Comparison of time-lapse pressure tomography and seismic tomography for characterizing a CO_2 plume in a deep saline formation

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Introduction

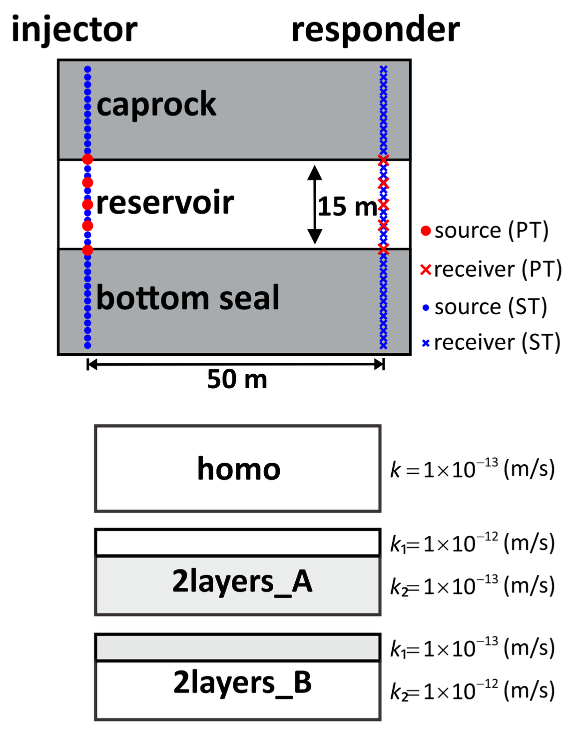
Geophysical surveys, such as seismic tomography (ST), are preferably used for characterizing reservoirs and CO_2 plumes, However, proper petrophysical model is required, which is usually nonlinear and indirectly related to the hydraulic conditions. Pressure tomography (PT) is a novel approach for tracking an evolving CO_2 plume by directly relating the CO_2 saturation to the variations in flow properties. By this approach, pressure transients are utilized for inverting the plume shape and estimating CO_2 saturation.

Objective

- Examine the inversion performance of cross-well PT and ST
- Compare and combine the inversion results by clustering them in an individual or joint way
- Calculate the CO_2 saturation by the mixed-phase specific storage in a single-phase proxy

Forward simulation

- **Model set-up**



- **Test sequence**

step 1: baseline study
- Implement PT by multilevel brine injection tests
- Implement ST by P-wave pulses

step 2: CO_2 injection
- Generate CO_2 plumes by different injection rates and durations (short, long)

step 3: shut-in
- Let the pressures recover (nearly) back to the initial condition
- Prepare the next experiments

step 4: repetition of PT and ST
- Implement PT by multilevel CO_2 injection tests
- Implement ST by P-wave pulses

Travel-time inversion

- **hydraulic travel time**

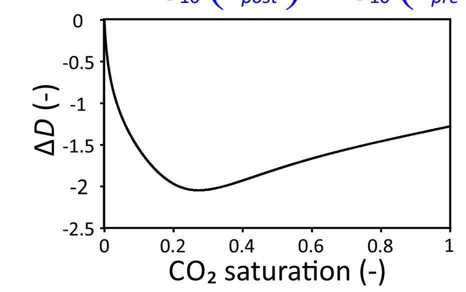
$$\sqrt{t_{\alpha,d}} = \frac{1}{\sqrt{6 f_{\alpha,d}}} \int_{x_1}^{x_2} \frac{ds}{D(s)}$$

pre- and post-injection [1,2]

$$D_{pre} = \frac{K_b}{S_{sb}} = \left(\frac{k}{\Phi}\right)\left[\frac{1}{(\mu_w c_w)}\right]$$

$$D_{post} = \frac{K}{S_s} = \left(\frac{k}{\Phi}\right)\left[\frac{\frac{k_{rw}}{\mu_w}\rho_w + \frac{k_{rn}}{\mu_n}\rho_n}{(S_w c_w + S_n c_n)(S_w \rho_w + S_n \rho_n)}\right]$$

$$\Delta D = \log_{10}(D_{post}) - \log_{10}(D_{pre})$$



- **seismic travel time**

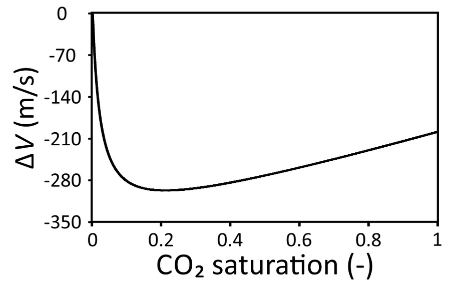
$$t = \int_{x_1}^{x_2} \frac{ds}{V}$$

Difference inversion [3]

$$\Delta t = t_{post} - t_{pre}$$

$$= \int_{x_1}^{x_2} \left(\frac{1}{V_{post}} - \frac{1}{V_{pre}}\right) ds$$

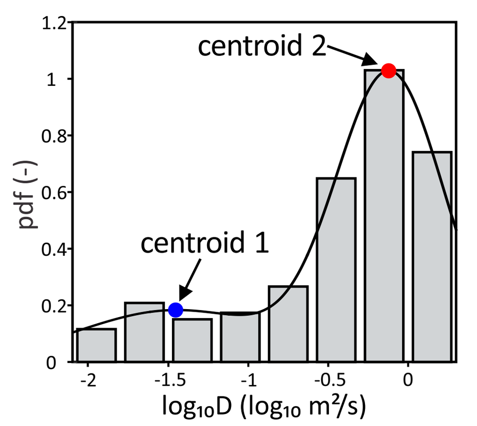
$$\Delta V = V_{post} - V_{pre}$$



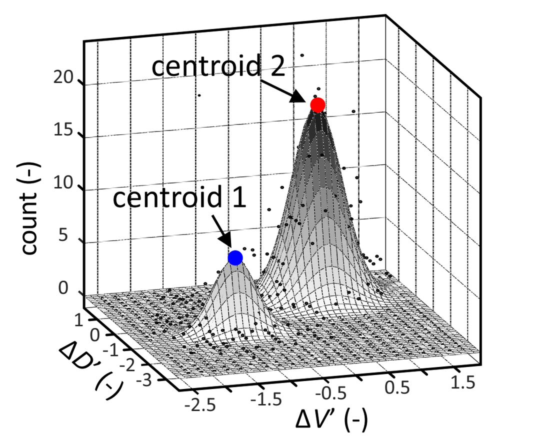
Clustering

- Base on a modified k-means approach
- Centroids of the clusters are determined by data histogram
- Data distribution is composed of two or more Gaussian functions
- Reservoir structure is reconstructed by clustering inverted diffusivities
- Plume extent is determined by clustering the diffusivity or velocity difference individually (1-D clustering) or jointly (2-D clustering)

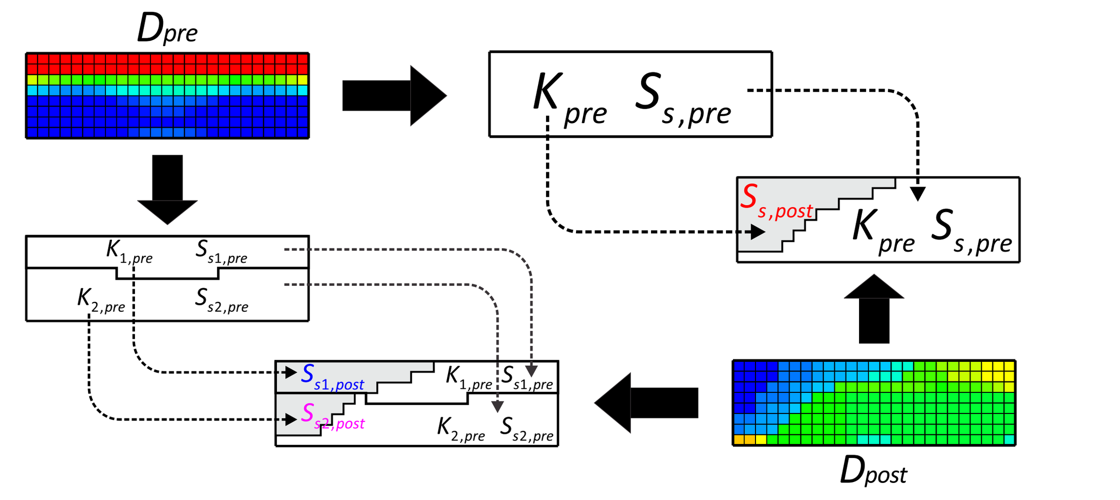
1-D clustering



2-D clustering



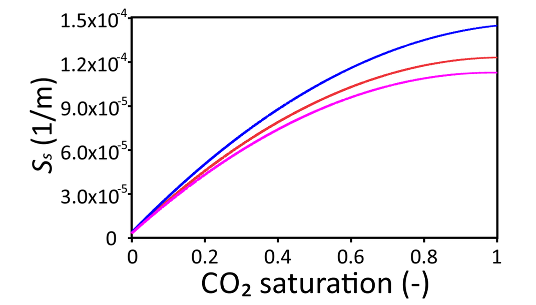
Zonal calibration



- **Saturation calculation**

$$S_{s,post} = \rho_s(\Phi S_w c_w + \Phi S_n c_n)$$

$$\rho_s = S_w \rho_w + S_n \rho_n$$



Results and discussion

Diffusivity and velocity tomograms

- Aquifer structure prior to CO_2 injection can be recognized from inverted diffusivity.
- Inverted velocity cannot reconstruct the hydrofacies.
- Inversion results from both PT and ST cannot reproduce the "true" diffusivities and velocities, as well as their differences.
- Direct transformation of the inverted values causes an underestimation of the CO_2 saturation

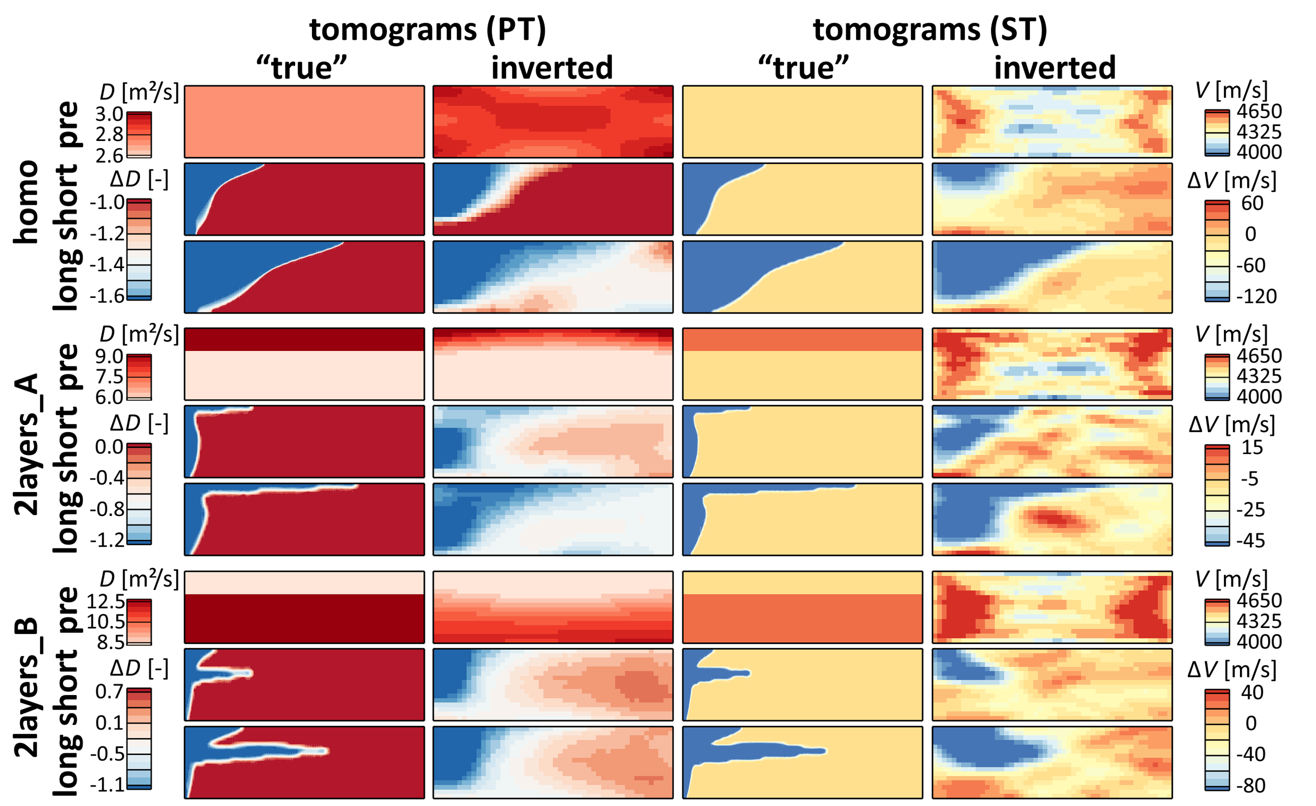


Figure 1. "true" vs. inverted results in three scenarios. The left and right two columns show the tomograms derived from PT and ST, respectively. For each scenario, the first row displays the diffusivity and velocity tomograms prior to CO_2 injection. The second and third rows give the results of diffusivity and velocity differences, respectively.

Individual and joint clustering structures

- Individual clustering results are comparable in the scenarios "homo" and "2layers_A"
- PT resolves the more vertical-like shape due to the larger variance of hydraulic travel times
- Heterogeneity masks the plume in the highly permeable layer for PT
- Combination of the results provides a better estimation of the main plume shape

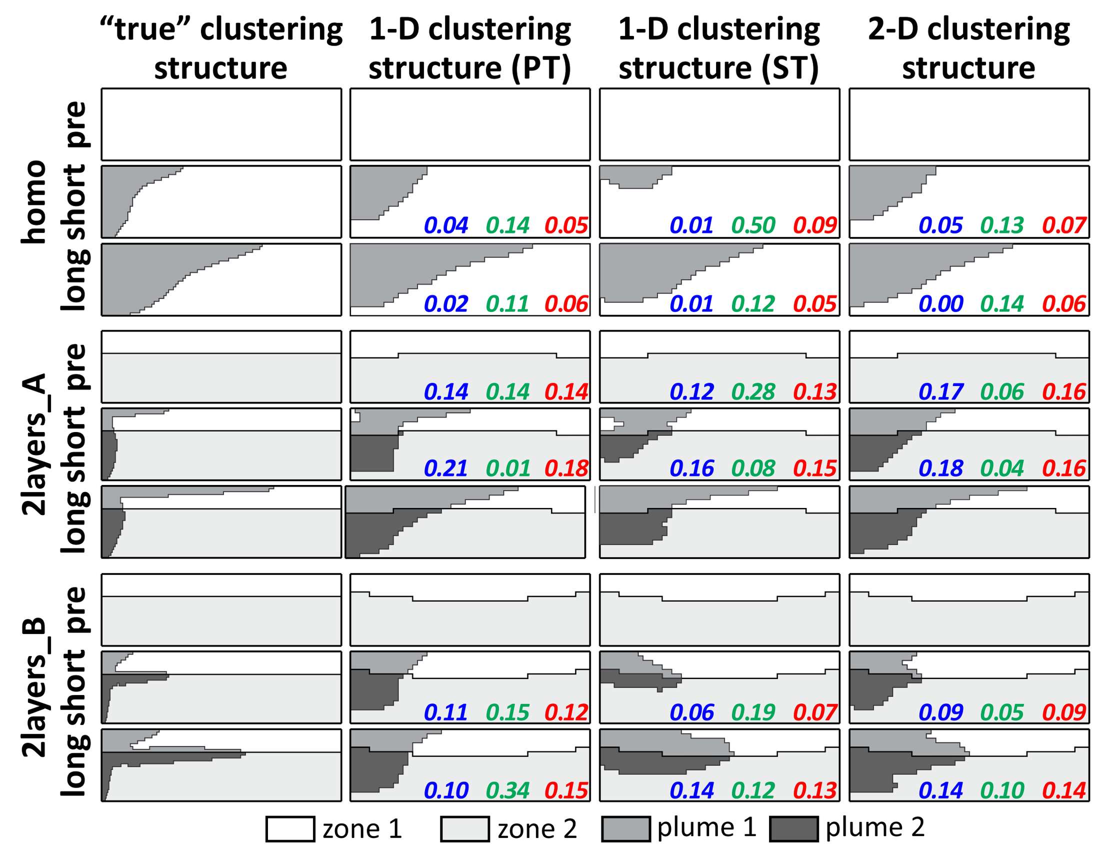


Figure 2. Individual and joint clustering results according to the inverted tomograms. The numbers in each tomogram present the information of pixel misclassification error rate (blue: overestimate rate; green: underestimate rate; red: total misclassification rate).

Calculated CO_2 saturations

- The errors between the "true" and calculated saturations (1-plume) show a strong correlation with the underestimation rate
- The errors of the joint clustering structures remain in a smaller range compared to the individual clustering structures
- Two secondary plumes are distinguished based on the identified aquifer structure
- Calibration of the mixed-phase specific storage (2-plume) provides insight in the saturation of each secondary plume

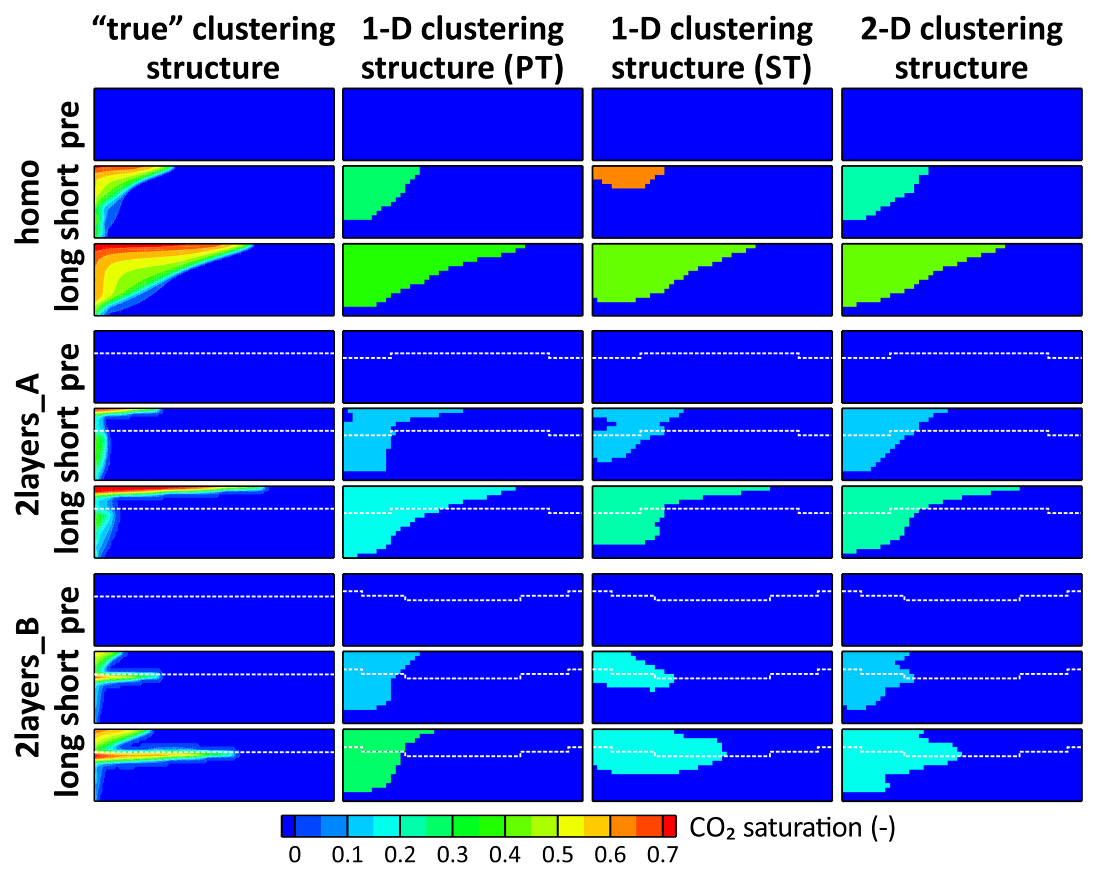


Figure 3. Average saturations of individual and joint clustering structures compared to "true" saturations. The plume is depicted with an integrated value of saturation. The white dot line indicates the boundary of two adjacent layers.

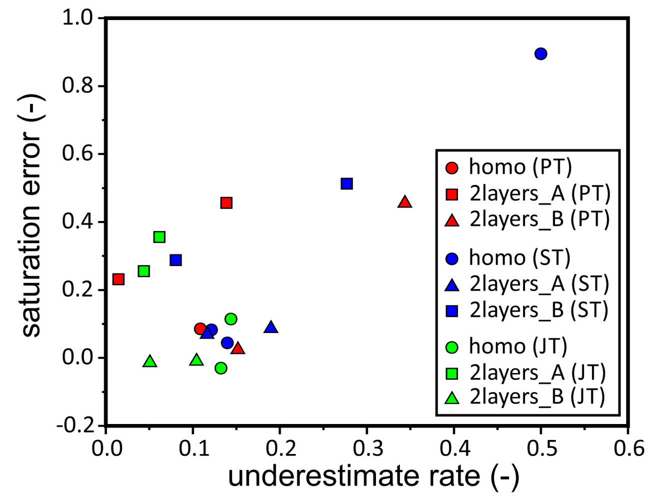


Figure 5. Underestimate rate vs. saturation errors. The saturation error is defined as the ratio of the the discrepancy between the calculated and "true" saturation and the "true" saturation.

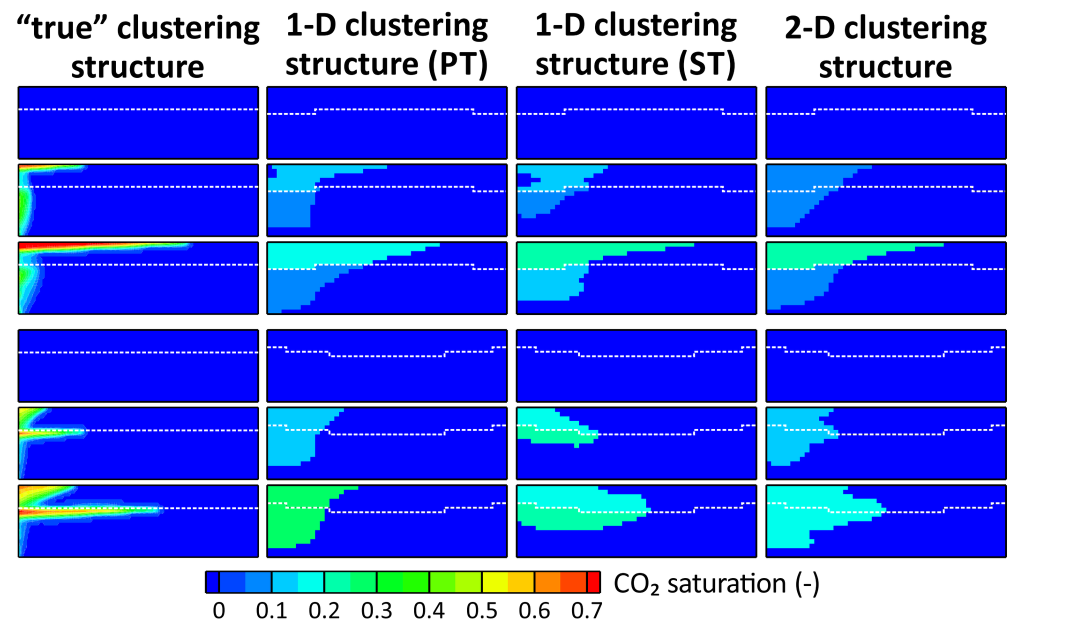


Figure 4. Saturations of individual and joint clustering structures comared to "true" saturations. The plume consists of two "secondary plumes", and each plume has an integrated saturation value. The white dot line indicates the boundary of two adjacent layers.

Conclusions

- The structure of the reservoir prior to CO_2 injection can be reconstructed by PT, which can be utilized as a prior information for the following zonal calibration.
- In general, the capability of reproducing the plume shape is comparable for PT and ST. However, neither PT nor ST can directly quantify the saturation by the inverted values.
- PT can resolve more vertical-like shape due to the larger variance of hydraulic travel times. Heterogeneity of the permeability can however readily mask the plume in highly conductive layer.
- Joint clustering can alleviate the underestimation of the plume shape, which is essential for reducing the errors of estimated saturations.
- **PT can complement ST by improving the delineation of plume shape and estimated saturations.**

References

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