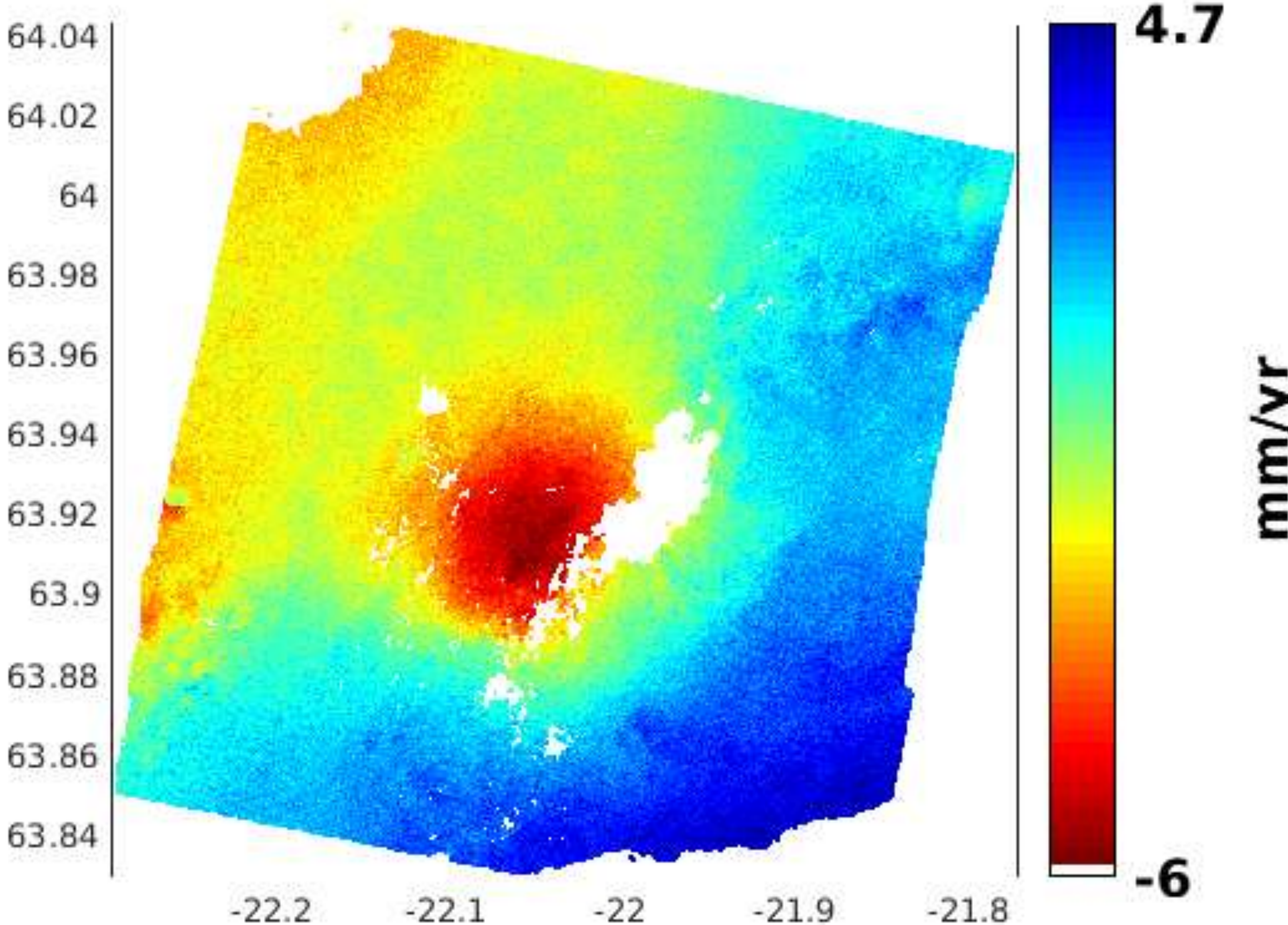
InSAR: Interferometric analysis of synthetic aperture radar images (time series)

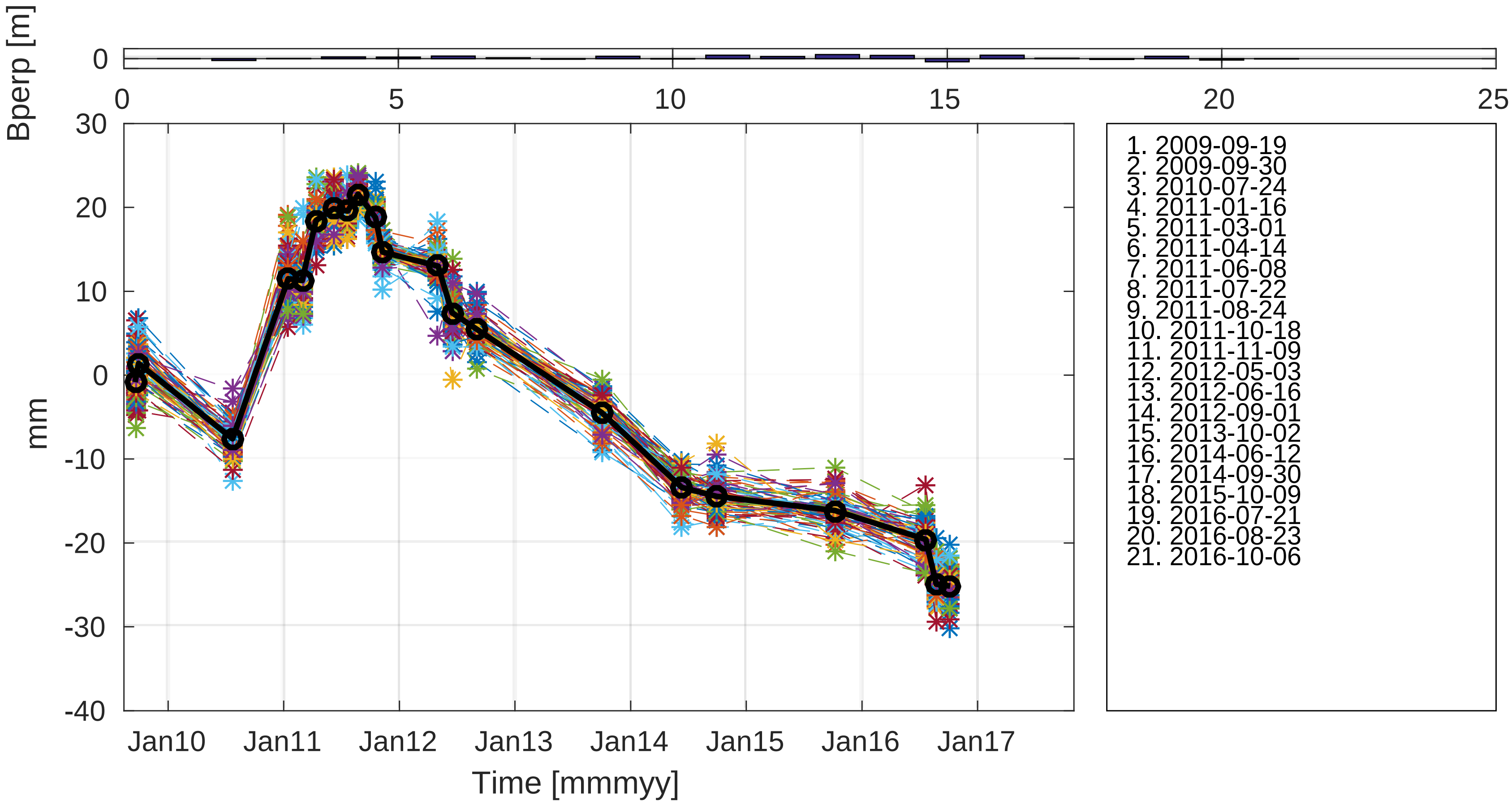


TerraSAR-X satellite

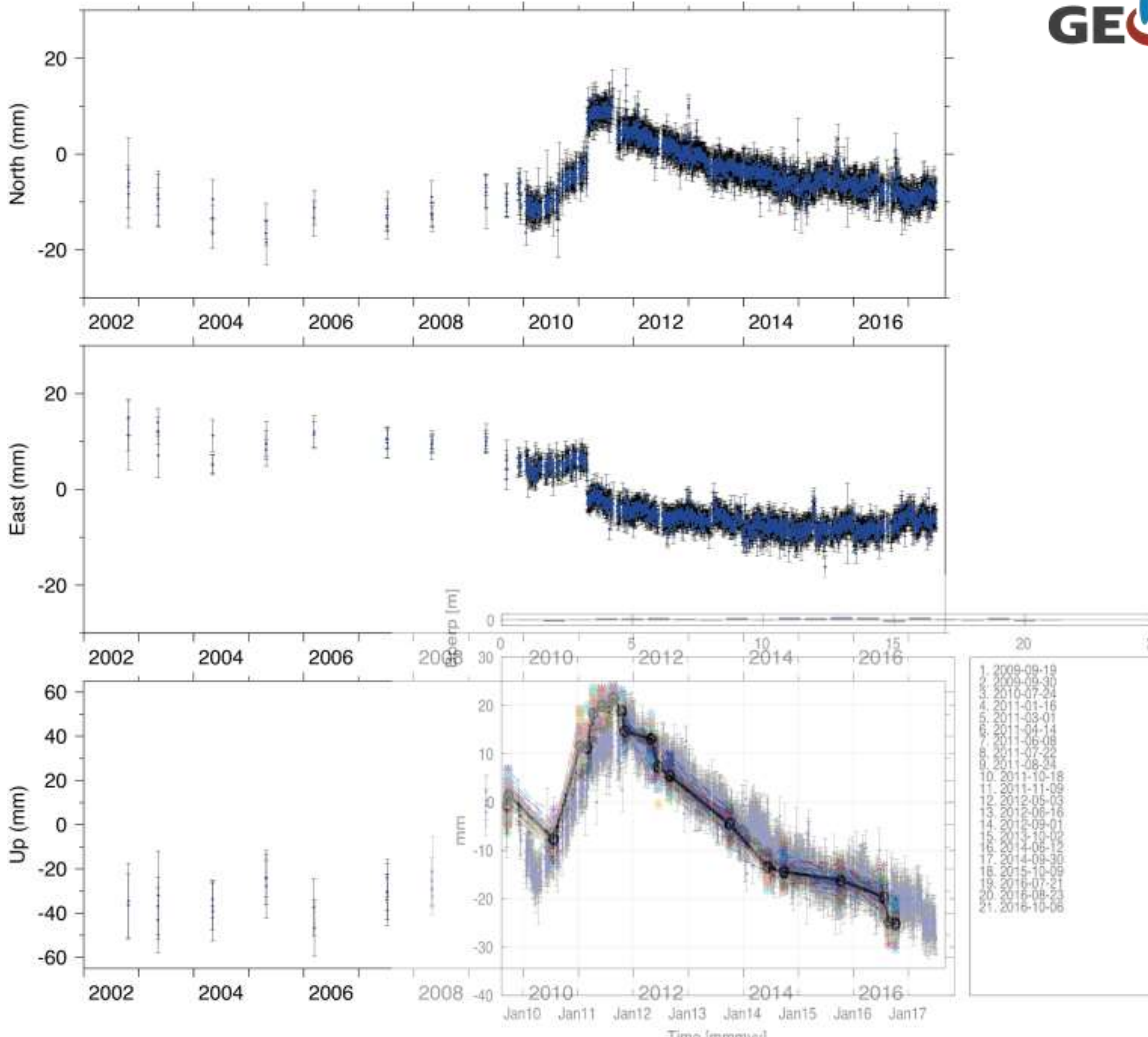
Line-of-sight change in radians:
2π = 15.5 mm

Line-of-sight: Average velocity field

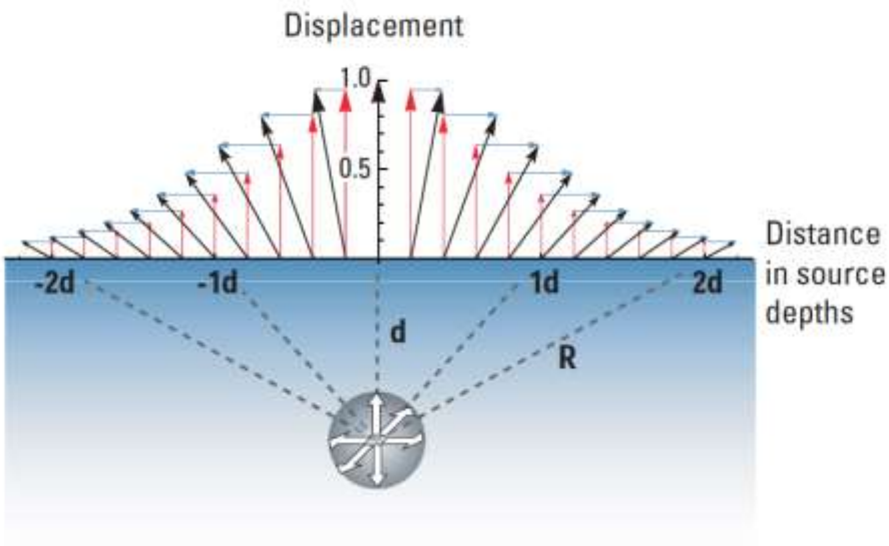




Bperp [m]
0
0
5
10
15
20
25
30
20
10
0
-10
-20
-30
-40
mm
Jan10
Jan11
Jan12
Jan13
Jan14
Jan15
Jan16
Jan17
Time [mmmyy]
1. 2009-09-19
2. 2009-09-30
3. 2010-07-24
4. 2011-01-16
5. 2011-03-01
6. 2011-04-14
7. 2011-06-08
8. 2011-07-22
9. 2011-08-24
10. 2011-10-18
11. 2011-11-09
12. 2012-05-03
13. 2012-06-16
14. 2012-09-01
15. 2013-10-02
16. 2014-06-12
17. 2014-09-30
18. 2015-10-09
19. 2016-07-21
20. 2016-08-23
21. 2016-10-06


North (mm)
East (mm)
Up (mm)
2002
2004
2006
2008
2010
2012
2014
2016
Bperp [m]
mm
Time [mmmyy]
Jan10
Jan11
Jan12
Jan13
Jan14
Jan15
Jan16
Jan17
1. 2009-09-19
2. 2009-09-30
3. 2010-07-24
4. 2011-01-16
5. 2011-03-01
6. 2011-04-14
7. 2011-06-08
8. 2011-07-22
9. 2011-08-24
10. 2011-10-18
11. 2011-11-09
12. 2012-05-03
13. 2012-06-16
14. 2012-09-01
15. 2013-10-02
16. 2014-06-12
17. 2014-09-30
18. 2015-10-09
19. 2016-07-21
20. 2016-08-23
21. 2016-10-06

Spherical pressure source model (Mogi): Interpretation

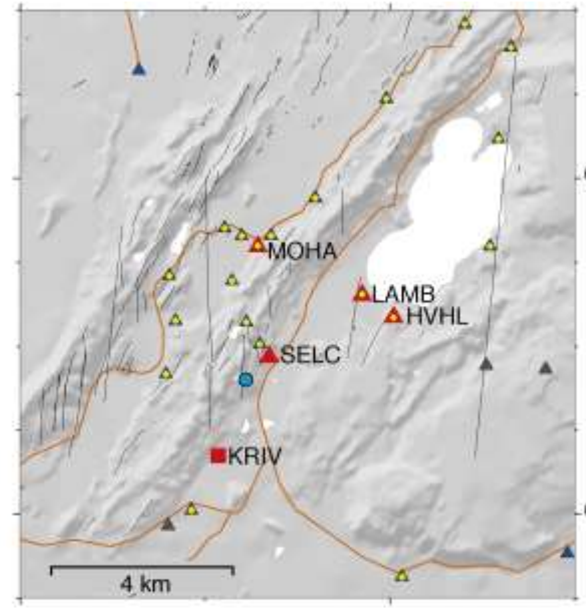


$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \alpha^3 \, \Delta P \frac{(1-\nu)}{G} \begin{pmatrix} \frac{x}{R^3} \\ \frac{y}{R^3} \\ \frac{d}{R^3} \end{pmatrix}$$

Magma Flow: Inflow can easily explain uplift (about 10-20 million m^3 of magma). Gradual deflation of same amount can not be explained by solidification of magma. Requires material “to leave”, e.g. to form the lower crust or by viscoelastic relaxation surrounding the intrusion.

Perturbation in flow of hydrothermal fluids: Pressure build up in a localized area at the roots of the geothermal system. Requires hydrothemral fluids at 3-5 km depth. More flow in than out to build up pressure. Requires temporary changes in permeability, inflow of new fluids, or addition of gas increasing pressure.

Combination magma flow / perturbation in deep roots of the geothermal system

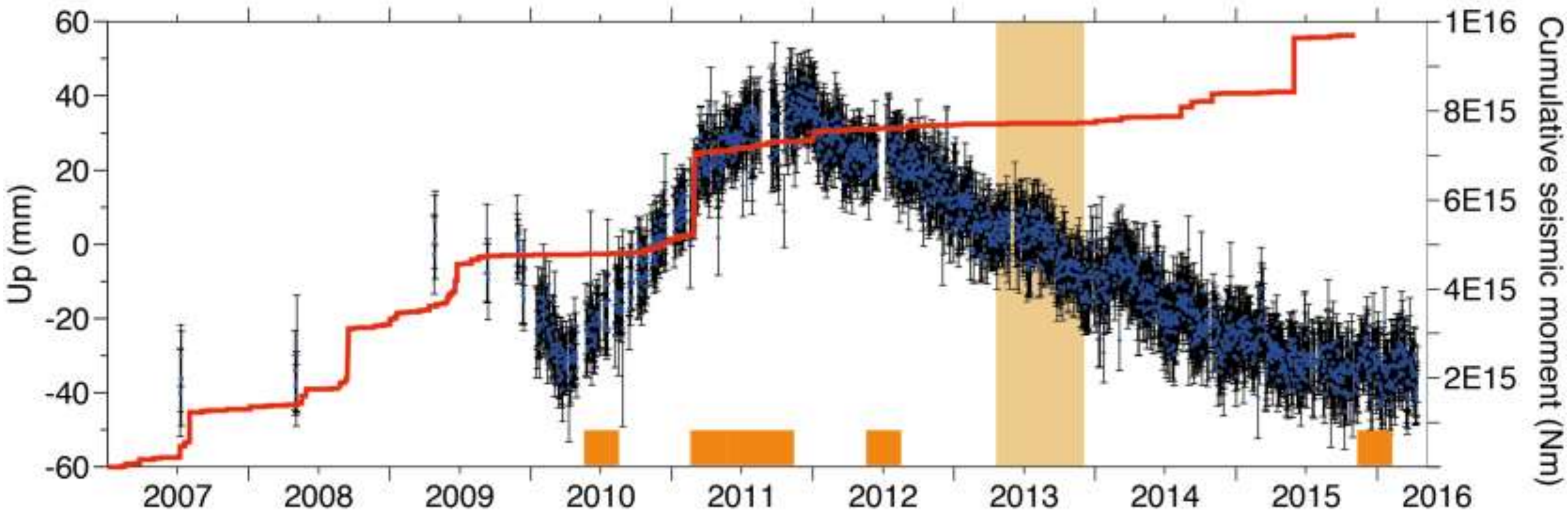


MultiGAS meter

MultiGAS station in Hveradalir, Krýsuvík.

Located next to a fumarole in an area of continuous geothermal activity

The sampling inlet of the MultiGAS station is located ~20 cm above the ground to avoid saturation of the CO_2 sensor.

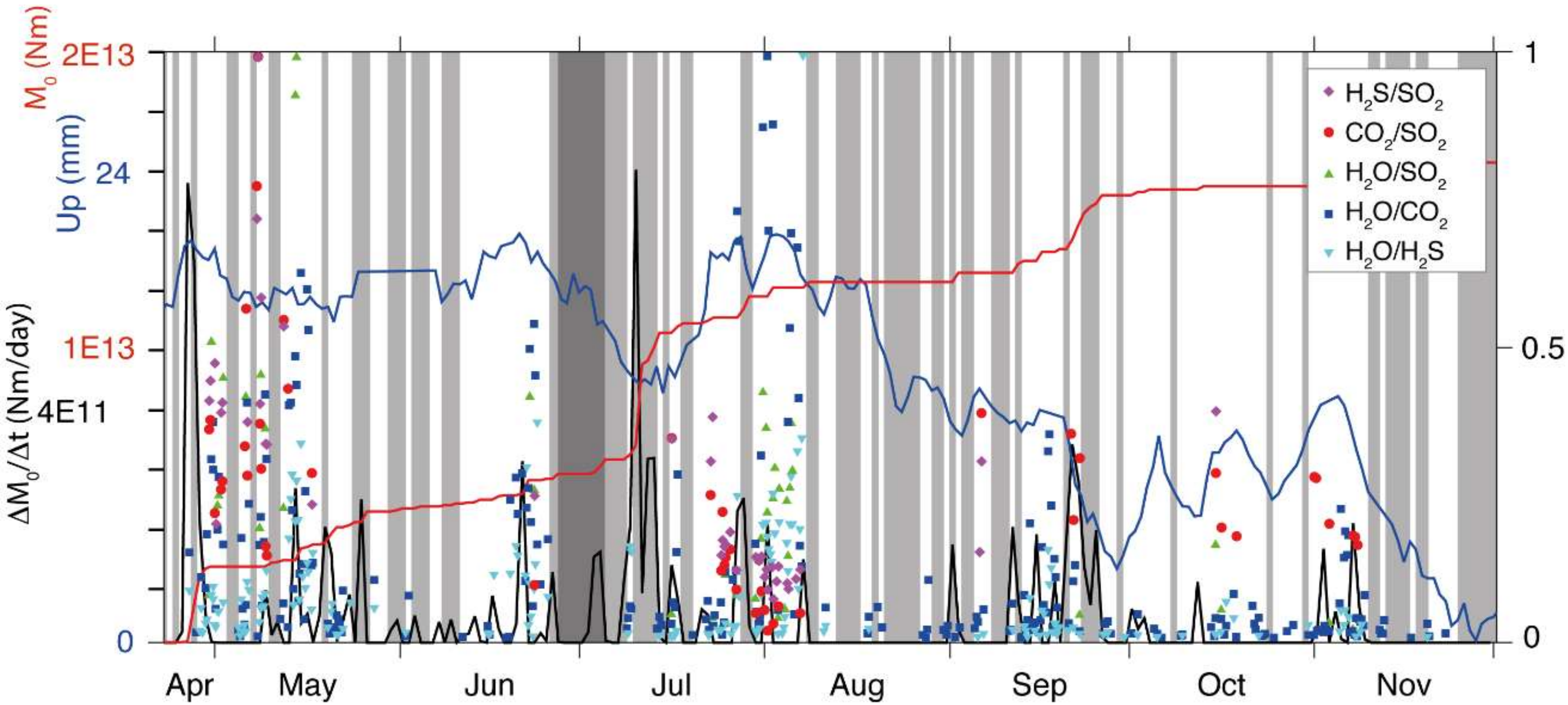


MOHA inflation/deflation periods from GPS time series (2007-2016)

Daily cumulative seismic moment.

Shaded band corresponds to the time period of the gas study (Multi-GAS)

Boxes show time periods of gravity surveys (difficult to interpret because of changes in ground water level



Normalized variations in gas correlated with geophysical observations

Distinct intervals with peaks of increased H_2O/CO_2 and H_2O/H_2S ratios.

SO_2 is detected during the same intervals allowing calculation of X/SO_2 ratios.

Red line: cumulative seismic moment (Nm).

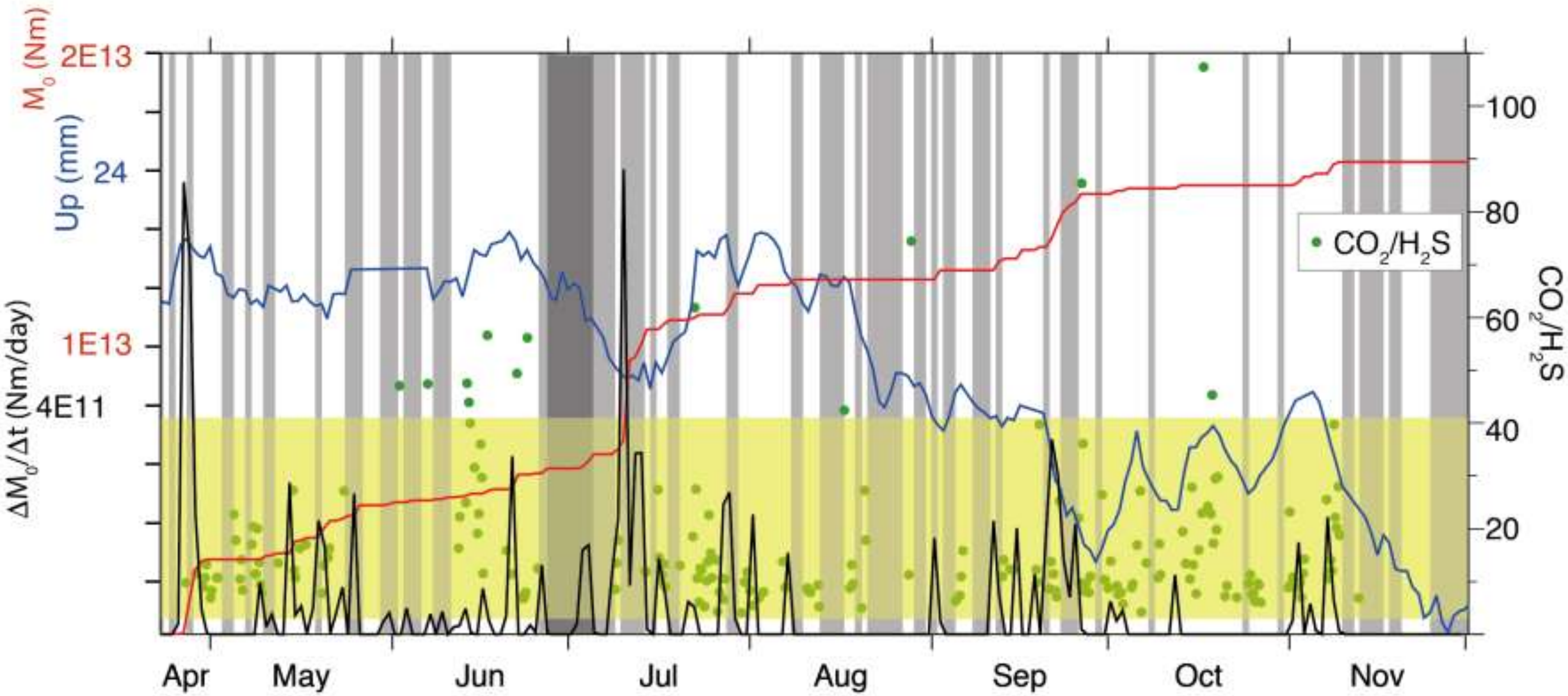
Black line: seismic moment per day (Nm/day).

Blue curve: Vertical crustal movements measured with GPS (mm).

Light grey intervals: rainy days (>2 mm/day).

Dark grey interval: station not operating.

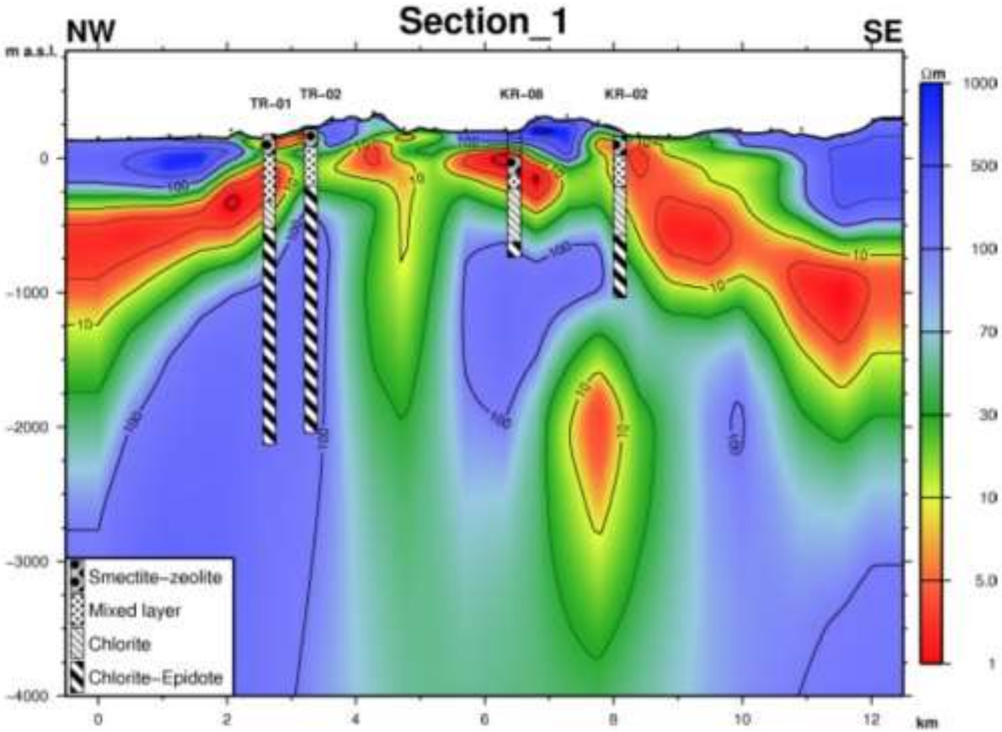
Peaks of increased H_2O/CO_2 and H_2O/H_2S ratios appear to follow episodes of recorded seismic events and crustal deformation.



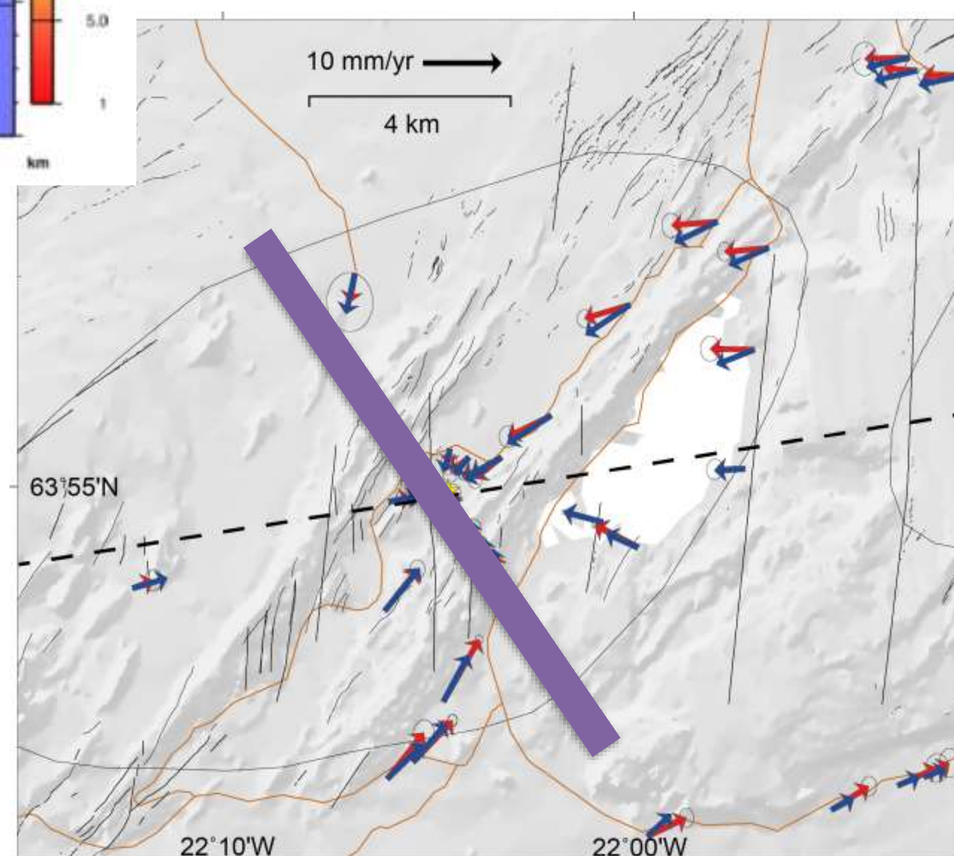
2013 Time series of CO_2/H_2S MultiGAS molar ratios compared with crustal movements

The CO_2/H_2S ratio does not show any visible variations related to seismicity or crustal deformation.

The yellow band corresponds to CO_2/H_2S ratios (3-41) from fumaroles in the Krýsuvík area (this study, Arnórsson, 1987, data from the Iceland GeoSurvey database).

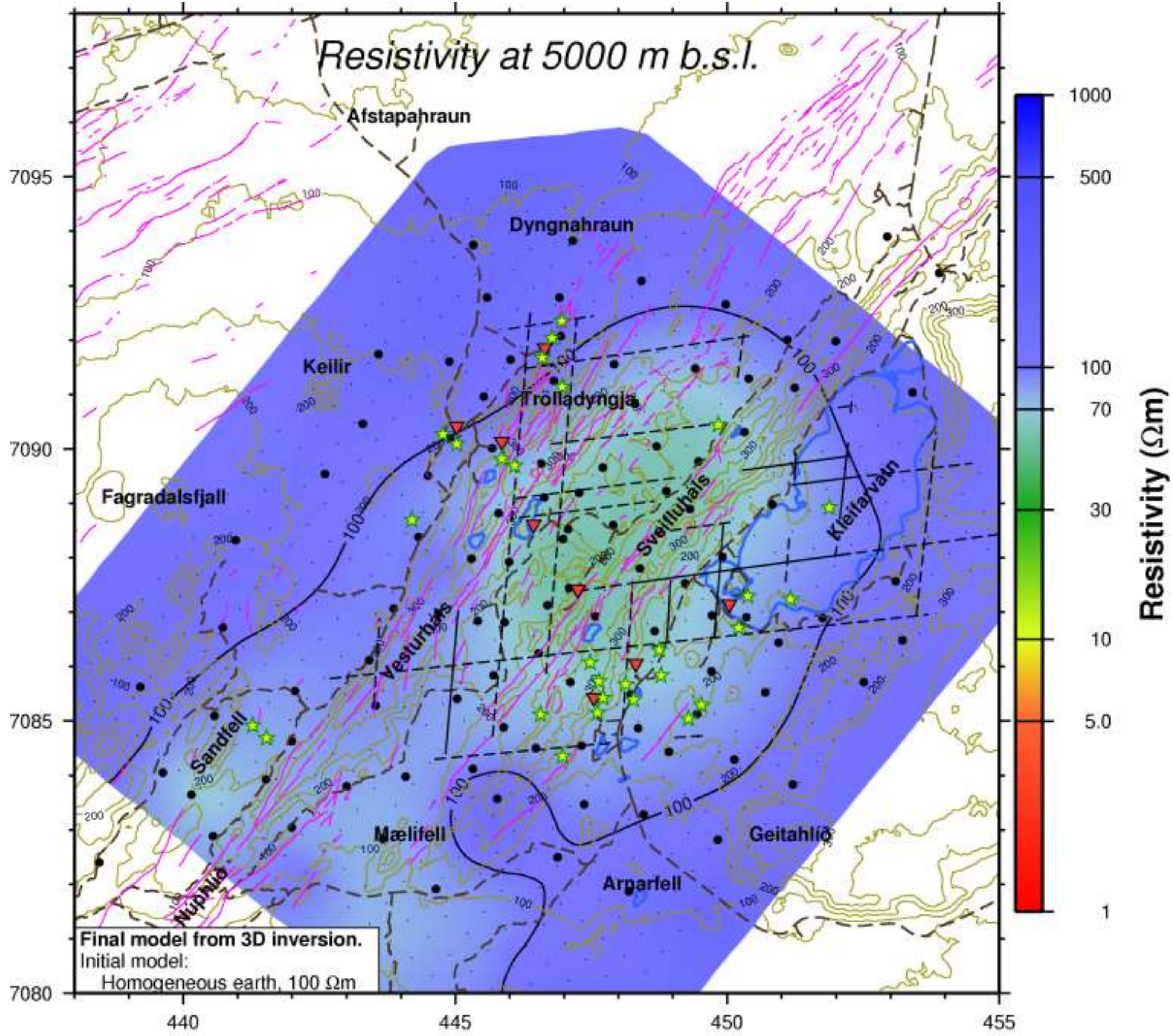


Deflation source 2012-2015

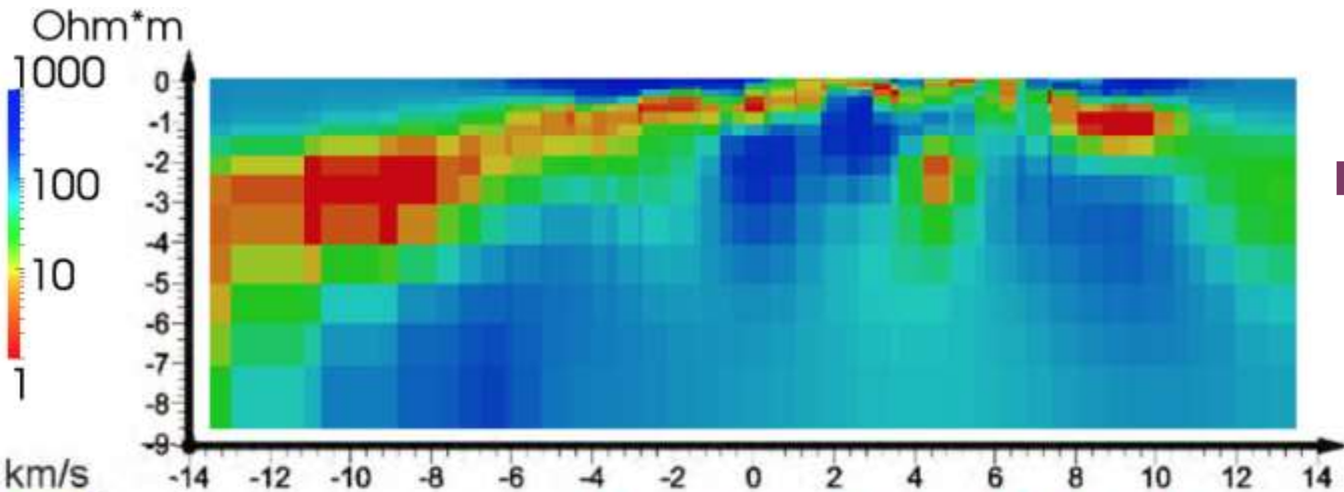


Hersir et al., 2015

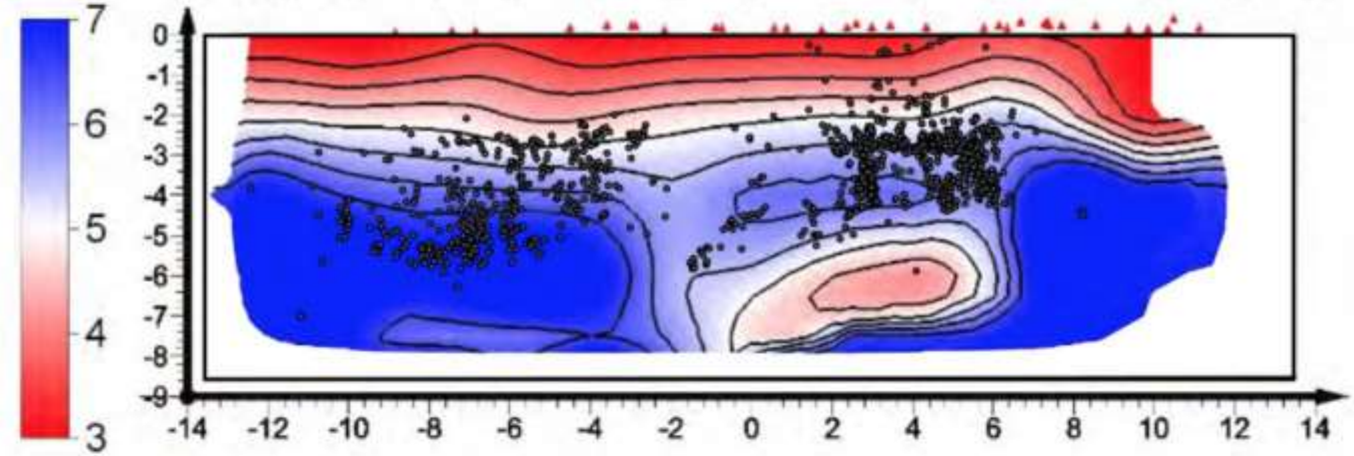
3D Inversion of Magnetotelluric (MT) Resistivity Data from Krýsuvík


Resistivity at 5000 m b.s.l.
Afstapahraun
Dyngnahraun
Keilir
Trölladyngja
Fagradalsfjall
Sveifluháls
Kleifarvatn
Vesturháls
Sandfell
Mælifell
Geitahlíð
Arnarfell
Núphlíð
Final model from 3D inversion.
Initial model:
Homogeneous earth, 100 Ωm
7095
7090
7085
7080
440
445
450
455
Resistivity (Ωm)
1000
500
100
70
30
10
5.0
1

Resistivity and P-wave velocity structure beneath Krísuvík



Hersir et al., 2013



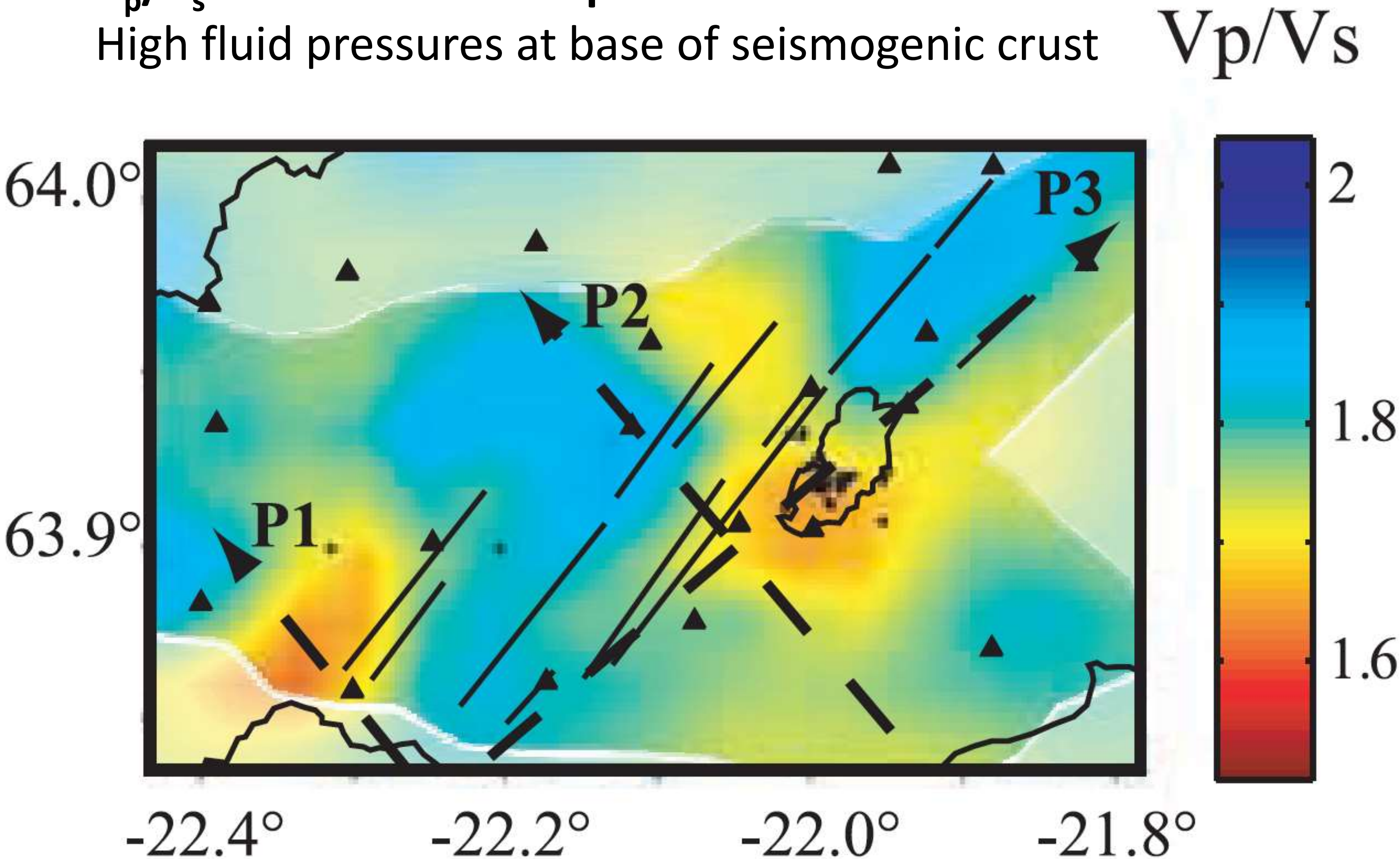
A. Franco, 2013

Kristjánsdóttir, 2013

Microseismicity in the Krýsuvík Geothermal Field, SW Iceland, from May to October 2009

V_p/V_s model at 6 km depth

High fluid pressures at base of seismogenic crust

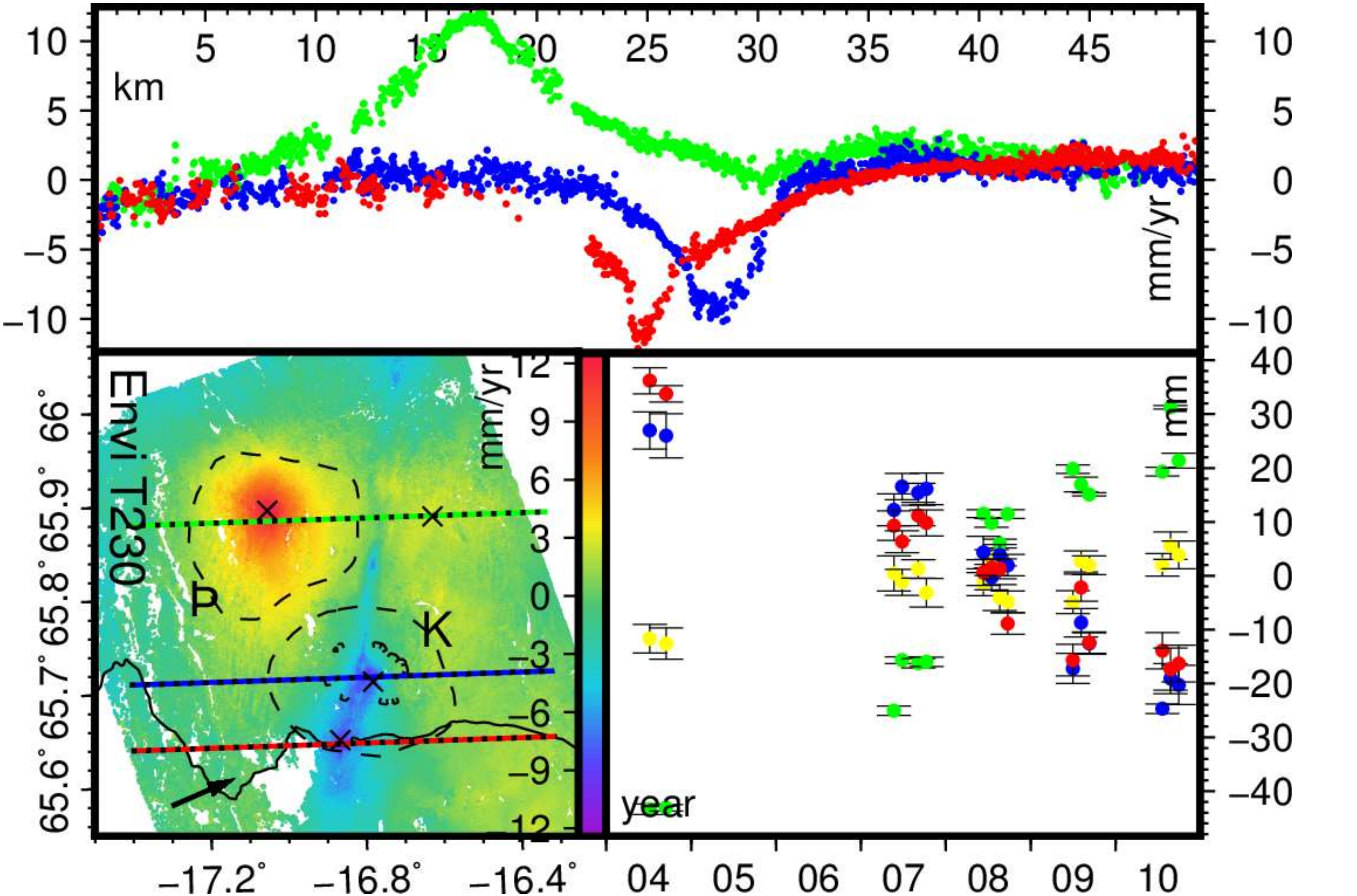


Deep downward fluid percolation driven by localized crust dilatation in Iceland

Laurent Geoffroy[1] and Catherine Dorbath[2]

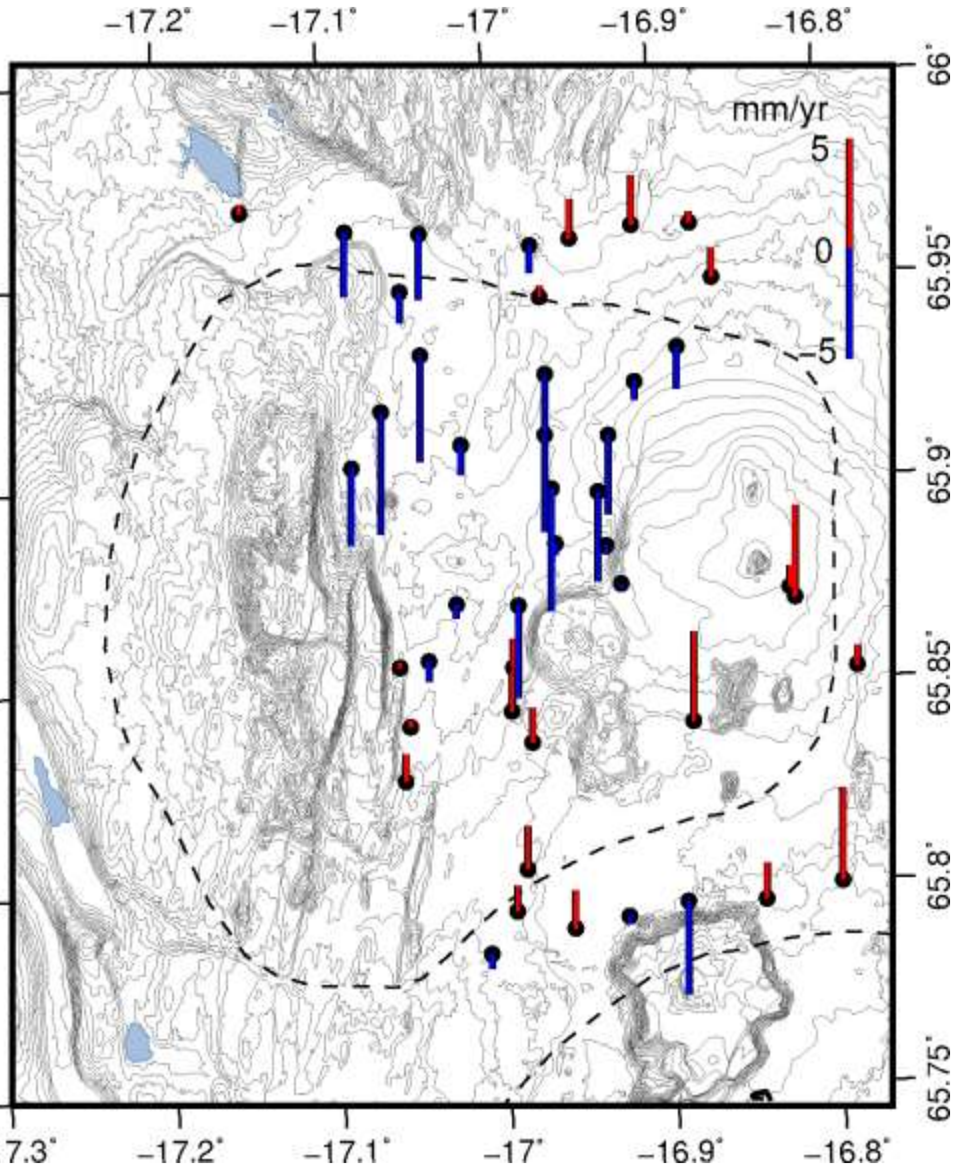
Geophysicla Research Letters, 2008

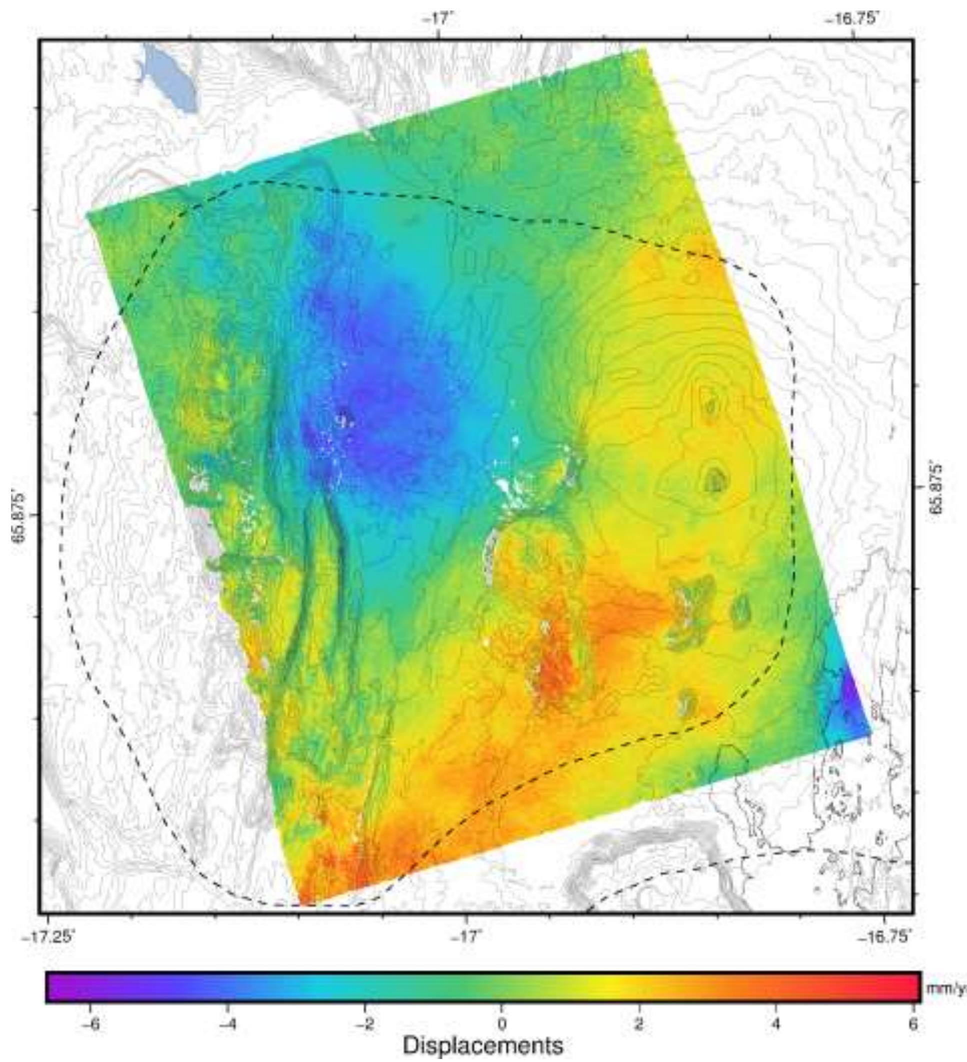
Þeistareykir, inflation 2007-2008



Þeistareykir, deflation after 2008

- 2011-2016 GPS vertical velocities
- 2013-2017 TerraSAR-X velocities





Conclusions

- Combination of GPS and InSAR is well suited to detect deformation in geothermal areas.
- Krísuvík geothermal area is located at the central axis of the Reykjanes Peninsula plate boundary deformation axis, affected by shearing and extension. No significant deformation in deep roots of its system detected 2001-2008.
- Two periods of inflation followed be deflation detected, due to pressure changes at 3-5 km depth under the geothermal area. The larger one has 8 cm of uplift, and same amount of subsidence.
- Similar periods of inflation followed by deflation at Þeistareykir and Hengill.
- Pressure change in roots of the geothermal system can explain observed deformation. Magma movements or build-up of pressure in a sealed part of the geothermal system can reproduce this behavior, followed by relaxation to pre-unrest conditions.