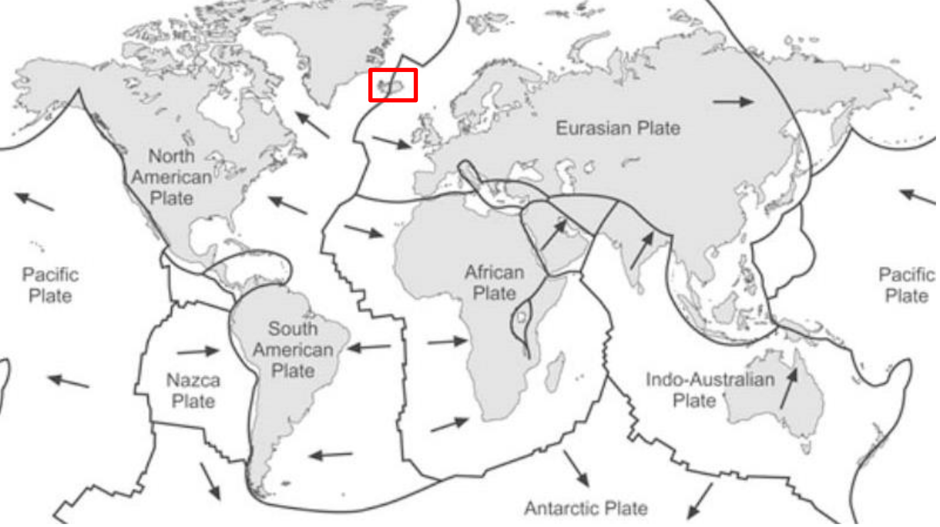

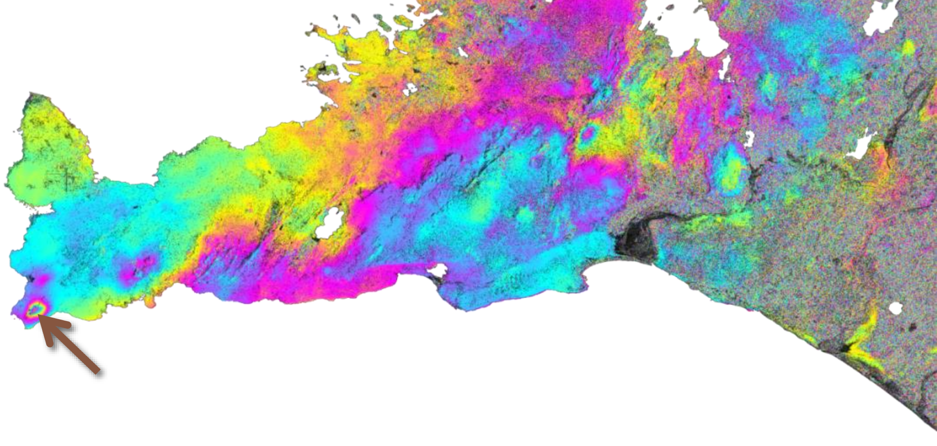

GROUND DEFORMATION DUE TO STEAM CAP PROCESSES AT REYKJANES, SW-ICELAND: EFFECTS OF GEOTHERMAL EXPLOITATION INFERRED FROM INTERFEROMETRIC ANALYSIS OF SENTINEL-1 IMAGES 2015-2017

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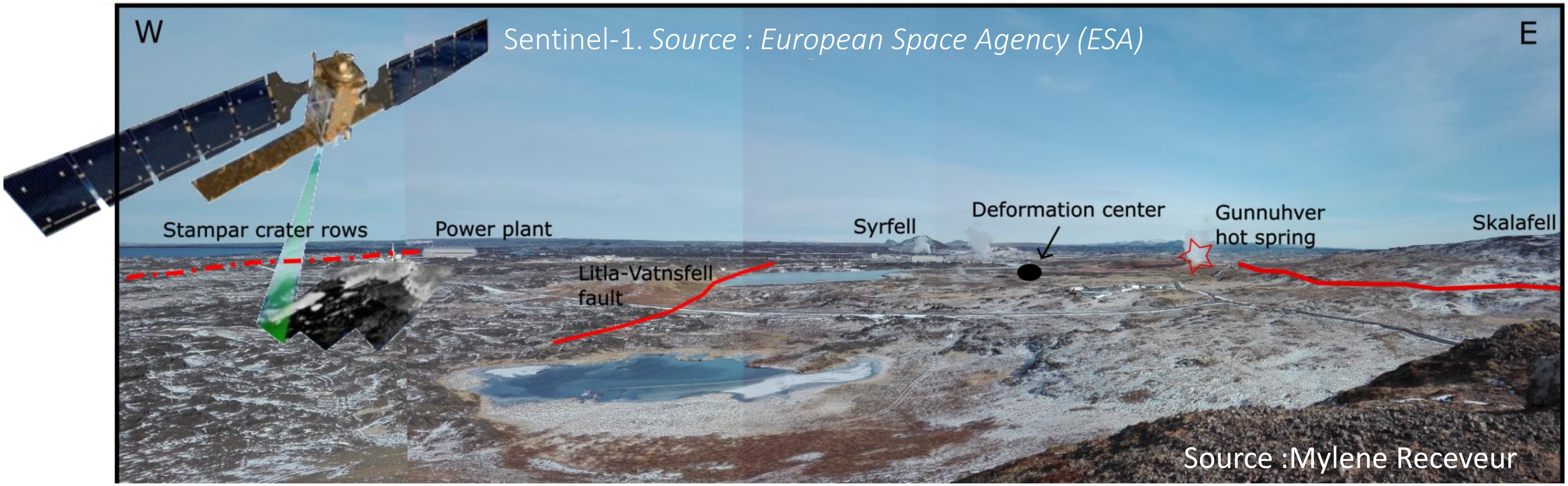
Final Master project - Completed in June 2018

Highlights

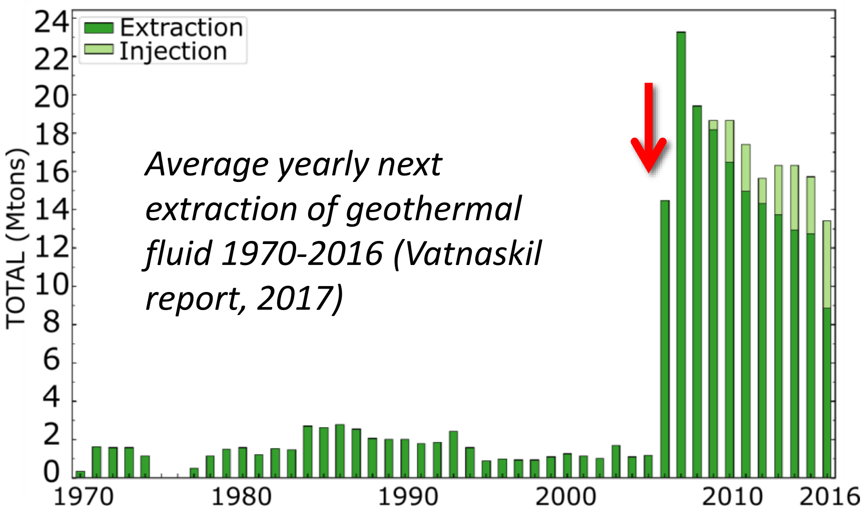
- Creation of average displacement maps from time series analysis of ground deformation using Sentinel-1 SAR data
- Determination of the characteristics of the deformation source at depth using probabilistic inversion
- Models of deformation processes within a steam zone using pressure and temperature data

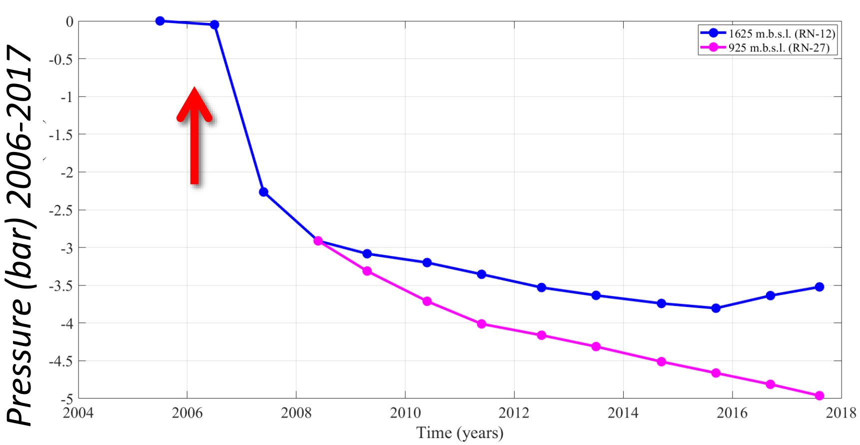


Introduction

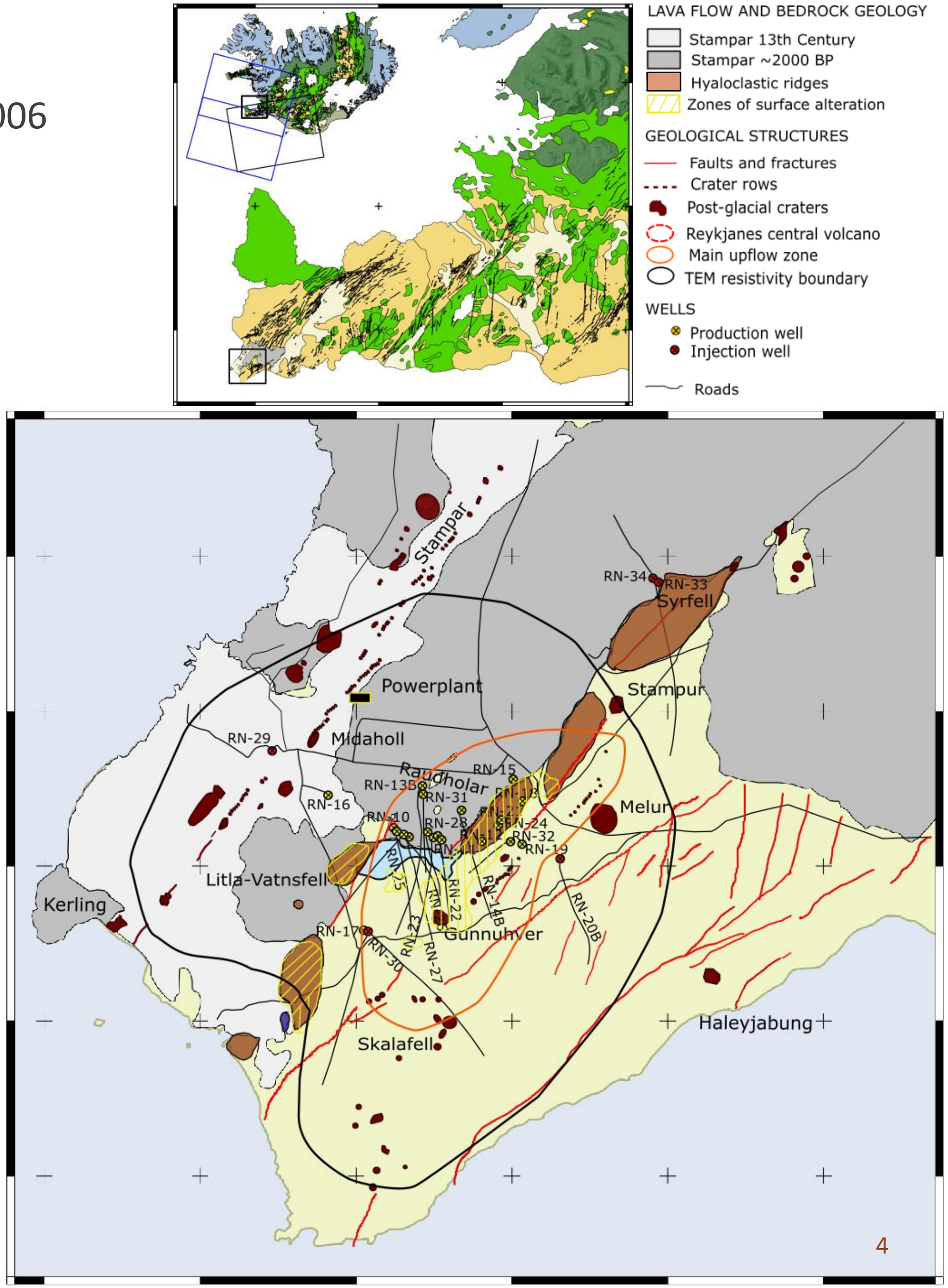
The Reykjanes geothermal system

- Commissioning of the 100 Mwe power plant in 2006
- 17 production and 5 injection wells in 2015-2017
- Injection since 2009

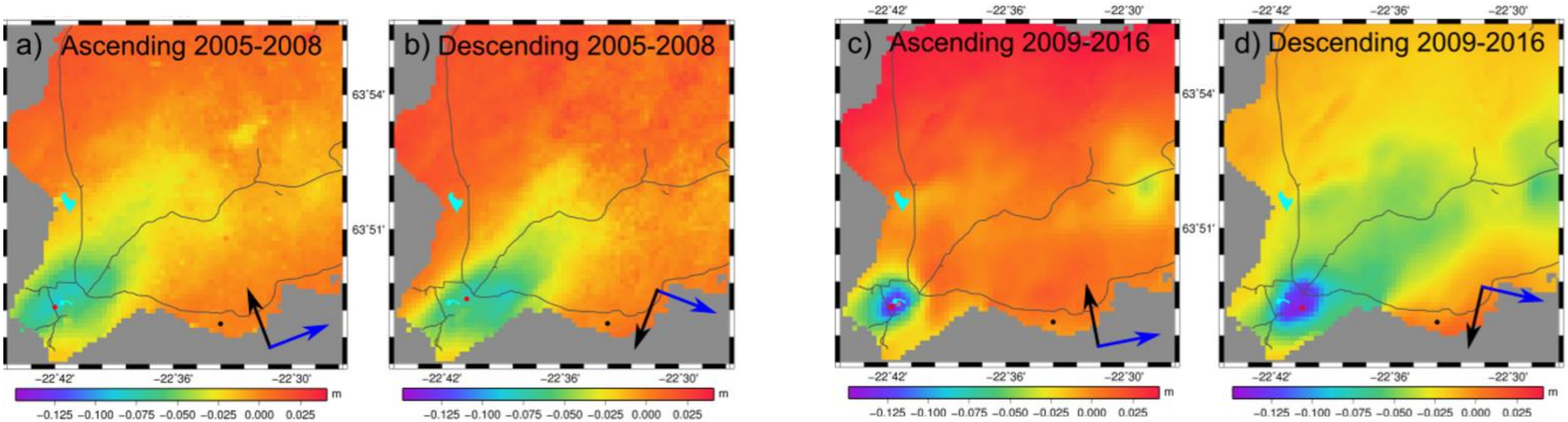




Source: HS-Orka; Thorvaldsson & Arnarsson, Vatnaskil report, 2017; Khodayar et al., 2016



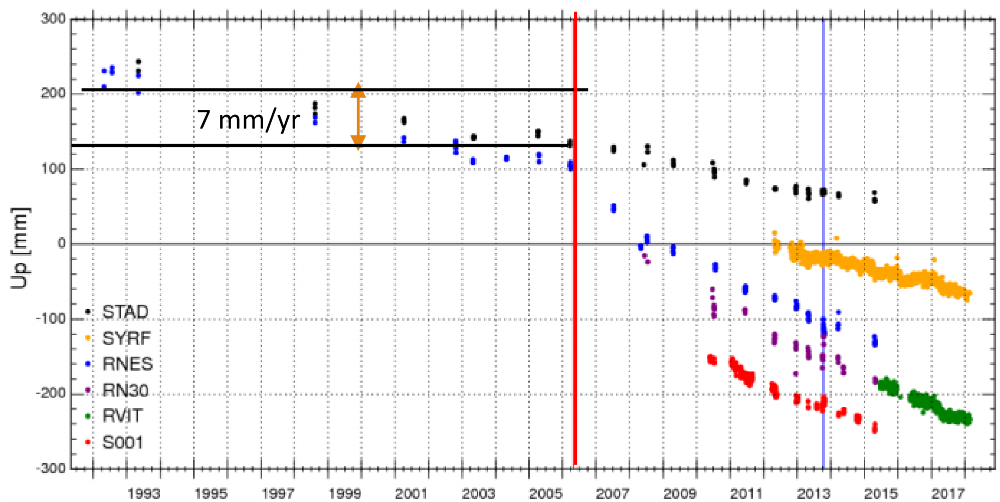
Previous deformation results *Parks et al. (2018)*



2005-2008
ENVISAT: ~ -30 mm/yr
Ellipsoidal source at 2 km depth
ΔV = -7.3 x 10^5 m^3/yr

2009-2016
TSX : ~ -22 mm/yr
Point pressure source at 1 km depth
ΔV = -1.5 x 10^5 m^3/yr

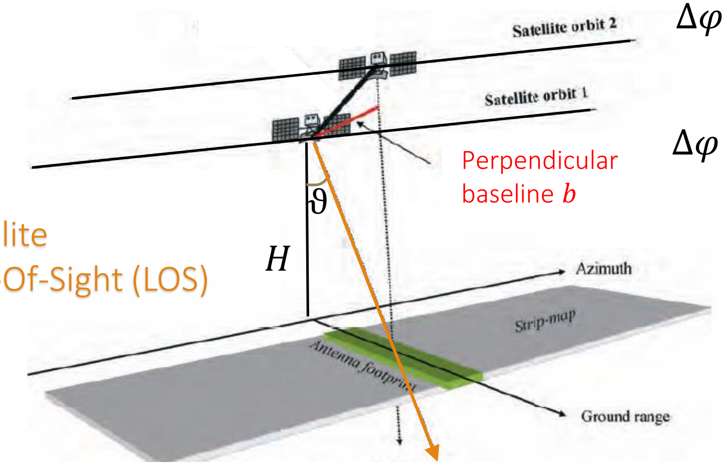
GPS Time series
1992-2018



Data processing and analysis

What is InSAR ?

Satellite
Line-Of-Sight (LOS)



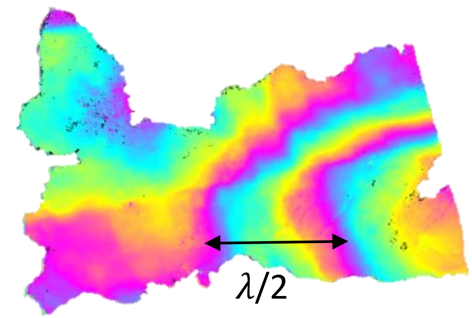
(Ferretti et al., 2007)

$$\Delta\varphi = \frac{4\pi}{\lambda} \times \left(\rho_{(t1)} - \rho_{(t2)}\right) = \boxed{\frac{4\pi}{\lambda} \times \Delta\rho}$$

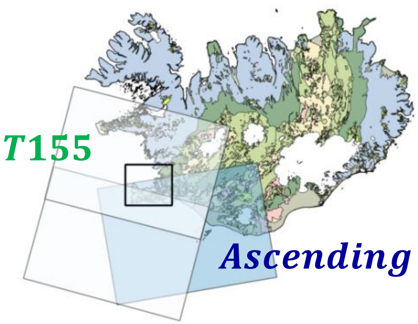
$$\Delta\varphi = \boxed{\varphi_{deformation}} + \boxed{\varphi_{atmospheric}} + \varphi_{orbit} + \varphi_{DEM\ error} + \varphi_{noise}$$

$$d_{LOS} = -\bar{d} \bullet \bar{u}$$

$$\bar{\boldsymbol{u}} = [\bar{\boldsymbol{u}}_E; \bar{\boldsymbol{u}}_N; \bar{\boldsymbol{u}}_{Up}]$$



λ(C-bands) = 5.6 cm



Descending T155

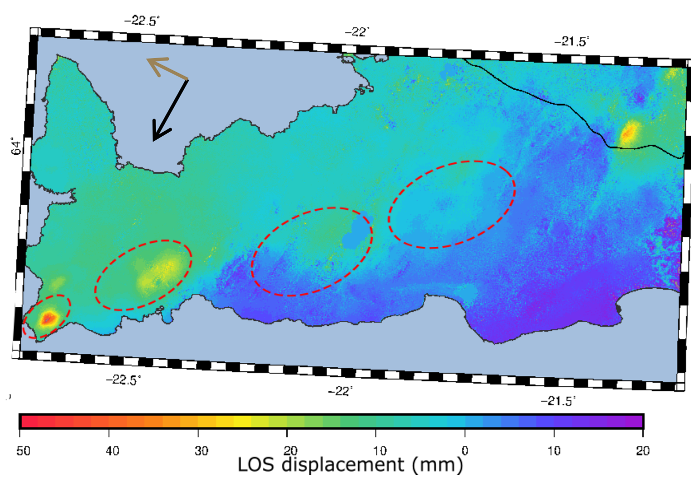
Ascending T16

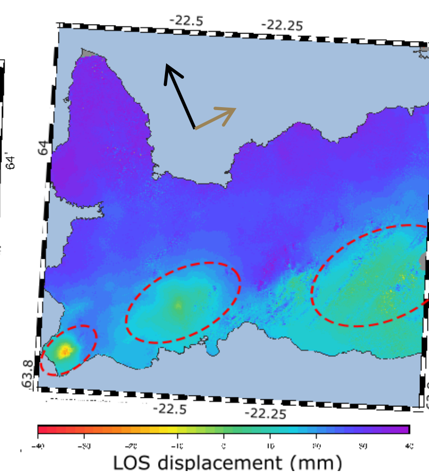
Sentinel-1 mission

- 2 satellites : S1A and S1B
- 1 image every 6 days since 2016
- 2 tracks: Ascending and descending acquisitions
- 5 x 20 m resolution

$\bar{\boldsymbol{u}}_{T155}$ = [−0.605 −0.123 0.787]

$\bar{\boldsymbol{u}}_{T16}$ = [0.545 −0.123 0.830]

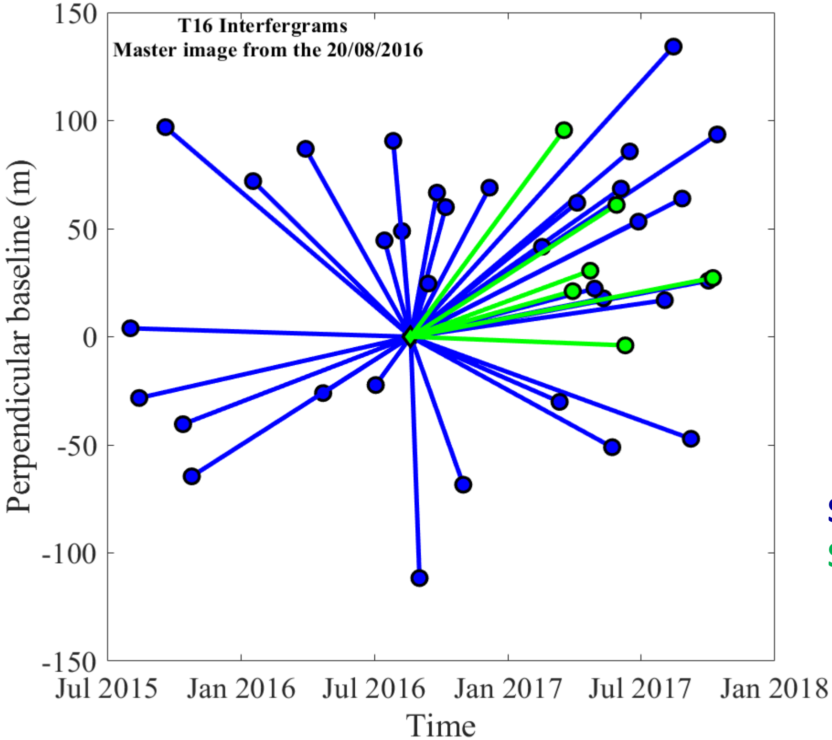




Perpendicular baseline

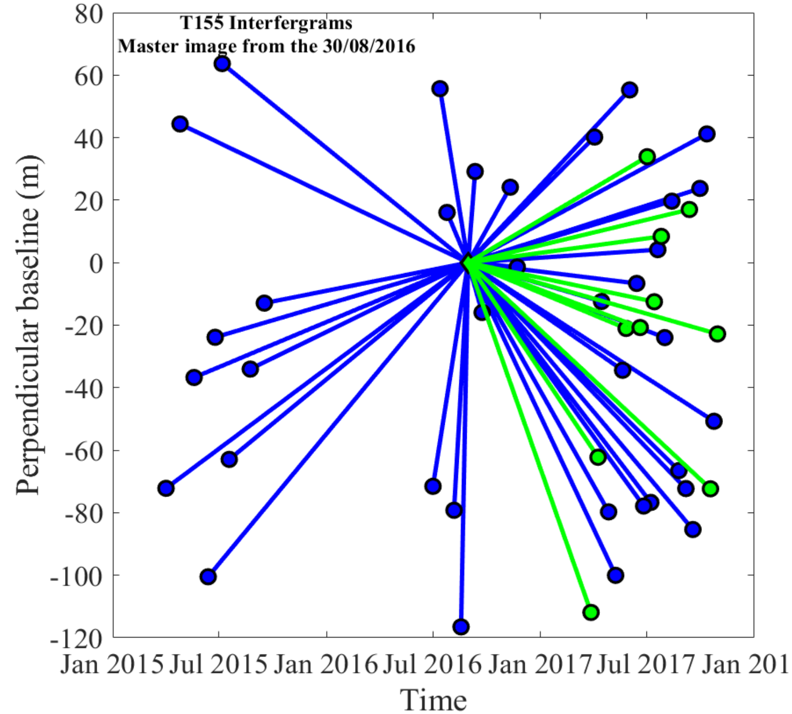
- Time spanned: October 2014 – January 2018
- Processing: ISCE software

ASCENDING TRACK



S1A
S1B

DESCENDING TRACK

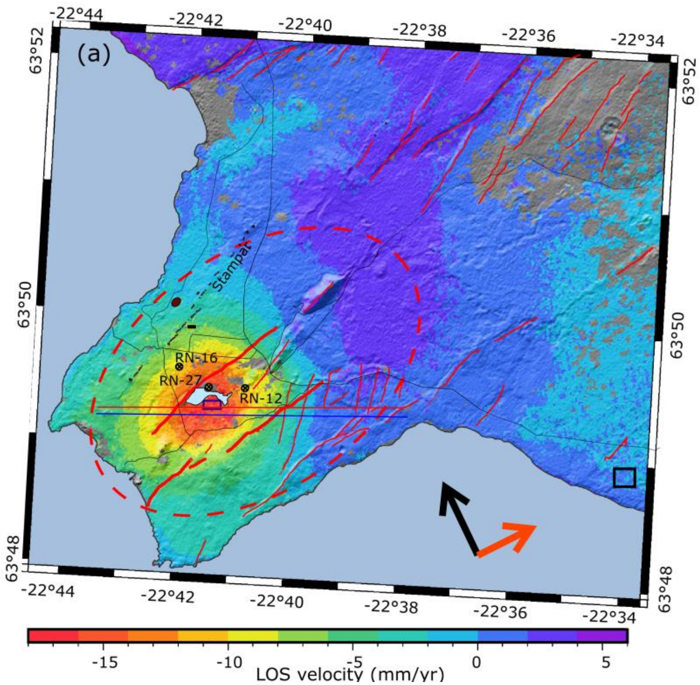


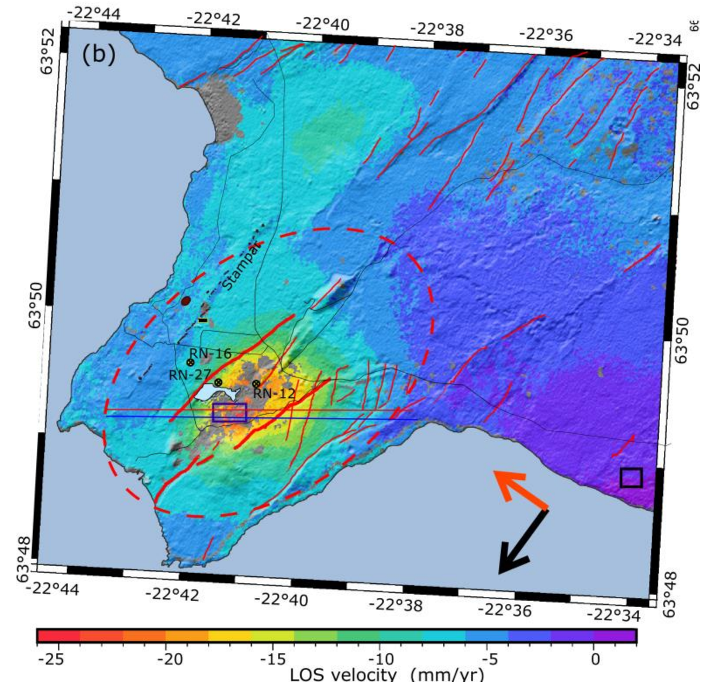
- 104 SAR images
- 39 interferograms
- 804 days

- 107 SAR images
- 47 interferograms
- 942 days

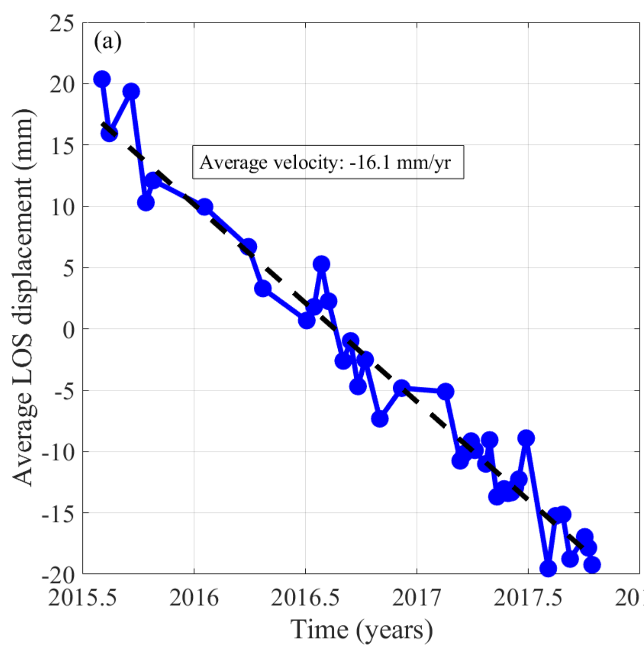
Velocity maps

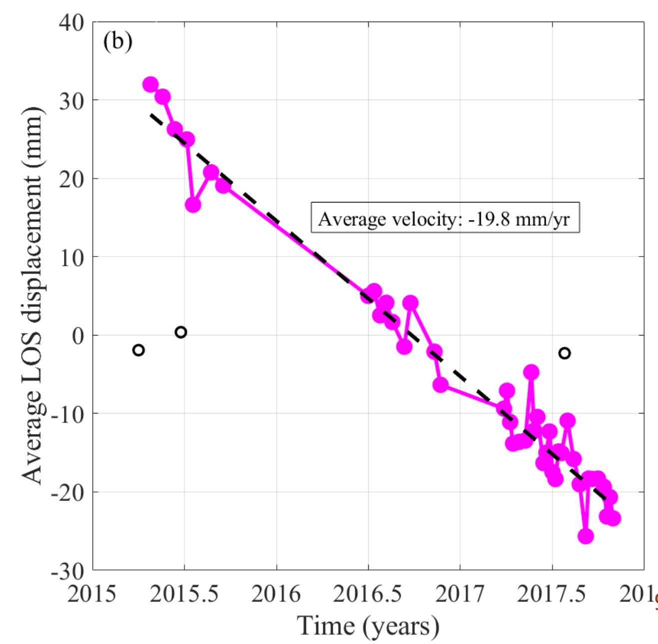
- Resolution: 40 x 40 m
- Sub-circular subsidence bowl centered on the most productive area
- Linear deformation: 16 mm/yr in the satellite LOS





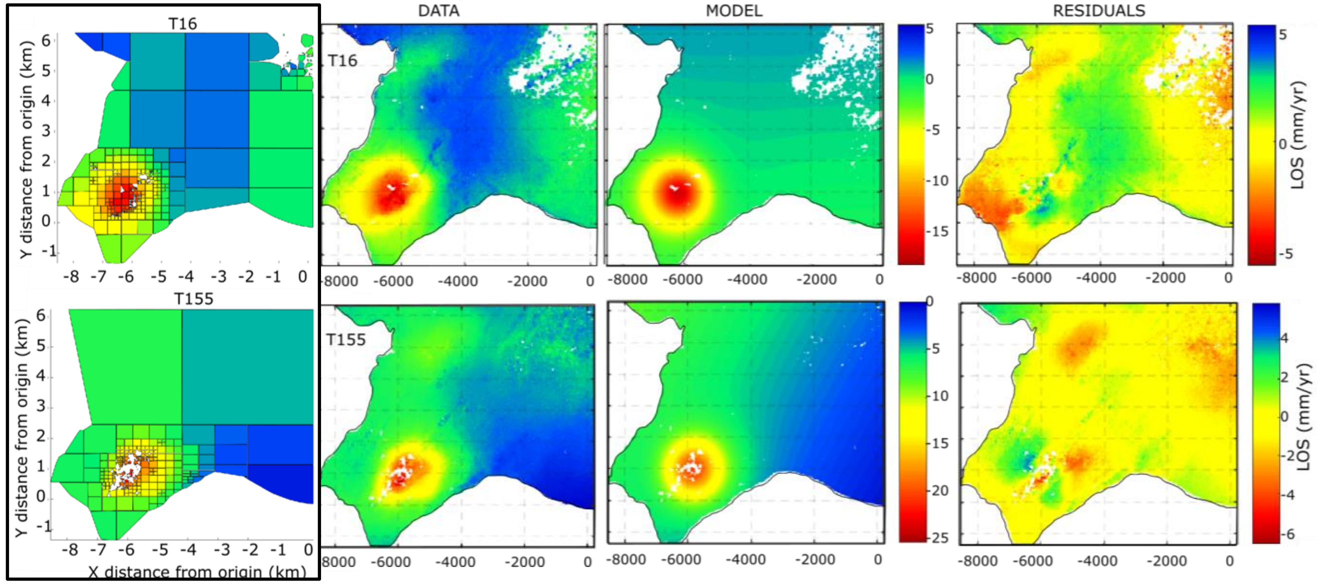
- Time series analysis for a set of point situated in the center of the most deforming area (black squares)





Analytical models

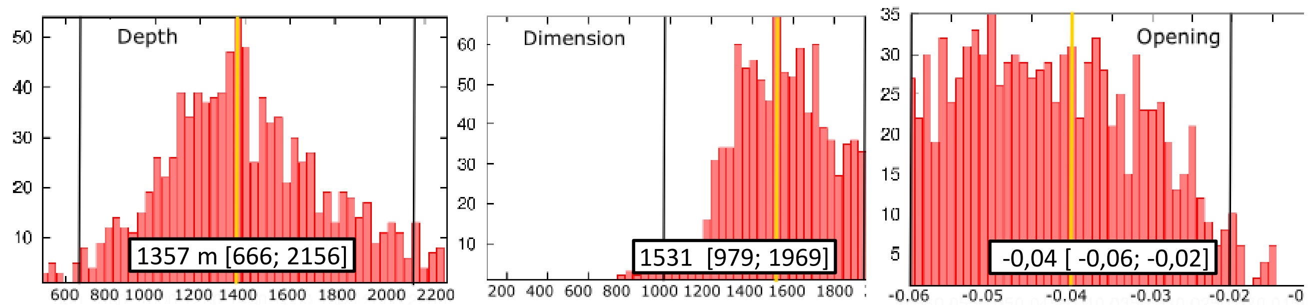
Quadtree sub-sampling



- Input: LOS velocity maps
- Probabilistic inversions
- Contraction of a rock body under ΔP in homogeneous, isotropic & elastic half-space
- 5 model parameters
- $\Delta V = 0{,}7 - 0{,}9 \times 10^5 m^3/yr$

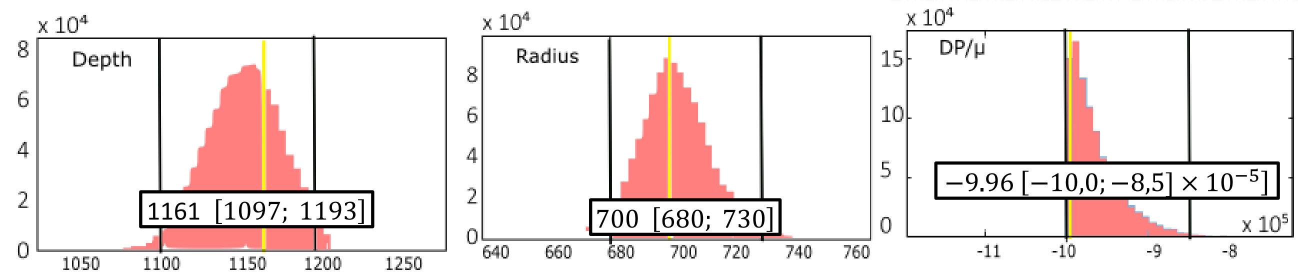
Okada sill with uniform closing

- Grid sub-sampling : ~3500 observations
- Bootstrap inversions (Drouin et al., 2017)



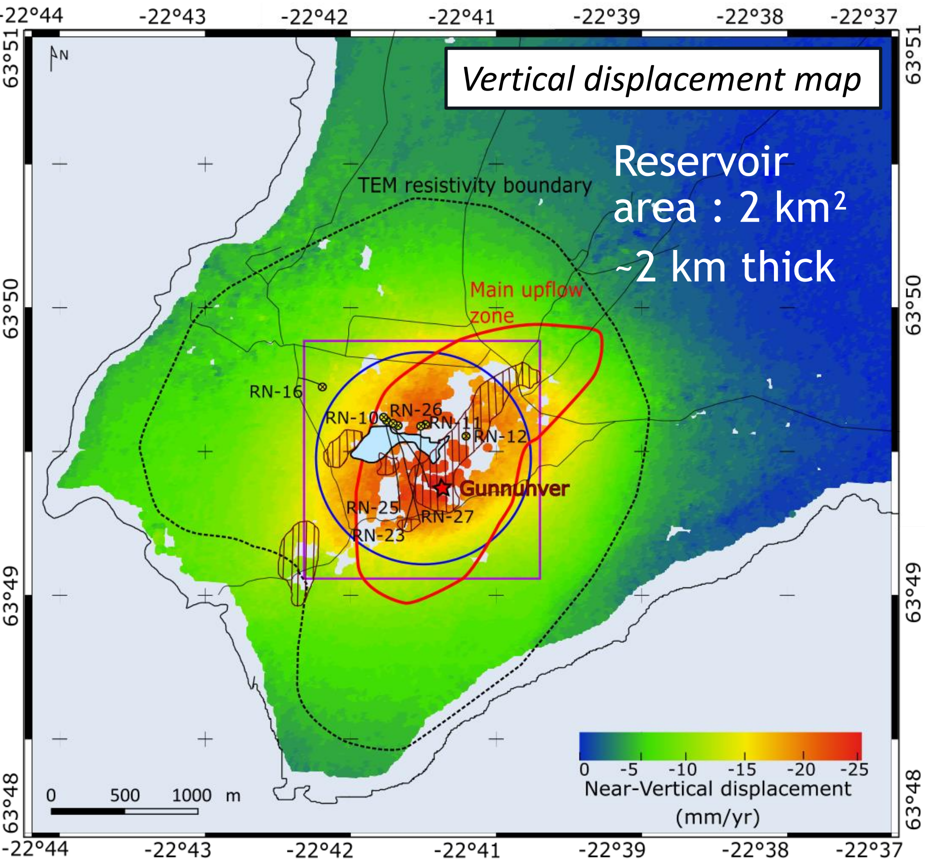
Penny shaped crack

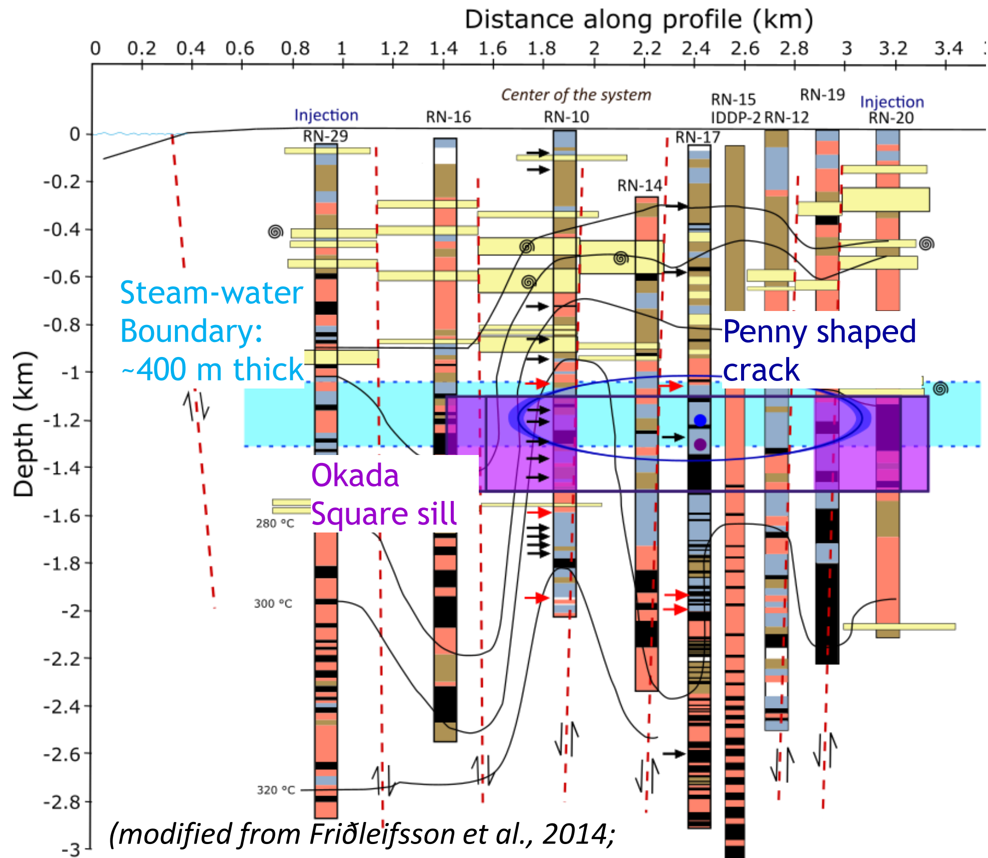
- Quadtree sub-sampling: ~350 observations
- Monte Carlo search (GBIS @ Bagnardi, 2017)



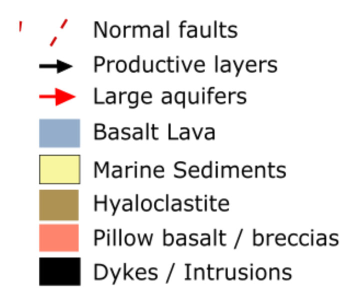
Interpretation

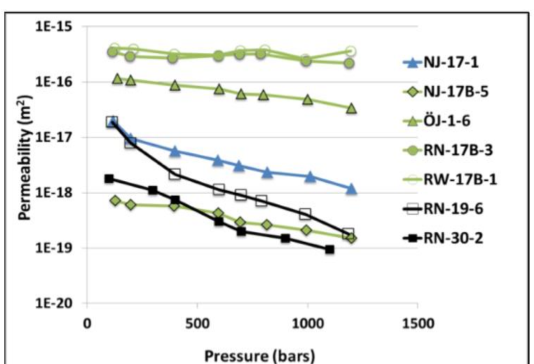
Relation between deformation sources and geological structure





(modified from Friðleifsson et al., 2014; Khodayar et al., 2016)





$$\sigma_e = \sigma_T - p_w$$

Reinsch et al., 2016

$$dv = \left(\frac{dv}{dT}\right) dT + \left(\frac{dv}{dP}\right) dP = v\alpha dT - vcdP$$

v : $specific\ volume$
P: $Pressure$
T: $Temperature$
α: $Coefficient\ of\ thermal\ expansion$
c: $Uniaxial\ poro\text{-}elastic\ expansion\ coefficient$

$$dv = \left(\frac{dv}{dT}\right) dT + \left(\frac{dv}{dP}\right) dP = v\alpha dT - vcdP$$

1) Pressure change

2) Cooling within a horizontal layer

3) Delayed rock compaction

In a Penny shaped crack:

$$\Delta P = \frac{\mu}{2a^3} \Delta V_{PSC}$$

with $\frac{\Delta P}{\mu}$ = -9.96 × 10^{-5}

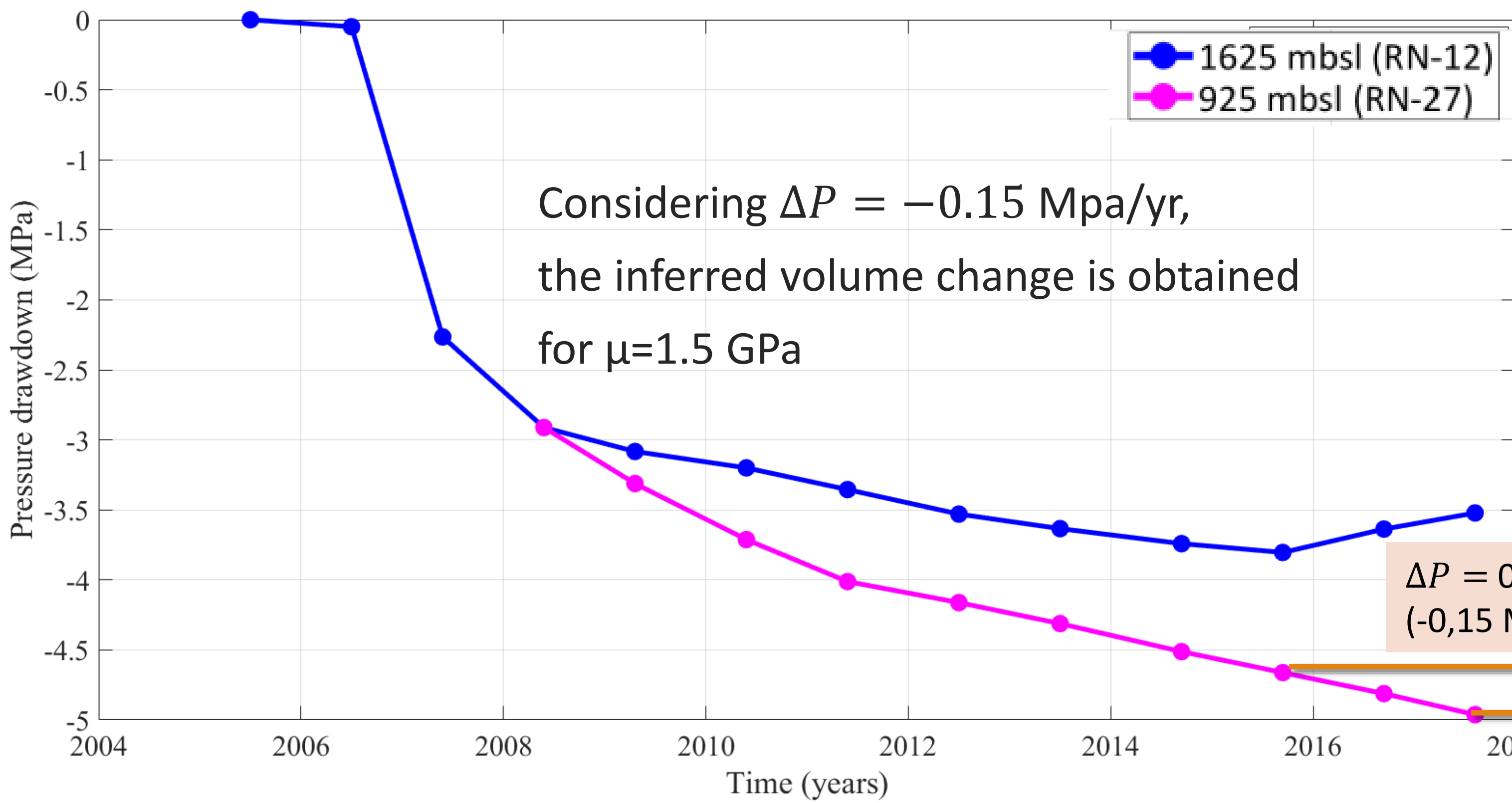
and $a = 700\ m$

ΔV_{PSC} = - 0.7 x 10^5 m^3/yr

If $\mu = (1 - 20)\ GPa$,

$\Delta P = 0{,}1\ to\ 2\ MPa/yr$

Source: Thorvaldsson & Arnarsson, Vatnaskil report, 2017; Khodayar et al., 2016)



Considering $\Delta P = -0.15$ Mpa/yr, the inferred volume change is obtained for μ=1.5 GPa

ΔP = 0,3 MPa in 2 years (-0,15 MPa/yr)

$$dv = \left(\frac{dv}{dT}\right) dT + \left(\frac{dv}{dP}\right) dP = v\alpha dT - vcdP$$

1) Pressure change

2) Cooling within a horizontal layer

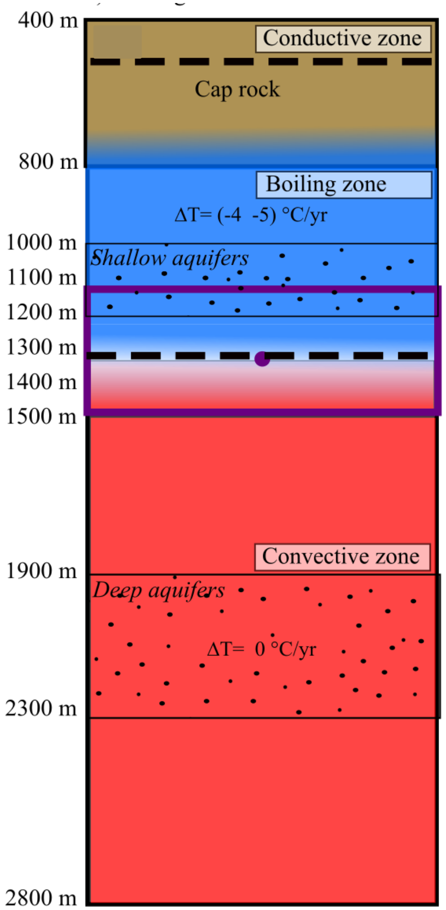
3) Delayed rock compaction

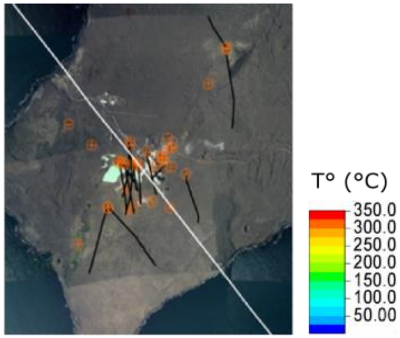
In the Okada layer

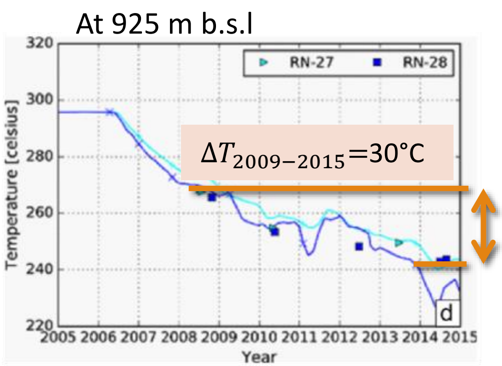
$$\Delta h = \gamma \alpha h \Delta T = -0{,}04\ m/yr$$

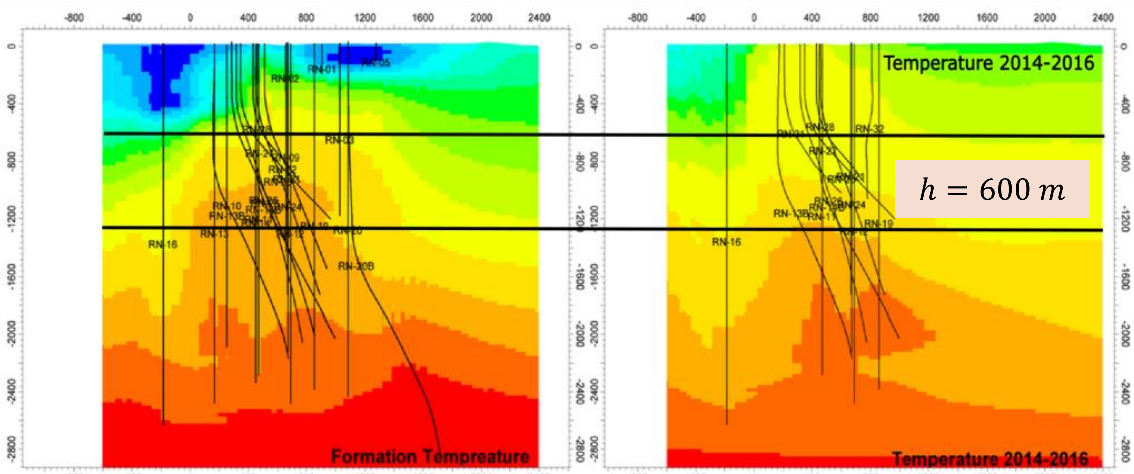
If $\gamma\alpha = (1-5) \times 10^{-5}\ °C^{-1}$
with $\Delta T = -4\ °C/yr$

$$h\ = 200\ to\ 1000\ m$$









(Khodayar et al., 2016, Conceptual model of the Reykjanes Geothermal System)

$$dv = \left(\frac{dv}{dT}\right) dT + \left(\frac{dv}{dP}\right) dP = v\alpha dT - vcdP$$

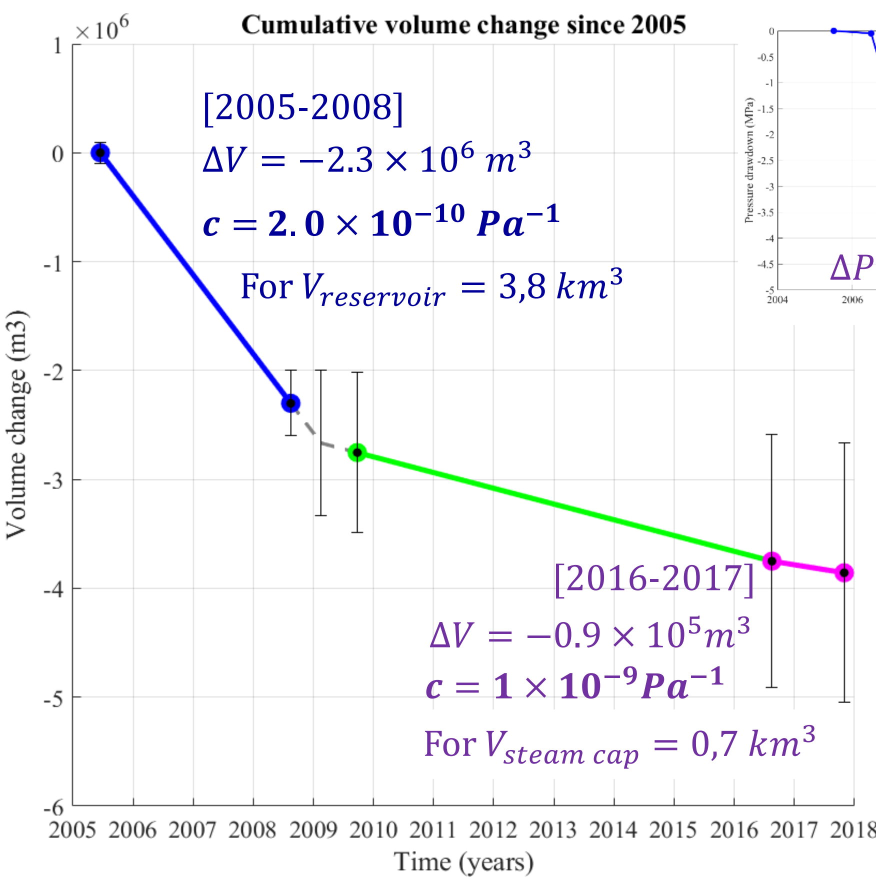
1) Pressure change

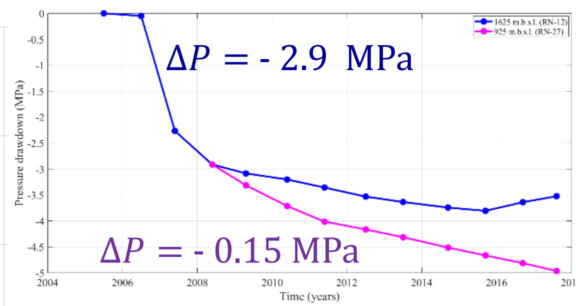
2) Cooling within a horizontal layer

3) Delayed rock compaction

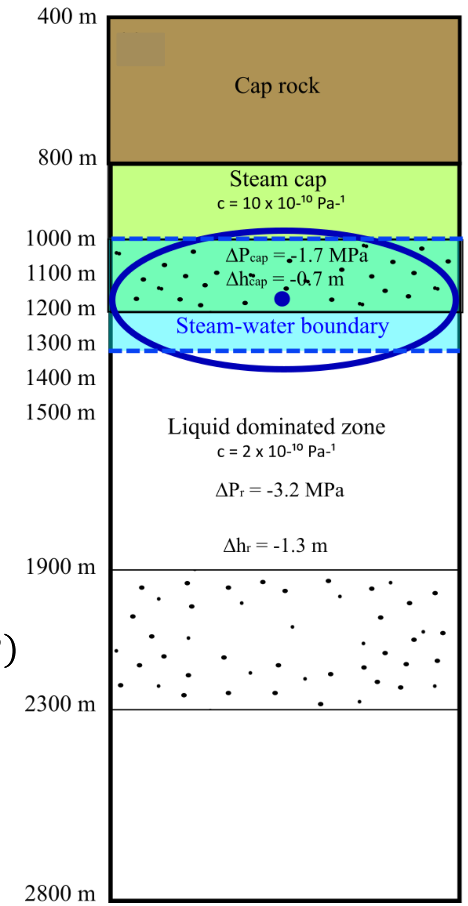
- Non-linear relationship between pressure and volume change
- Change in isothermal compressibility (steam zone)

$$\Delta V = c\Delta PV$$





$$\Delta V_{reservoir} + \Delta V_{steam\ cap}$$
$$= (-2{,}6 \times 10^6) + (-1{,}3 \times 10^6)$$
$$= -3{,}9 \times 10^6 m^3$$
$$= \Delta V_{tot(2005-2017)}$$



Conclusion

- Steam cap processes explain continued subsidence at Reykjanes in 2015-2017

Reinjection, decrease in production rate → Decreased boiling & steam recharge → Pressure & Temperature decline in steam zone → Steam condensation / re-saturation

- Geothermal fields in New Zealand (i.e. Samsonov *et al.,* 2011; Brockbank, 2011; Bromley *et al.,* 2015)
  - Analysis using ERS and Envisat data
  - Subsidence due to creep deformation in highly altered/compressible layers under slow diffusion of pressure decline

- Sentinel-1 InSAR successfully captures deformation using only two years of data. Ideal location at Reykjanes (flat & vegetation free area)

- Can be used to guide re-injection to maintain reservoir pressure and preserve steam zone

- **Future:** Numerical modeling of deformation processes with more constraints on *coefficient of thermal expansion* and *compressibility*

Thanks for your attention !

QUESTIONS ?

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Near-vertical and near-east displacements

	$[\bar{\boldsymbol{u}}_E; \bar{\boldsymbol{u}}_N; \bar{\boldsymbol{u}}_{Up}]$
$\bar{\boldsymbol{u}}_{T16} + \bar{\boldsymbol{u}}_{T155}$	[0.060, 0.246, **1.617**]
$\bar{\boldsymbol{u}}_{T16} - \bar{\boldsymbol{u}}_{T155}$	[**-1.149**, -0.001, 0.043]