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Multigeophysical Inversion and Play-Fairway Analysis in the Hengill Volcanic System

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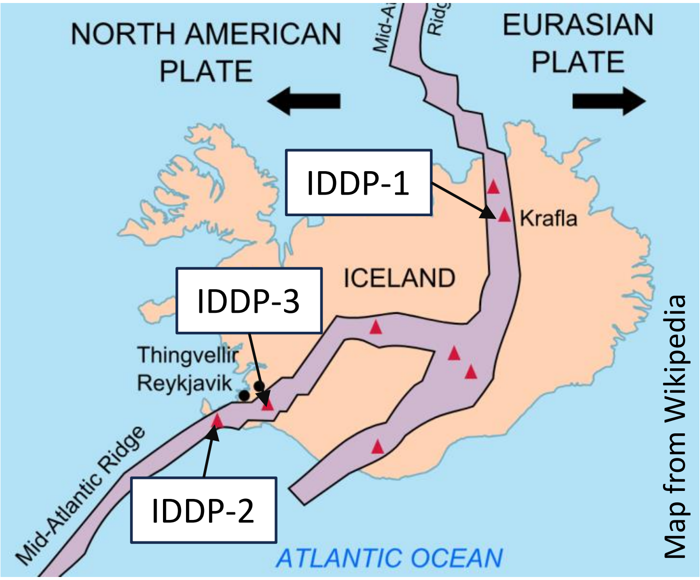
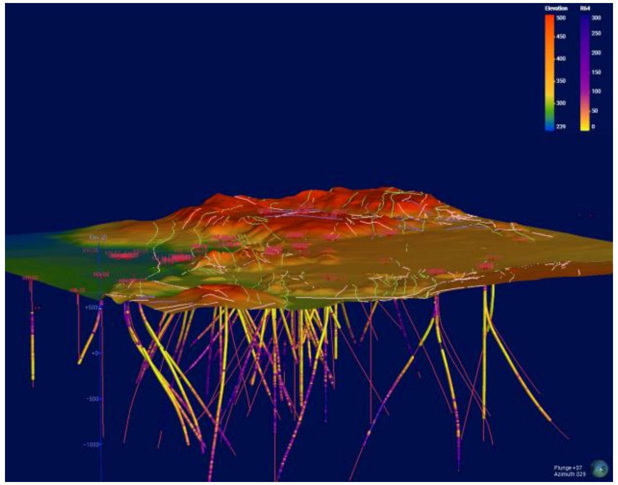
[1]Equinor, [2]Reykjavik Energy (OR), [3]Reykjavik University, [4]ETHZ, [5]NORSAR

The Iceland Deep Drilling Project (IDDP)





Hengill (figure from OR/ISOR)

Objectives of our study

- Contribute to siting IDDP-3
- Multigepophysical inversion (MGI)
- Geothermal PFA
- Part of Geothermica DEEPEN project

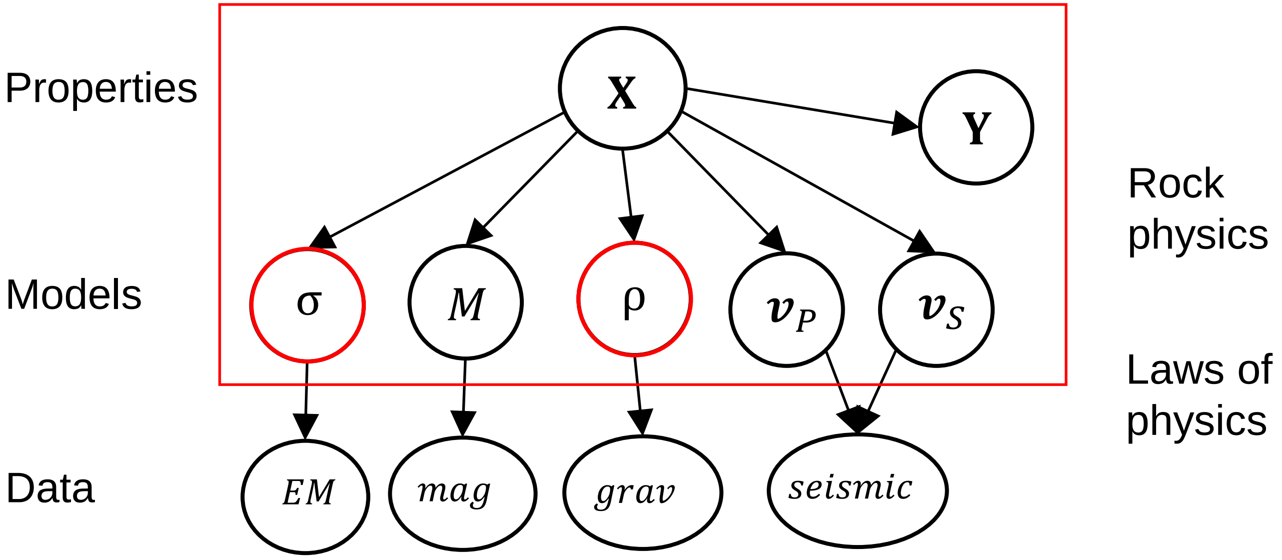
Purpose of IDDP:

- Drill SC geothermal systems (T> 374 oC, P>22 MPa)
- Assess economic potential of SC resources

Multigeophysical inversion (MGI)

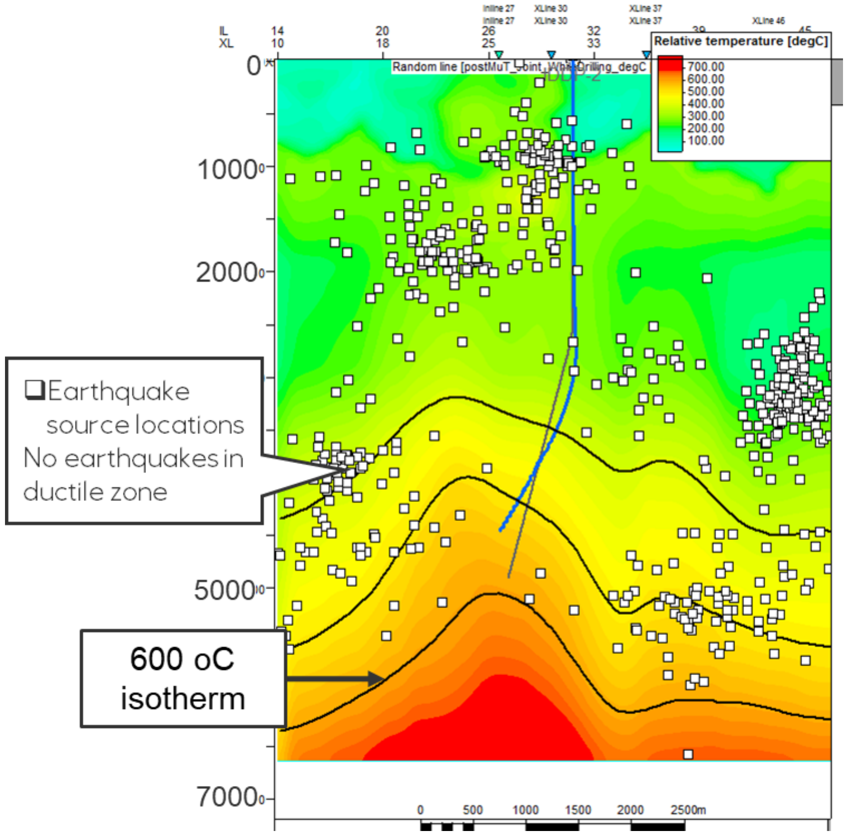
IDDP-2 at TD (4659 mMD):

- Inversion: 535 ± 50 °C
- Horner plot: ~530 °C



Bayesian network for MGI

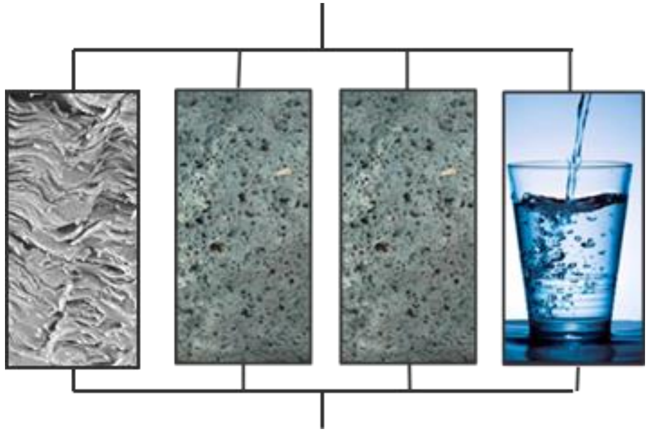
$$p(\mathbf{X}|m_1,\cdots,m_n) = C\prod_{i=1}^{n} p(m_i|\mathbf{X})p(\mathbf{X};\lambda)$$

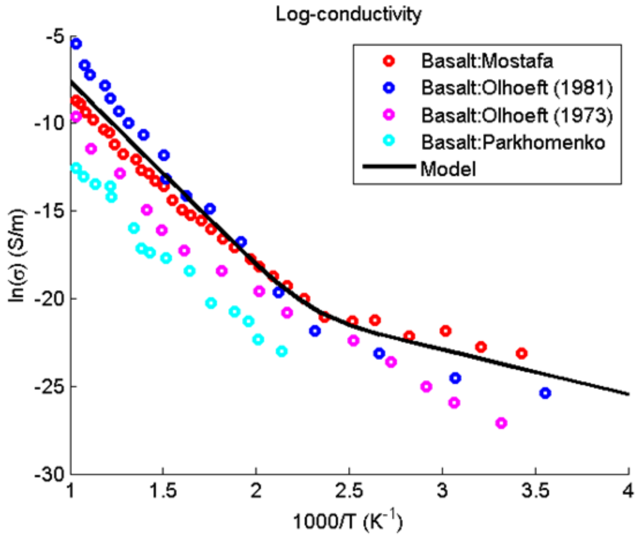


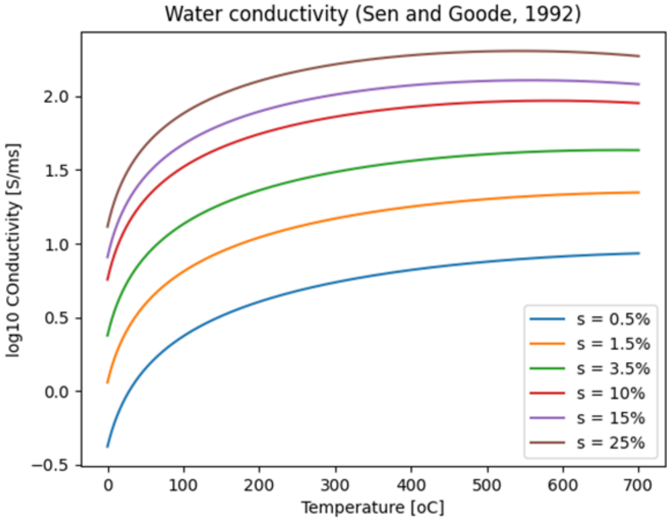
Subsurface temperature from MT and gravity

Hokstad, K. and Tänavsuu-Milkeviciene, K., 2017. Temperature Prediction by Multigeophysical Inversion: Application to the IDDP-2 Well at Reykjanes, Iceland, GRC, Transactions, **42,** 1141-1152.

Electric conductivity (resistivity)





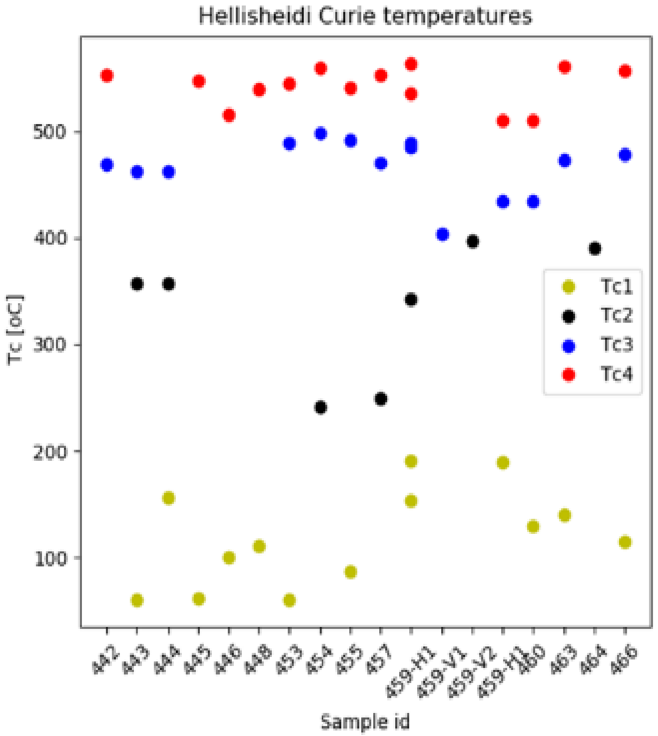


- Parallell coupling with
  - Igneous rock (basalt)
  - Pore-water (salts)
  - Clay (cation exchange in smectites)

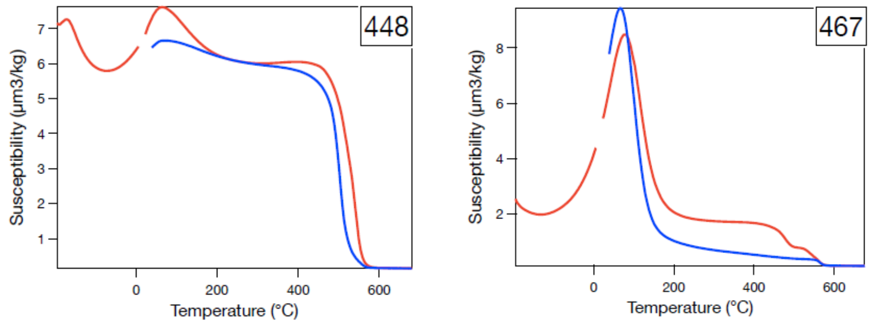
- Cation exchange capacity
  - Waxman-Smits equation

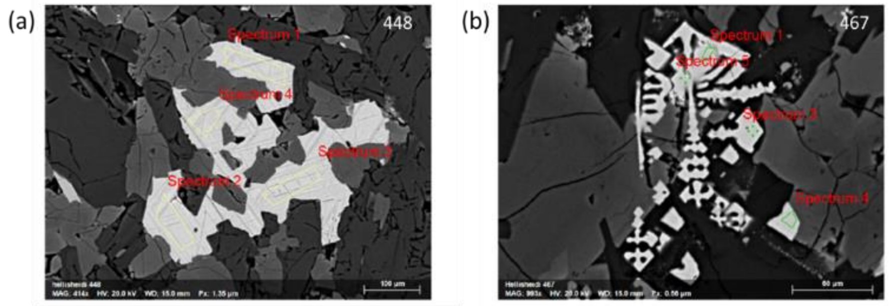
Hokstad, K. and Tänavsuu-Milkeviciene, K., 2017. Temperature Prediction by Multigeophysical Inversion: Application to the IDDP-2 Well at Reykjanes, Iceland, GRC, Transactions, **42,** 1141-1152.

Magnetization – Samples from Hellisheiði



MagLab measurements by Nathan Church and Geertje ter Maat, NTNU

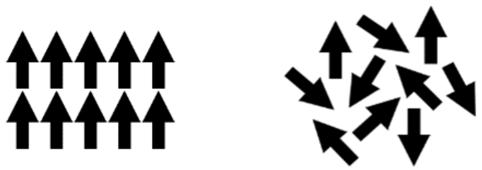


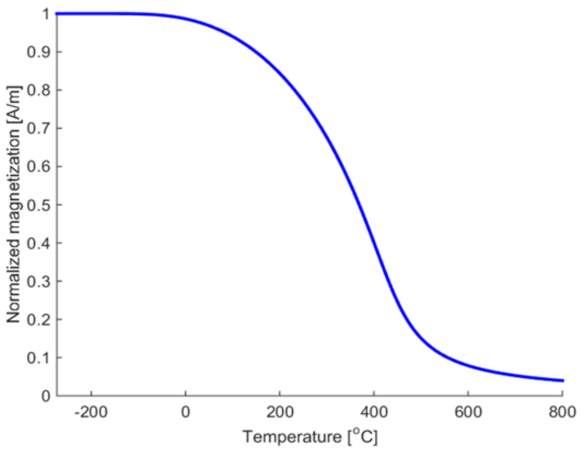


EDS measurements by Claudia Kruber, Equinor

Hokstad, K. and Kruber, C., 2023. Multigeophysical inversion for geothermal exploration, GRC, Transactions, **47,** 2939-2960.

Magnetization forward model





Ising (1925) model

Spin-spin and spin-field interactions

$$\varepsilon = -J\sum_{<ij>}\sigma_i\,\sigma_j - \mu_B H\sum_j \sigma_j$$

Macroscopic magnetization

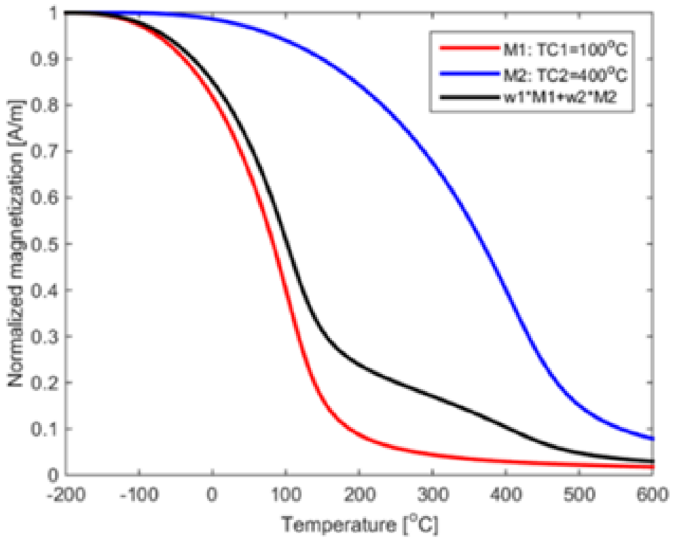
$$\frac{M}{M_0} = \tanh\left[\frac{T_C M}{T M_0} + \frac{CH}{T M_0}\right]$$

Susceptibility

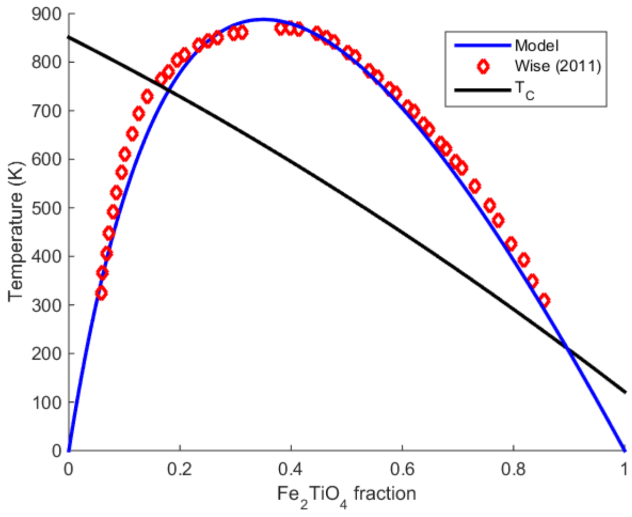
$$\chi = \frac{M(T,H) - M(T,0)}{H}$$

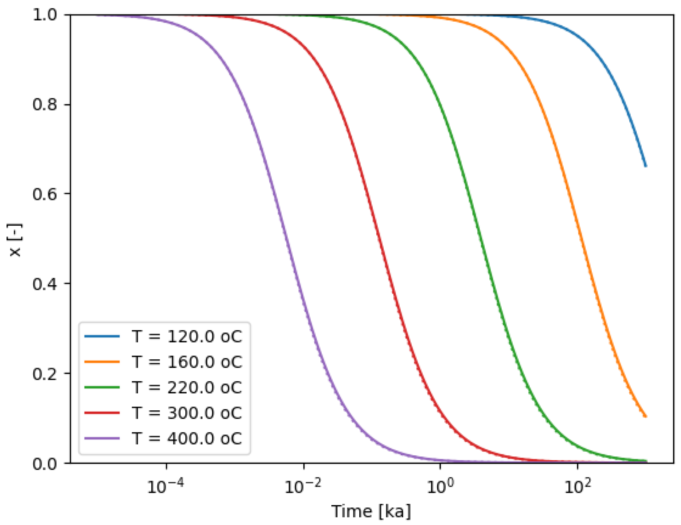
High-temp approximation: Curie-Weiss law

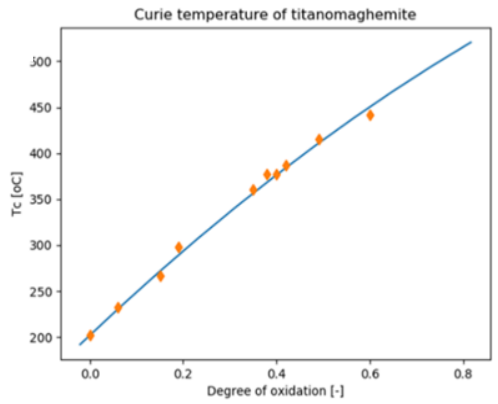
$$\chi \simeq \frac{C}{T - T_C}$$



Exsolution and oxidation







Curie temperature (Moskowitz and Banerjee;1981)

Spinodal exsolution

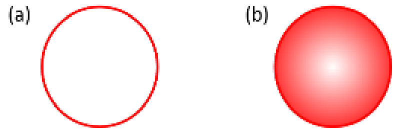
$$\frac{\partial^2 G}{\partial u^2} = -2W + k_B T\left[\frac{(1+h)}{u} + \frac{(1-h)}{v}\right] = 0$$

- Curie temperature from Lattard et al. (2006)
- Model calibration using data from Wise et al. (2011)

Oxidation: Mixed 1st/2nd order Arrhenius

$$\frac{dx}{dt} = -\left(\frac{k_1 - k_2}{x_0}\right)x^2 - k_2 x$$

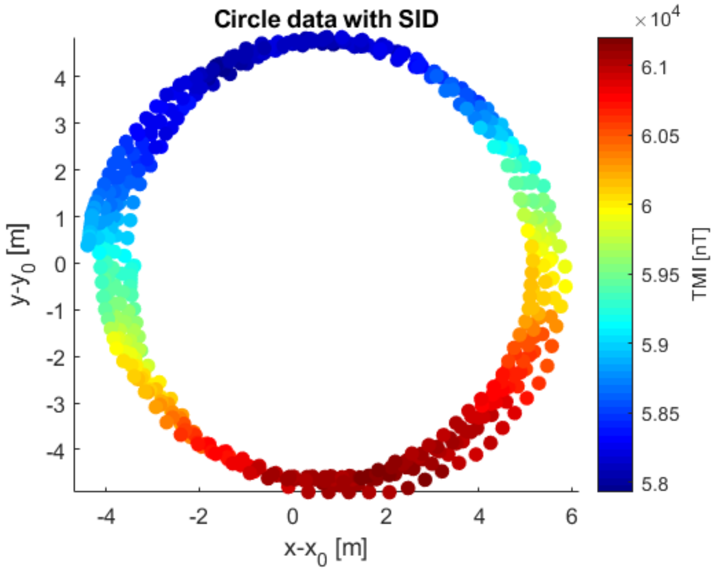
$$k_i = Ae^{-\frac{E_i}{RT}}$$

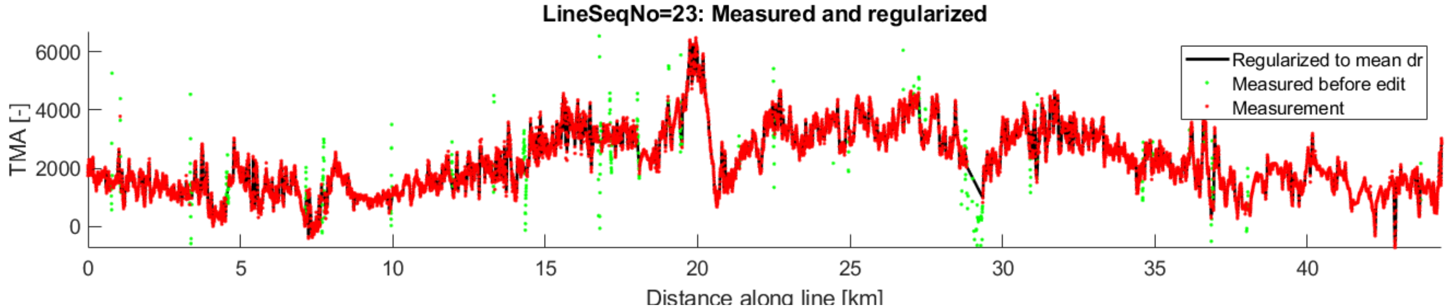


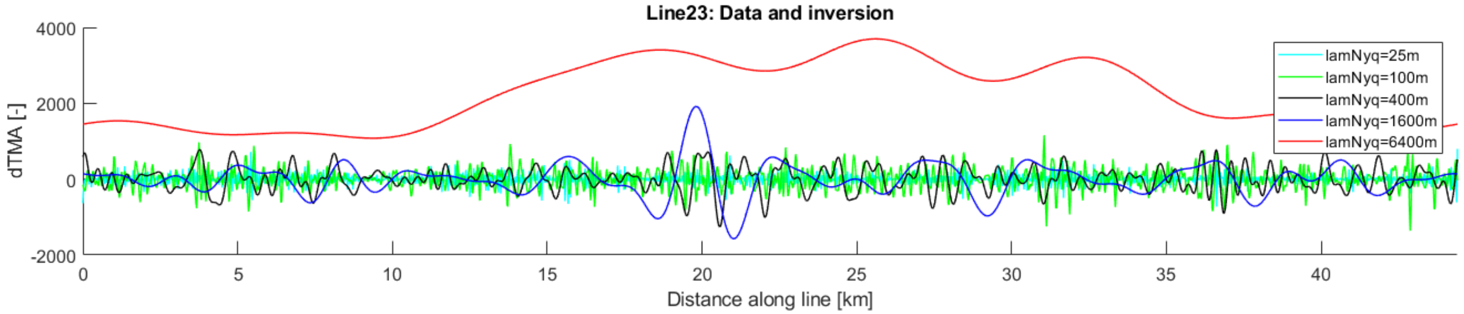
Hellisheiði
Hi-Res magnetics

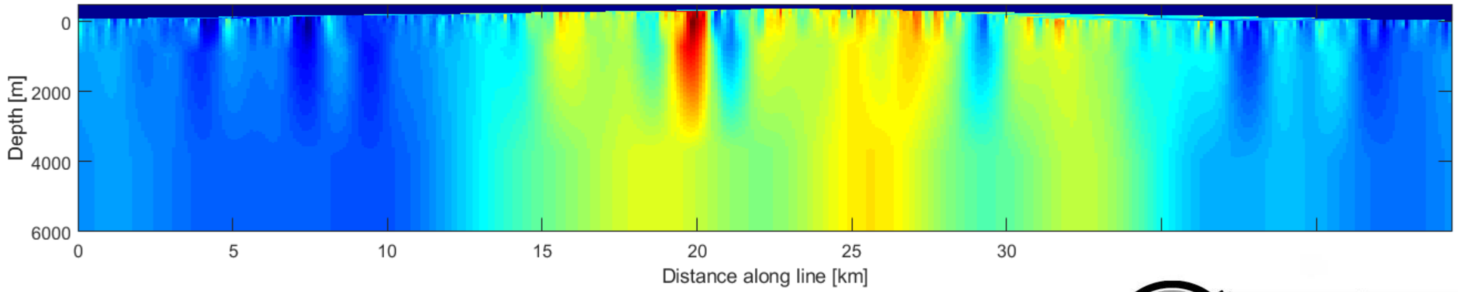
Reykjavik

Selfoss









P-wave velocity, S-wave veocity, density

Thermal expansion coefficient:

$$\Phi = \int_{T_0}^{T} \alpha(T')dT' = a_0\left[(T - T_0) - 20\left(\sqrt{T} - \sqrt{T_0}\right)\right]$$

- Hacker et al. (2003)

$$\rho_m(T) = \rho_0 e^{-\Phi}$$

$$K_m(T) = K_0 e^{-\delta_T \Phi}$$

$$\mu_m(T) = \mu_0 e^{-\Gamma_T \Phi}$$

$$v_{P_m}(T) = \sqrt{\frac{K_m(T) + (4/3)\mu_m(T)}{\rho_m(T)}}$$

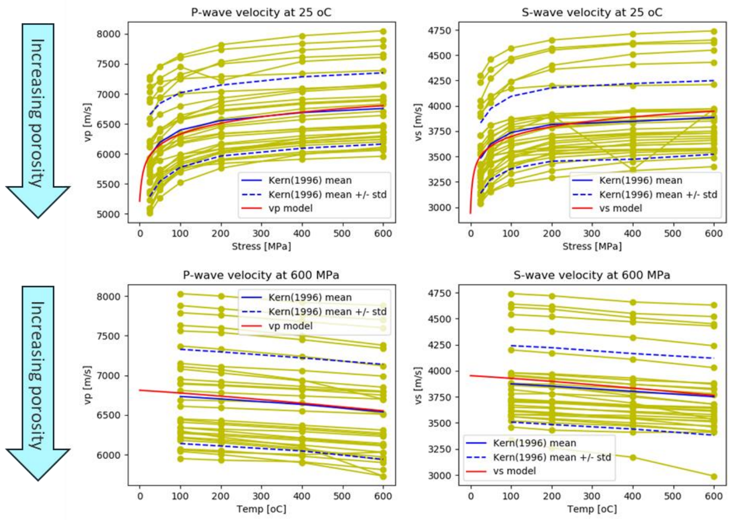
$$v_{S_m}(T) = \sqrt{\frac{\mu_m(T)}{\rho_m(T)}}$$

Porosity, effective stress and clay:

$$v_P(T, \phi, V_{cl}, \sigma') = v_{P_m}(T) - A_P\phi - B_P V_{cl} + C_P\left(\sigma' - D_P e^{-\beta\sigma'}\right)$$

- Han et al. (1986)
- Eberhardt-Phillips et al. (1989)

- Effective stress is first order
- Temperature is 2nd order



Lab measurements from Kern et al. (1996)

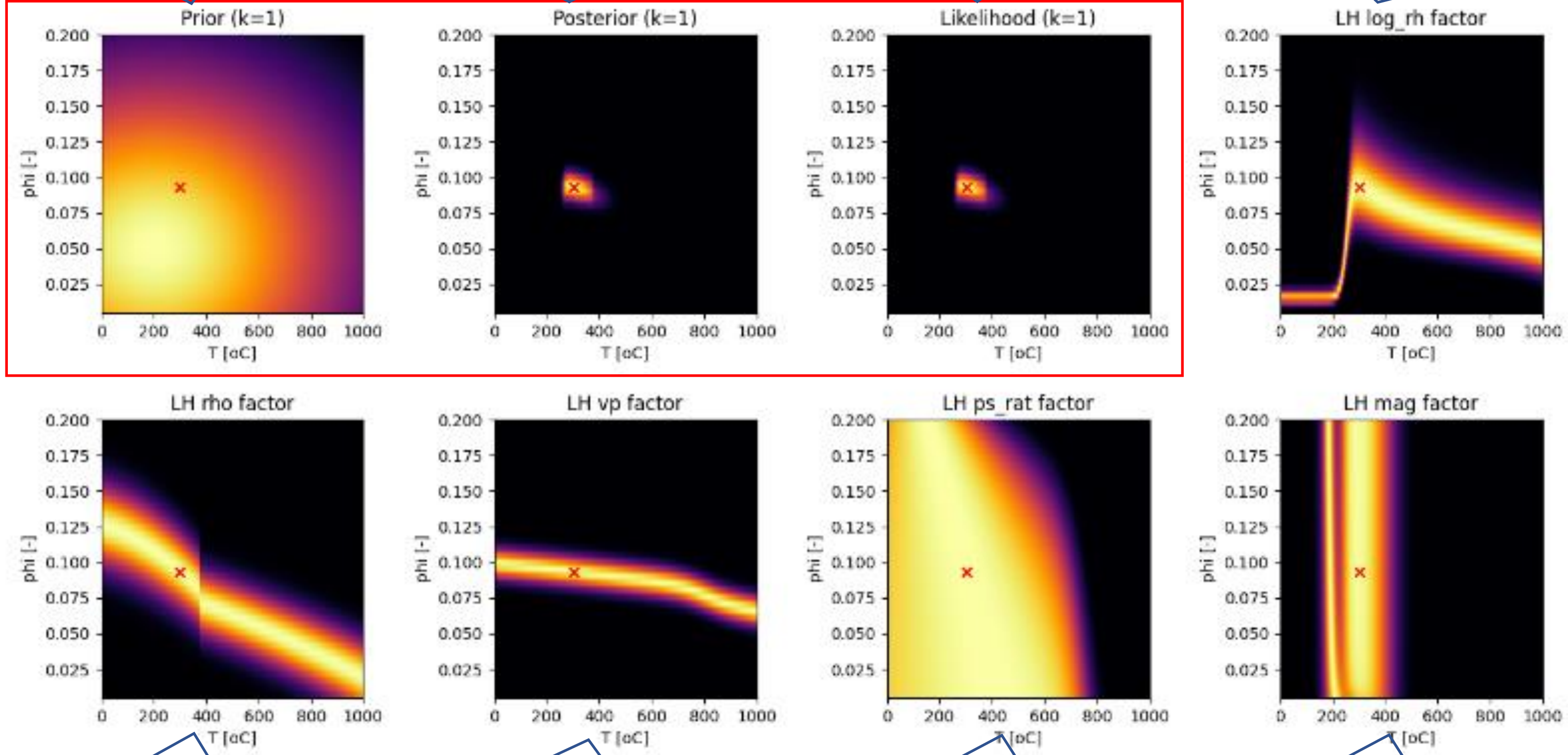
Bi-variate multigeophysical inversion

Prior distribution

Posterior distribution

Likelihood:
Product of 5 factors

Resistivity:
Trade-off between temp and porosity

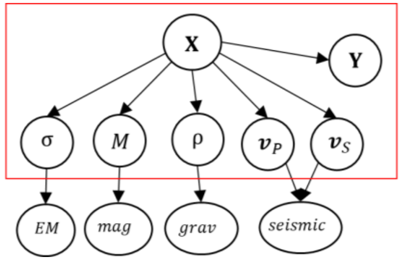


Density:
Trade-off between temp and porosity

P-wave velocity:
Mainly sensitive to porosity

vp/vs-ratio:
Sensitive to magma

Magnetization:
Sensitive to temperature



Joint distributions for temperature and porosity

- Posterior
- Likelihoods
- Prior

$$p(\mathbf{X}|m_1, \cdots, m_n) = c\prod_{i=1}^{n} p(m_i|\mathbf{X})p(\mathbf{X}; \lambda)$$

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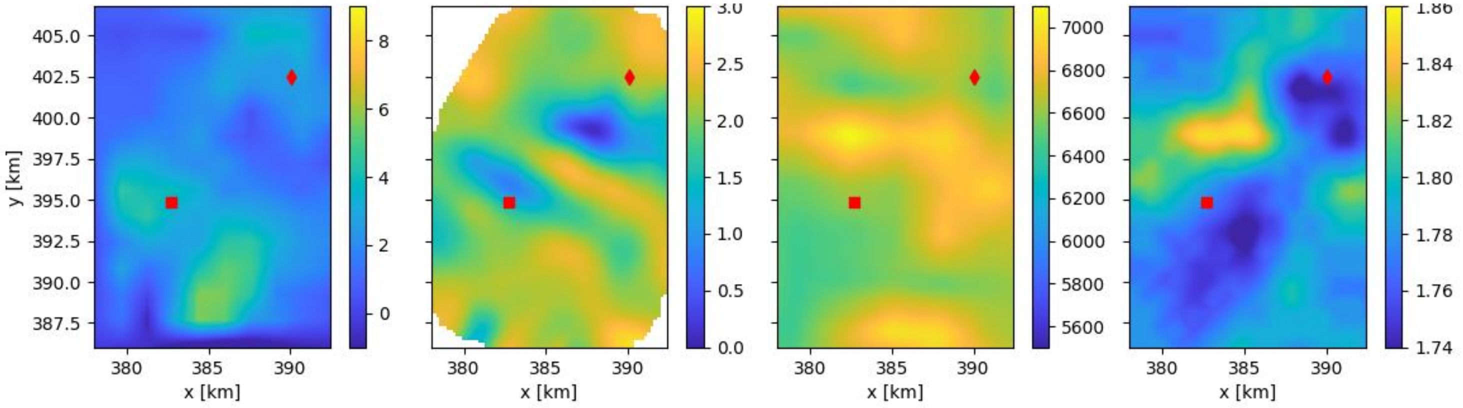
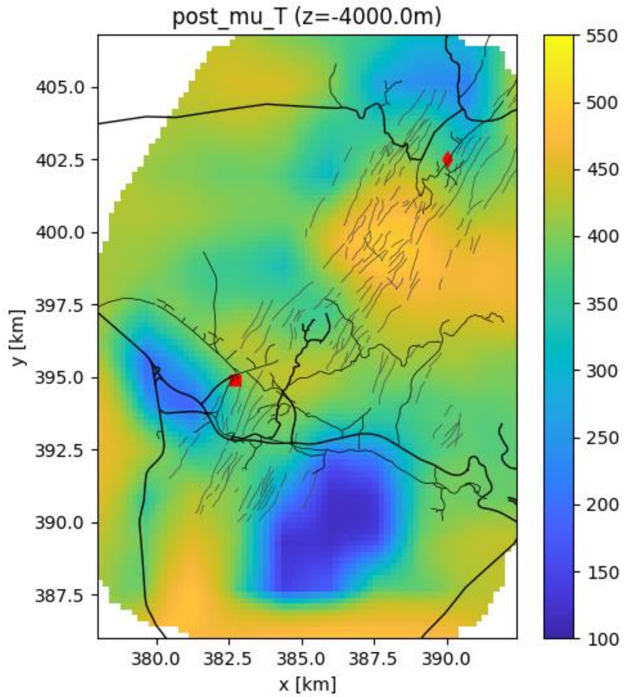
Multigeophysical inversion (Hengill)



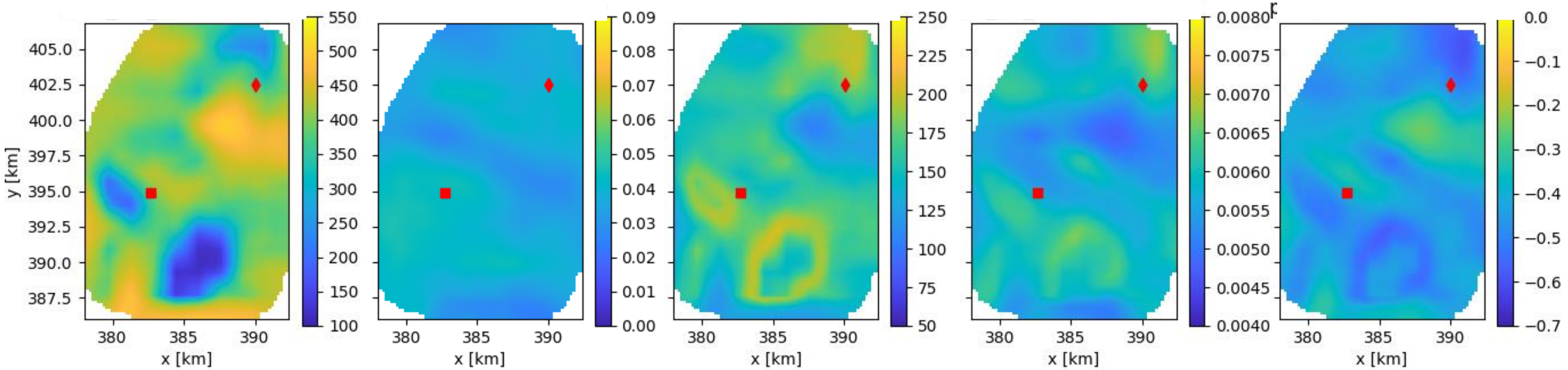
Magnetization (Hokstad and Kruber 2023)

Resistivity (Benediktsdóttir et al., 2021)

P-wave velocity and v_P/v_S-ratio (Obermann et al., 2022)



Posterior mean temperature [°C]



Temperature [°C]

Porosity [-]

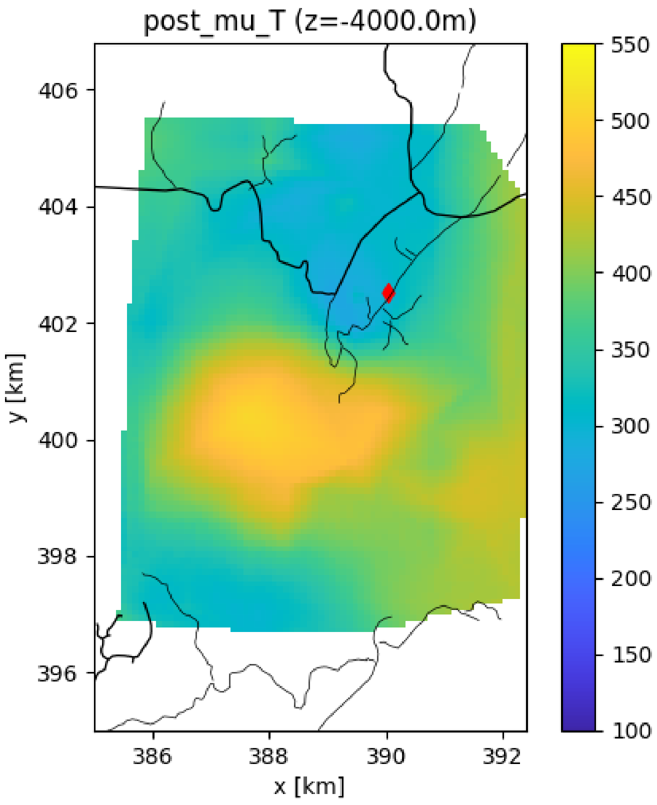
Temp. variance [°C]

Porosity variance [-]

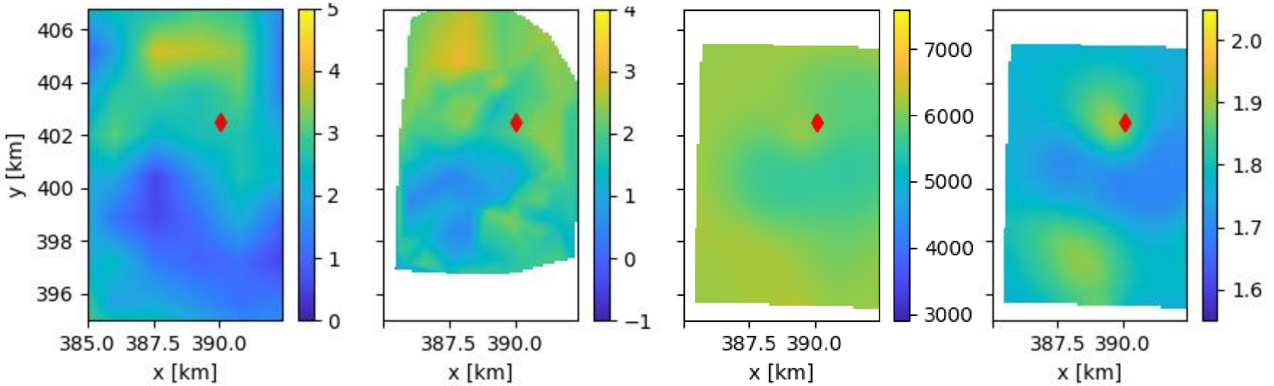
Correlation[-]

Horizontal cross-sections at z=4000m (MSL)

Multigeophysical inversion (Nesjavellir)



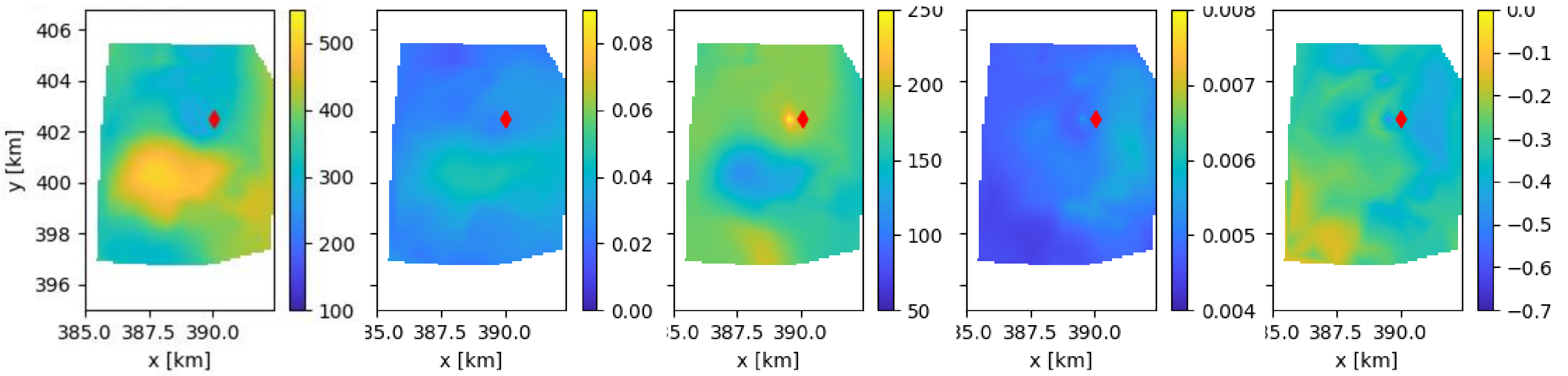
Posterior mean temperature [ºC]



Magnetization (Hokstad and Kruber 2023)

Resistivity (OR/ISOR, WIP)

P-wave velocity and v_P/v_S-ratio (Amoroso et al., 2022)



Temperature [ºC]

Porosity [-]

Temp. variance [ºC]

Porosity variance [-]

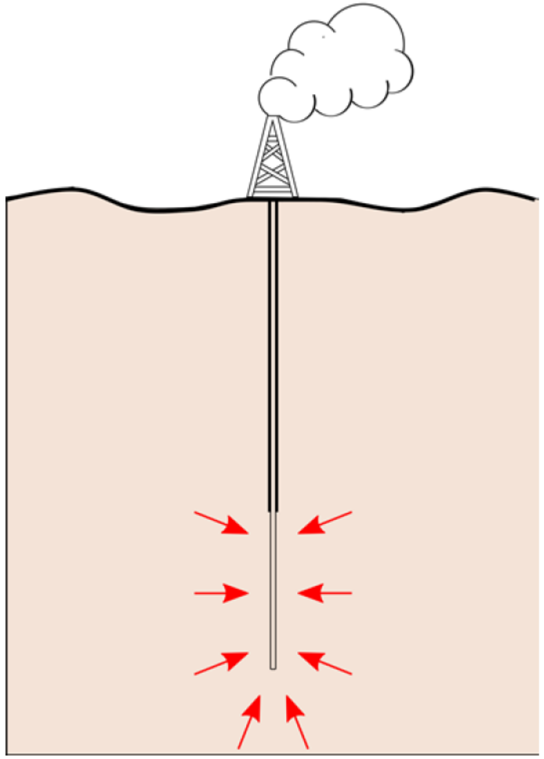
Correlation[-]

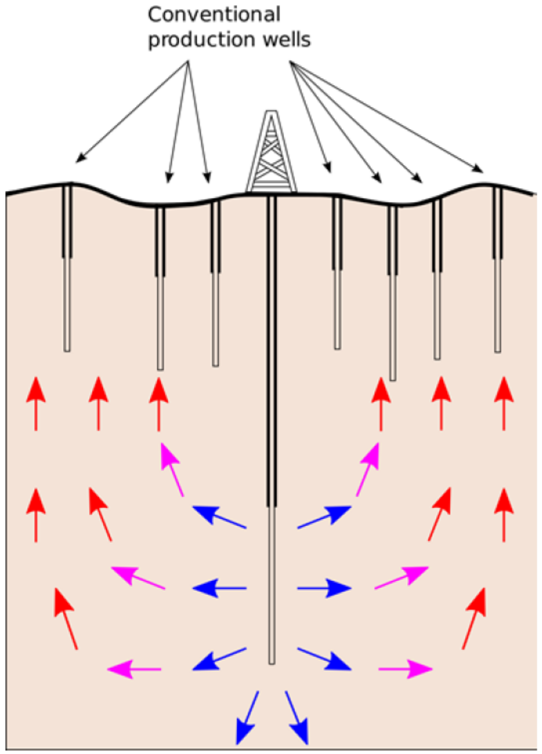
Horizontal cross-sections at z=4000m (MSL)

Play-fairway analysis

Geothermal PFA

- Heat source
- Permeability
- Fluid
- Seal (SC/SH)





Hybrid strategy for SC/SH systems (from Gunnarsson et al., 2022)

- Developed mainly in the US (Pauling et al., 2023)
- Extended to SC/SH systems (Kolker et al., GRC, 2022)
- Poux and O'Brien (2020)

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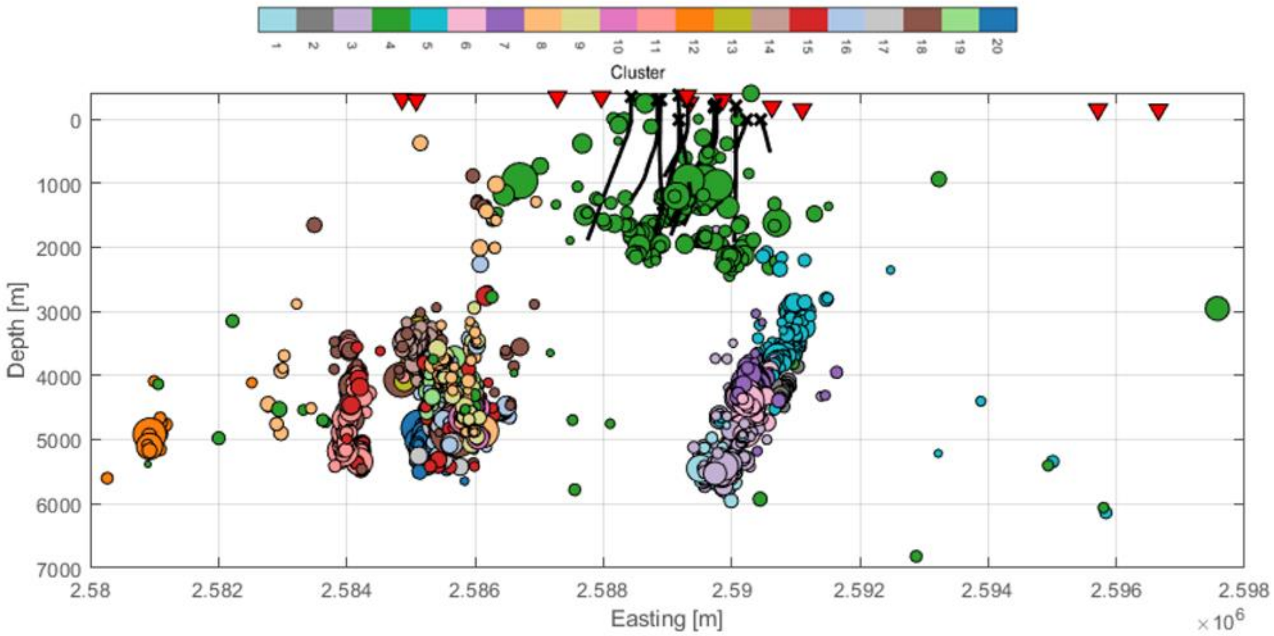
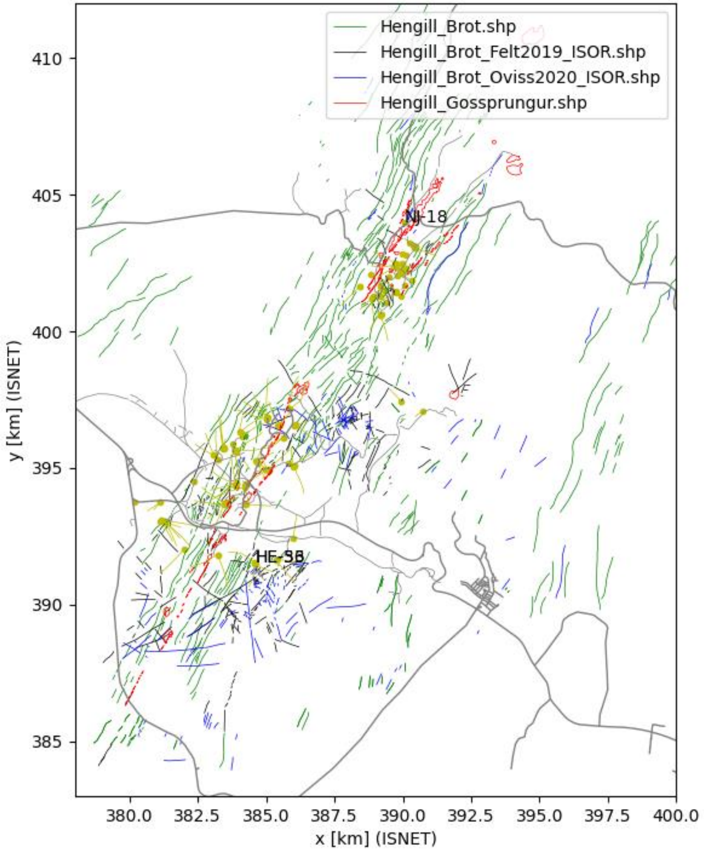
Faults and fissures

- Fault density and distance to faults
- Fault intersections and fault-fissure intersections

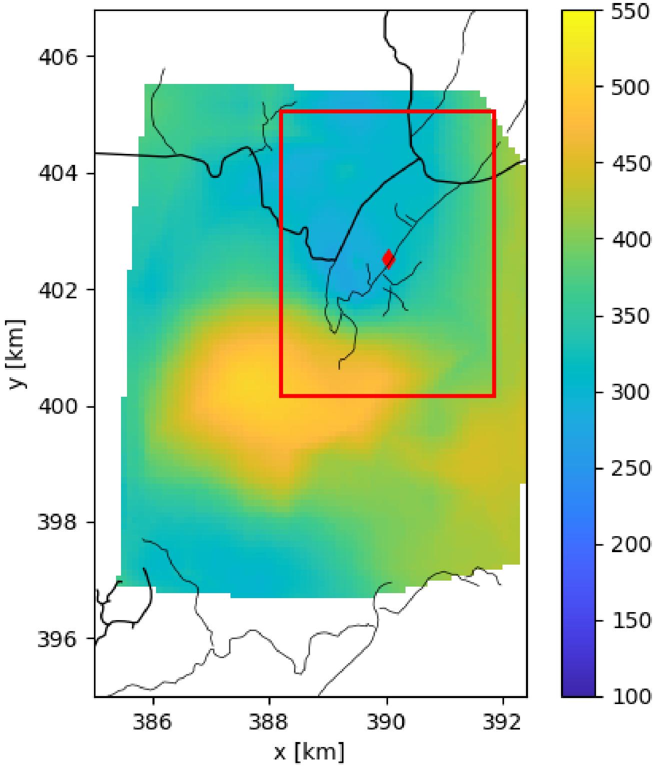


Microseismicity (figure from Goertz-Allmann et al., GRC, 2023)



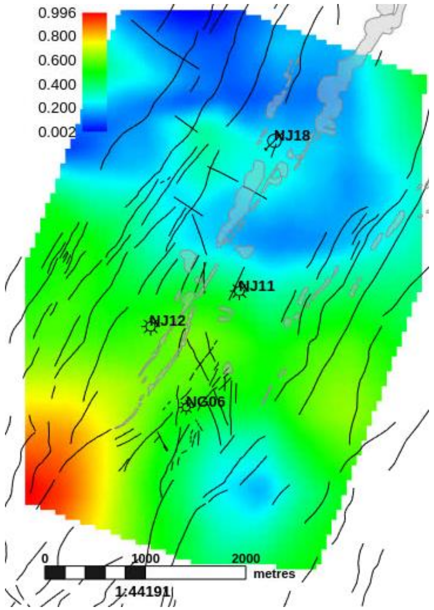
Faults and fissures (data from OR/ISOR)

Play-fairway analysis (Nesjavellir)

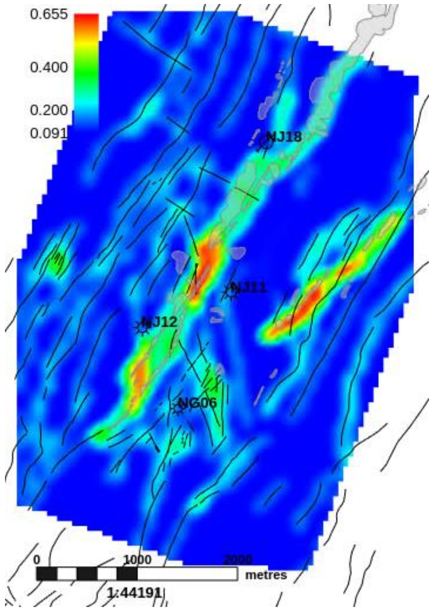


Posterior mean temperature [ºC]

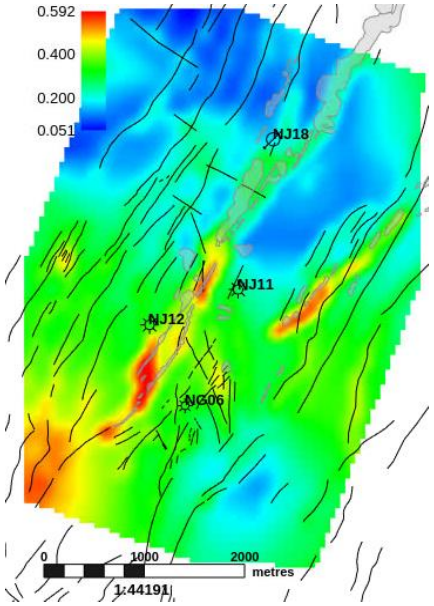
Favorability maps at z=4000m (MSL)



Heat favorability



Permeability favorability



Total favorability

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Conclusions

- Multigeophysical inversion (MGI) for geothermal exploration
  - Utilizing MT, seismic, (gravity), magnetics
- Bivariate inversion for temperature and/or porosity
- Demonstrated on field data and models from Hengill
- MGI used as part of PFA

Nesjavellit power plant

Acknowledgements

DEEPEN partnership:

- Amanda Kolker, Nicole Taverna, Hannah Pauling (NREL)
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- Pilar Sánchez-Pastor, Sin-Mei Wu (formerly ETH)
- Carsten F. Sørlie, Claudia Kruber (Equinor)

Others:

- Kenneth Duffaut, Arild Buland, Marcel Naumann, Bjørn M. Sæther (Equinor)
- Jo Eidsvik, Nathan Church, Geertje ter Maat (NTNU)

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- We thank DEEPEN partners for sharing field data and models from the Hengill geothermal area
- We thank Equinor and OR for permission to publish this work

- Thank you for your attention!

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