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
Highlights

• Time series analysis from 2015 to 2017 using Interferometric analysis of C-band Sentinel-1A and Sentinel-1B data

• Determination of the parameters for the deformation source using probabilistic inversion

• Models of deformation processes, considering pressure/temperature and production data
- High temperature geothermal system
- 17 production and 5 injection wells in 2015-2017
- Commissioning of the 100 Mwe power plant in 2006

Average yearly next extraction of geothermal fluid 1970-2016 (Vatnaskil report, 2017)

Pressure (bar) 2006-2017

Source: HS-Orka; Thorvaldsson & Arnarsson, Vatnaskil report, 2017; Khodayar et al., 2016
Inferred cumulative vertical displacement: -0.26 m

Contraction towards the center of deflation: 0.14 m.

2005-2008
Envisat T173: -33 mm/yr
Envisat T138: -28 mm/yr

2009-2016
TSX T26: -24 mm/yr
TSX T110: -21 mm/yr

2005-2016
Inferred cumulative vertical displacement: -0.26 m
Contraction towards the center of deflation: 0.14 m.

Parks et al. (2018)
**Sentinel-1 mission: two satellites, two tracks**

- 104 and 107 Single Look Complex images from T16 and T155 between October 2014 – January 2018
- 1 image every 12 days, 5 x 20 m resolution
- Processing: ISCE software

\[
d_{LOS} = -\bar{d} \cdot \bar{u}
\]

\[
\bar{u}_{T16} = [-0.545 \ 0.123 \ 0.830]
\]

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

**Geometry for ascending and descending near-polar orbits.**

**Projection of heading \( h \) and LOS vectors \( l \) onto the ground plane (Wortham, 2014).**
Perpendicular baseline

- 40 interferograms
- 804 days

- 47 interferograms
- 942 days
Velocity maps

- Resolution: 40 x 40 m
- Sub-circular subsidence bowl centered on the most productive area (Gunnuhver hot spring)
- 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):
Decomposition into near-vertical and near-east displacement components

\[
n_U = \frac{dA + dD}{1.617}
\]

\[
n_E = \frac{dA - dD}{-1.149}
\]

Near-vertical:
- \(-25\) mm/yr
- +4 mm/yr

Near-east:
- +4 mm/yr
- -10 mm/yr
**Horizontal Okada sill with uniform closing and contracting penny shaped crack**

- Input: LOS average velocity maps
- Contraction of a rock body under pressure change in a homogeneous, isotropic and elastic half-space
- 5 model parameters
- Results: source at 1 km depth closing by a constant rate of 4 cm/yr or a volume change $\Delta V = 0.9 \times 10^5 m^3/yr$
Relation between deformation sources and geological structure

Reservoir volume: 3.8 km$^3$
Average reservoir thickness: 2 km
Micro-scale porosity: 15%
Steam cap thickness: 300-400 m
Steam cap volume: 0.6-0.8 km$^3$

(modified from Friðleifsson et al., 2014; Khodayar et al., 2016)
\[ dv = \left( \frac{dv}{dT} \right) dT + \left( \frac{dv}{dP} \right) dP = v\alpha dT - v\beta dP \]

\[ \Delta V_{tot(2005-2017)} = -3.9 \times 10^6 m^3 \]

\( v \): specific volume

\( P \): Pressure

\( T \): Temperature

\( \alpha \): Coefficient of thermal expansion

\( \beta \): Uniaxial poro-elastic expansion coefficient
In a Penny shaped crack

\[ \Delta P = \frac{\mu}{2a^3} \Delta V \]

\[ \Delta V_{PSC} = -0.7 \times 10^5 m^3/yr \]

with \( a = 700 m \)

\( \mu = (1 - 20) GPa \)

\( \Delta P = 0.1 \) to \( 2 \) MPa/yr

\( \Delta P = 0.15 \) MPa/yr if \( \mu = 1.5 \) GPa

1) Pressure change

2) Cooling within a horizontal layer

3) Delayed rock compaction
In the Okada layer
\[ \Delta h = \gamma \alpha h \Delta T \]
\[ = -0.04 \text{ m/yr} \]

With \( \gamma \alpha = (1 - 5) \times 10^{-5} \circ C^{-1} \)

If \( h = 400 \text{ m} \)
\( \Delta T = -10 \text{ to } -2 \circ C/\text{yr} \)

If \( \Delta T = -4 \circ C/\text{yr} \)
\( h = 200 \text{ to } 1000 \text{ m} \)

1) Pressure change
2) Cooling within a horizontal layer
3) Delayed rock compaction

\( dv = \left( \frac{dv}{dT} \right) dT + \left( \frac{dv}{dP} \right) dP = v\alpha dT - v cdP \)
Non-linear relationship between pressure and volume change

Change in isothermal compressibility (steam zone)

\[ \Delta V = c \Delta PV \]

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

\[ c = 1 \times 10^{-9} \text{Pa}^{-1} \]

\[ c = 2 \times 10^{-10} \text{Pa}^{-1} \]

\[ \Delta V_{\text{tot}(2005-2017)} = \Delta V_{\text{reservoir}} + \Delta V_{\text{steam cap}} = -2.6 \times 10^6 - 1.3 \times 10^6 = -3.9 \times 10^6 \text{m}^3 \]
Conclusion

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

- Decrease in the rate of volume change:
  - 2006-2009: $-7.3 \times 10^5$ m$^3$/yr
  - 2009-2016: $-1.5 \times 10^5$ m$^3$/yr
  - 2015-2017: $-0.9 \times 10^5$ m$^3$/yr

- Migration of the modelled source from about 2.2 km to 1 km depth

- Change in subsidence pattern

- Combination of pressure, temperature and compressibility change in steam cap can explain 2015-2017 deformation

Future

- Numerical modeling of deformation processes
- Use geodetic studies to guide reinjection and preservation of the steam cap
Thank you!

QUESTIONS?
References


