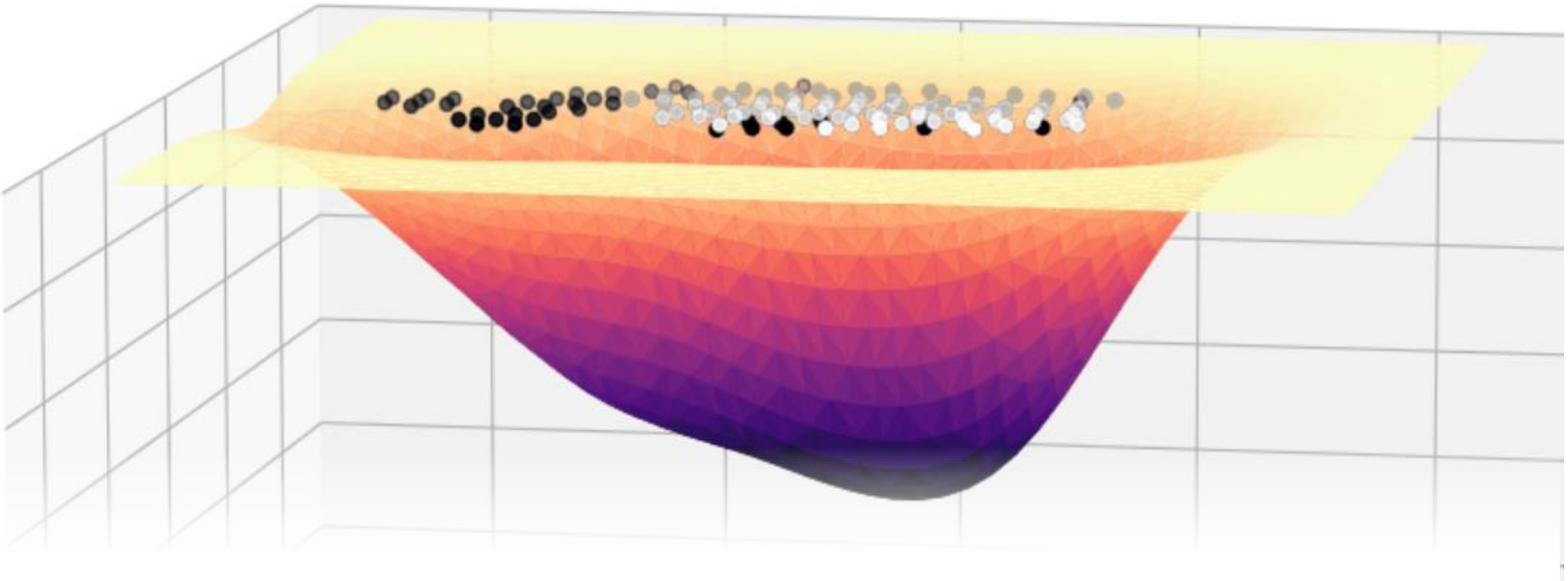


Derivation of a geophysical source model for gas storage cavern convergence related surface displacements from ten years of InSAR at the storage cavern site Epe (Germany)

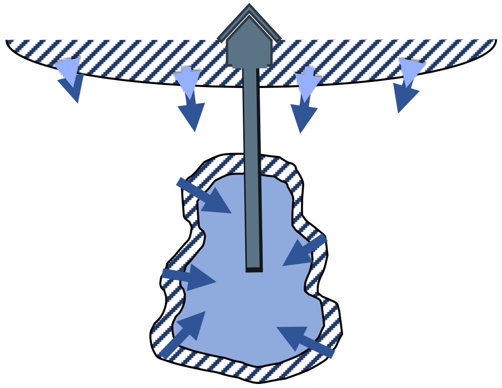
Alison Seidel, Markus Even, Hansjörg Kutterer, Malte Westerhaus

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages

Introduction and Motivation



Subsidence monitoring:

- Storage caverns in salt rock experience convergence that translate to surface subsidence
- Surface deformation has to be closely monitored to prevent damage to infrastructure
- Measurement with various geodetic methods subsidence monitoring: (Levelling, GNSS, MT-InSAR)

Cavern displacement modelling:

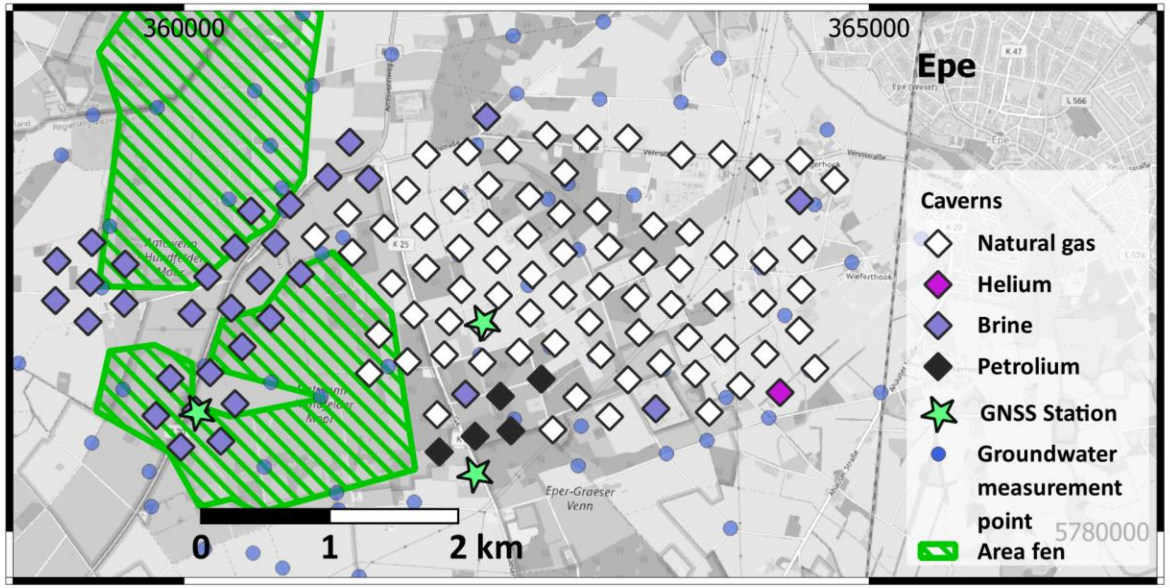
- Predict displacements in all three displacement vectors or long term trends
- Conventional model parametrization:
  - Spatial: circular subsidence bowl
  - Temporal: linear subsidence rates with seasonal variation

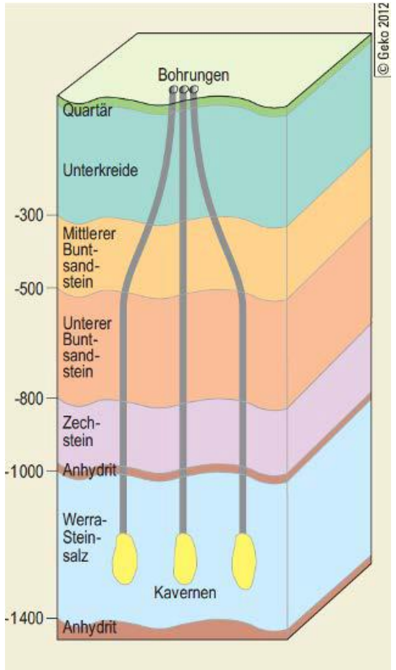
Why derive a more complex model? Or model at all?

Area of study:

- Storage cavern field Epe (NRW)

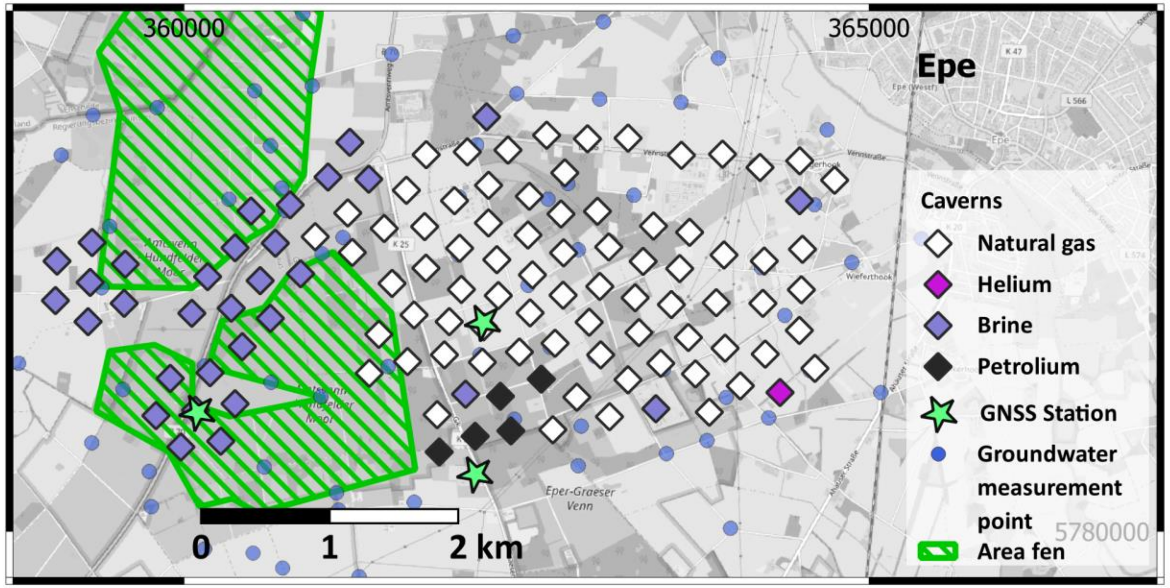
Area of study: Epe storage cavern field

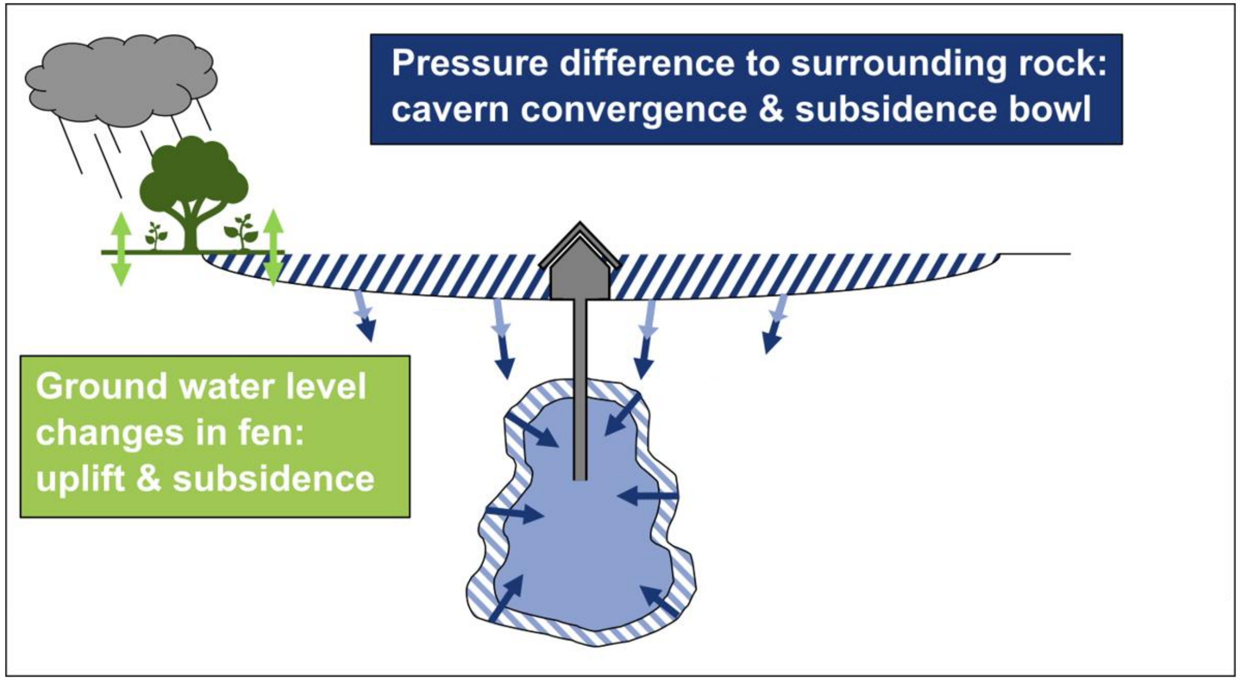




- Cavern storage field Epe (Salt layer: Zechstein)
- Northwestern Germany
- 114 Caverns, Depths about 1100 m
- Gas storage caverns, oil storage caverns, brine production

Epe storage cavern field



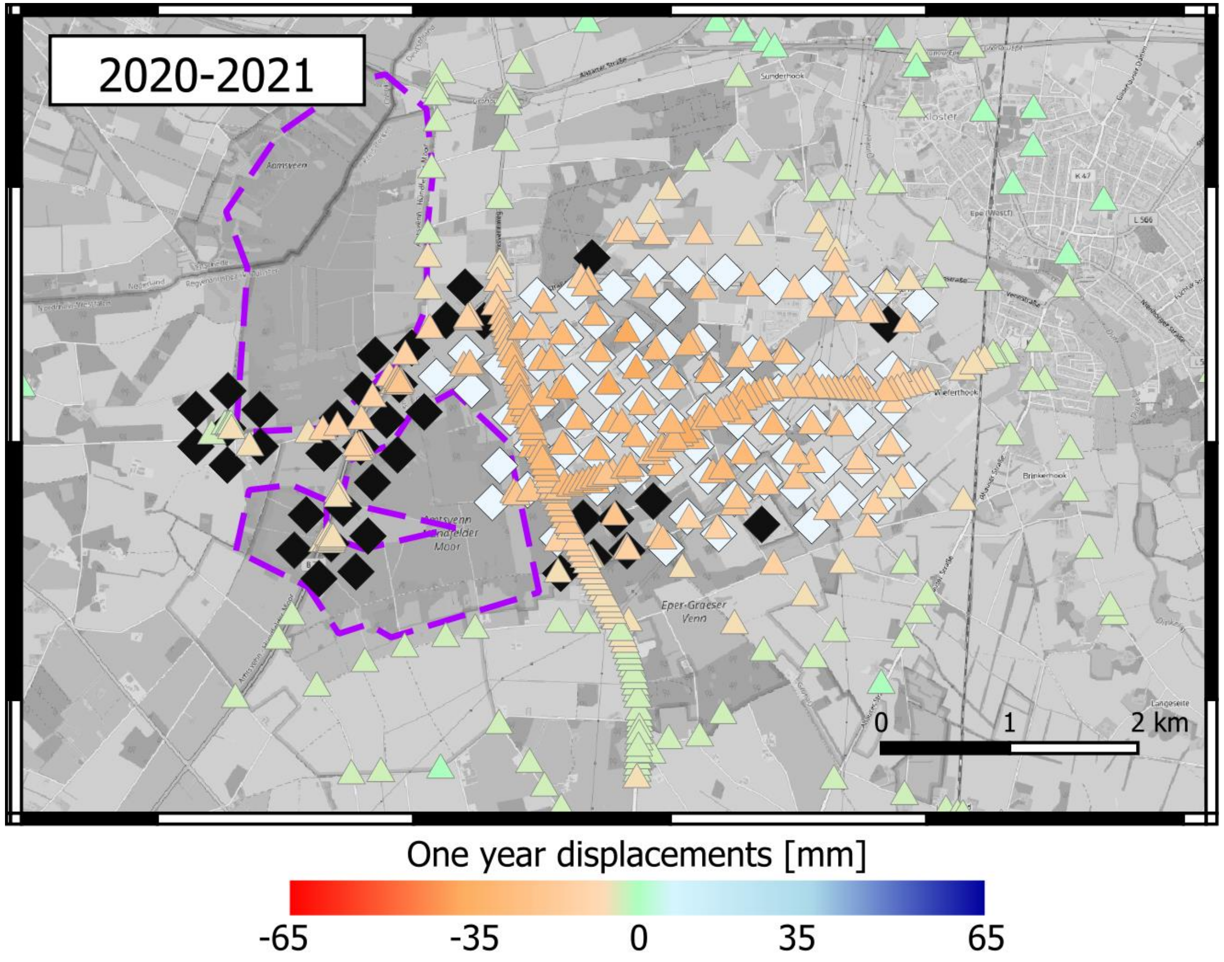


- Additional strong surface displacement source in Epe:
  - Fen in the western field
- Seasonal displacements related to groundwater
- Groundwater measurements available throughout the cavern field

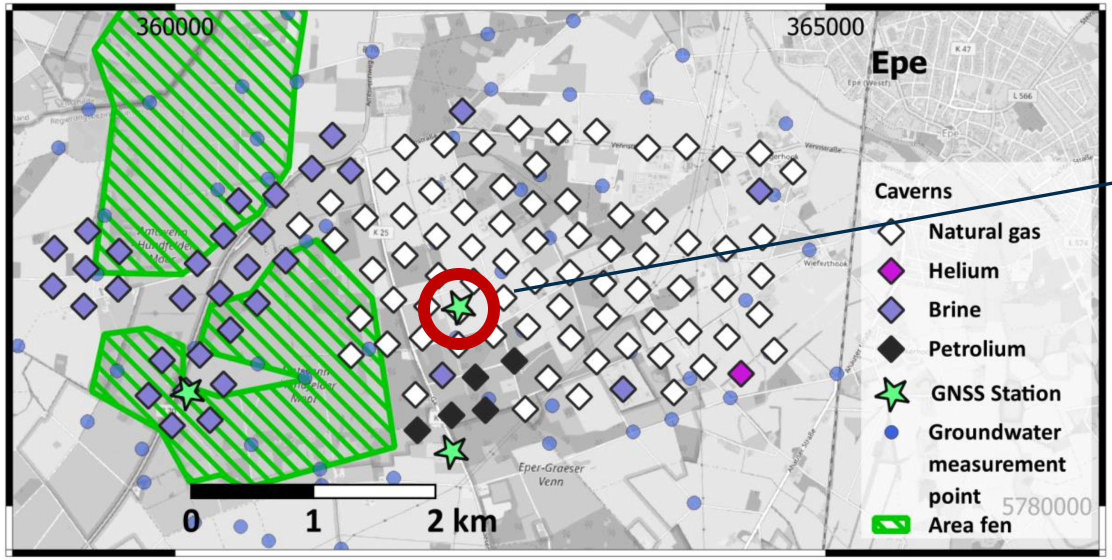
How to identify if deformation is caused by caverns or groundwater?

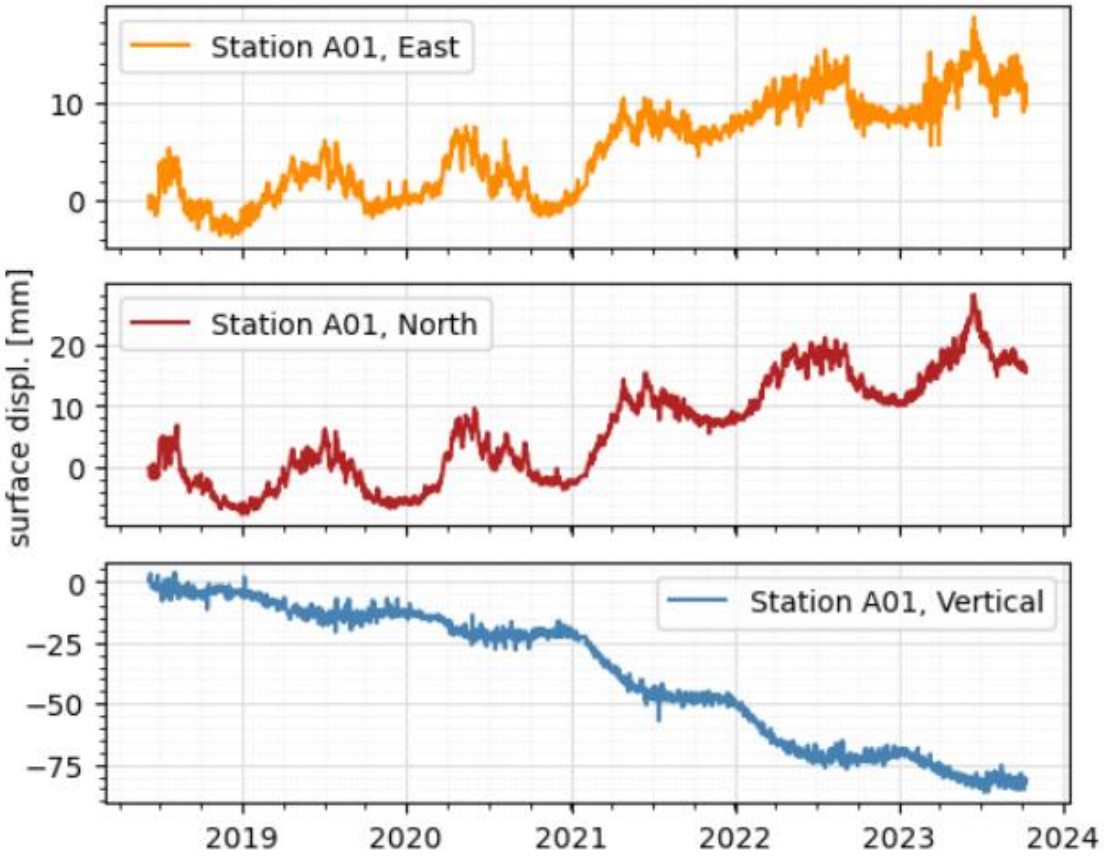
Monitoring: Levelling

- Annual leveling campaigns in early summer
- Dense spatial coverage
- Measurements on roads and infrastructure
- Center and amount of subsidence changes significantly depending on the year



Monitoring: GNSS

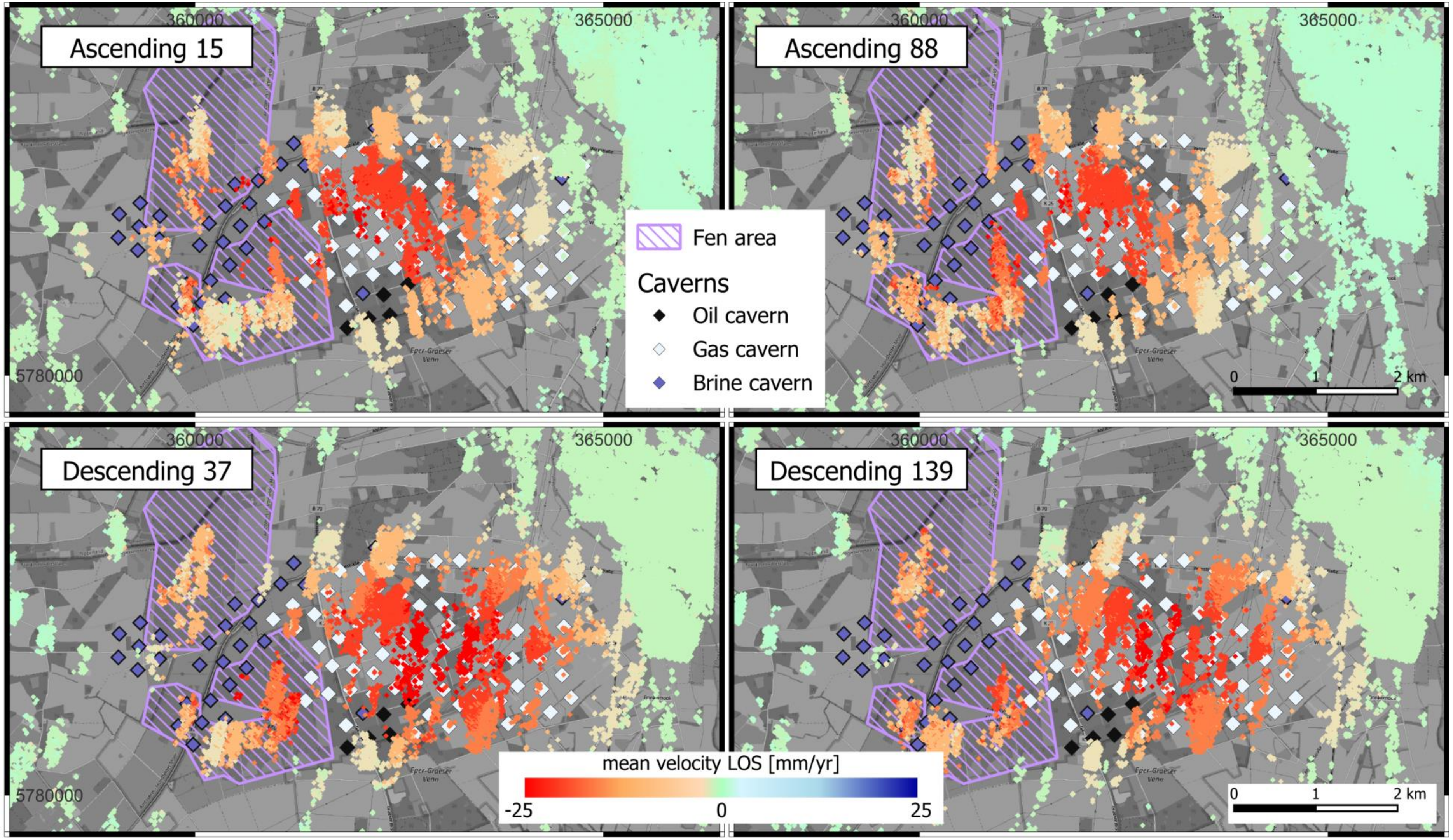




- Three GNSS stations on infrastructure
- Local reference station
- High temporal resolution, thee component displacements
- Distinct cyclic pattern and subsidence trend

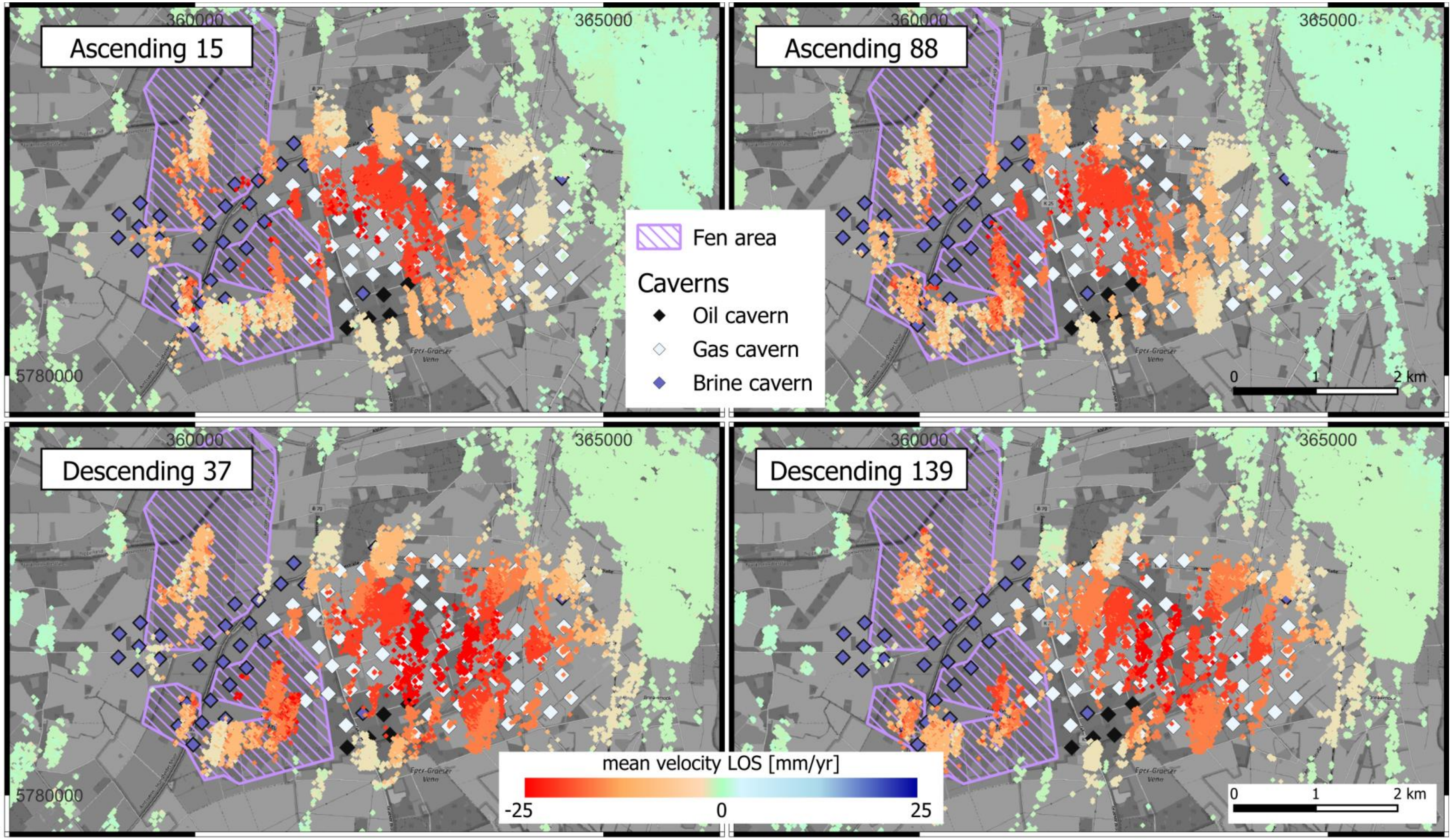
Monitoring: InSAR

- Sentinel-1 SAR C-band data from 2015-2025
- Four tracks:
  2 ascending, 2 descending
- Time series processing:
  Persistent Scatterers (PS) & Distributed Scatterers (DS)
- Processing:
  StaMPS based and modified SqueeSAR-like DS algorithm by
  Even, 2019



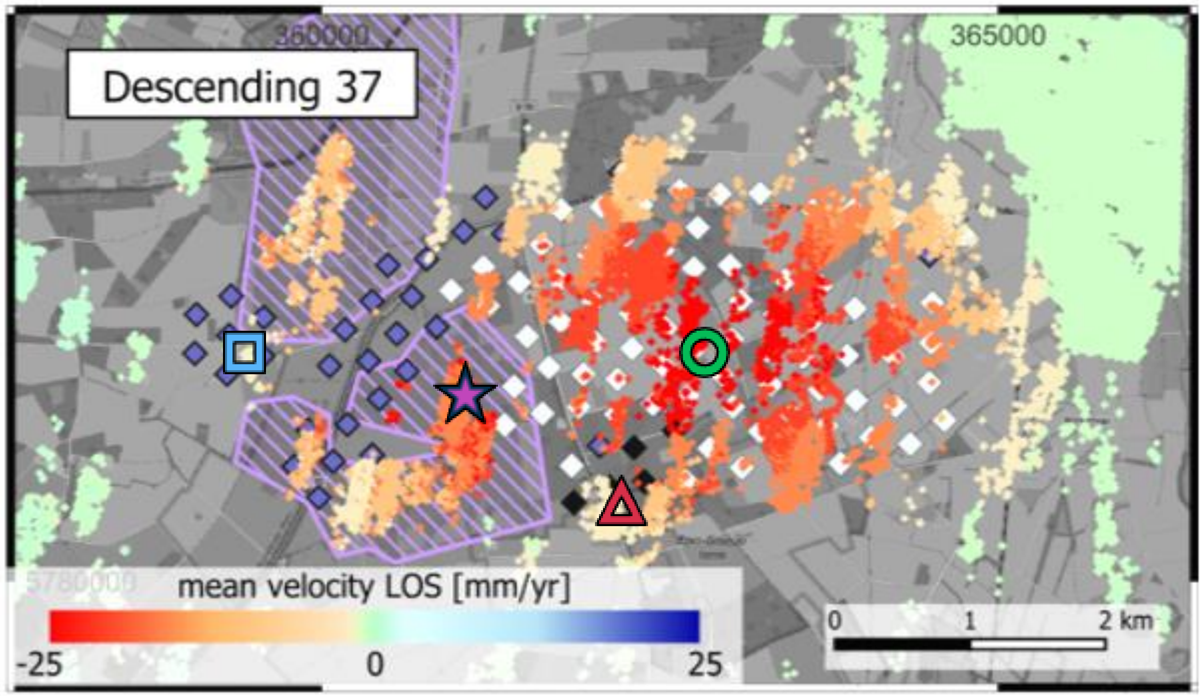
Monitoring: InSAR

- Inclusion of DS provides dense distribution of scatterers, temporal resolution: 6-12 days
- Different tracks show slightly different displacement patterns



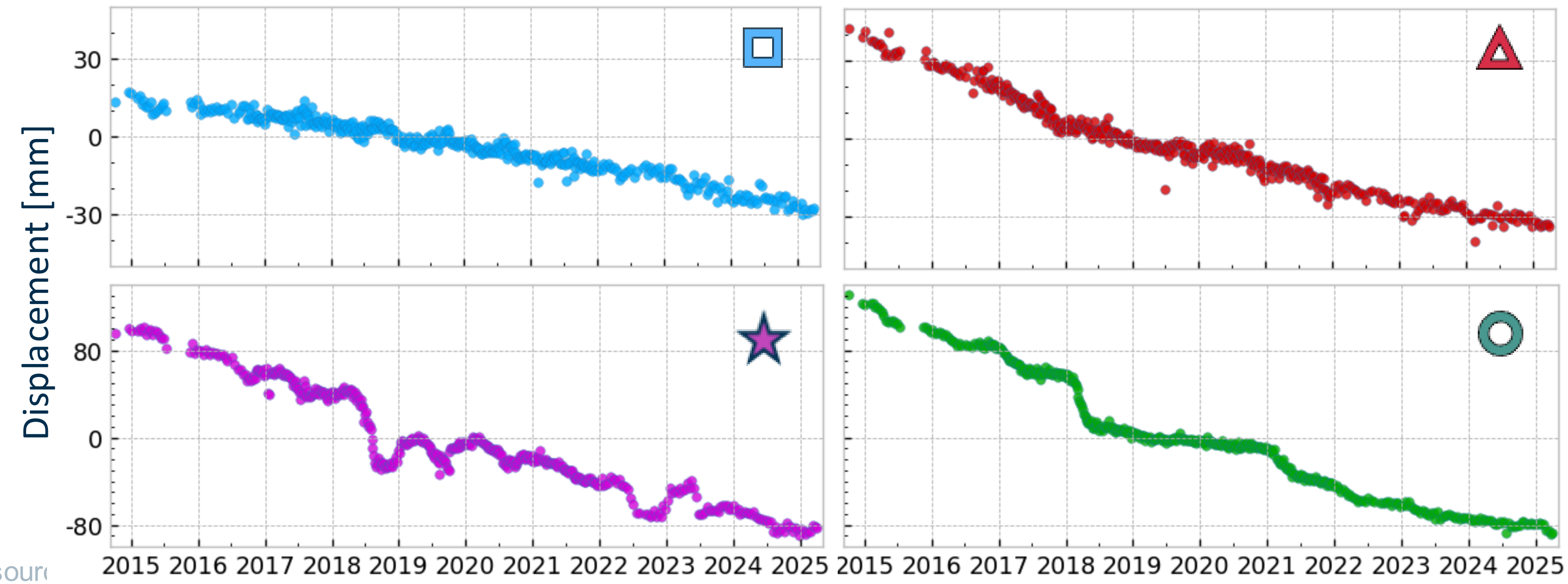
Monitoring: InSAR

- Time series show very different patterns throughout the cavern field
- Scatterers (DS) in the fen provide additional information about cavern caused displacements, but are superposed by strong seasonal signal



Spatiotemporal complex displacement field!

Causes?

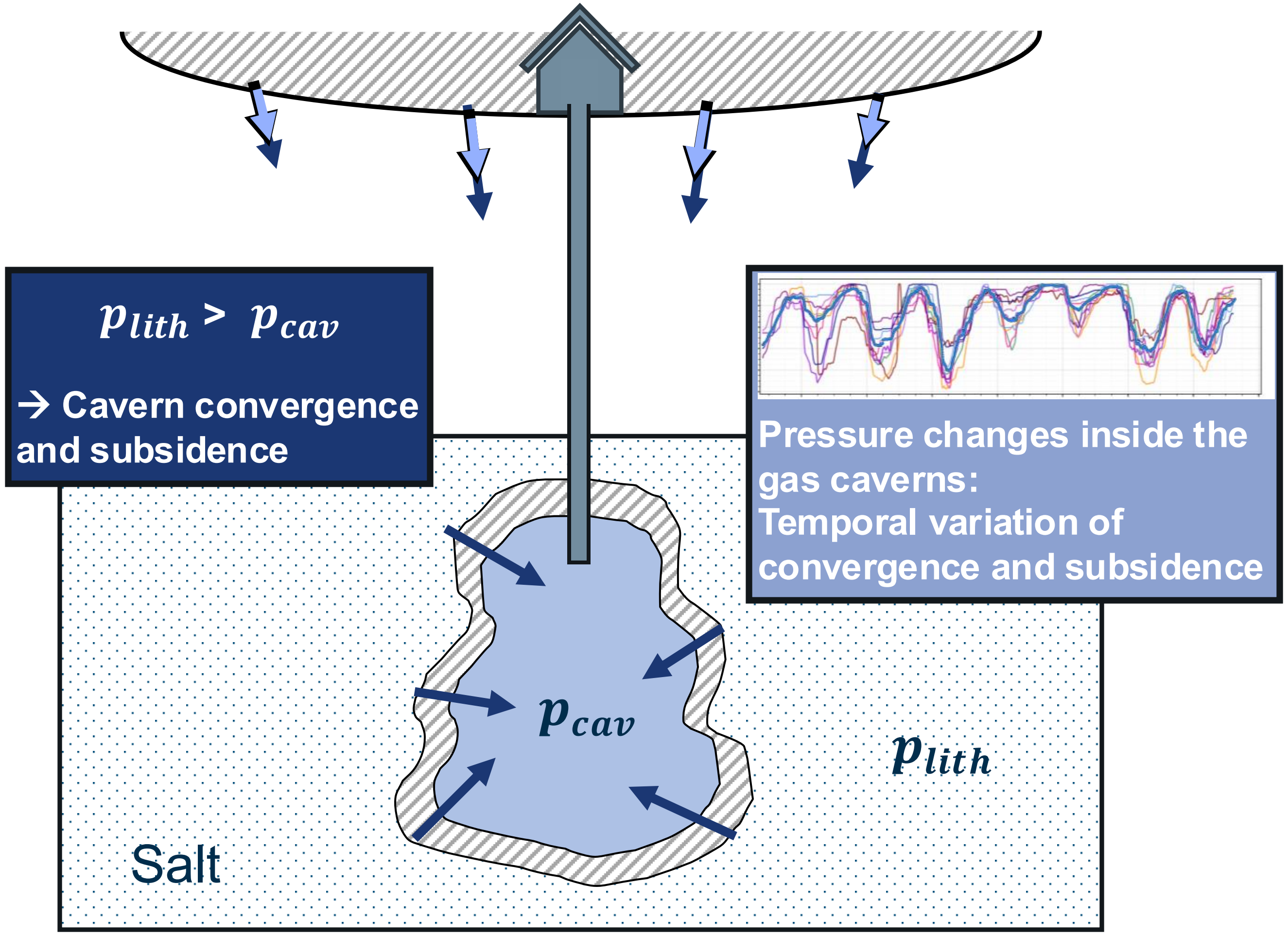


Subsidence at cavern fields
Storage Cavern (Geo)physics

- Caverns are artificially created in salt layers for brine production
- Filled with gas for energy storage
- Pressure inside the storage caverns is kept lower than surrounding lithostatic pressure to ensure sealing
- Salt is viscoelastic → **Volume loss** over time

  → Amount depends on the **pressure difference** between cavern inside and lithostatic pressure

- Cavern convergence propagates to the surface → **Surface subsidence**
- Pressure changes in gas caverns cause varying **convergence speeds**



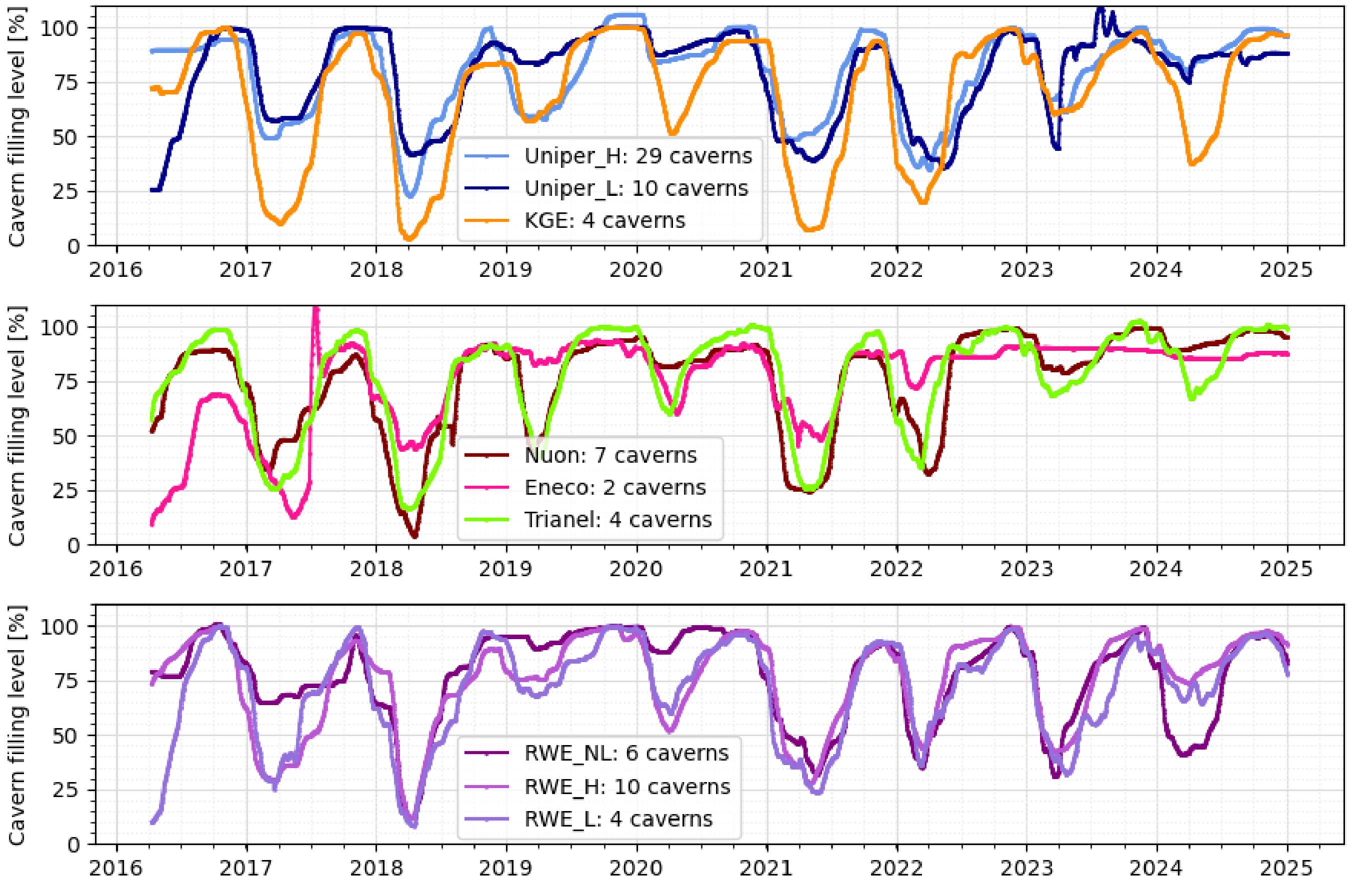
→ Surface displacement is strongly influenced by cavern filling levels!

Epe storage cavern field
Gas cavern filling levels

- Gas caverns are operated by six different providers with different gas types
- Daily mean cavern filling levels are available online (*https://agsi.gie.eu/#/.*) for all providers
- Annual cycles of filling and depletion, but variations for different providers
- Minimum cavern filling levels (and with this max convergence) vary strongly from year to year

→ complex, inhomogeneous deformation field in time and space expected

How to obtain sufficient spatiotemporal coverage for monitoring?

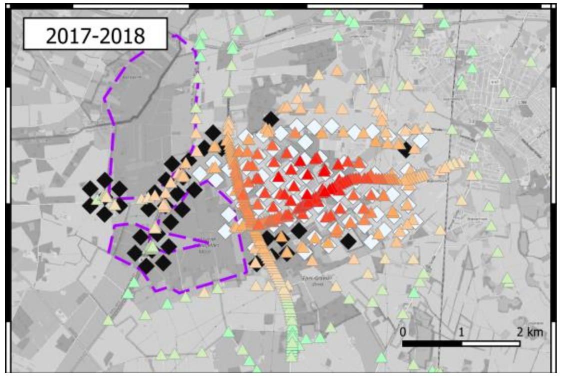


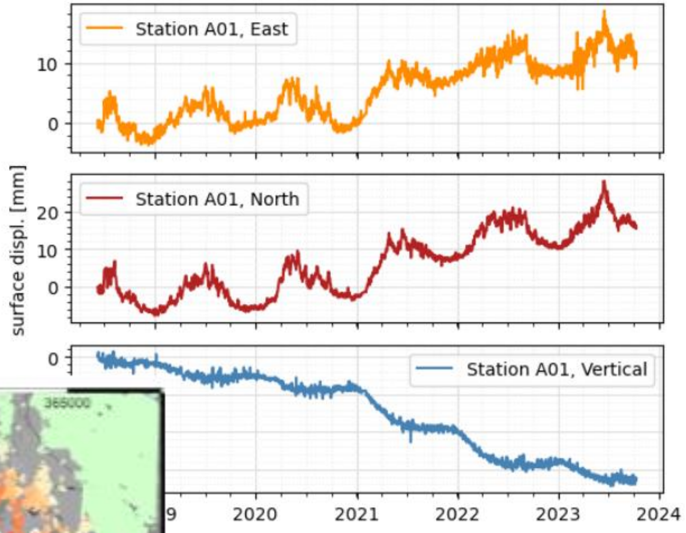
Why model?

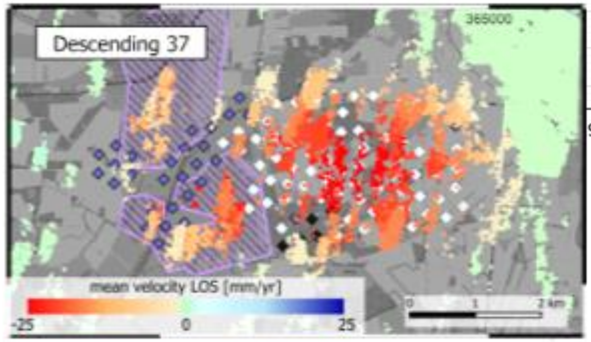
Spatiotemporal coverage

- Levelling: 1D displacements, annual temporal coverage
- GNSS: 3D displacements, punctual spatial coverage
- InSAR: 1D/(2D) displacements, moderate spatiotemporal coverage

- → very sparse data on horizontal north-south displacements
- → even combining all measurements, big spatial data gaps still exist







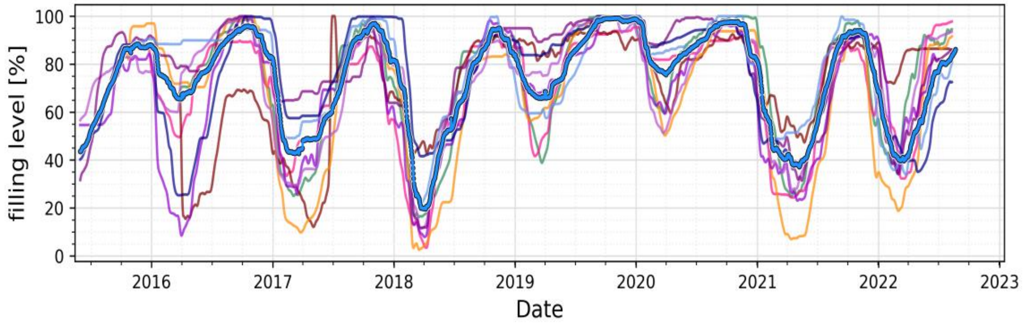
Signal source identification

- At least 2 strong signal sources (water levels, cavern convergence) superpose
- Cause of certain displacements can be unclear without relation to source mechanism
  → potential cause of damage to infrastructure

Can the cavern convergence caused surface displacements be modeled with a simple physical source model?

Source model from Geophysics

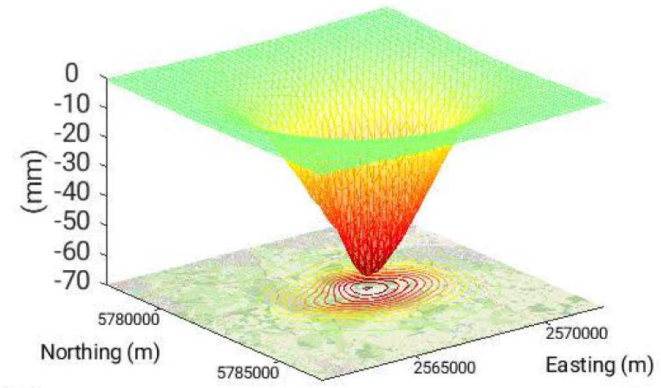
Cavern filling levels (t)



Model

Local parameters

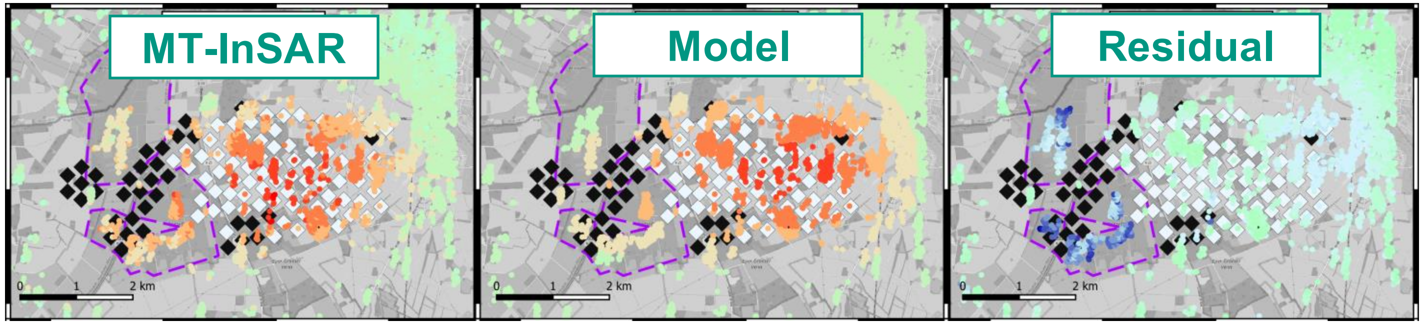
3D Surface displacements (t)



(from Even et al., 2021)

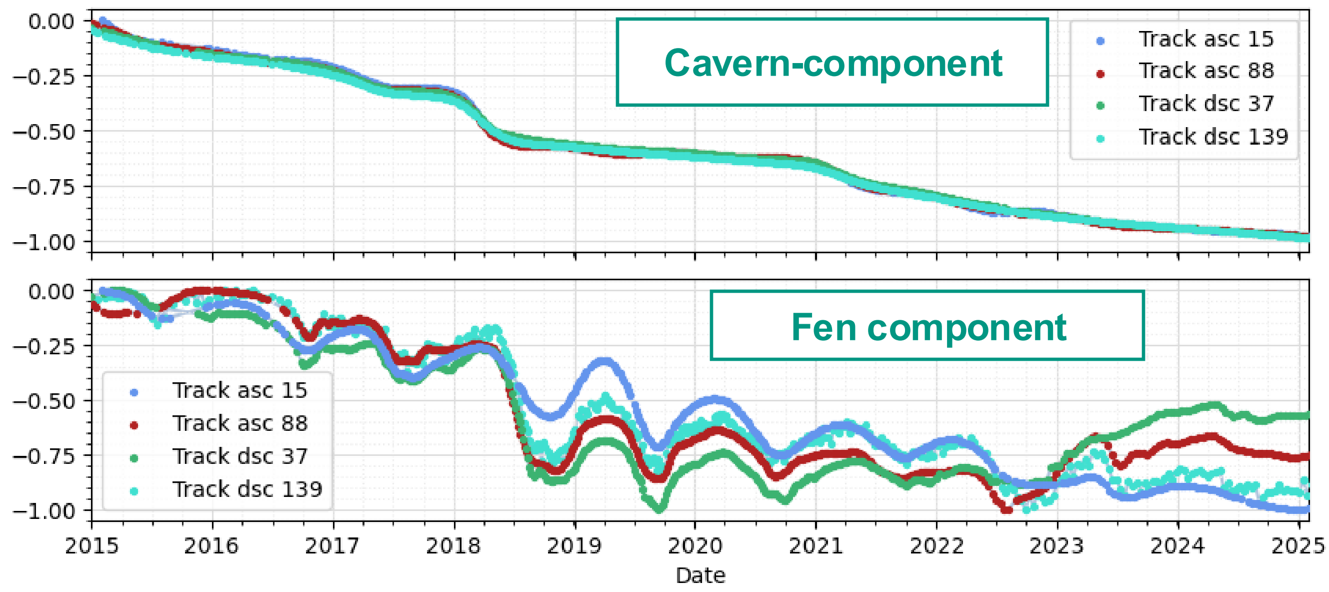
Optimization

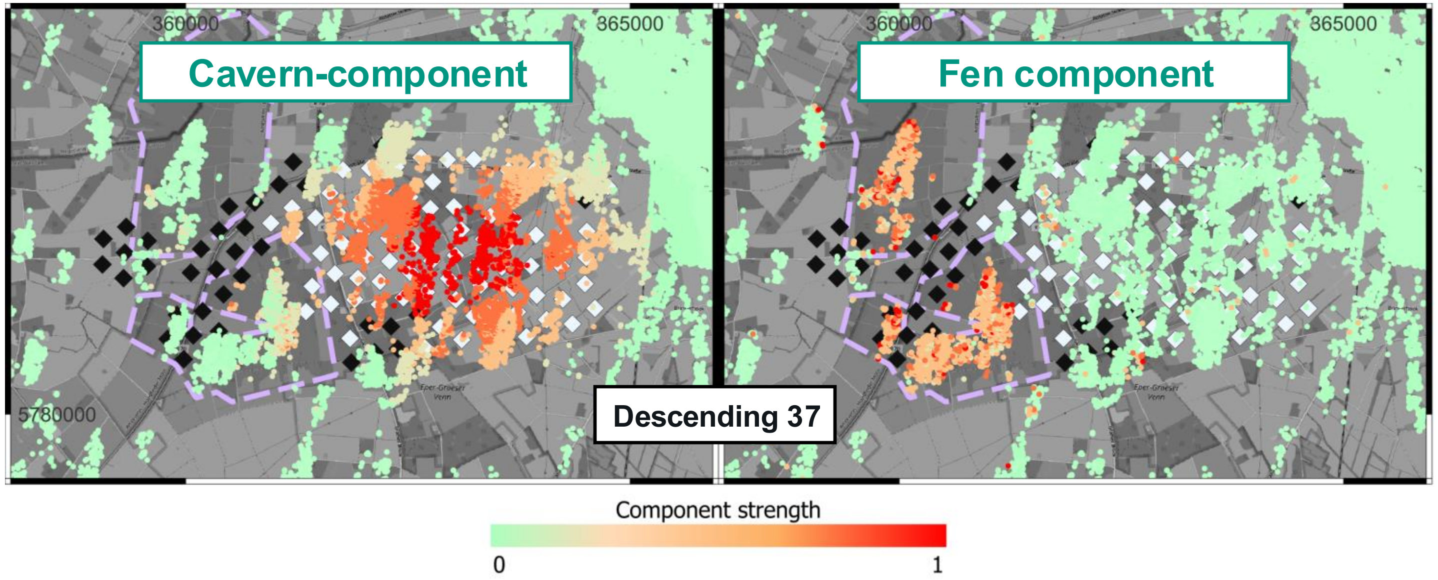
'cleaned' from other correlated displacements with Independent component analysis



Data preparation with ICA

- To prevent fitting the model to strong signals of other sources, all MT-InSAR tracks are investigated with Independent Component Analysis
- Three similar components are found in each dataset that can be linked to caverns (1) and fen (combination of 2)
- Fen-components were inverted back and subtracted from original time series





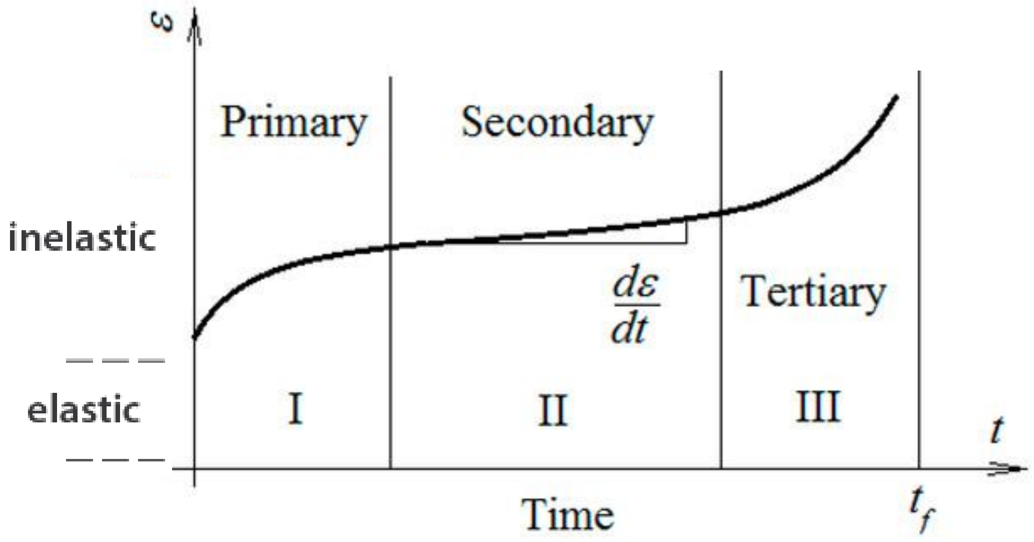
Source model:

Geophysics: Gas cavern volume change:

Norton creep law (as in Ślizowski et al., 2010) + **Elastic** and **viscoelastic Elements**

Based on pressure difference

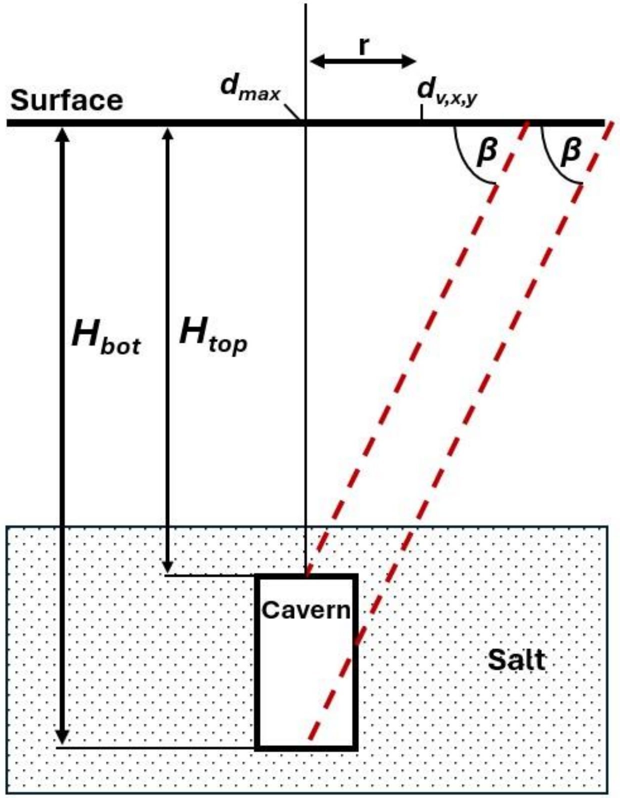
+



Adapted from Katouzian and Vlase, ,2020

Geotechnics: Propagation to the Surface:

Sroka-Schober Model (as in Sroka et al., 2017)



Model: (Gas) Cavern volume change
with a common model for salt rock deformation

$$\Delta V_{cavern}(t) = \Delta V_{elastic} + \Delta V_{primary\ creep}(t) + \Delta V_{steady\ creep}(t)$$

$$\Delta V_{elastic} = \frac{p_{cav} - p_{lith}}{E_1}$$

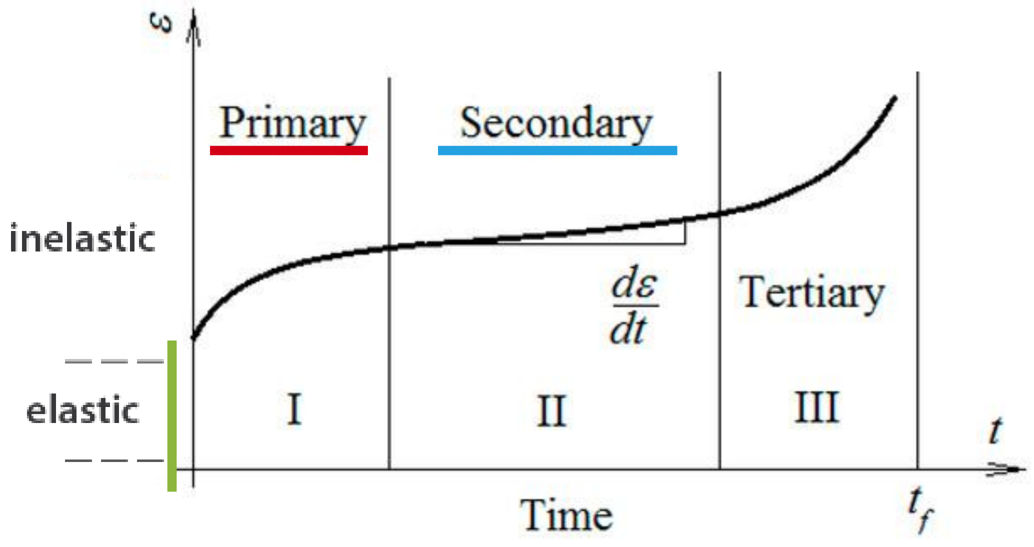
$$\Delta V_{primary\ creep}(t) = \frac{p_{cav} - p_{lith}}{E_2}\left[1 - \exp\left(-\left(\frac{E_2}{\eta}\right)t\right)\right]$$

$$\Delta V_{steady\ creep}(t) = A \cdot e^{-\left(\frac{Q}{RT}\right)} \cdot (p_{cav} - p_{lith})^n$$

$p_{cav} = pressure\ inside\ cavern$
$p_{lith} = lithostatic\ pressure$
$E_1 = Youngs\ Modulus\ (elastic)$
$E_2 = Youngs\ Modulus\ (viscoelastic)$
$\eta = viscosity$

$A = creep - rate - coefficient$
$n = stress\ exponent$
$Q = activation\ energy$
$T = Temperature$
$R = Boltzmann\ constant$

Cavern volume change is described as combination of instantaneous elastic and time dependent viscoelastic deformation as well as steady creep



Adapted from Katouzian and Vlase, ,2020

Model: (Gas) Cavern volume change
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$$\Delta V_{elastic} = \frac{p_{cav} - p_{lith}}{E_1}$$

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$\eta = viscosity$

$A = creep - rate - coefficient$
$n = stress\ exponent$
$Q = activation\ energy$
$T = Temperature$
$R = Boltzmann\ constant$

- The strain is the pressure difference:

$$p_{diff} = p_{cav} - p_{lith} + \boxed{C}$$

→ p_{cav} is approximated from cavern filling levels
→ p_{lith} is approximated from cavern depth and a simple model of local geological layers

But: only mean filling levels per provider are available, not for individual caverns!

→ Actual pressure differences are unknown!

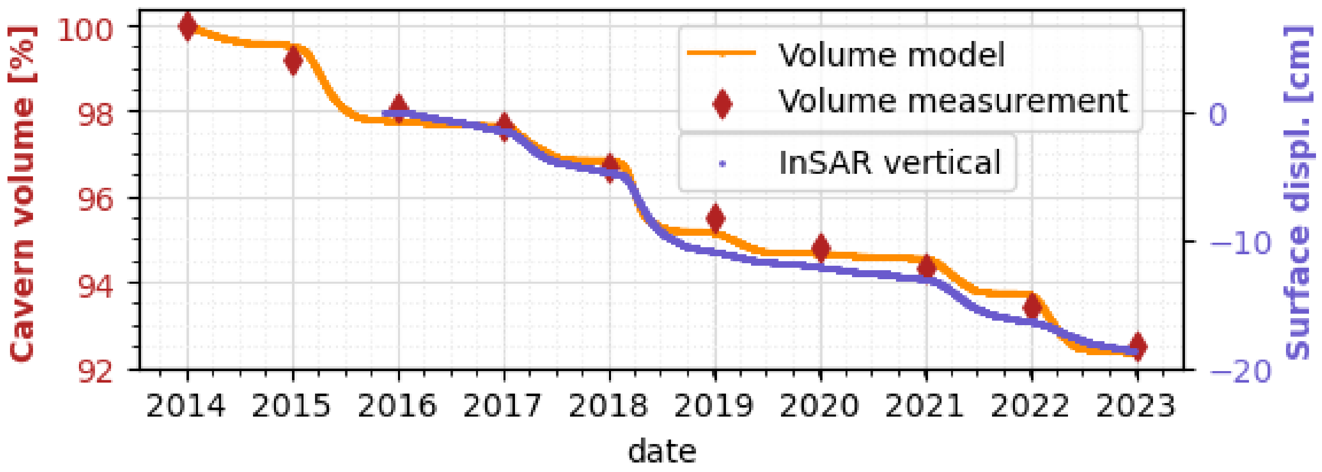
- Optional: Additional parameter C for each (Gas) cavern (constant over time) to alter pressure difference

Model: (Gas) Cavern volume loss

Steady creep described through Norton creep law
(as in Ślizowski et al., 2010)

$$\frac{dV}{dt} = \boxed{A} \cdot e^{\frac{-Q}{R \cdot T}} \cdot (p_{cav} - p_{lith})^{\boxed{n}}$$

$A = creep - rate - coefficient$
$n = stress\ exponent$
$Q = activation\ energy$
$T = Temperature$
$R = Boltzmann\ constant$
$p_{cav} = pressure\ inside\ cavern$
$p_{lith} = lithostatic\ pressure$

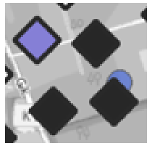


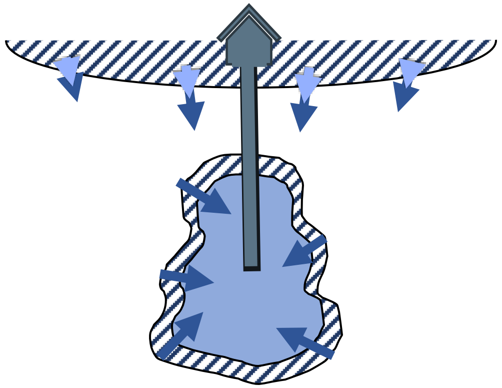
- Exponential relationship between convergence and pressure difference
- Input: cavern filling levels
- Derivation of **A** and **n** with Optimization from InSAR
  → constant over time and for the entire cavern field
- T is assumed constant: only small variation over time

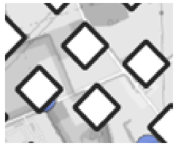
→ Calculate volume loss in daily temporal resolution for each gas cavern

$A = 6.23 \cdot 10^{-4}$
$n = 4.46$

Model: Cavern volume loss

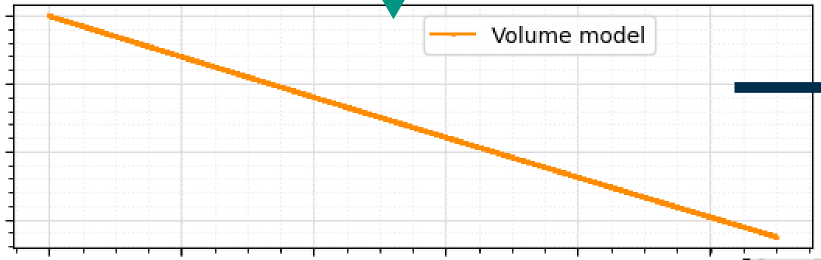




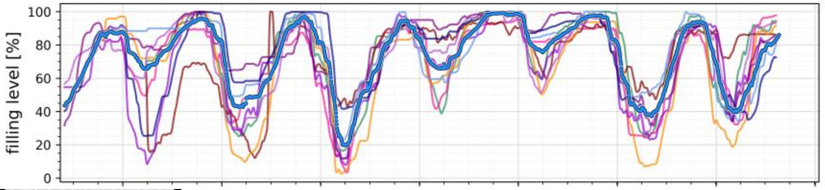


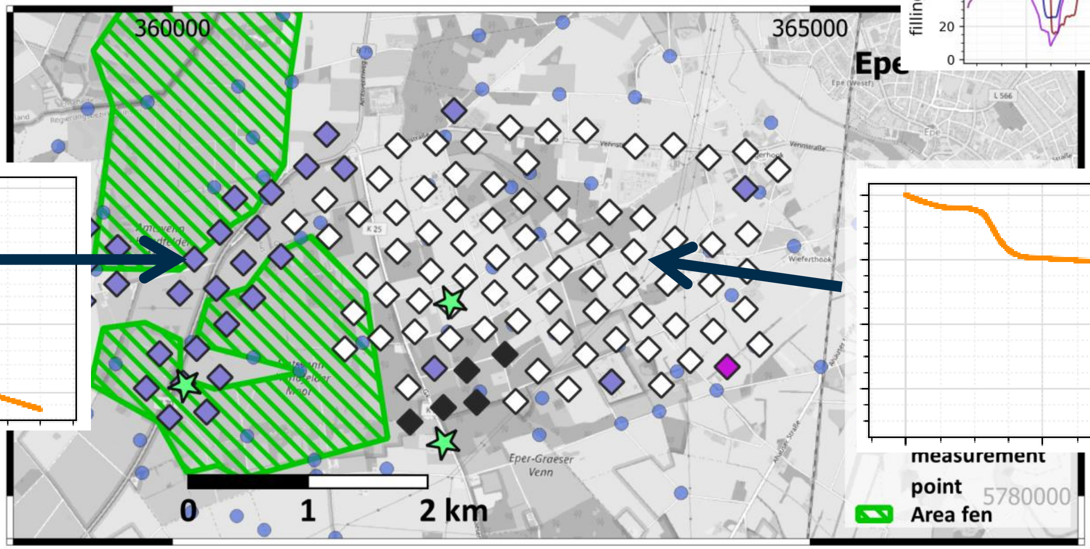
Oil and **brine** filled caverns:
linear convergence rate

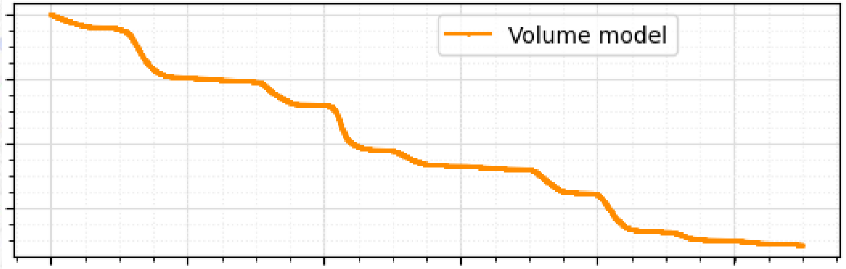
Oil: 0.2 % per year
Brine (production) 0.6 % per year
Brine (idle) 0.3 % per year
(from Sroka, A., et al., 2017)



Gas caverns:
Filling level dependent convergence







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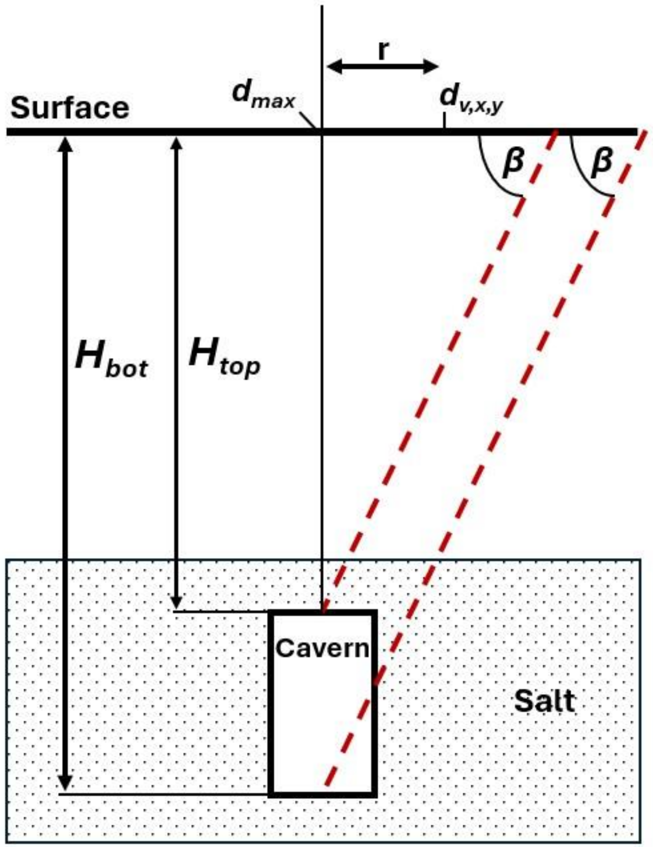
Model: Propagation to the surface

Sroka-Schober Model

(as in Sroka, A., et al., 2017)



$$d_{max}(t) = \frac{\alpha \cdot \Delta V(t)}{H_{top} \cdot H_{bot}} \tan^2 \boxed{\beta}$$

$$d_v(r,t) = d_{max}(t) \cdot e^{\left(-\pi \frac{r^2}{H_{top} \cdot H_{bot}} \cdot \tan^2 \beta\right)}$$

$$d_x(r,t), d_y(r,t) = -\boxed{B \cdot} T_{x,y}$$

a = *Coefficient of volume loss*
ß = *angle of main influences*
H_{top} = *Depth of cavern roof*
H_{bot} = *Depth of cavern floor*

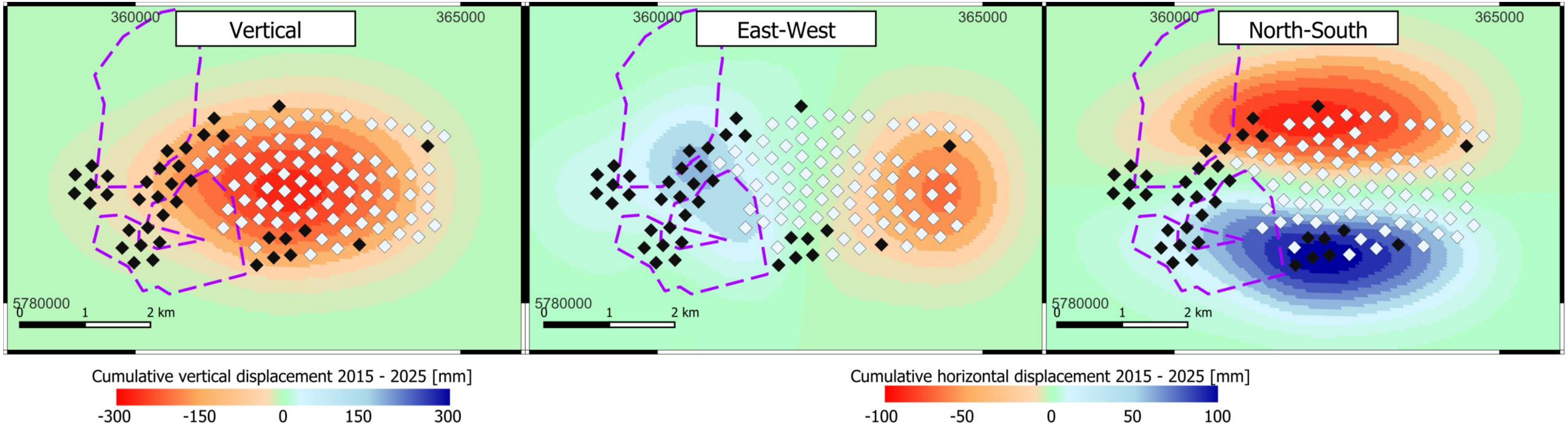
r = *distance to measurement point*
B = *horizontal movement factor*
T = *Tilt vector*

- Each cavern is assumed as a cylindrical source of displacement
- Signals of multiple caverns superpose
- Input: Cavern volume curves
- Derivation of **ß** and **B** with Optimization from InSAR
  → constant over time for the entire cavern field

ß = 34°
B = 580 m

Model: Results

Cumulative surface displacement of 10 years

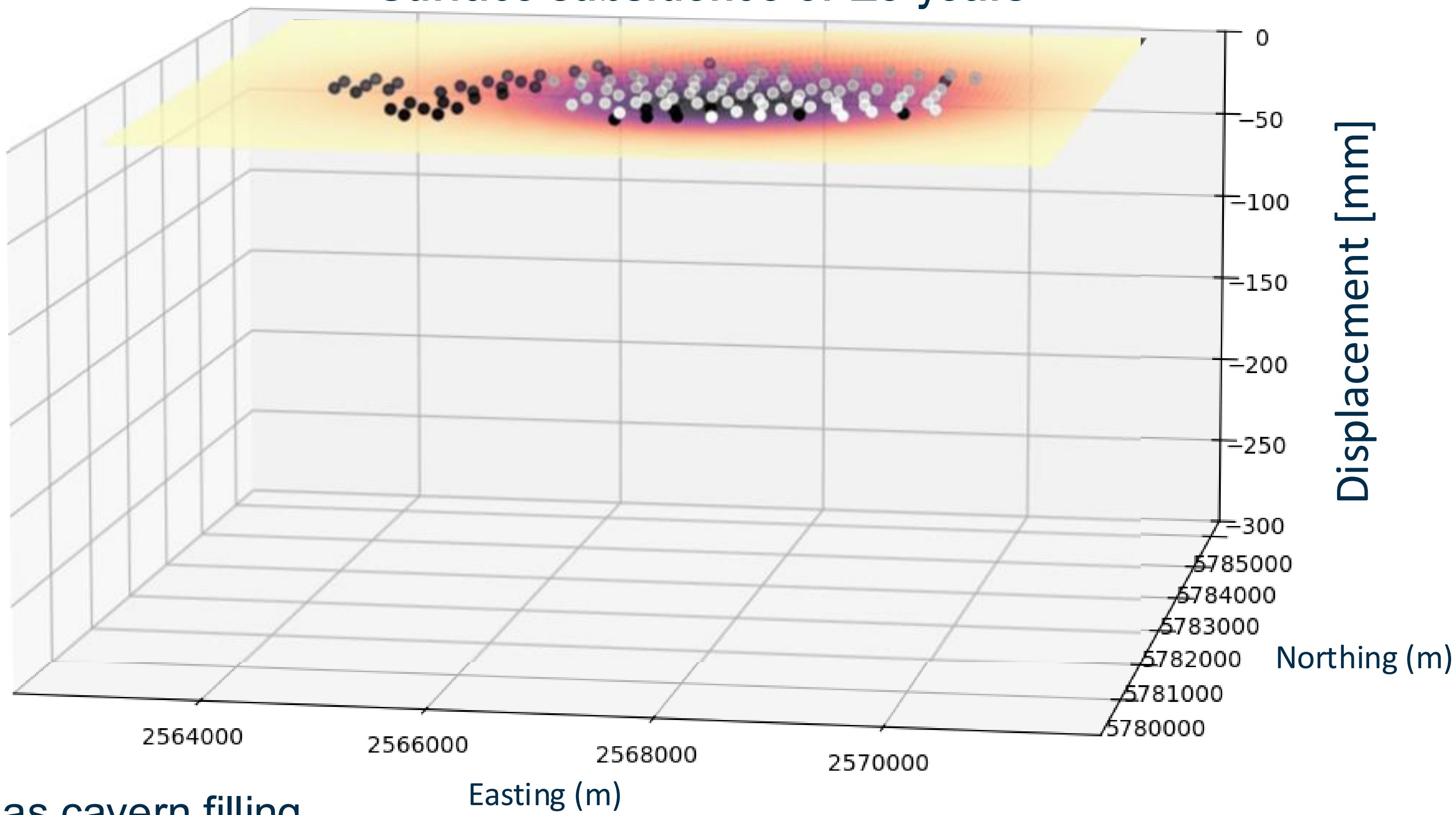


- Vertical displacements show elongated subsidence bowl
- East-West displacements are more irregularly shaped, due to cavern distribution
  - maximum is smaller than minimum
- North-South displacements are more symmetrical

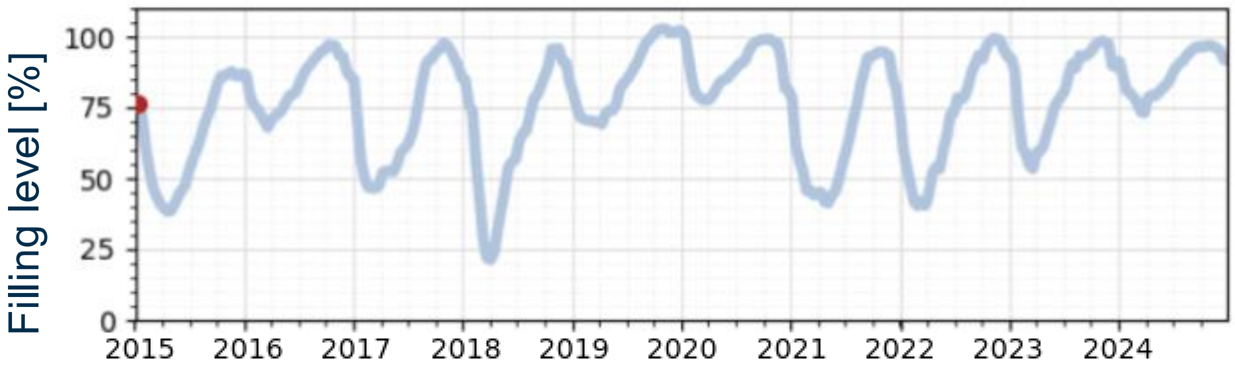
Model: Results

- Subsidence shows spatial inhomogeneity, and temporal irregularity
- Years with low minimum pressure in winter show significantly higher subsidence than years with high minimum pressure

Surface subsidence of 10 years



Mean gas cavern filling



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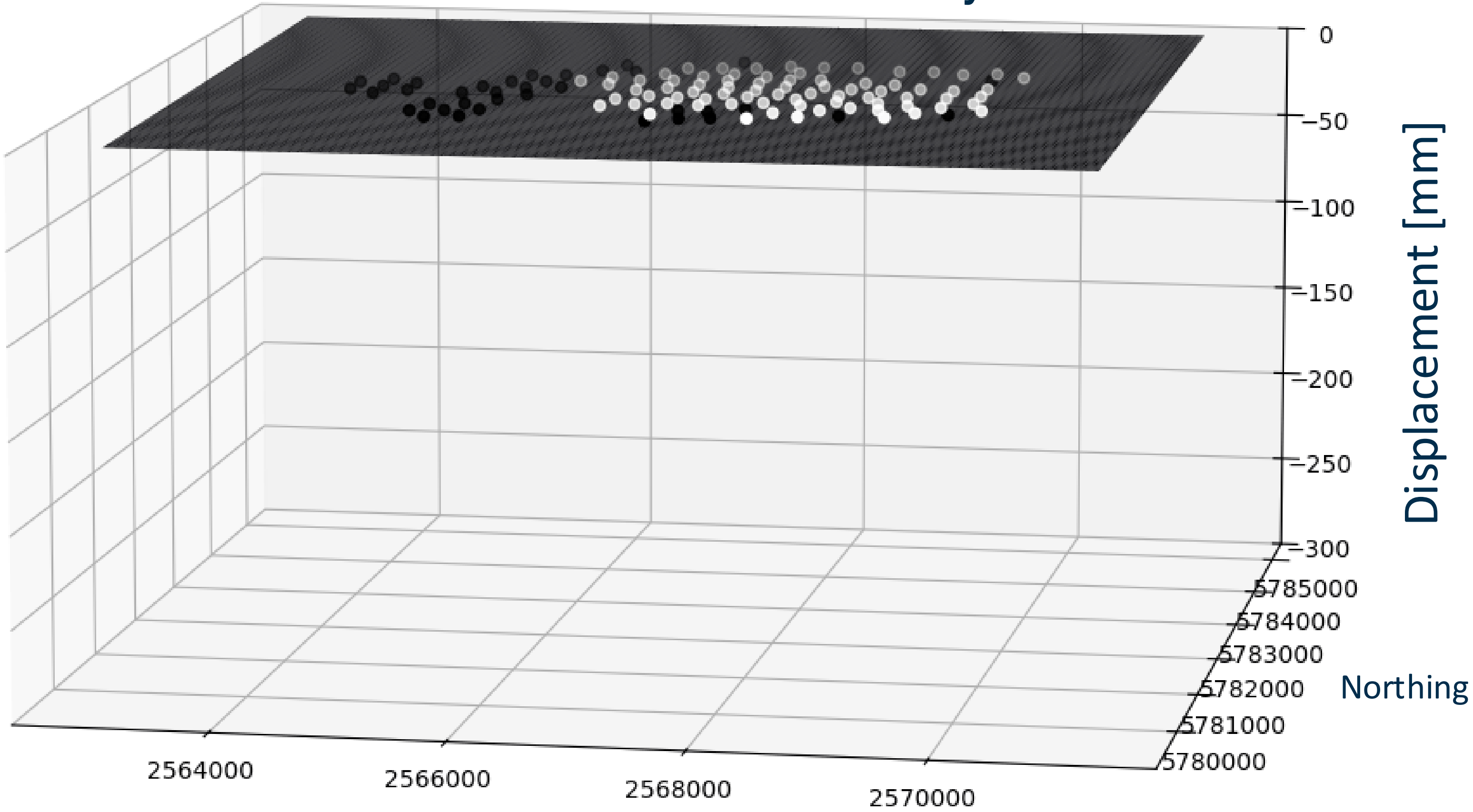
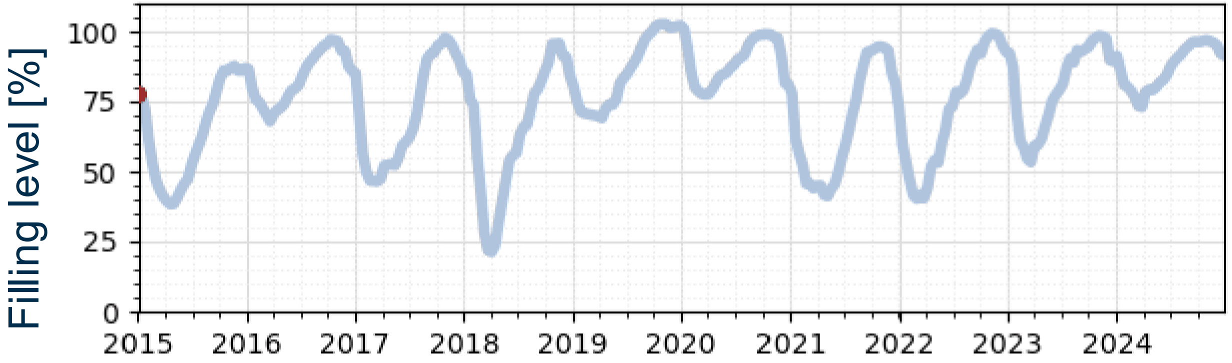
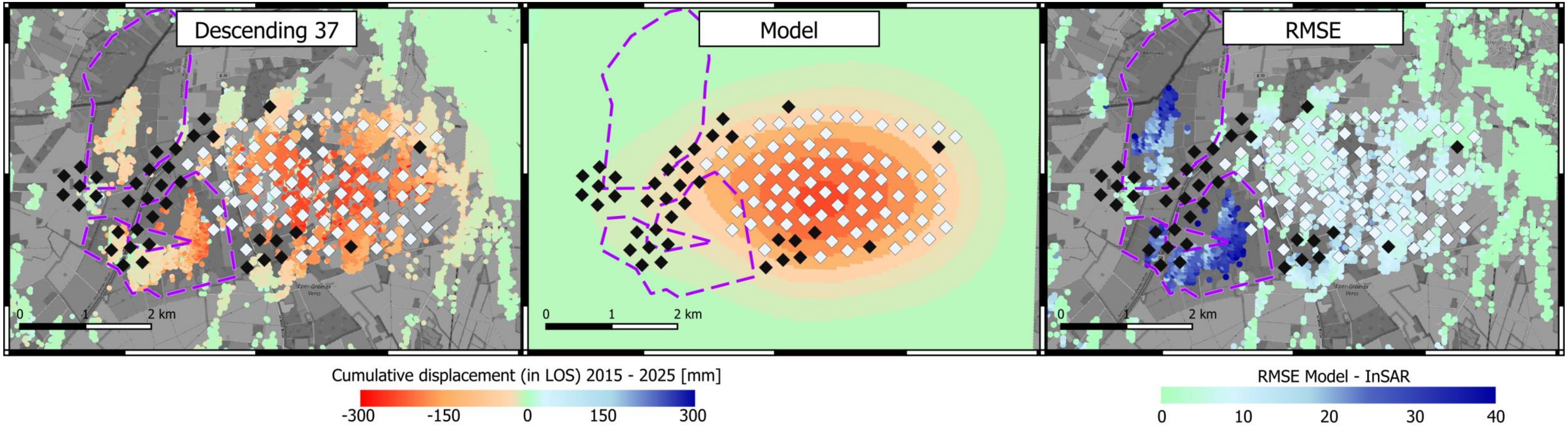
Surface subsidence of 10 years



Mean gas cavern filling

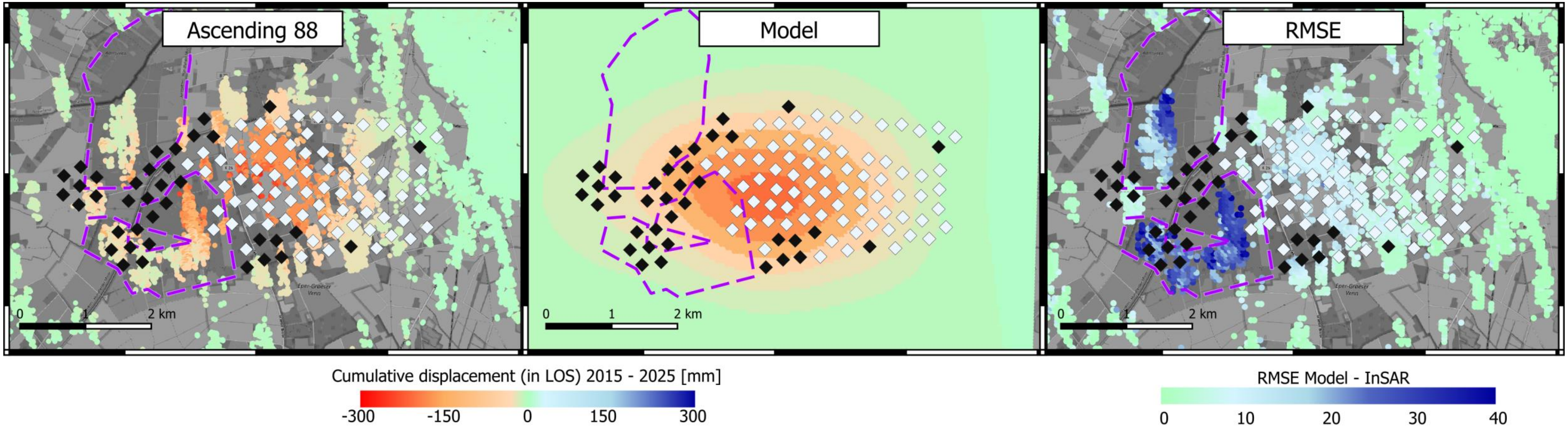


Model validation: Comparison with InSAR



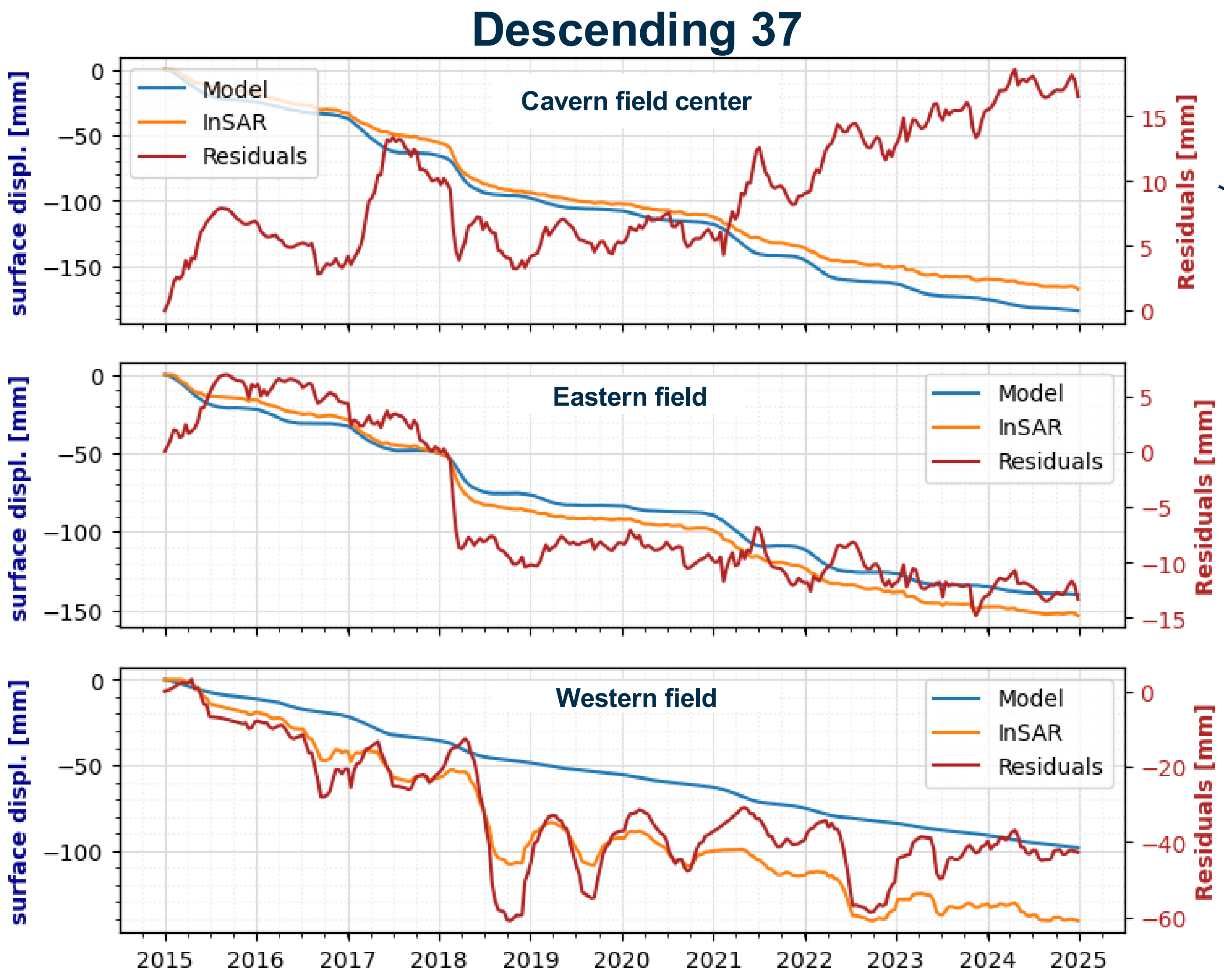
- Model and InSAR show strong agreement in spatial pattern and magnitude of displacement
- Error is highest in the Fen, as was to be expected
  → Model does not describe groundwater related displacements
- RMSE is slightly higher in the center of the gas cavern field

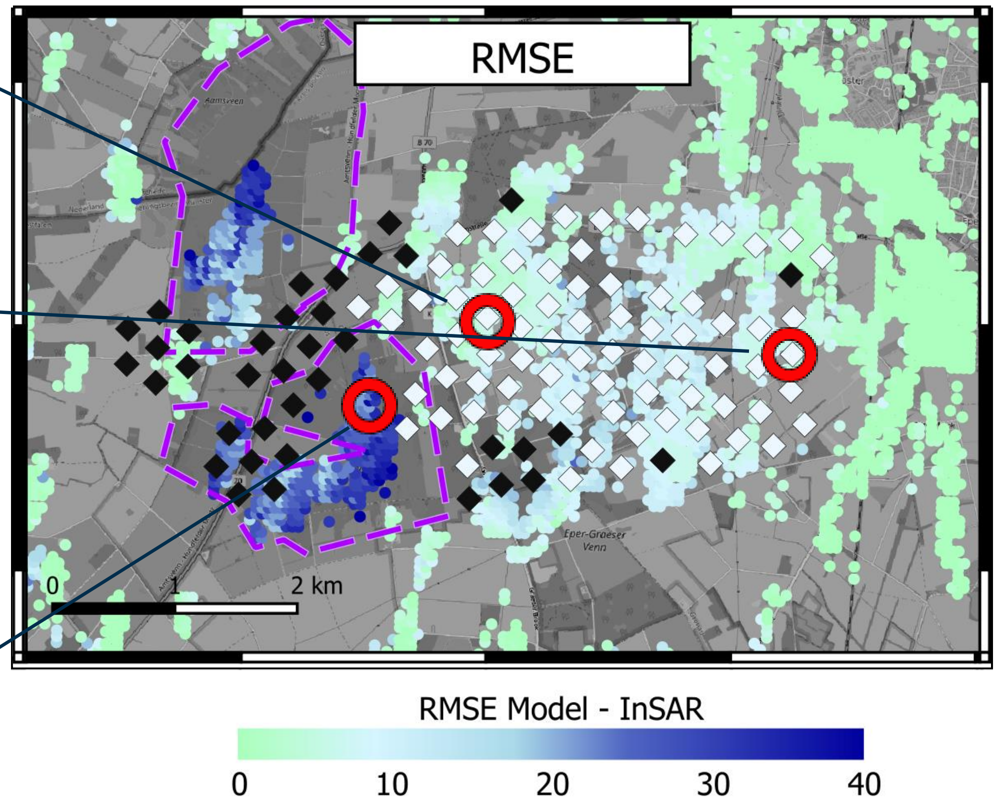
Model validation: Comparison with InSAR



- Model and InSAR show strong agreement in spatial pattern and magnitude of displacement
- Error is highest in the Fen, as was to be expected
  → Model does not describe groundwater related displacements
- RMSE is slightly higher in the western part of the gas cavern field

Model validation: Comparison with InSAR





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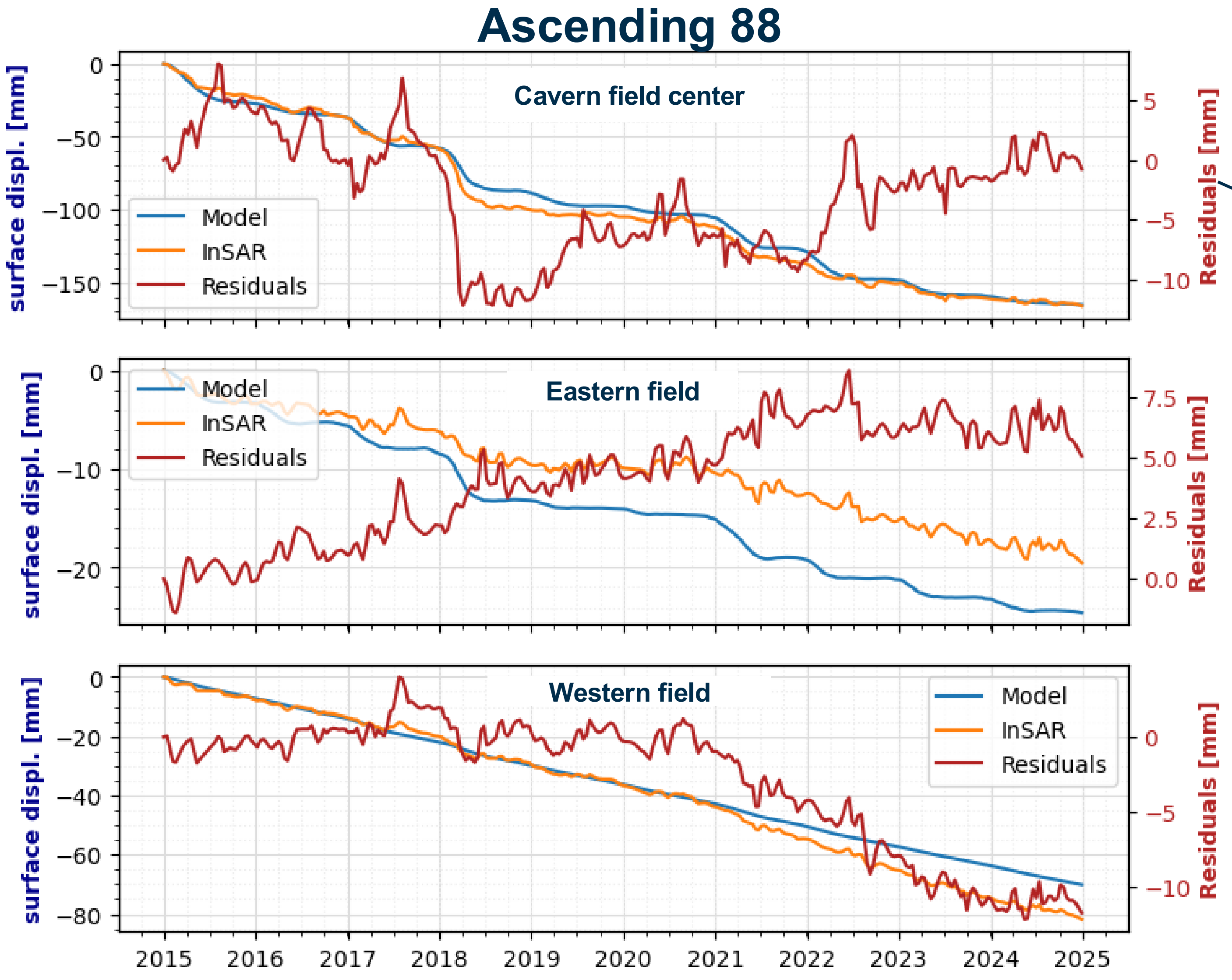
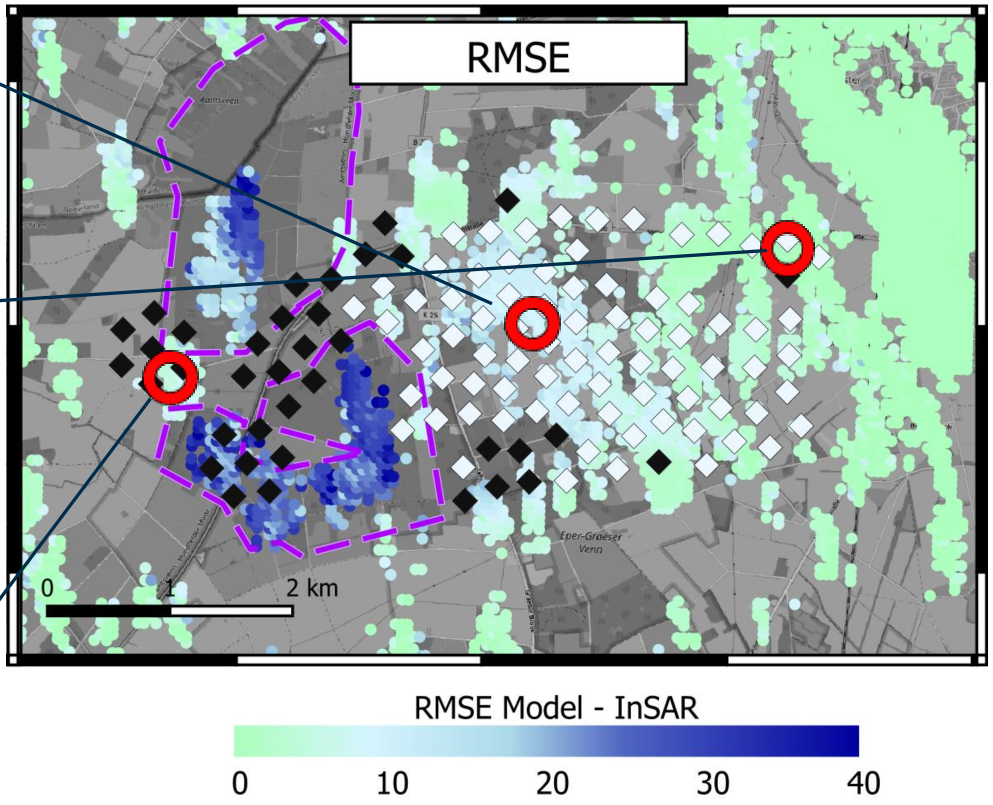
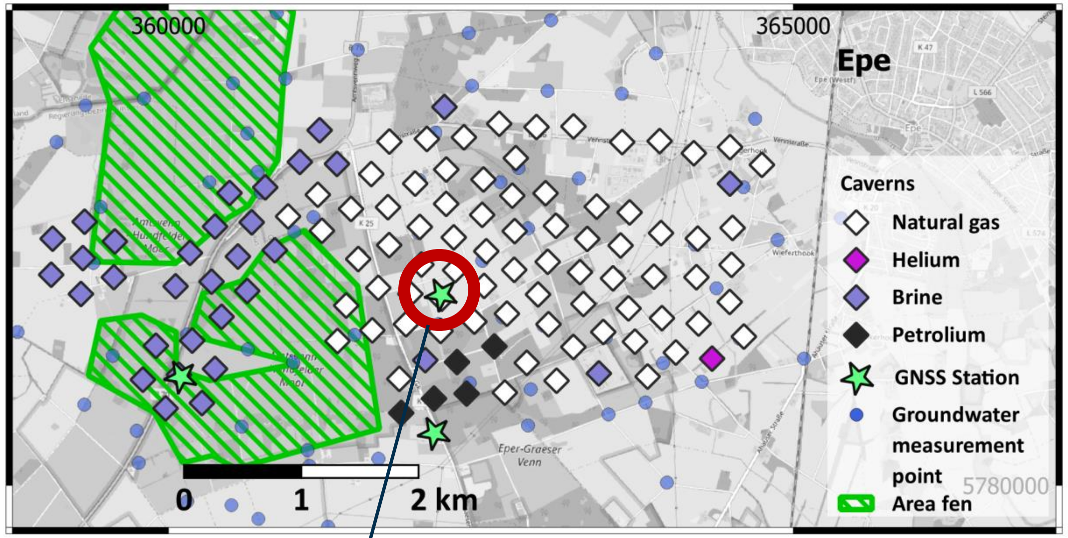
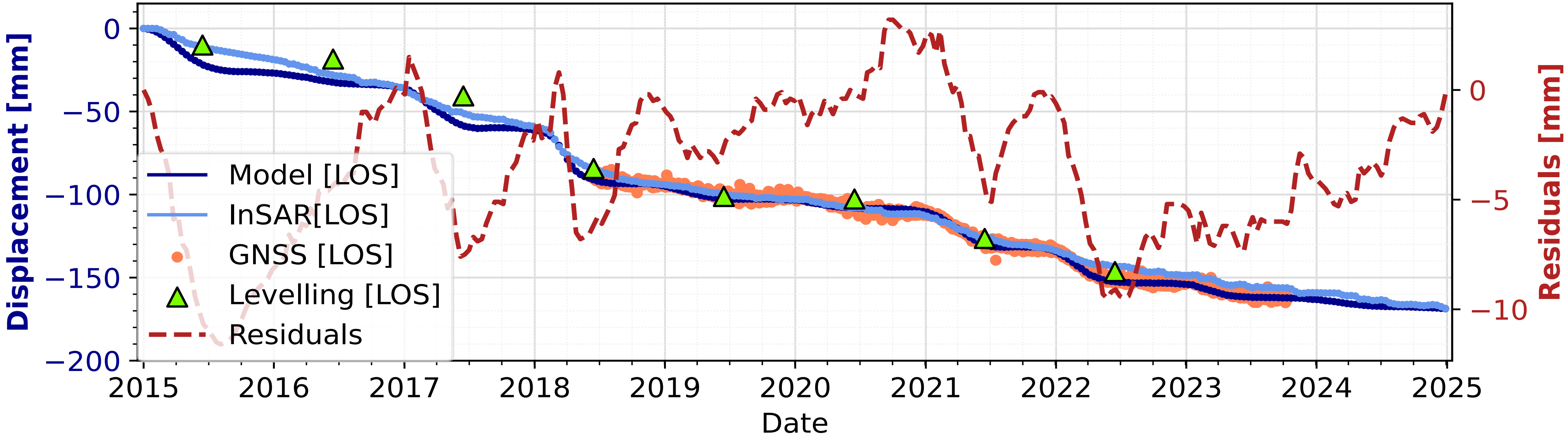




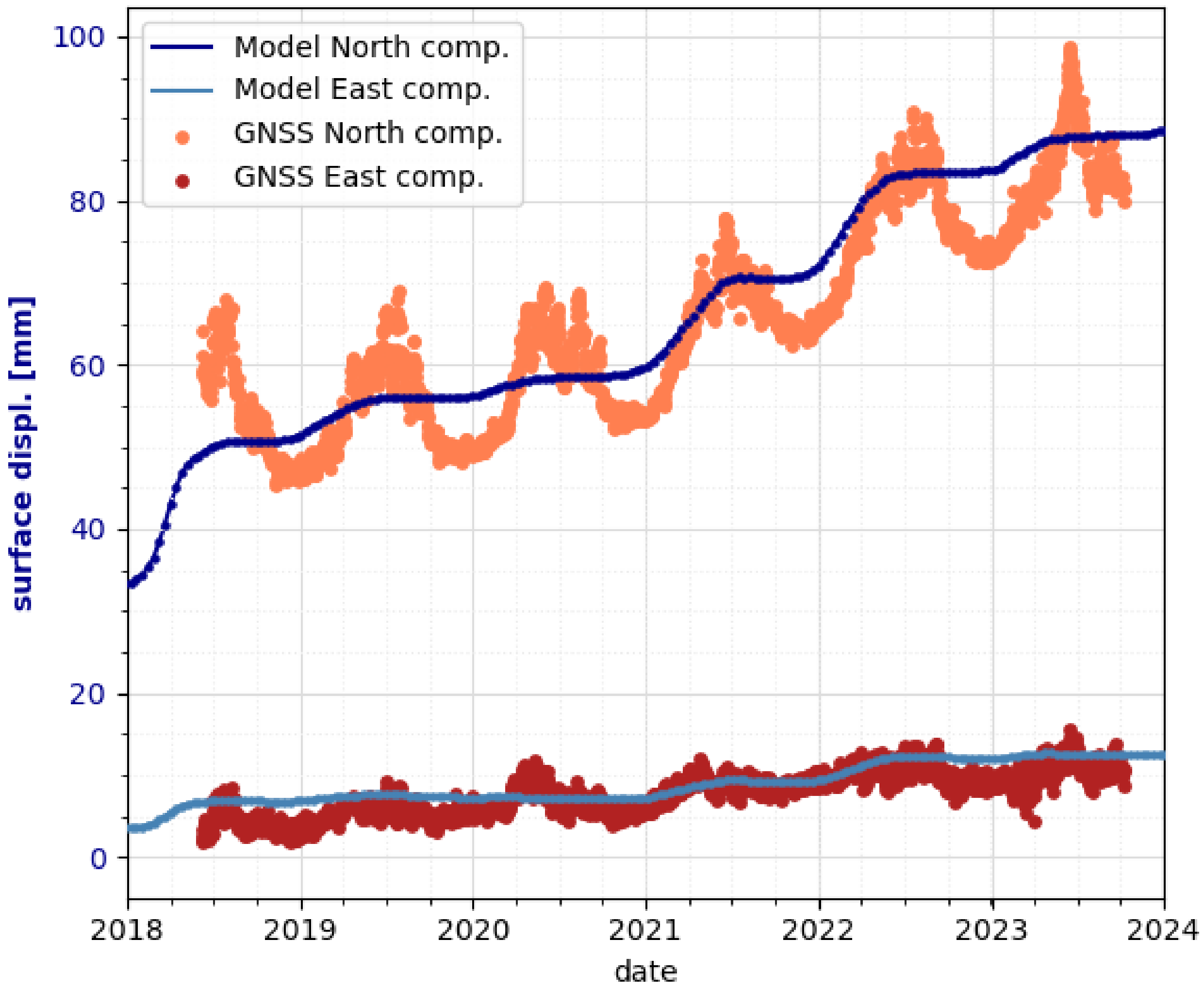
Model validation:
All geodetic methods

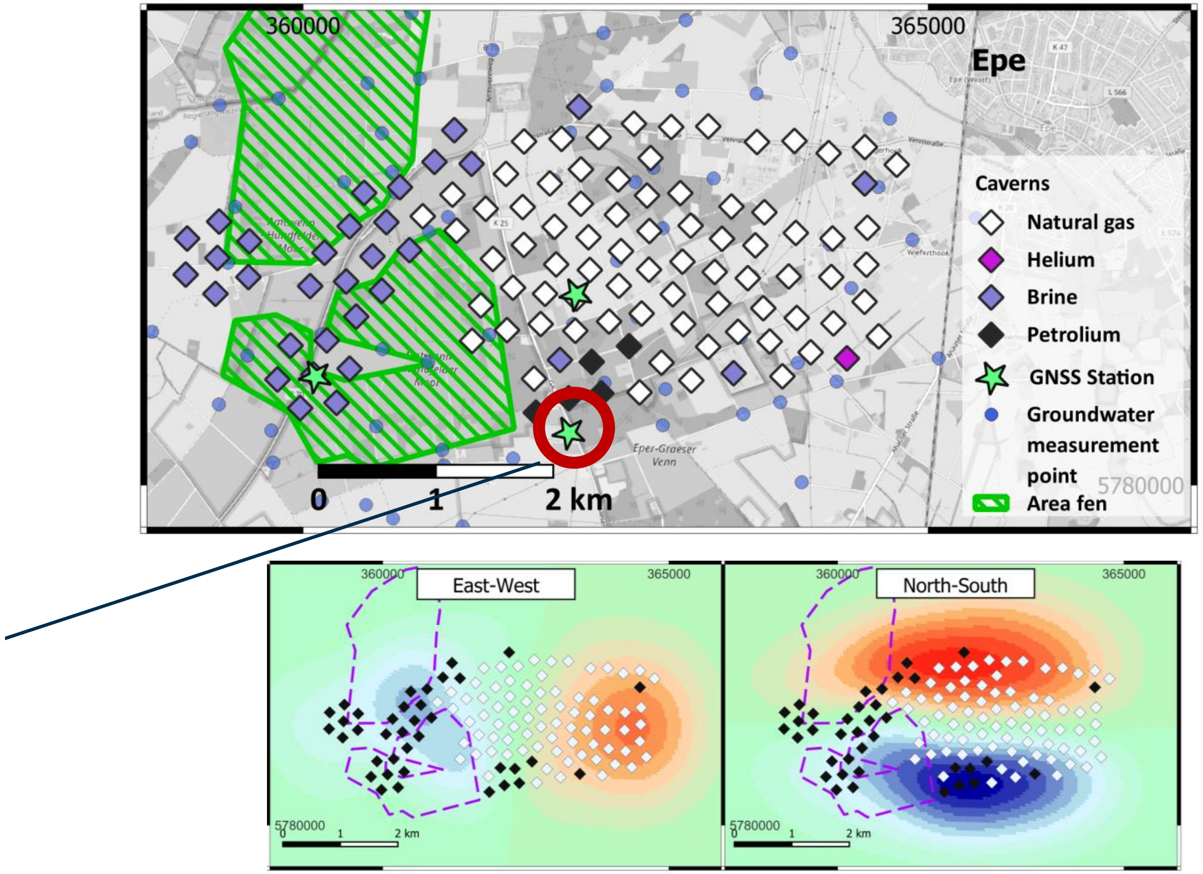
- GNSS and levelling based displacements can be projected to LOS to be compared to InSAR.
- Model and all displacement measurements at GNSS-Station A01 show a highly similar displacement curve
- Residuals are in the range of a few mm





Model validation:
Horizontal Components

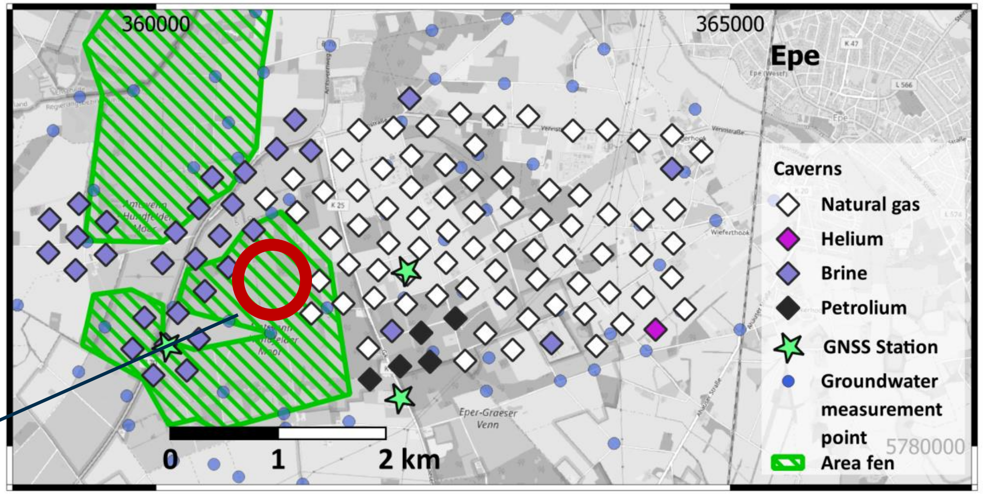


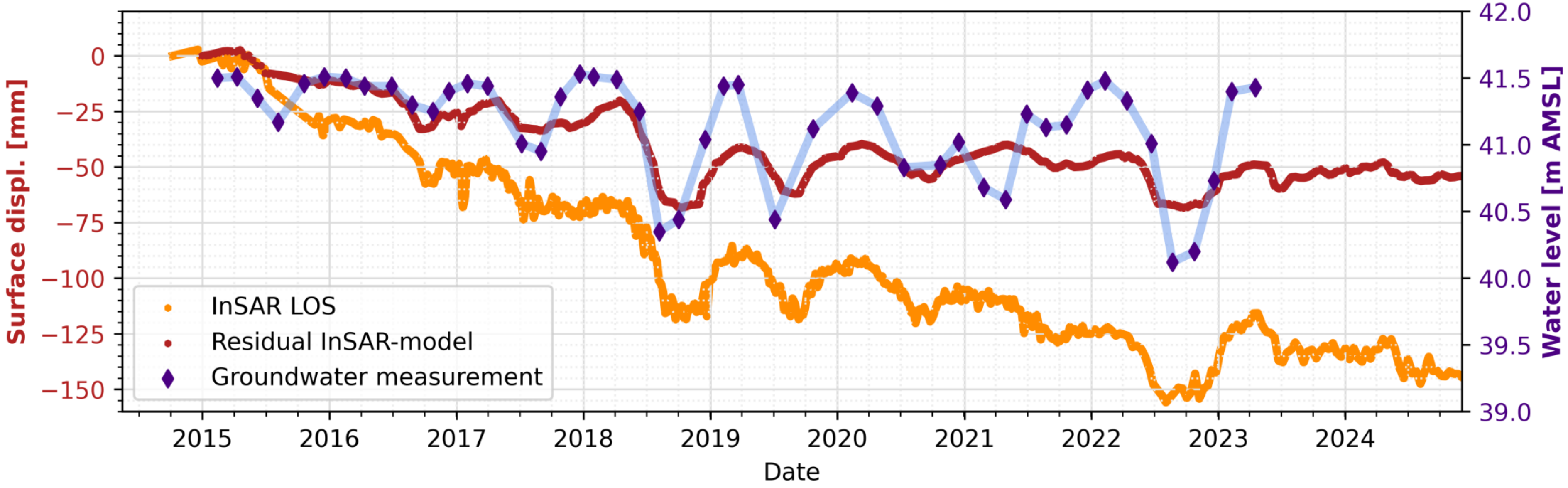


- GNSS Station A3 shows stronger seasonal pattern in horizontal components
- Magnitude of displacement and general trend do agree with the model

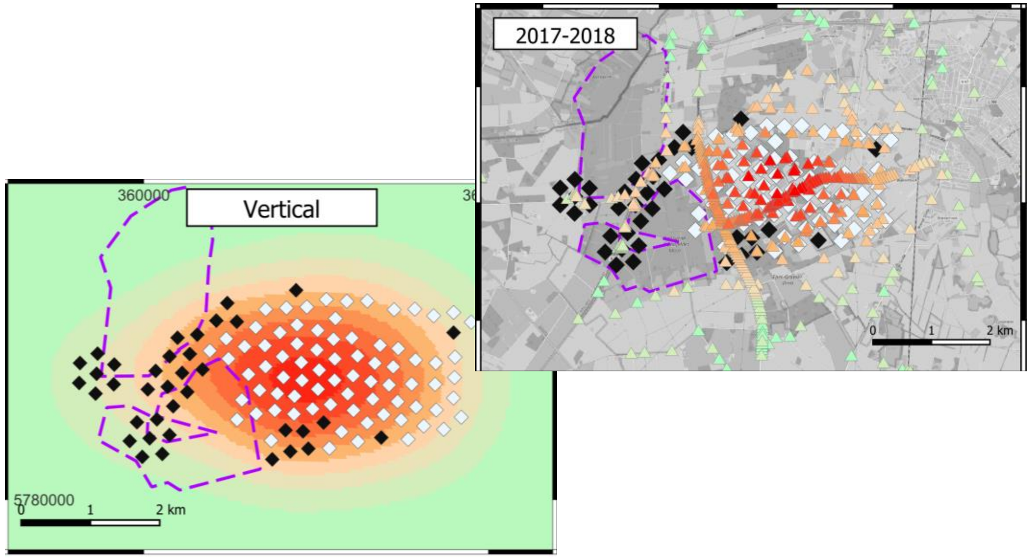
Model validation:
Residuals in the fen

- Model explains only small part of displacements in the fen
- Residuals in the fen show similar temporal behavior as groundwater measurements





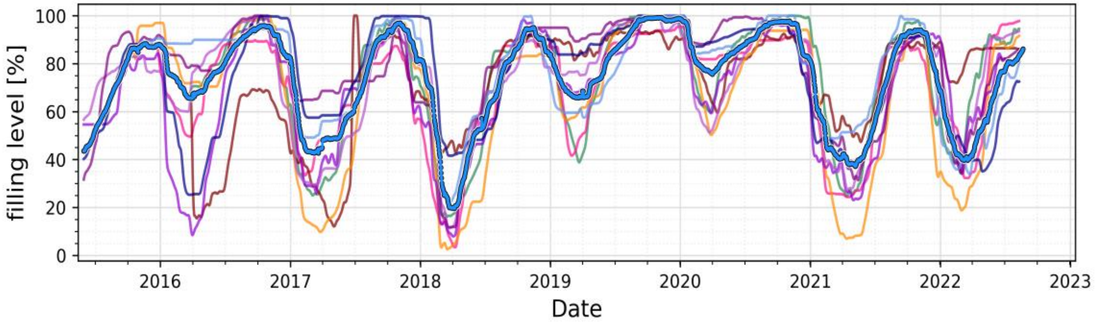
Discussion:
What can this model be used for?



- This model can **not**:
  - Replace actual displacement measurements
  - Reliably and accurately forecast surface deformation everywhere in the cavern field

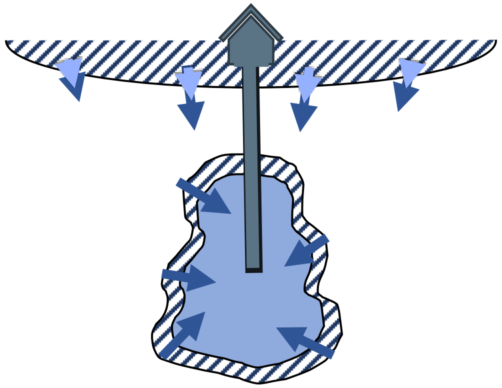
- This model **currently** can **not**:
  - Describe actual physical properties of the salt rock at Epe through the derived local parameters (A, n)
  - Describe the actual volume change of individual caverns

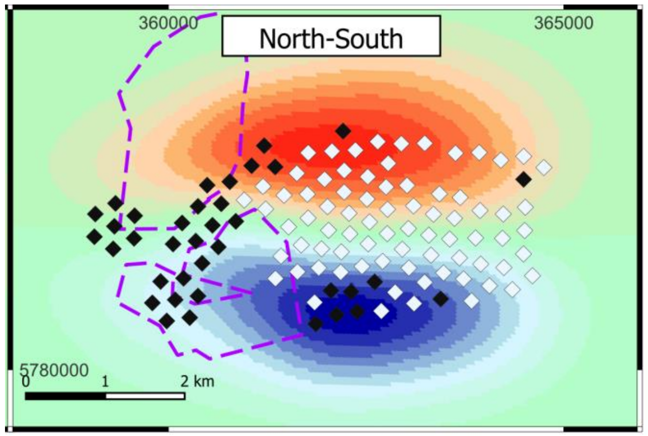
→ Potentially possible if the actual pressure data of individual caverns could be used instead of mean filling levels



Discussion:
What can this model be used for?

- What this model **can** do:
  - Show that a significant amount of the observed displacements in Epe can be **causally related to cavern usage**
  - Provide physically founded estimations for displacements where (in space and time) no measurements are available or possible, particularly for **horizontal displacements**
  - Support differentiating cavern caused displacements from other displacements
  - Support processing and interpretation of measurements
  - Reveal how strongly low filling levels affect the surface displacements and presumably cavern convergence
  - Show that long time series of InSAR data can provide the spatiotemporal coverage to constrain local parameters even in a model setting based on many approximations



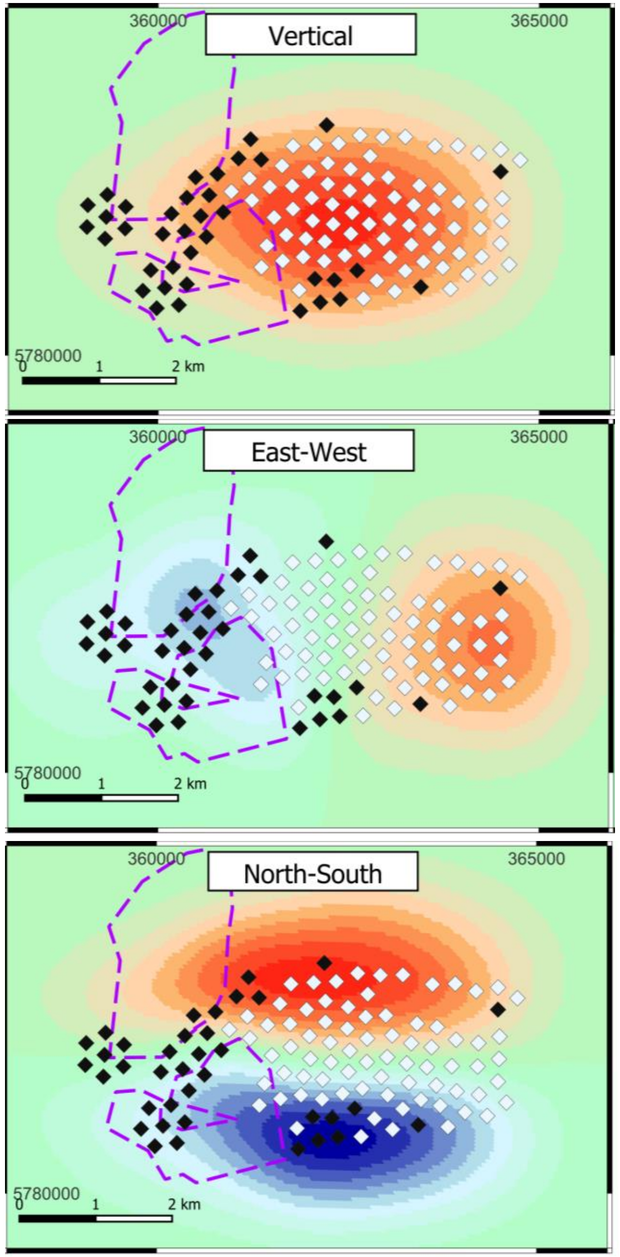


Conclusions

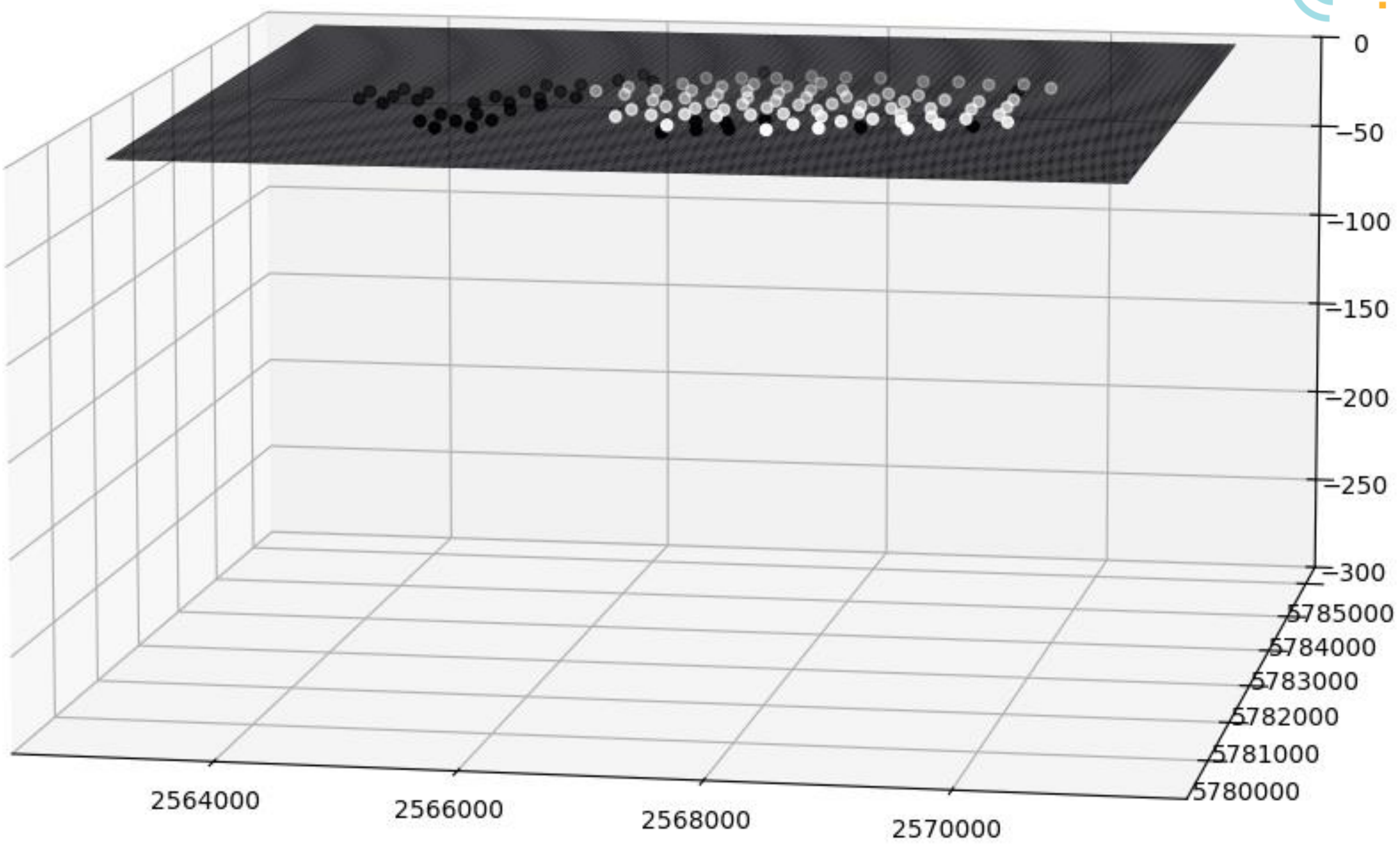
- Deriving a geophysical source model for Epe based on cavern filling levels enables physically founded estimations for **3D surface deformation** caused by cavern convergence in the **entire cavern field** with **high temporal resolution**
- Model results and measurements highly agree, even though the model relies on many assumptions and approximations
- Higher accuracy and physically meaningful parameters could be derived if pressure data from individual caverns could be used

Possible future improvements:

- Include more accurate geological information
- *Include groundwater level related displacement model for the fen*
- Compare with ML-modeling (Physically Informed Neural Networks)



Thank you for your attention!



Karlsruher Institut für Technologie

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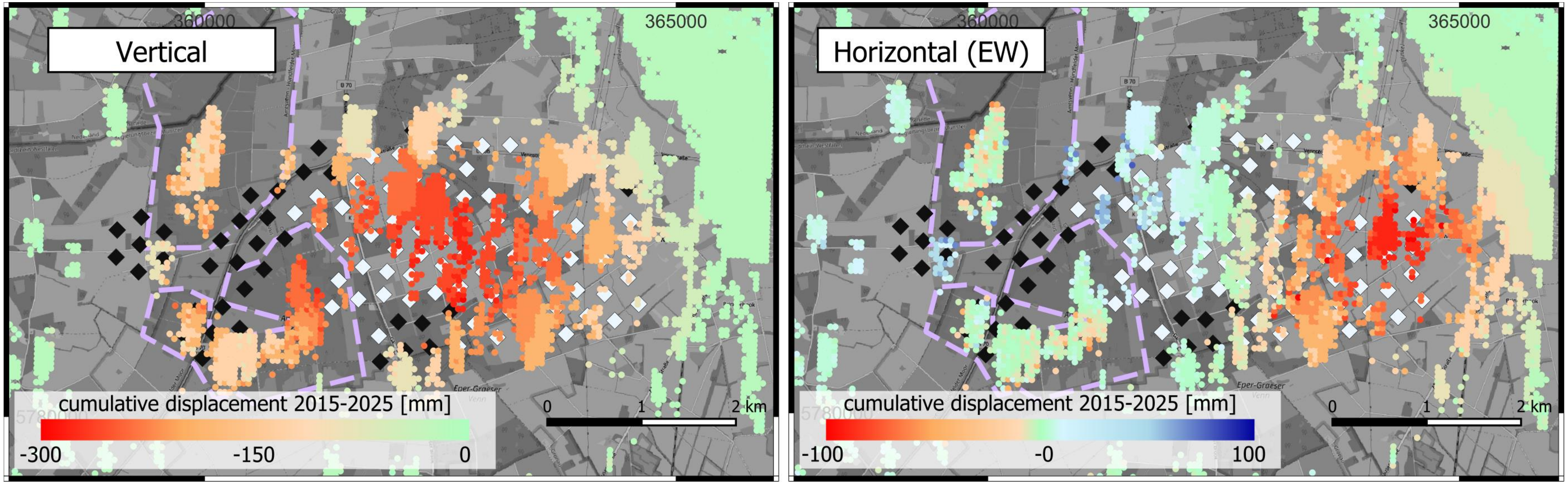
Monitoring: InSAR
Derived vertical and horizontal components



- Derivation of horizontal and vertical components from four tracks (Grid: 50 m x 50 m)
- Vertical displacements show subsidence bowl
- Horizontal displacements are less certain, no data in one (assumed) maximum