3D muon-tomography of an underground crack zone
inversion methodology and validation by drills

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Outline

- Crack zone imaging introdution
- Formulation of a Bayesian reconstruction algorithm
- Inversion results on a real case („Királylak” meaurements)
- Outlook

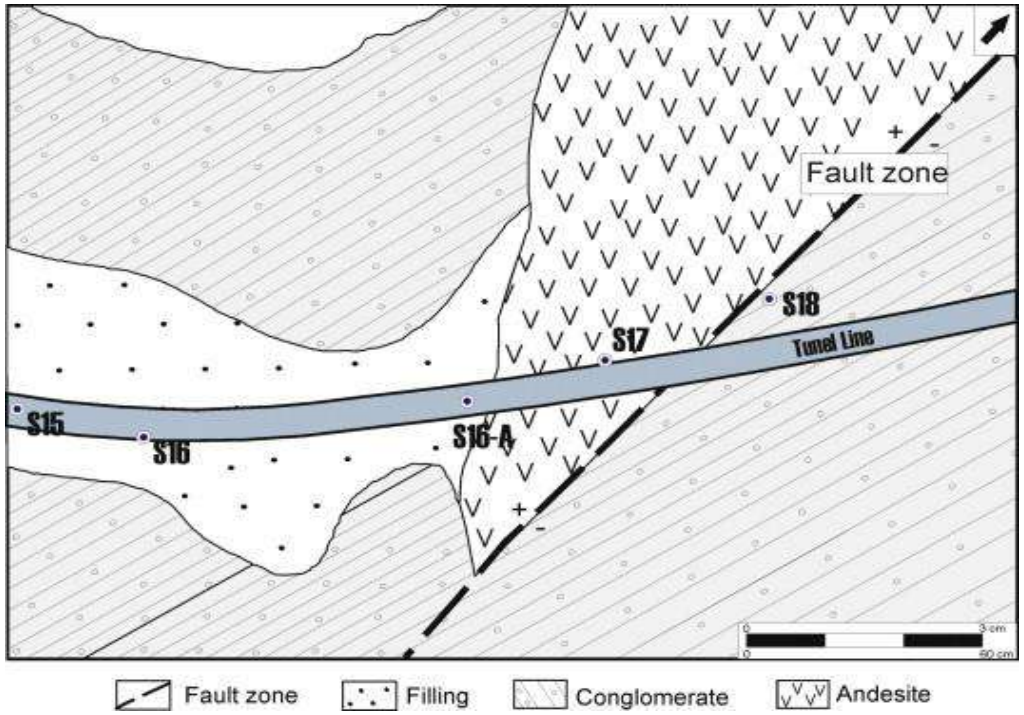
Why crack zone imaging is interesting

- Crack zones are low density regions (created by termohydraulic erosion or tectonic movement)
- Dangerous for the civil infrastructure of construction

Landslide (image: NASA)

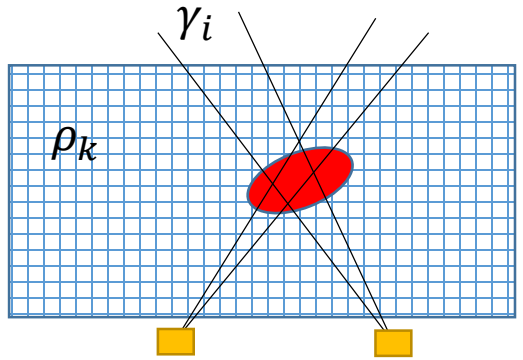
Tunnelling through fault zone

2013 Kun, Onargan. Tunn. Undergr. Space Technol. **33**, 34-45.



Mathematical background of density reconstruction

- Base equation of the (linearized) inverse problem: $\boldsymbol{\gamma} = \mathbf{F}\boldsymbol{\rho}$ (density-lengths; Jacobian matrix; density voxel vector)



- Issues: imperfect mapping to voxel grid, underdetermination, limited detector positioning, inhomogeneous statistics, systematic uncertainties, etc…
- Regularization: Bayes criterion, Maximum Likelihood, linearization, 2D simplification
  → parameter bias and artifacts, but the back-projection of the measurement uncertainty weights can be used for filtering. Weigth matrix: $\mathbf{W}$
- Functional to be minimized follows from the weighted least squares:

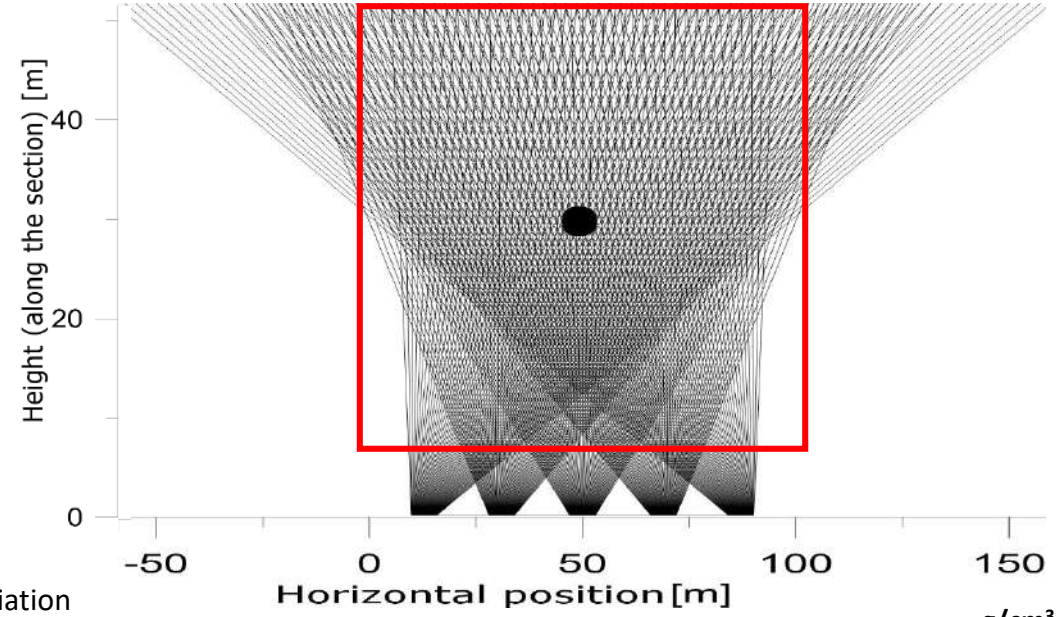
$$Q^{(0)} = Q_{\boldsymbol{\gamma}}^{(0)} + Q_{\boldsymbol{\rho}}^{(0)} = \left(\boldsymbol{\gamma} - \mathbf{F}\boldsymbol{\rho}\right)^T \mathbf{W}_{\gamma} \left(\boldsymbol{\gamma} - \mathbf{F}\boldsymbol{\rho}\right) + \left(\boldsymbol{\rho} - \boldsymbol{\rho}^{(0)}\right)^T \mathbf{W}_{\boldsymbol{\rho}}^{(0)} \left(\boldsymbol{\rho} - \boldsymbol{\rho}^{(0)}\right)$$

Maximum Likelihood — Bayes parameters to be fitted

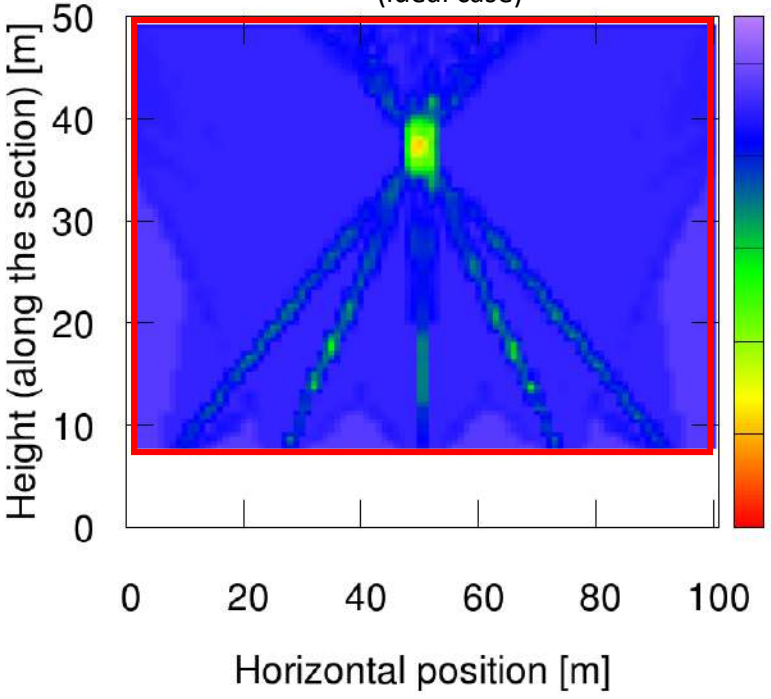
- Estimation of the density distribution: $\boldsymbol{\rho}^{(1)} = \left(\mathbf{R} + \mathbf{W}_{\boldsymbol{\rho}}^{(0)}\right)^{-1} \left(\mathbf{F}^{\mathbf{T}} \mathbf{W}_{\gamma} \boldsymbol{\gamma} + \mathbf{W}_{\boldsymbol{\rho}}^{(0)} \boldsymbol{\rho}^{(0)}\right)$
  where $\mathbf{R} = \mathbf{F}^T \mathbf{W}_{\mathbf{d}} \mathbf{F}$ is the Fischer matrix

Test on synthetic data

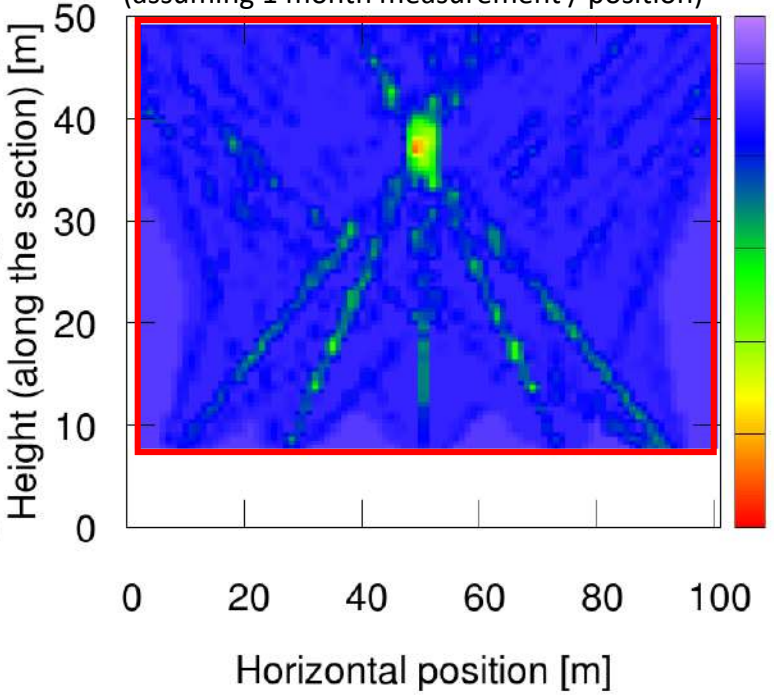
- 5 underground measurement assumed
- 3 m diameter cavity in the middle



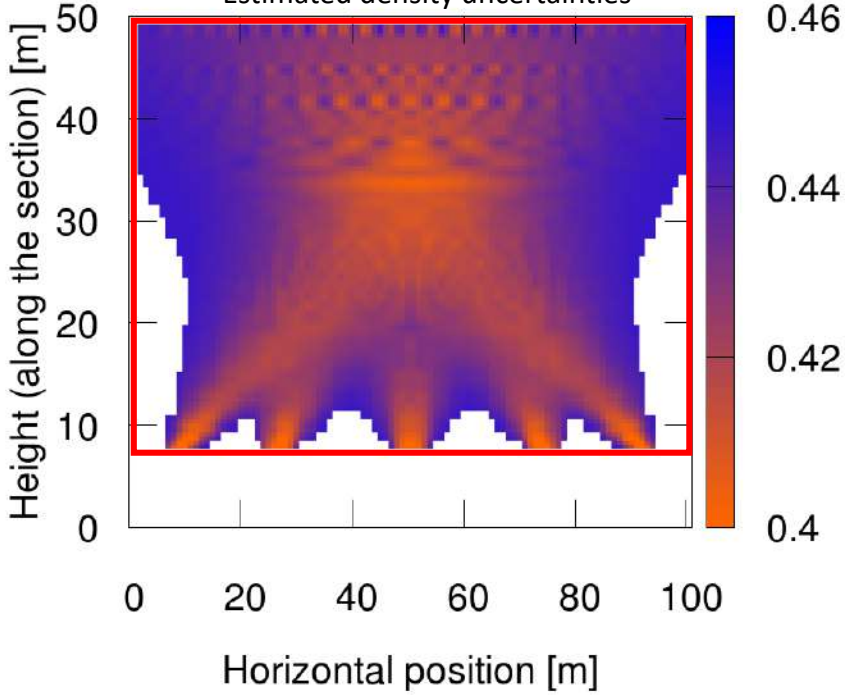
Density values
(ideal case)



Density values + statistical deviation
(assuming 1 month measurement / position)

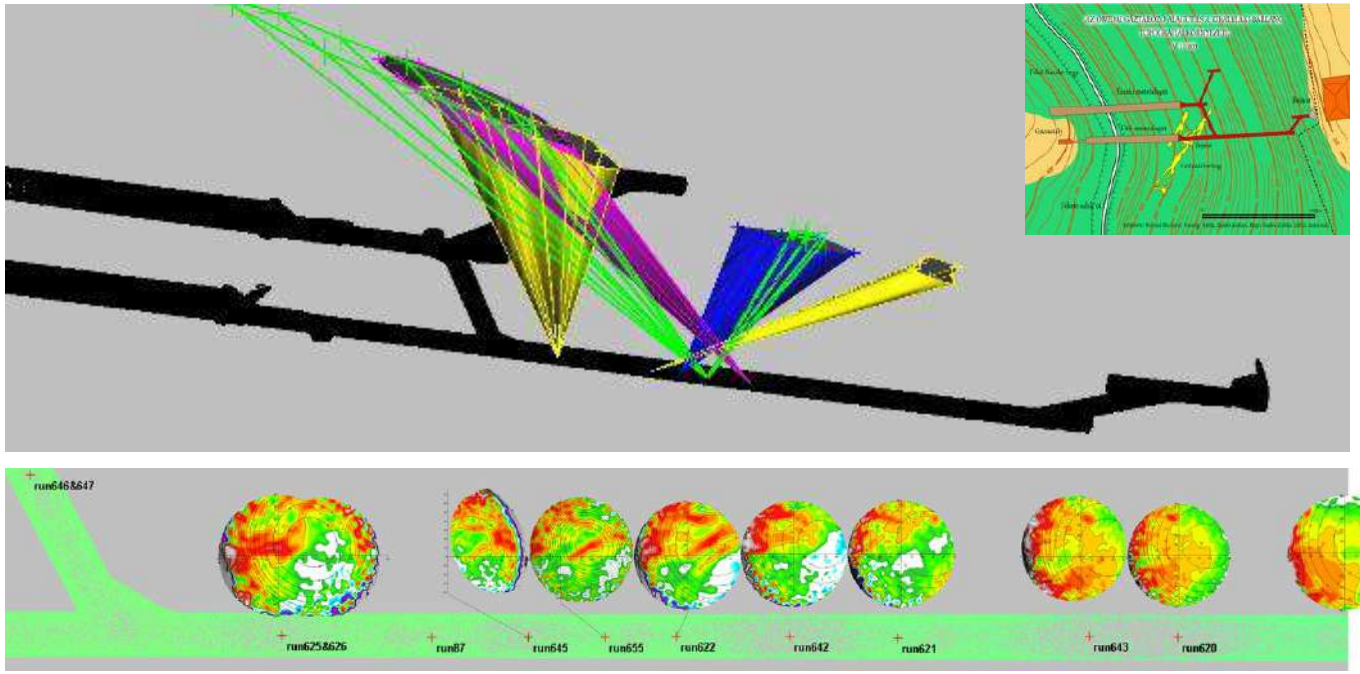


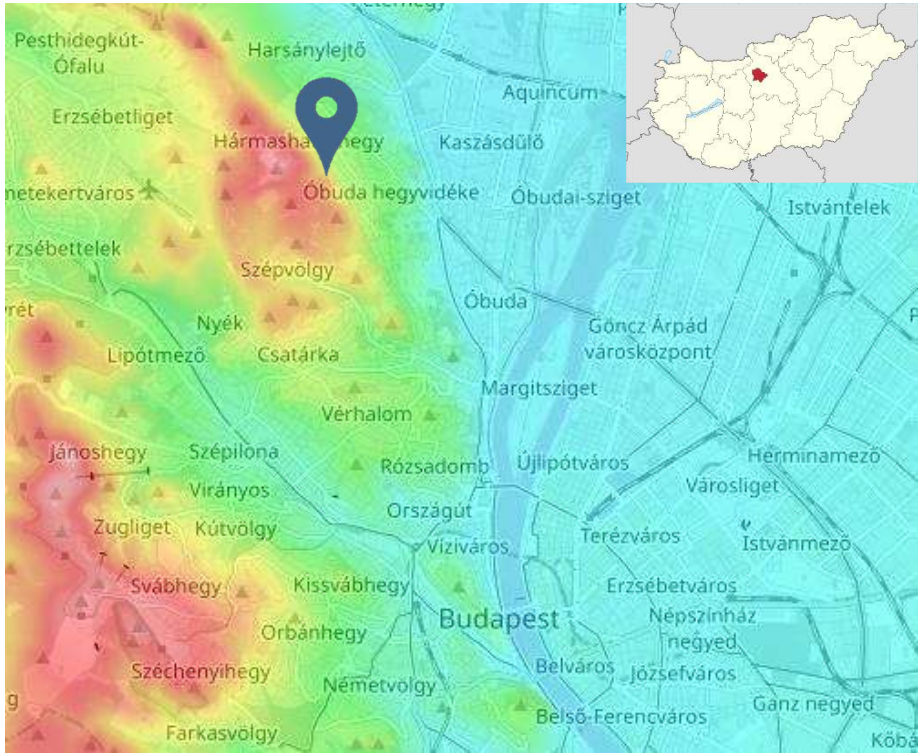
Estimated density uncertainties



Imaging of crack zones in Budapest from the „Királylaki” tunnels

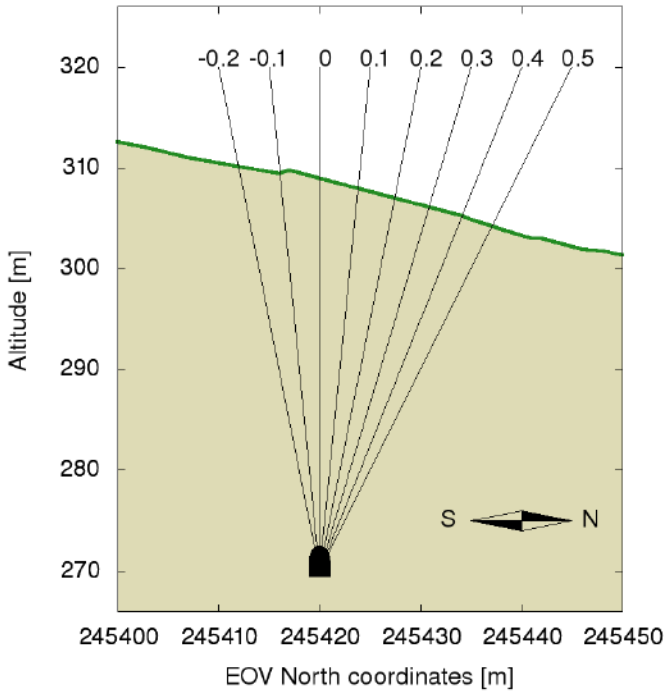
- Multiple anomalies found -> cavities?
- Beginning with „triangulation”
- Where to drill? (closest point of the anomalies)

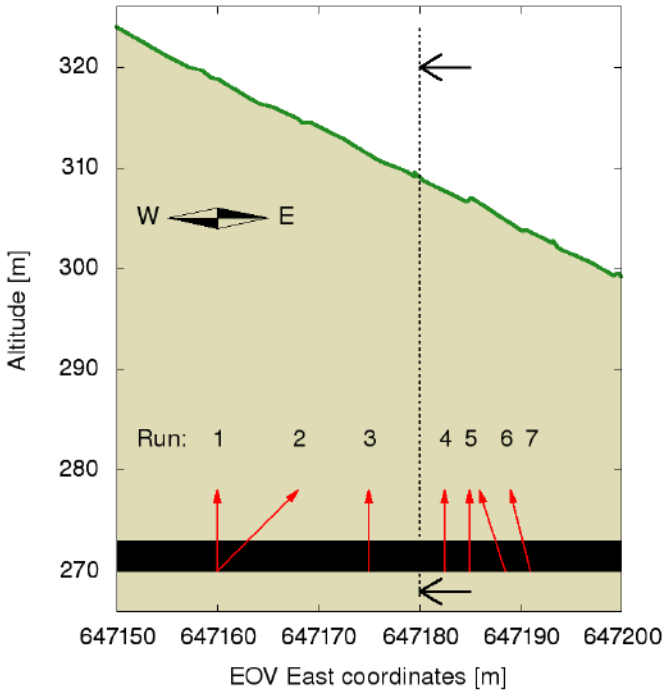


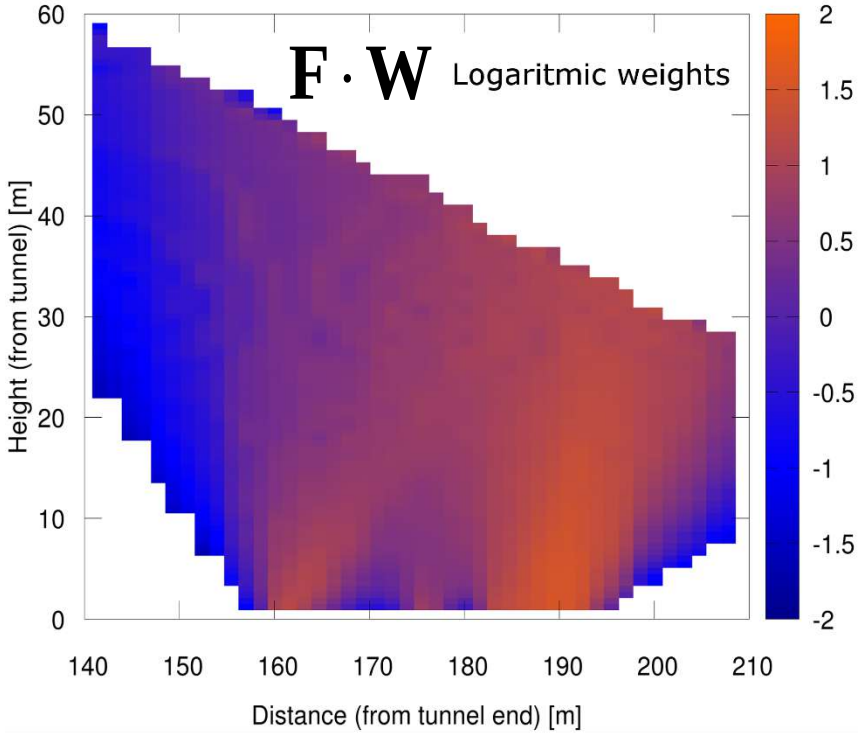


Configuration of the measurements

- Bayesian inversion applied on the measurements
- Positions along a straight line -> 2+1D slicing (stability, convergence, comp. time)

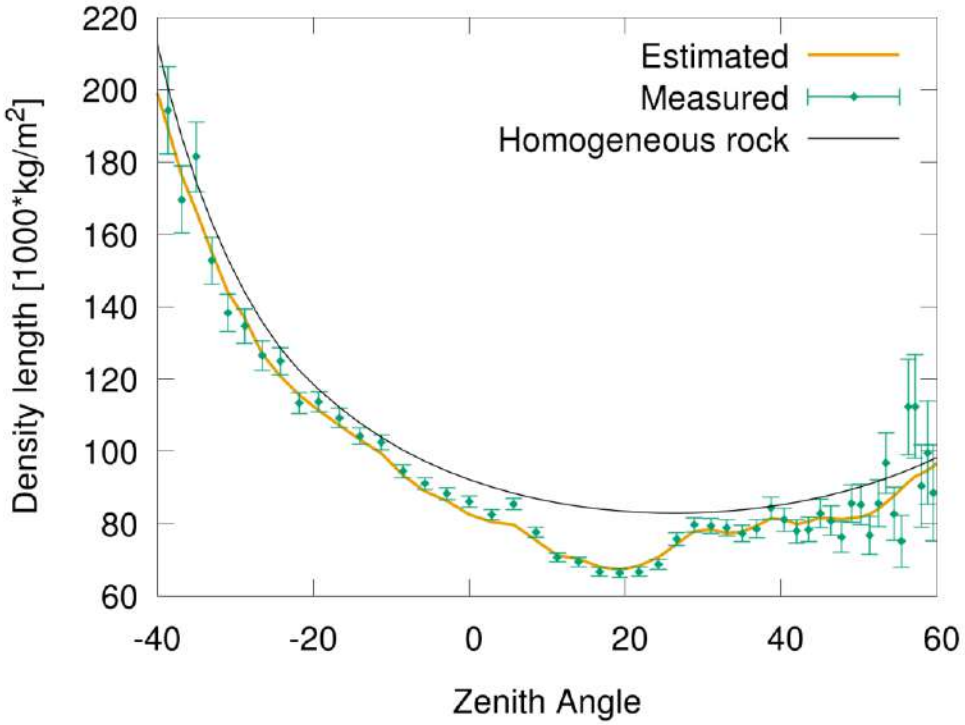


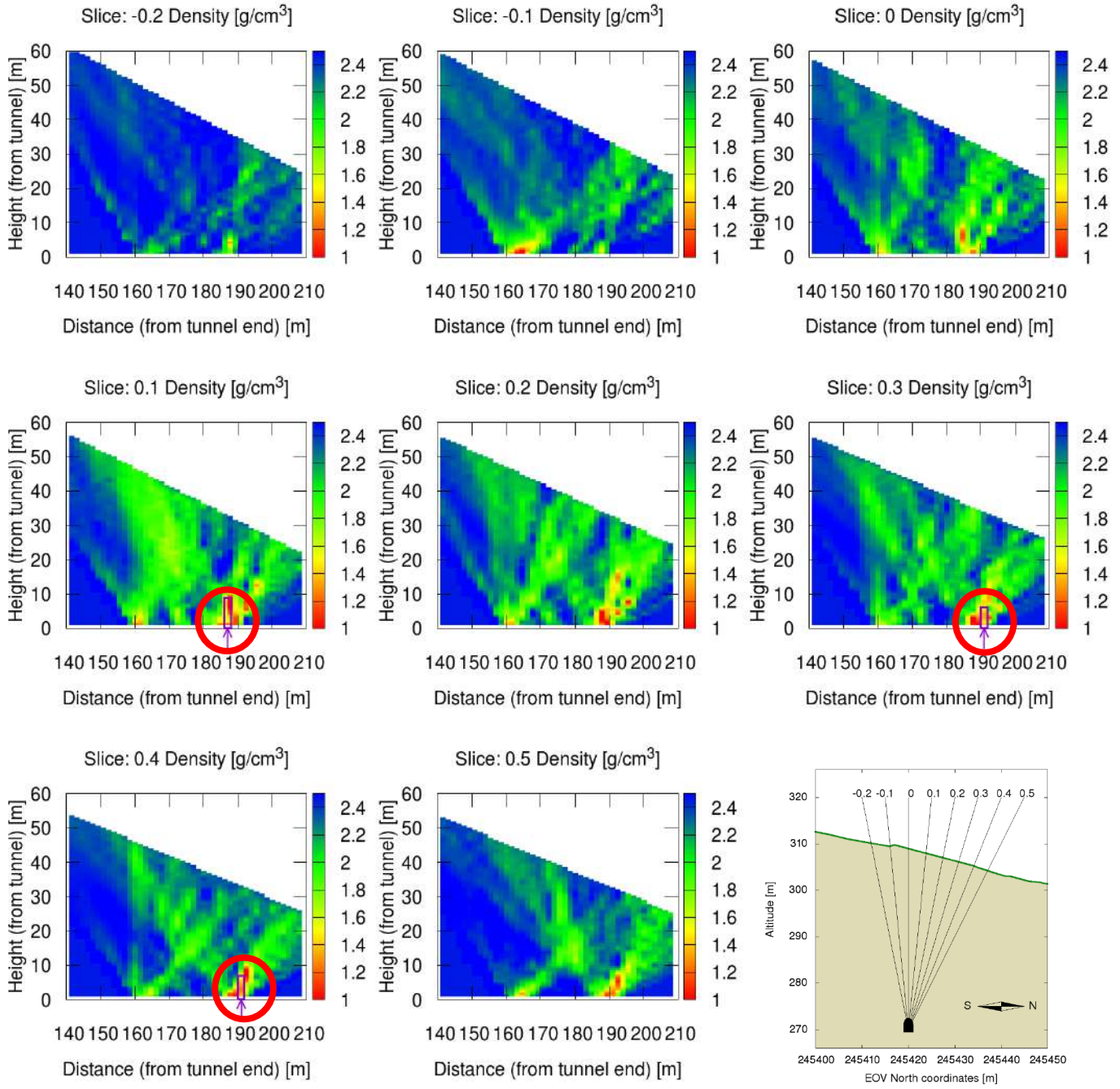




Inverse solution

- Density distribution results showing significant anomalies crosswise
- No anomaly in south (-0.2) -> homogeneous density
- Validation drills indicated

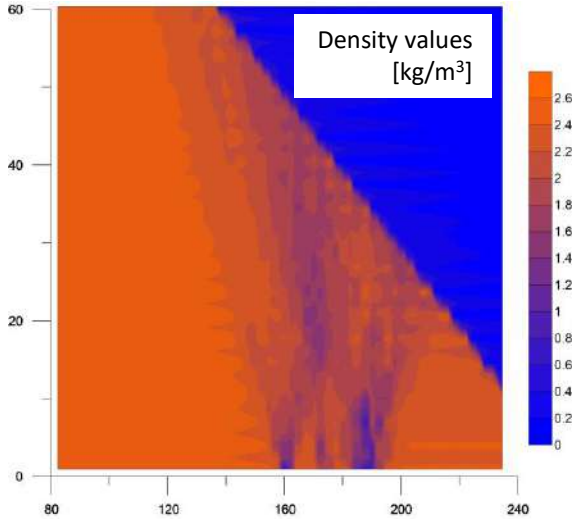




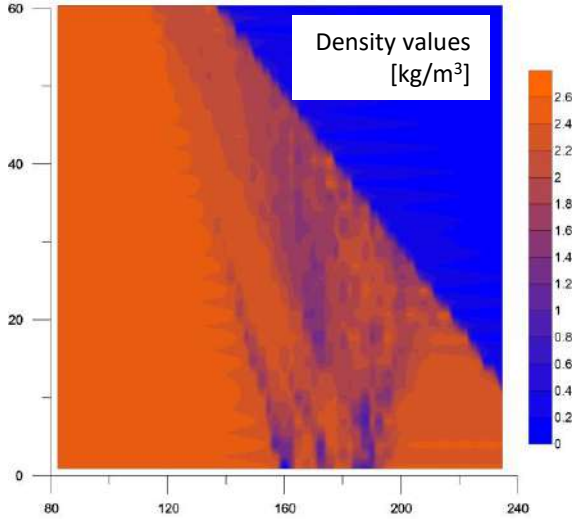
Parameter distribution and sensitivity

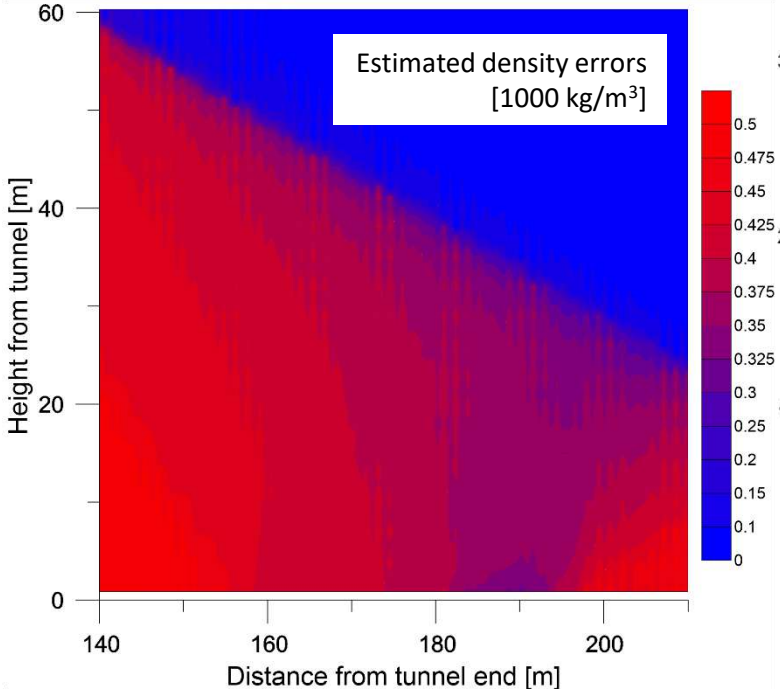
- Estimated density uncertainty converges to the Bayesian canstraint (in low-sensitivity region)
- The distribution of density values peak around the assumed solid rock density (extra humb due to the anomalies)
- The distribution of estimated errors (residual distribution) has an almost zero mean Gaussian shape distribution (minimal Bayesian bias)
- Results are not sensitive to the Bayes condition

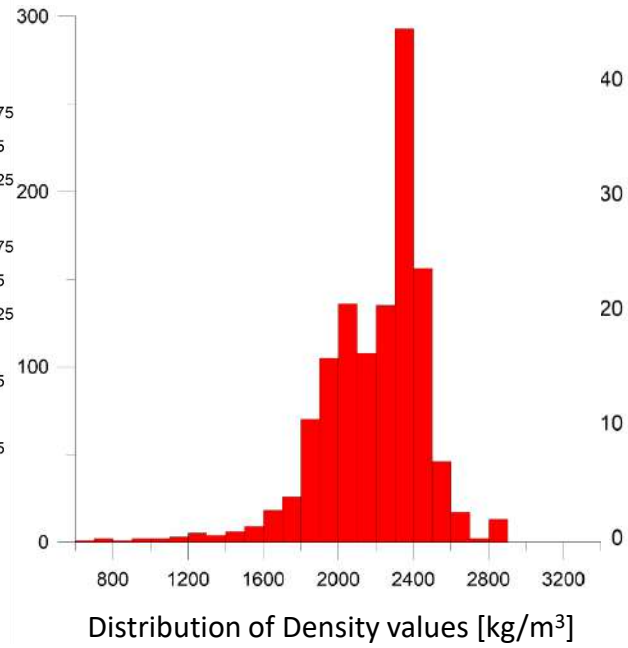
Bayes condition: 5

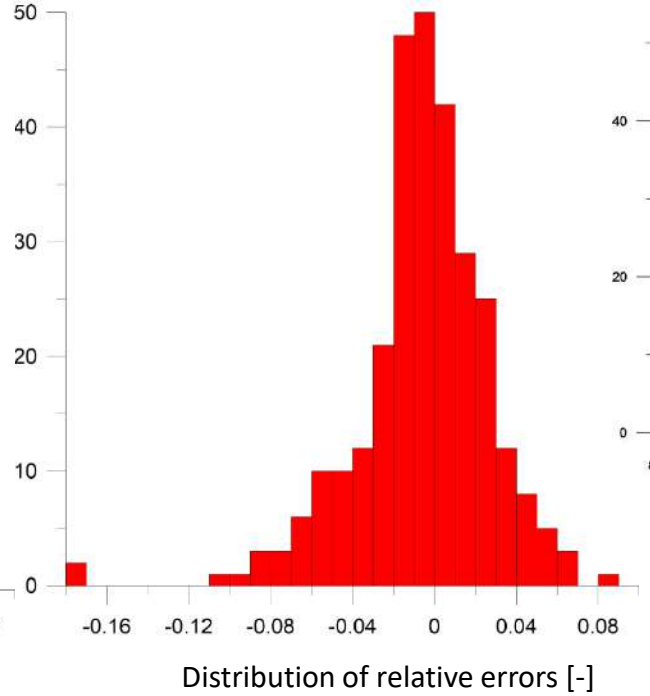


Bayes condition: 1



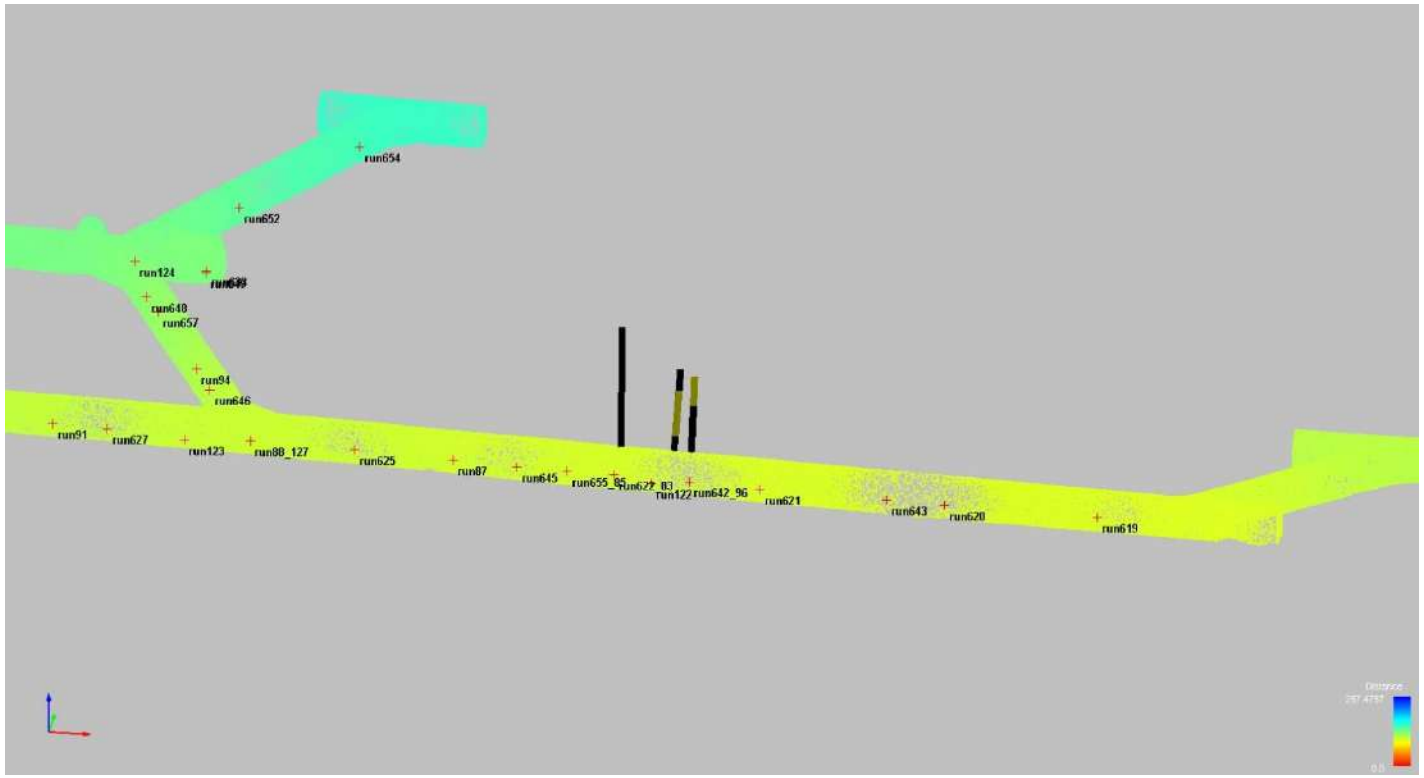




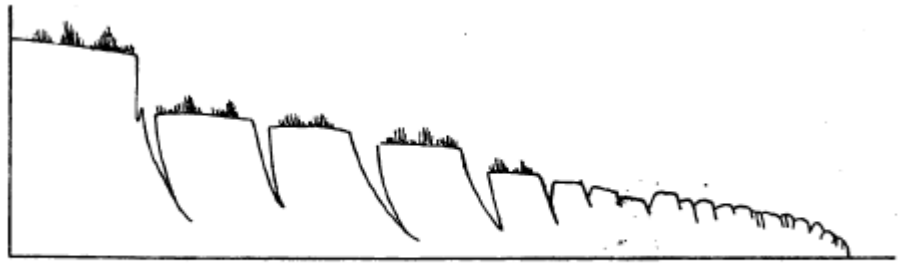


Validation by core drills

- Exploratory drills (5—10 m length) into the anomalies
- The altered dolomite powder found (~1.8 g/cm^3) besides the base rock (~2.6 g/cm^3)

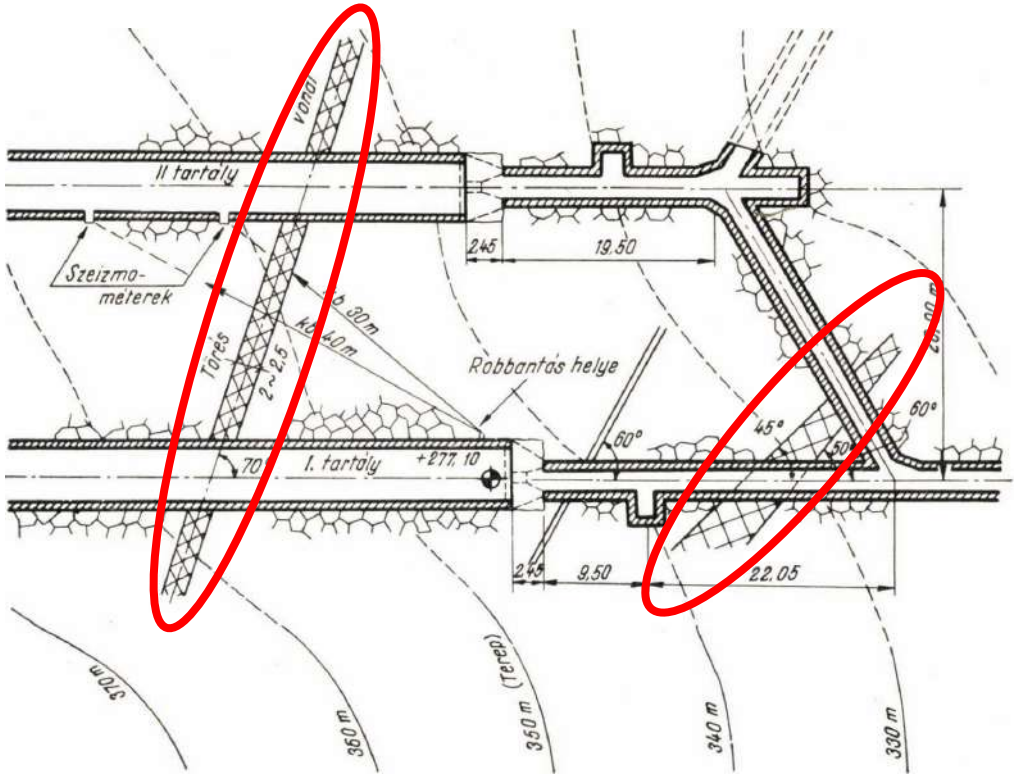


History and perspectives of the results

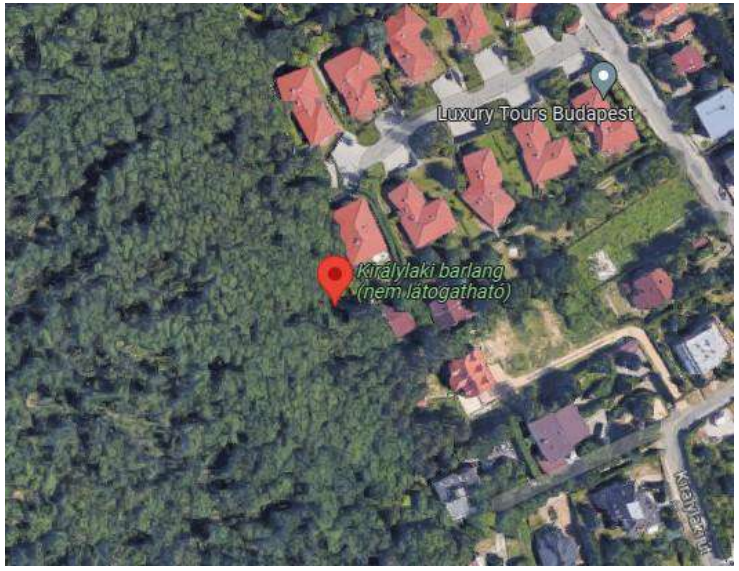


113. ábra. **Hungarian geological book from 1929 reported landslides in the region**

Schafarzik, Vendl: Geológiai kirándulások Budapest környékén



Secret documentation from the 60s for the construction of a gas reservoir

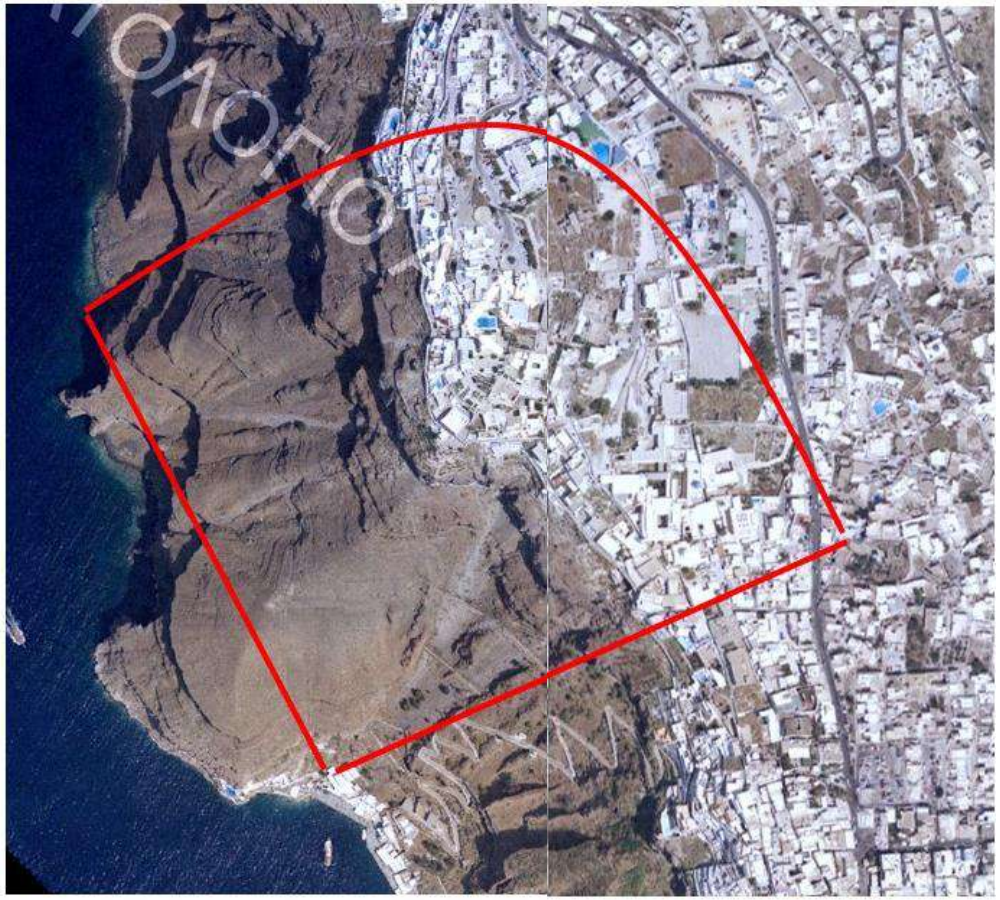


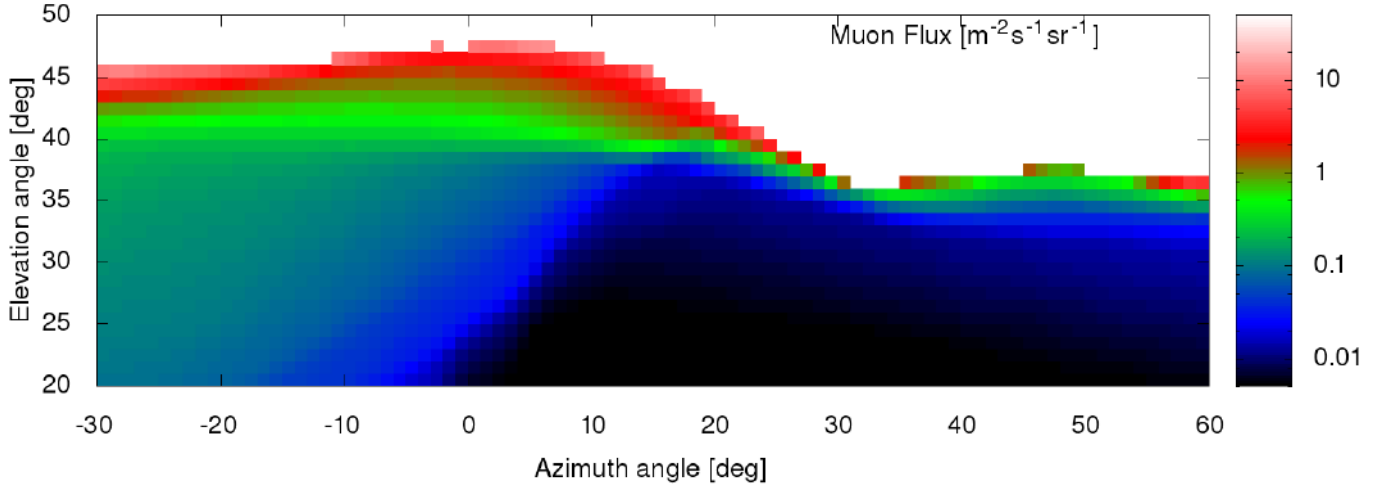
New housing estates next to the entrance of the Királylaki tunnels

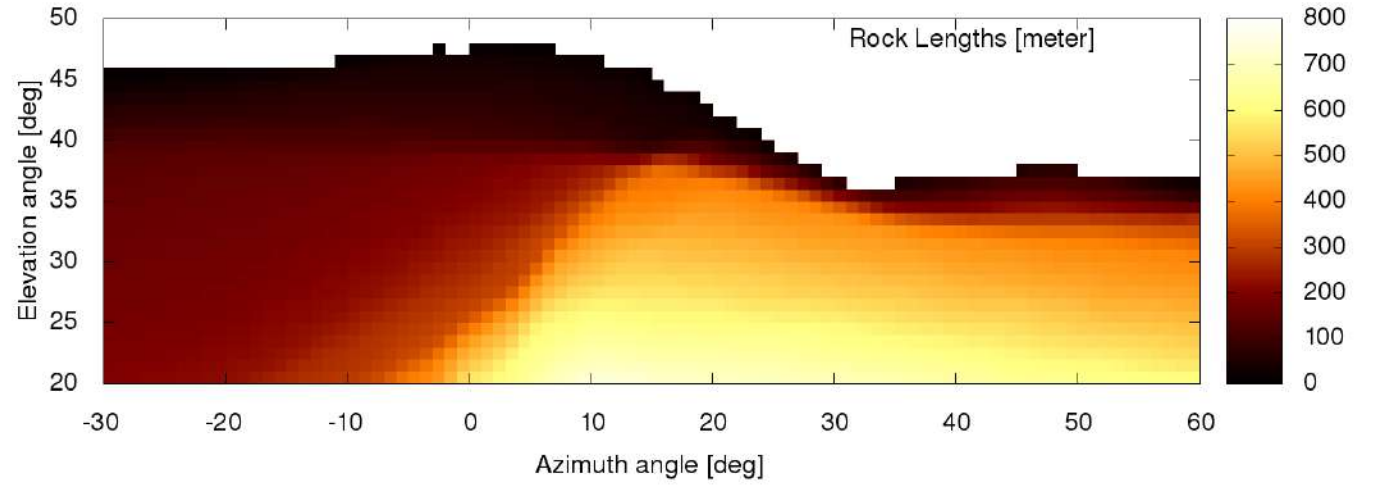
->

Possibility of danger should be re-examined?

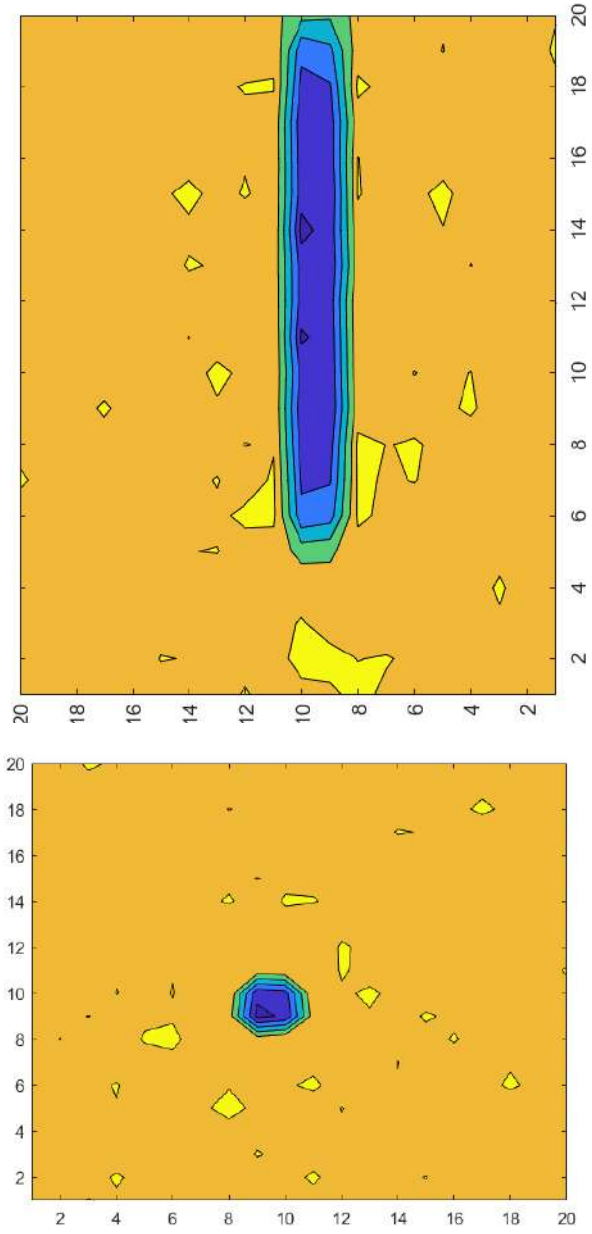
Further possible landslide imaging project: Santorini (Greece)



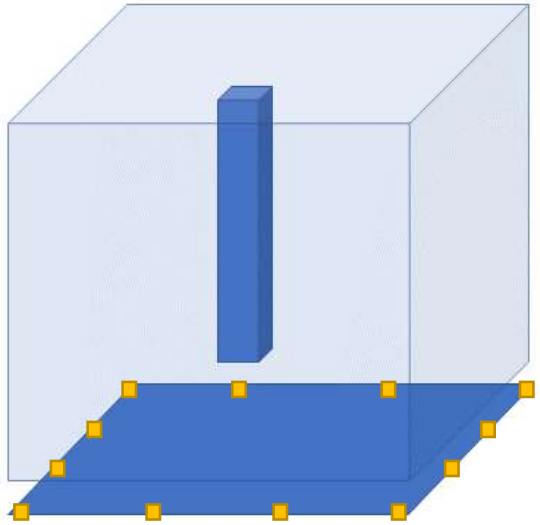


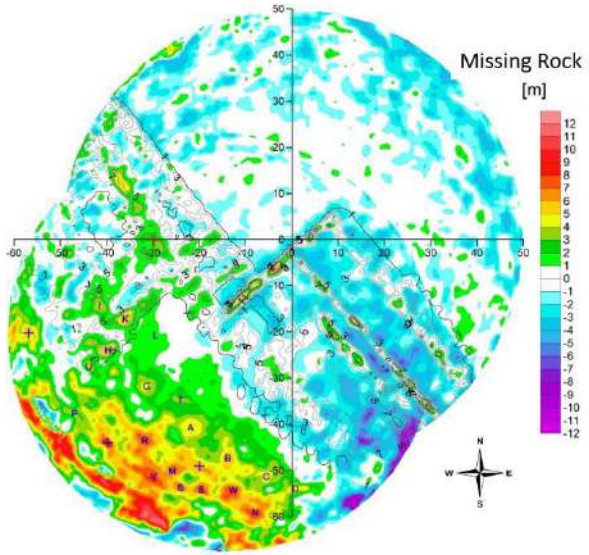


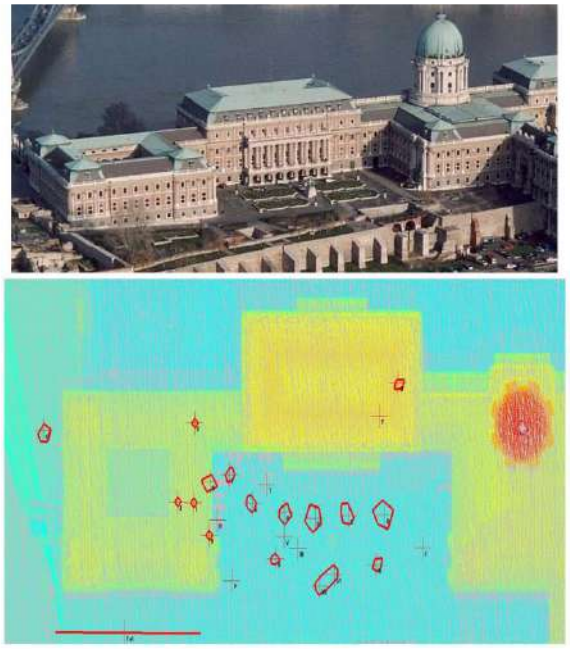
Towards 3D inversion and further applications



- Direct 3D inversion implementation on the way
- Test on an ideal case of a vertical shaft
- Inversion results (central slices)



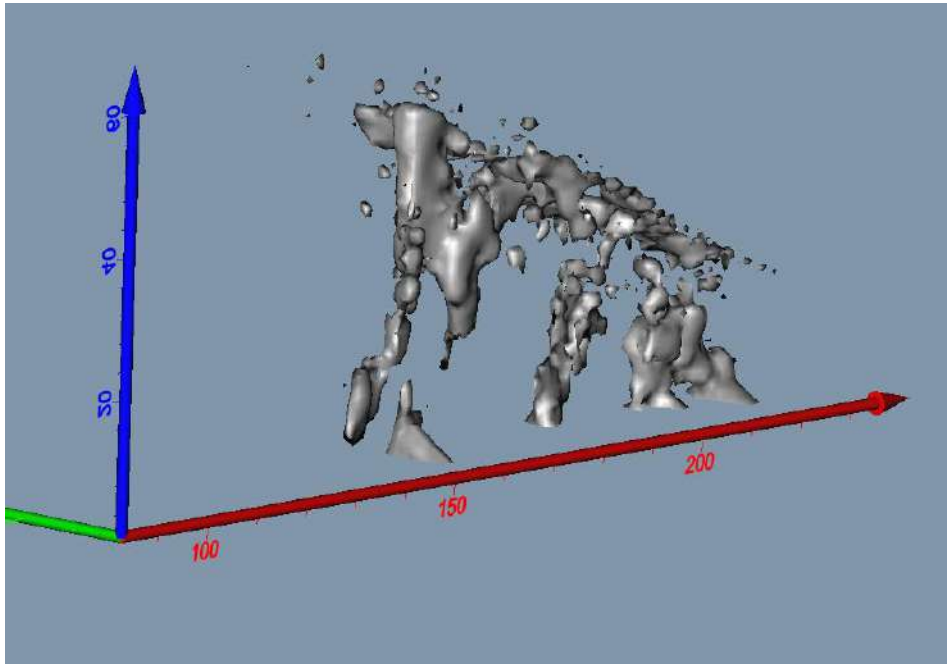


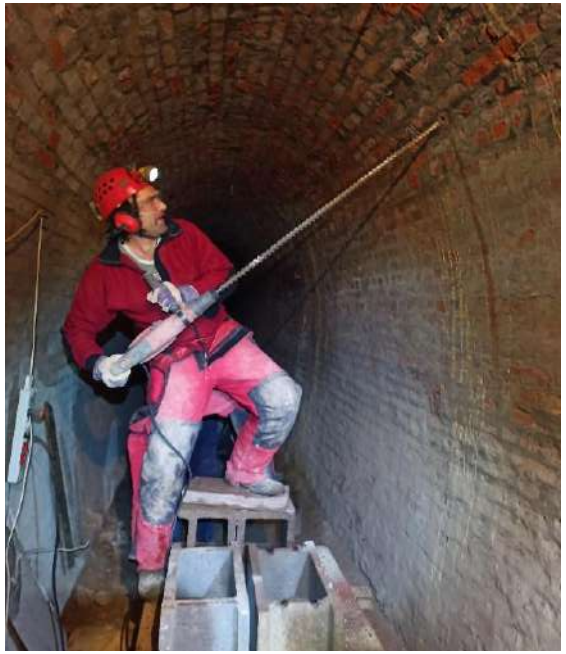


Applications expected i.a. Buda Castle anomalies
(see G. Surányi's presentation)

Summary

- Crack zone imaging important for civil engineering (landslides, tunneling)
- Possible by muography („Királylak” measurement case, validated by drills)
- A 3D inversion method demonstrated (applying Maximum Likelihood and Bayesian approach)
- Paper submitted by L. Balázs et al.





Thank you for your attention!

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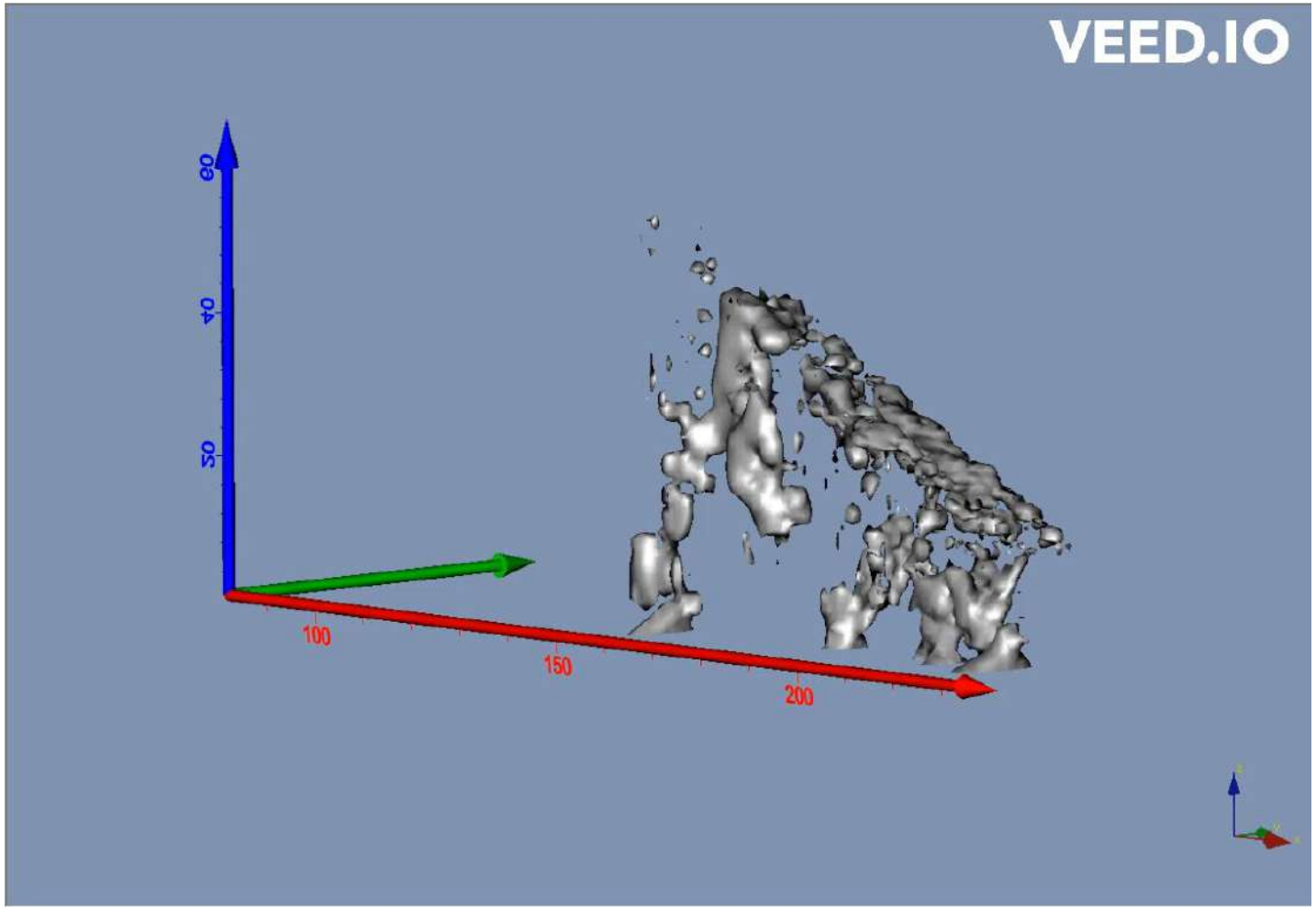
- Hungarian OTKA, no. FK-135349
- H2020 MSCA RISE, INTENSE 2018, no. 822185

Backup slides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Point-response mapping