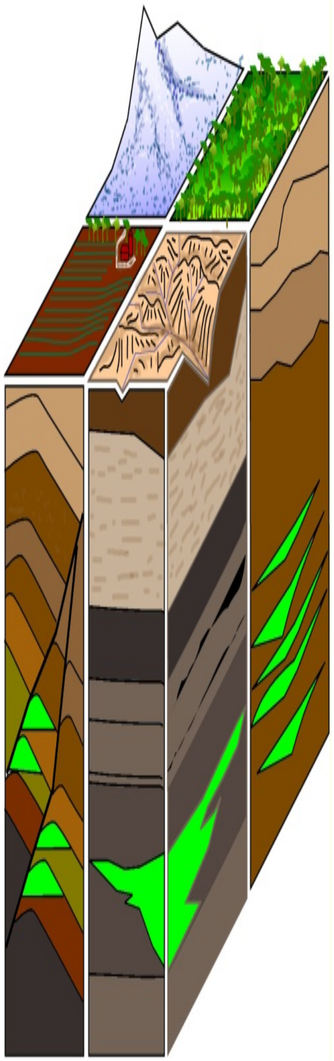

Pressure-Anomaly Based Leakage Detection

JP Nicot, Mehdi Zeidouni, Alex Sun, and K.-Won Chang

Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

Progress Review of STAR Grant Research on Carbon Geosequestration

Washington, D.C. – January 7, 2013

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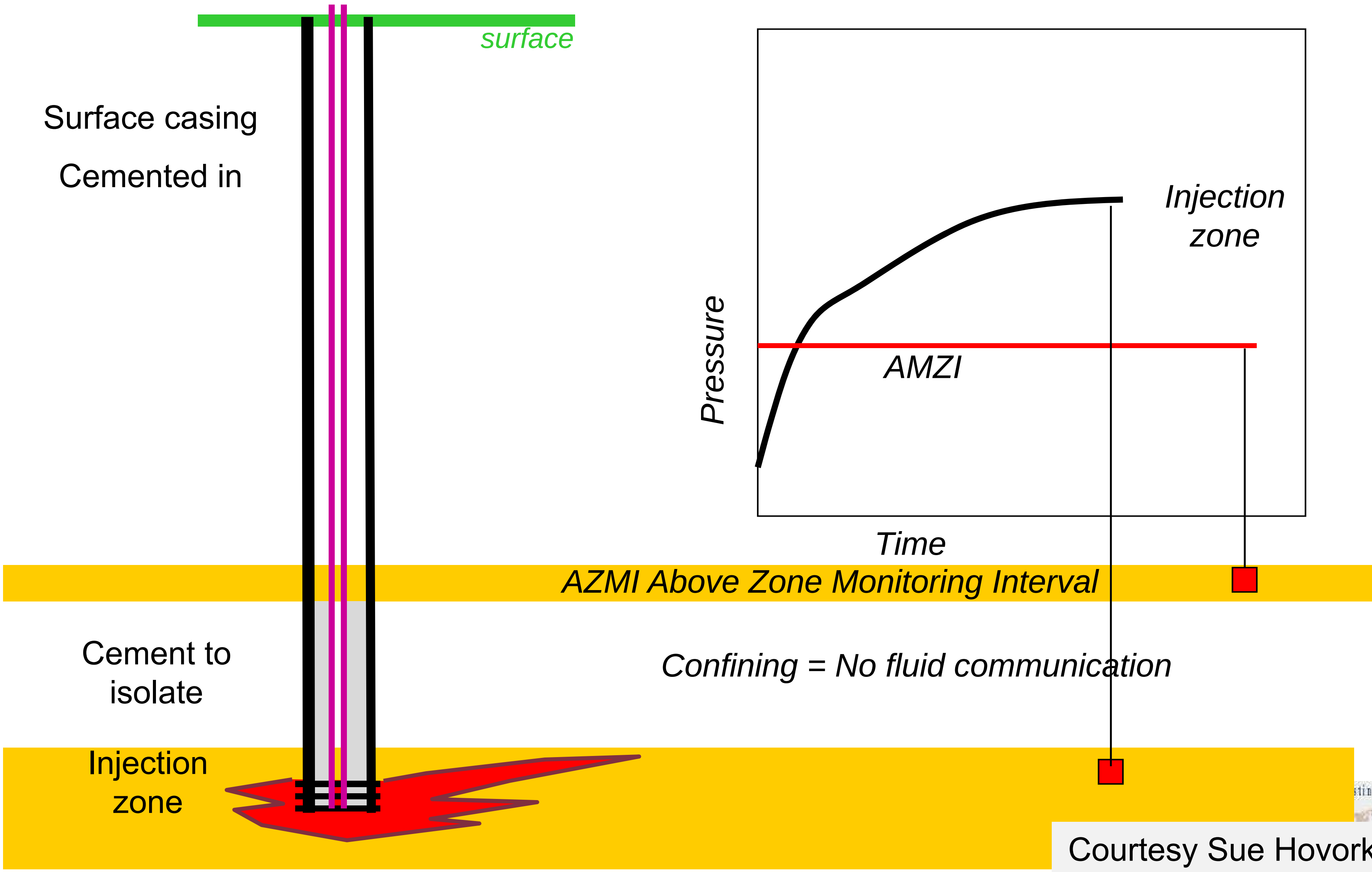
"Expert-Based Development of a Standard in CO_2 Sequestration Monitoring Technology"

- STAR R834384 addresses the requirement for a GS project to develop a monitoring plan (UIC Class VI)
- focuses on 5 well-known fields:
  - Soil gas approaches
  - Groundwater monitoring and tracers
  - **Pressure and temperature monitoring**
  - Well-based techniques
  - Seismic techniques
- Above-Zone Monitoring Intervals (AZMI) measurements at Cranfield, MS and other fields
- In-Zone IZ monitoring

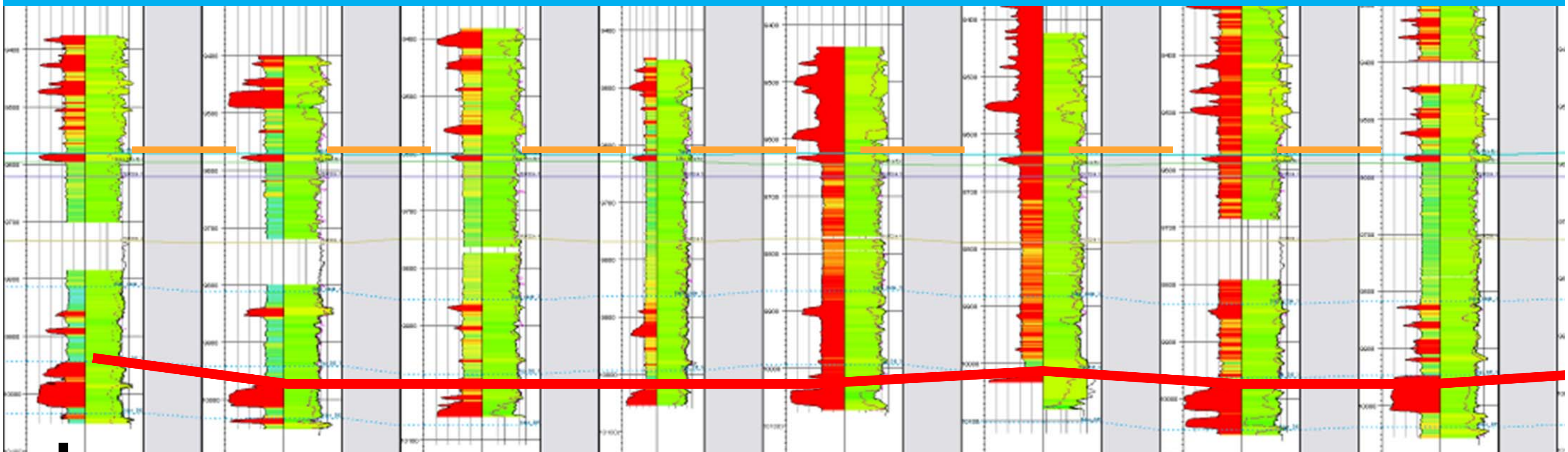
Using AZMI pressure to assess storage permanence



Courtesy Sue Hovorka

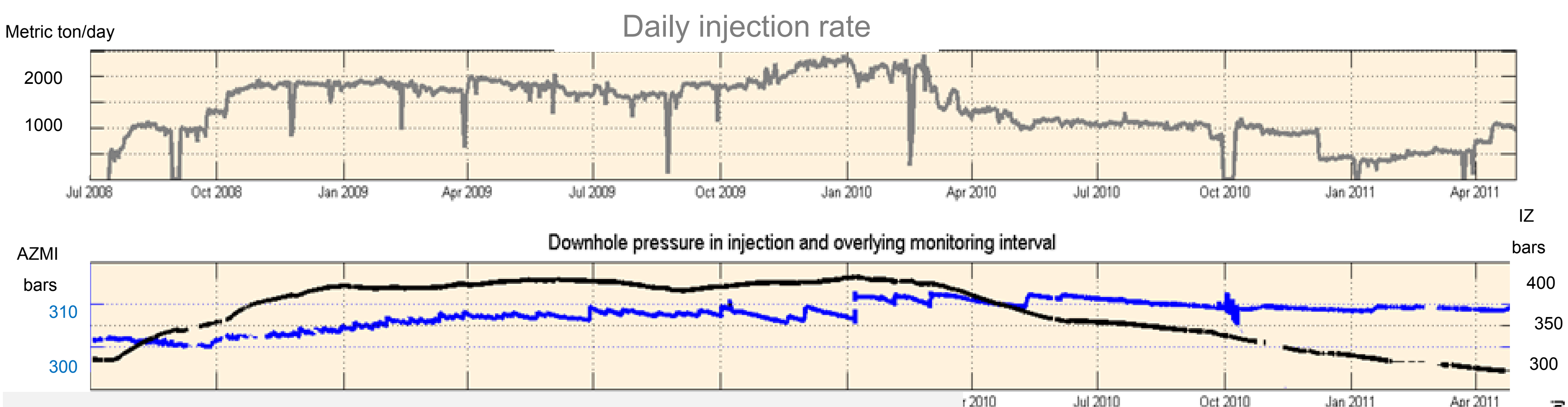
Pressure Monitoring

Above-Zone Monitoring Interval (AZMI) –leakage **detection**



30 m

Within Injection Zone (IZ) reservoir management



Tao, Bryant, Meckel, IJGGC accepted ms, available online

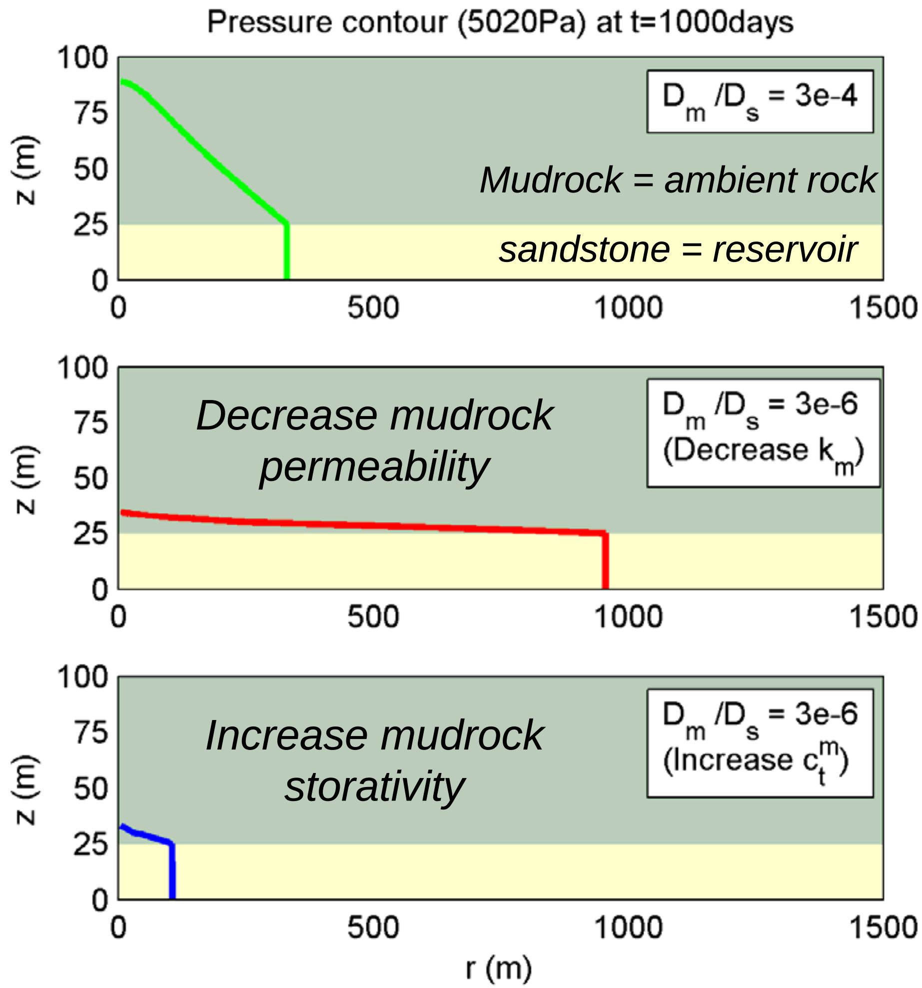
Pressure monitoring subtask

- Presenting results from on-going modeling work:
- Set the stage: how is pressure attenuated, how is it transmitted from IZ to AZMI? (KWC)
- How big is the pressure signal, can we detect it? (MZ)
- Can we locate the leak if there is one? (AS, MZ)
- Optimize location of monitoring wells (AS)

Role of the ambient rock during CO_2 injection

- Pressure propagation is governed by ratios of mudrock/sandstone permeability and storativity and relative thickness of formations

- Permeable and compressible surrounding rock reduces pressure propagation within a reservoir



From Chang, Hesse, Nicot in review WRR, 2013

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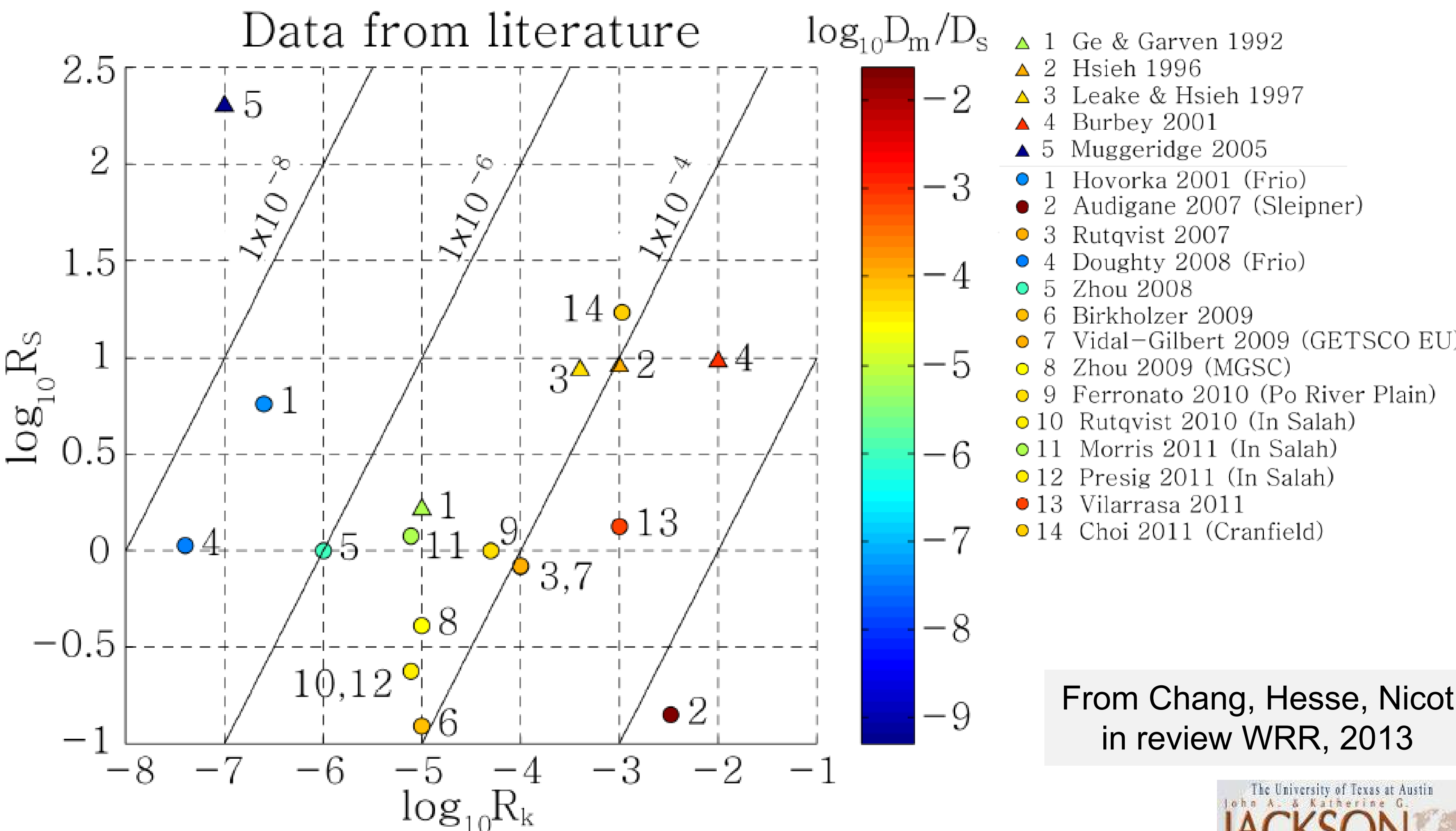
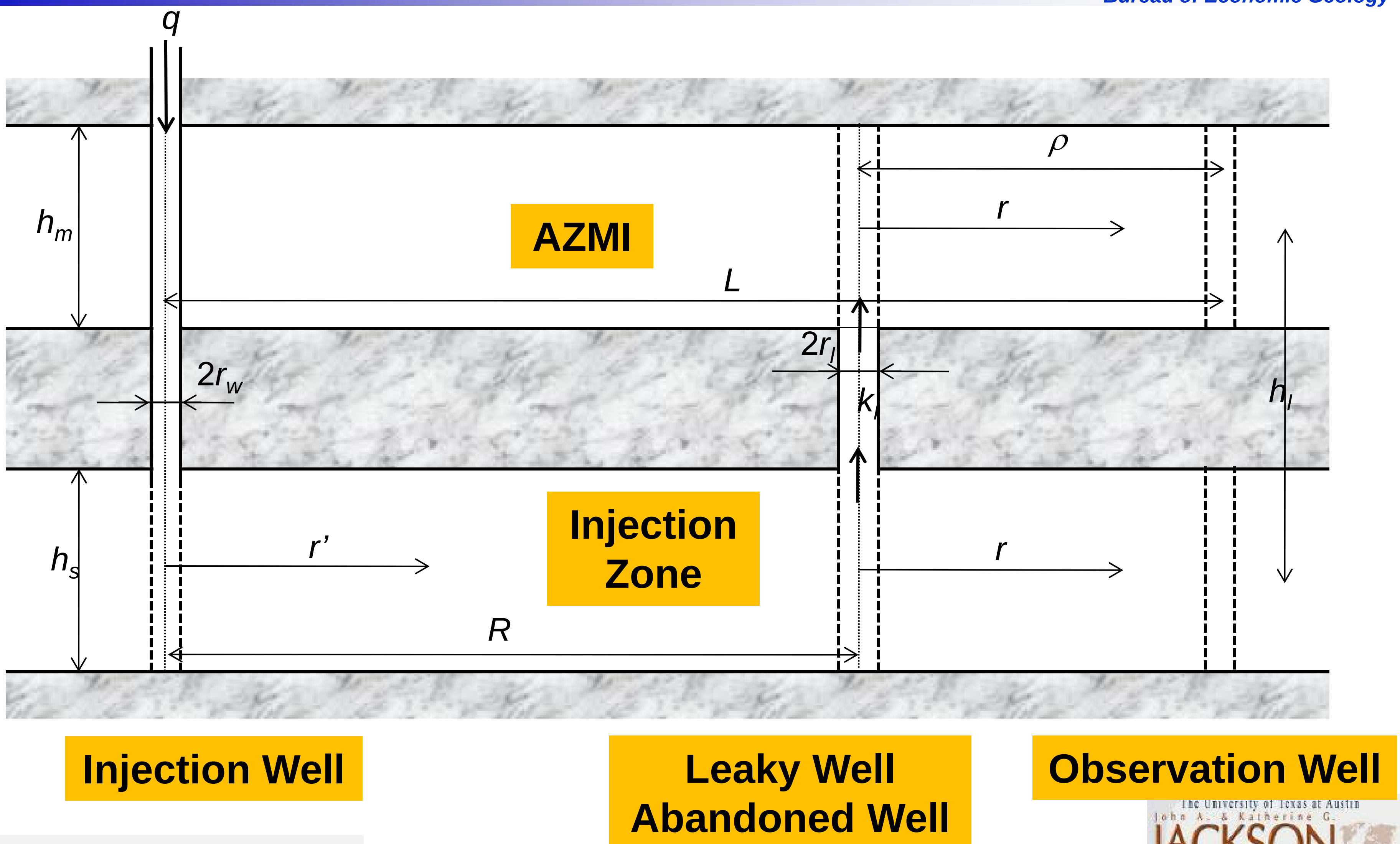
Pressure diffusion: pumping / CO_2 injection



From Chang, Hesse, Nicot in review WRR, 2013

Development of a leaky well analytical model: Pressure signal magnitude



Zeidouni, JPSE in review

Analytical solution (single-phase flow)

$$\bar{P}_{mD} = \frac{\bar{q}_{lD}(s) K_0\left(\sqrt{\frac{s}{\eta_D}}\rho_D\right)}{T_D r_{lD}\sqrt{\frac{s}{\eta_D}} K_1\left(\sqrt{\frac{s}{\eta_D}} r_{lD}\right)}$$

$$\bar{q}_{lD} = \frac{\dfrac{K_0\left(\sqrt{s}R_D\right)}{s^{3/2}K_1\left(\sqrt{s}\right)}}{\dfrac{K_0(\sqrt{s}r_{lD})}{r_{lD}\sqrt{s}K_1(\sqrt{s}r_{lD})} + \dfrac{K_0\left(\sqrt{\frac{s}{\eta_D}} r_{lD}\right)}{T_D r_{lD}\sqrt{\frac{s}{\eta_D}} K_1\left(\sqrt{\frac{s}{\eta_D}} r_{lD}\right)} + \dfrac{1}{\alpha}}$$

Zeidouni, JPSE in review

Asymptotic solution

$$P_{mD} = \frac{1}{(1+T_D)}\left(-\frac{\gamma}{2}-\frac{1}{2}\ln\left(\frac{R_D^2}{4t_D}\right)\right)-\frac{q_{lD}}{2T_D}\left(\kappa+\ln\left(\frac{\rho_D^2}{\eta_D}\right)\right)$$

$$q_{lD} = \frac{1}{(1+1/T_D)}\left(1-C(t_D)\left(\kappa+\ln\left(R_D^2\right)\right)\right)$$

$$C(t_D)=\frac{1}{\left(\kappa-2\gamma+\ln(4t_D)\right)}-\frac{\gamma}{\left(\kappa-2\gamma+\ln(4t_D)\right)^2}+\frac{\gamma^2-\frac{\pi^2}{6}}{\left(\kappa-2\gamma+\ln(4t_D)\right)^3}-\frac{\gamma^3-\frac{\pi^2}{2}\gamma+2\xi(3)}{\left(\kappa-2\gamma+\ln(4t_D)\right)^4}$$

$$\kappa = \frac{2T_D}{\alpha\left(T_D+1\right)}+\ln\left(\frac{\eta_D^{\frac{1}{(T_D+1)}}}{r_{lD}^2}\right)$$

Zeidouni, JPSE in review

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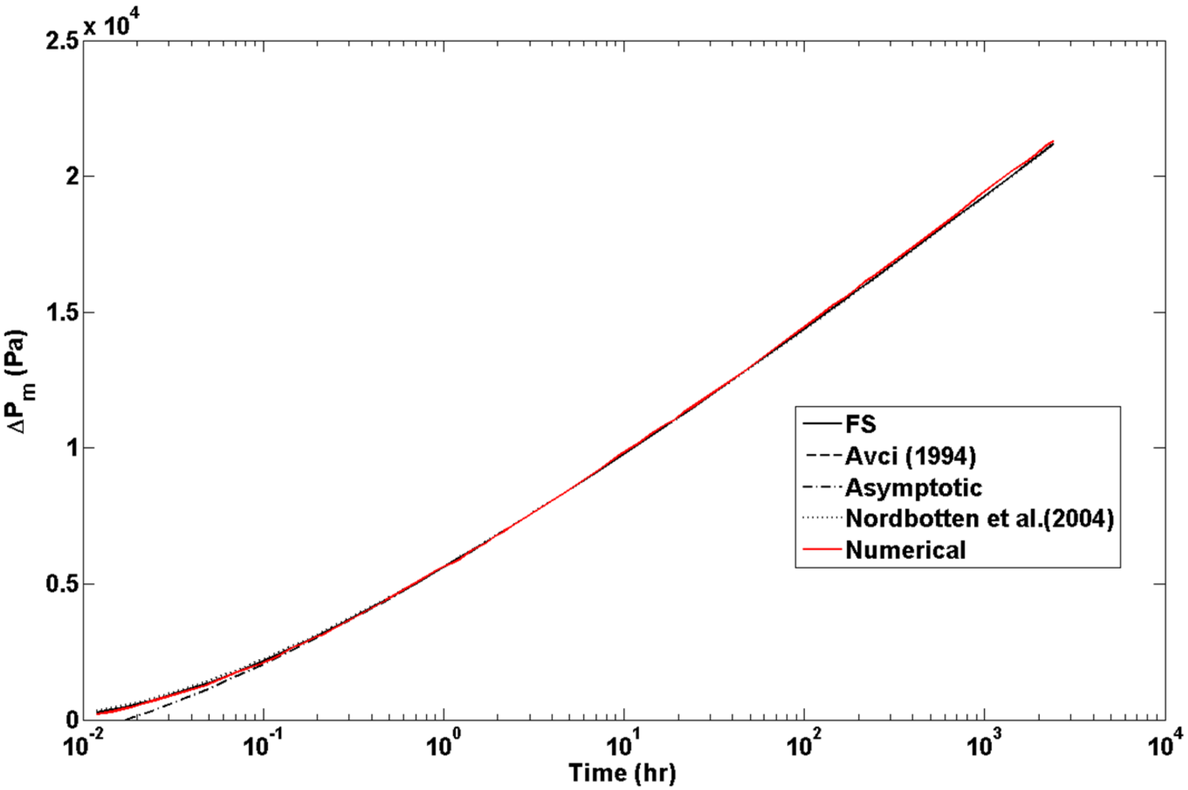
Asymptotic solution

$$P_{mD} = \frac{1}{(1+T_D)}\left(-\frac{\gamma}{2}-\frac{1}{2}\ln\left(\frac{R_D^2}{4t_D}\right)\right)-\frac{q_{lD}}{2T_D}\left(\kappa+\ln\left(\frac{\rho_D^2}{\eta_D}\right)\right)$$

$$q_{lD} = \frac{1}{(1+1/T_D)}\left(1-C(t\right.$$

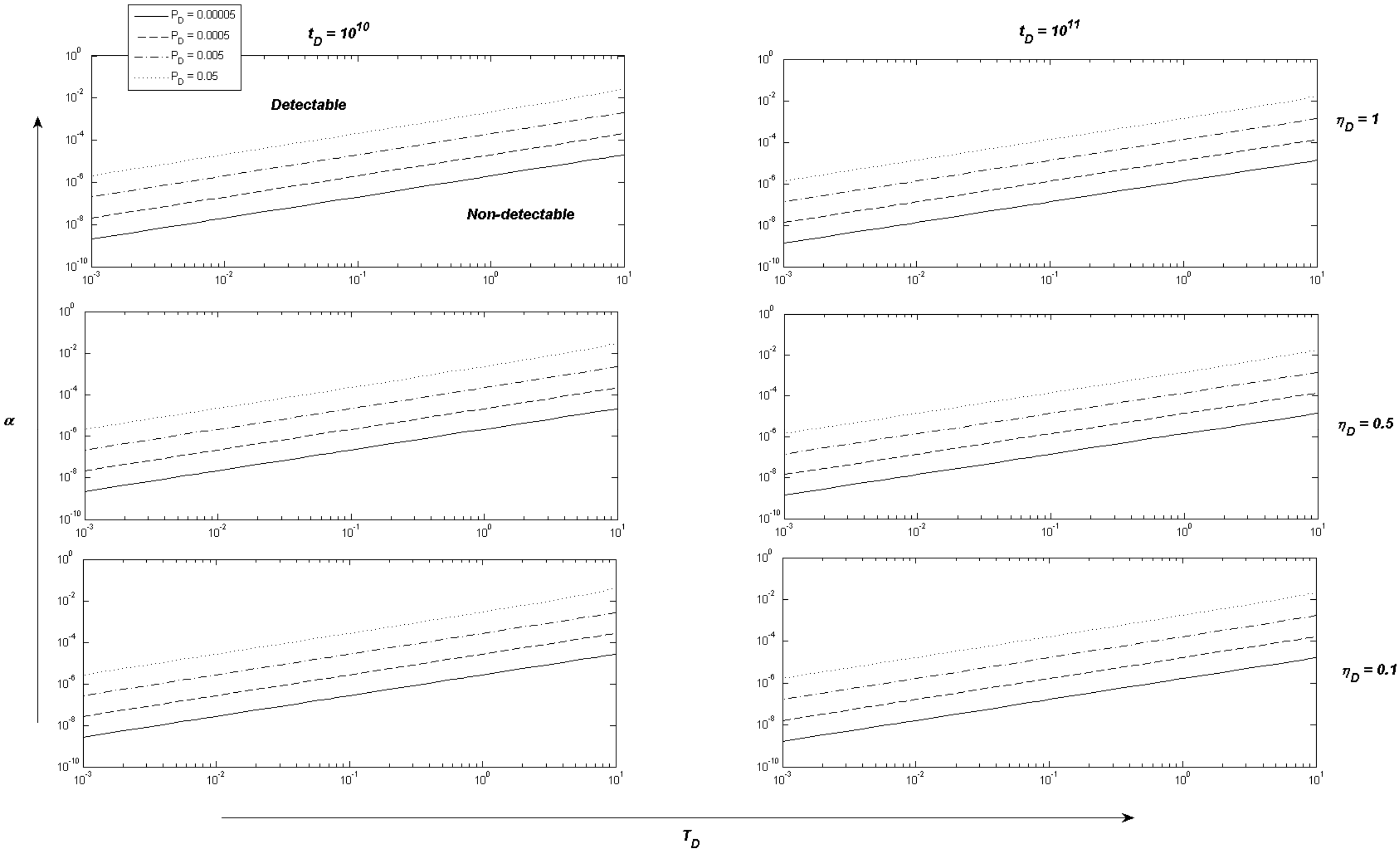
$$C(t_D)=\frac{1}{(\kappa-2\gamma+\ln(4t_D))}-\ldots$$

$$\kappa = \frac{2T_D}{\alpha(T_D+1)}+\ln\left(\ldots\right.$$

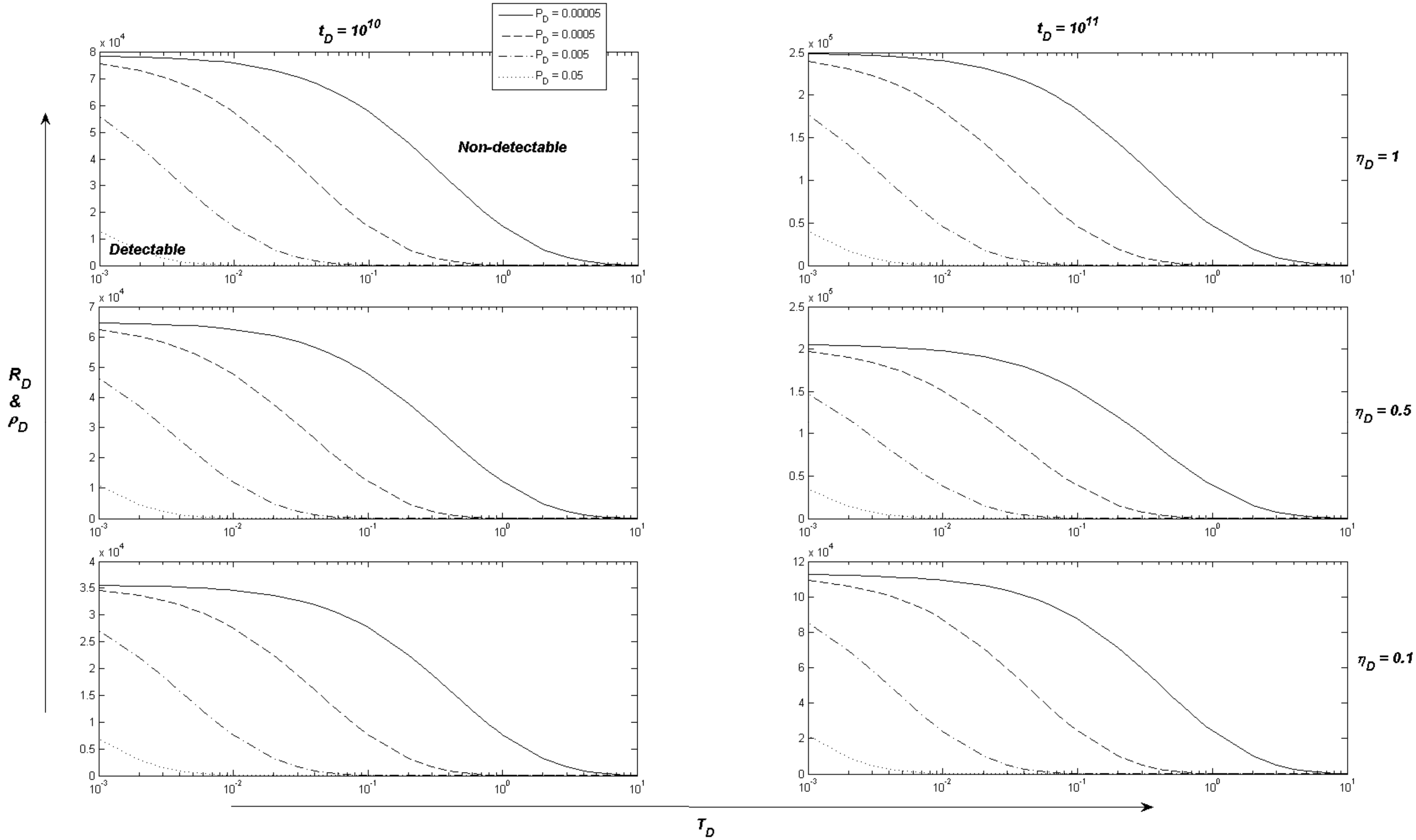


Zeidouni, JPSE in review

Detection type-curves



Detection type-curves



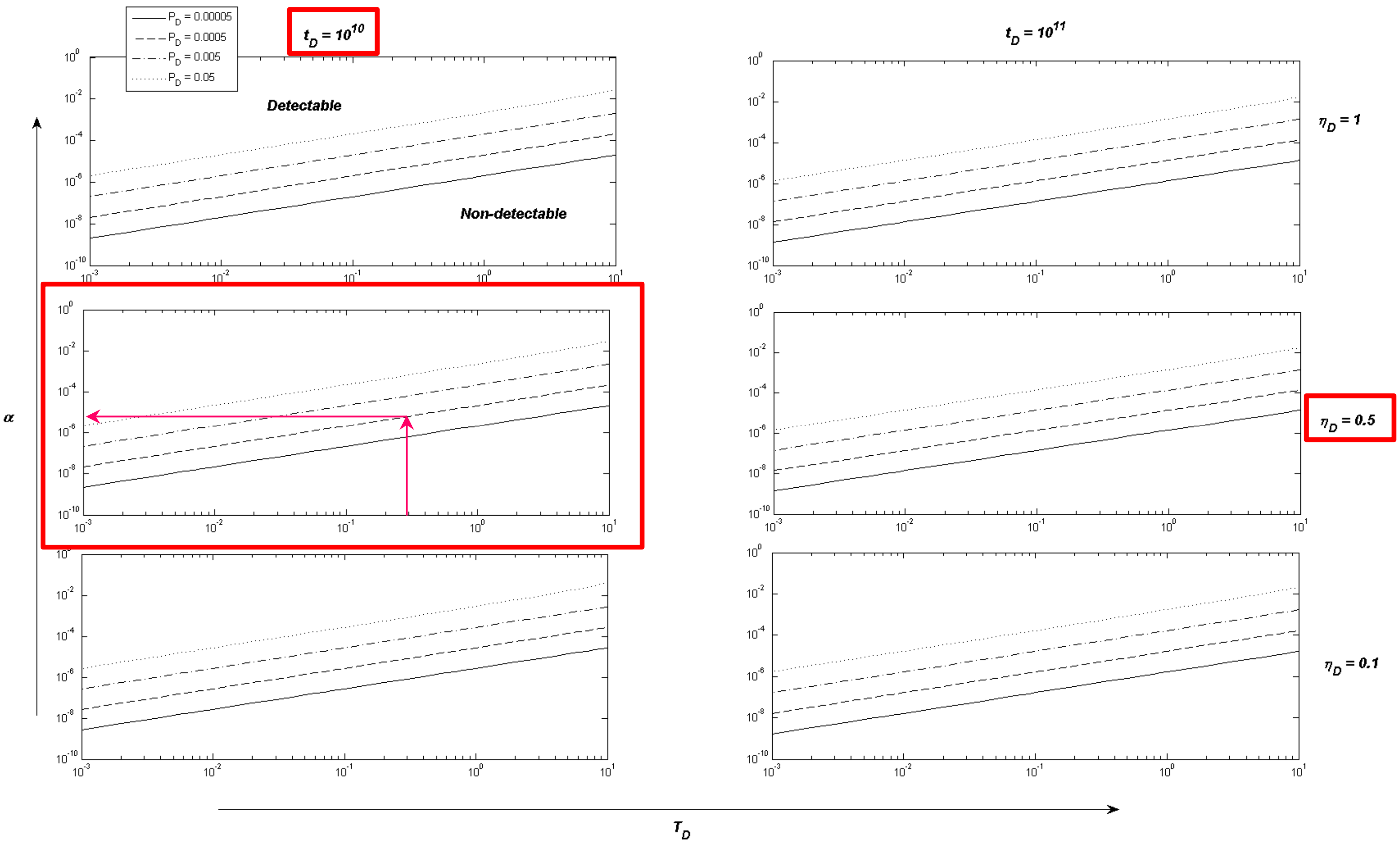
Cranfield Example

- η_D*=0.5 (diffusivity ratio),* T_D*=0.28 (transmissivity ratio)*
- t = 1 yr equivalent to $t_D=10^{10}$ *(dimless time)*
- ΔP = 0.15 psi ~to P_D = 0.0005 *(dim pressure threshold)*
- $\alpha = 6 \times 10^{-6}$ *(leakage coefficient)*
- and assuming $R_D = \rho_D = 2500$

$$R_D = \frac{R}{r_w} \qquad \rho_D = \frac{\rho}{r_w} \qquad L_D = \frac{L}{r_w} \qquad \alpha = \frac{r_l^2 k_l}{2khh_l} \qquad T_D = \frac{k_a h_a}{kh} \qquad \eta_D = \frac{\eta_a}{\eta}$$

$$P_D = \frac{2\pi kh}{q\mu B}\left(P_i - P\right) \qquad t_D = \frac{\eta t}{r_w^2} \qquad q_{lD} = \frac{q_l}{q}$$

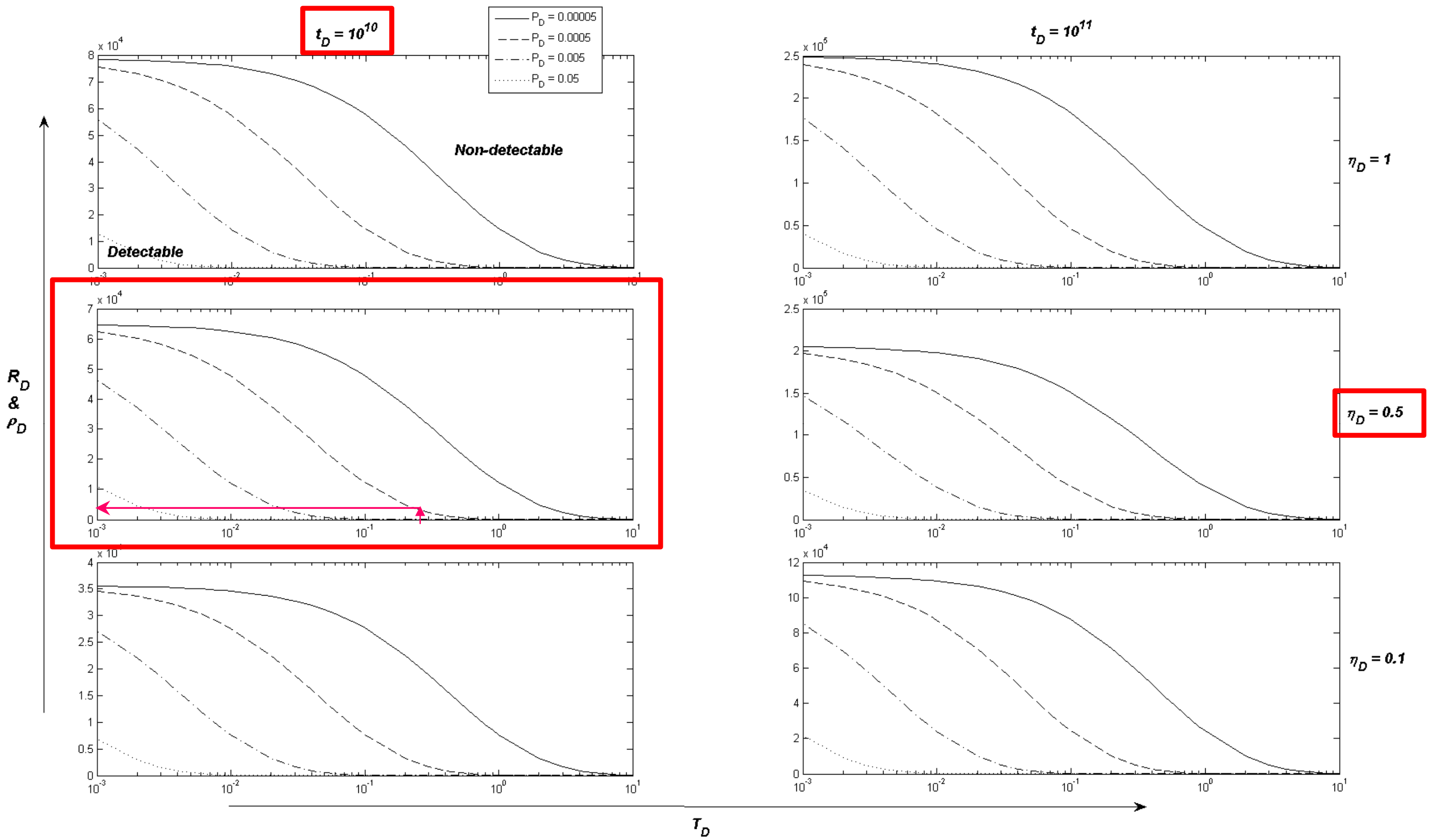
Detection type-curves



α > 6 x 10^{-6} is detectable

kl > 400 mD is detectable

Detection type-curves



R_D and ρ_D < 2500 are detectable

R and ρ < 250 m are detectable

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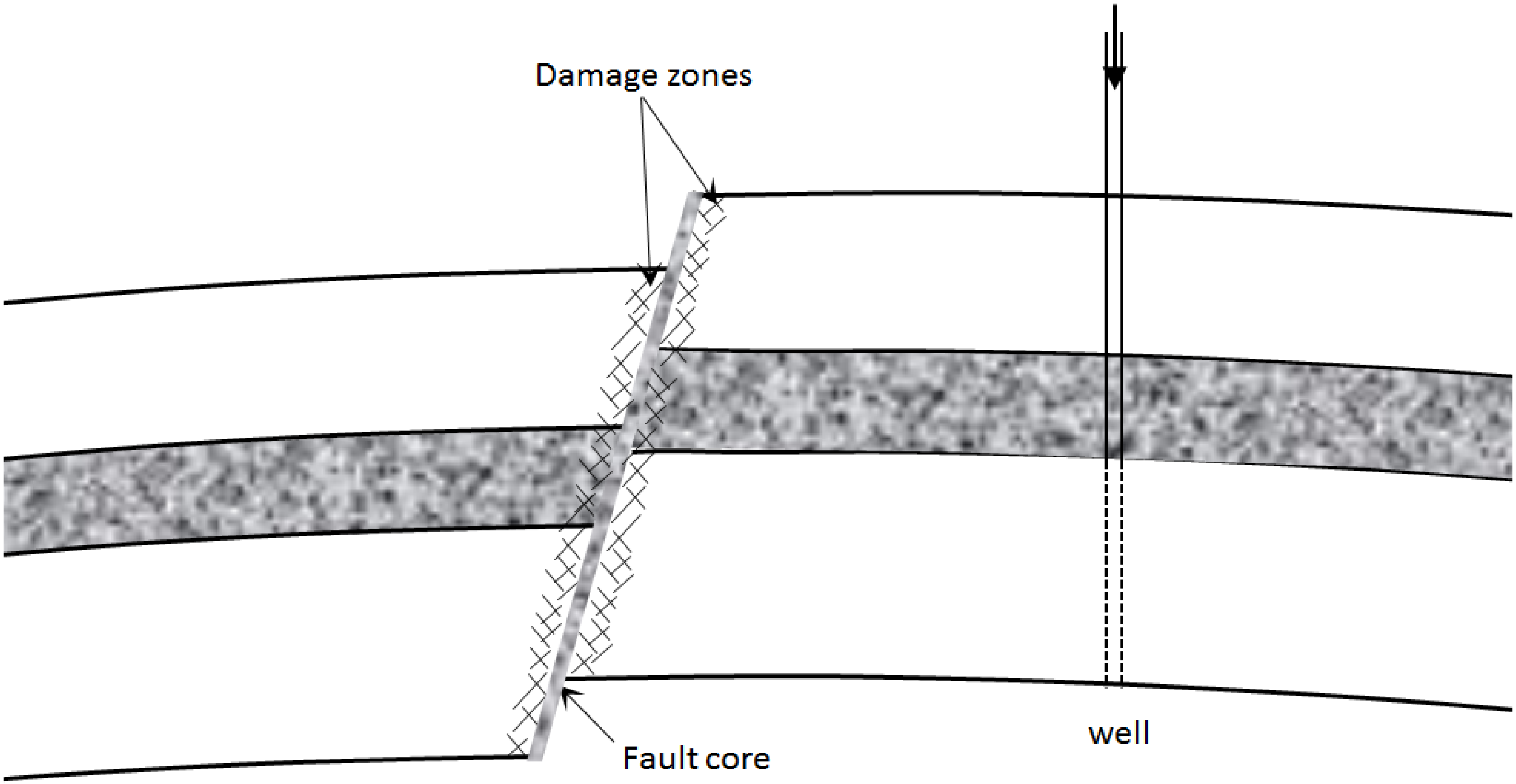
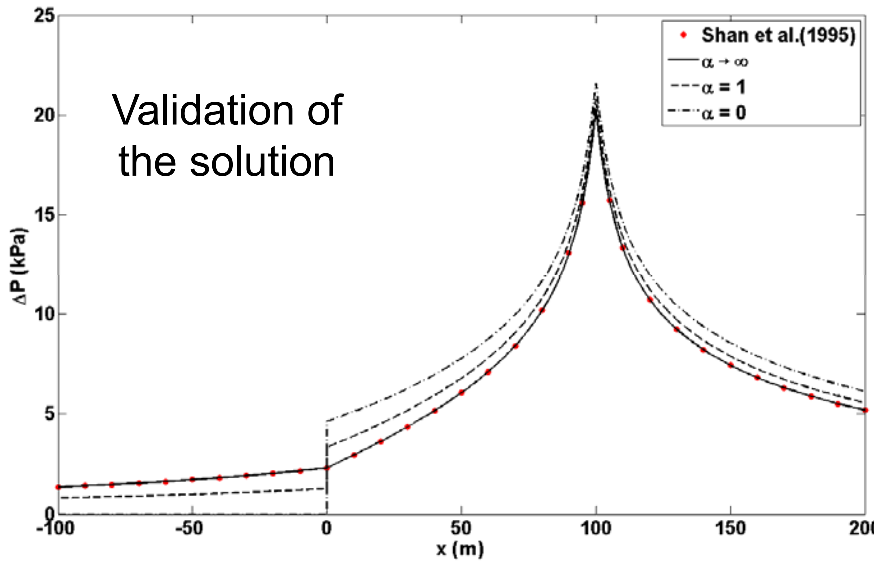
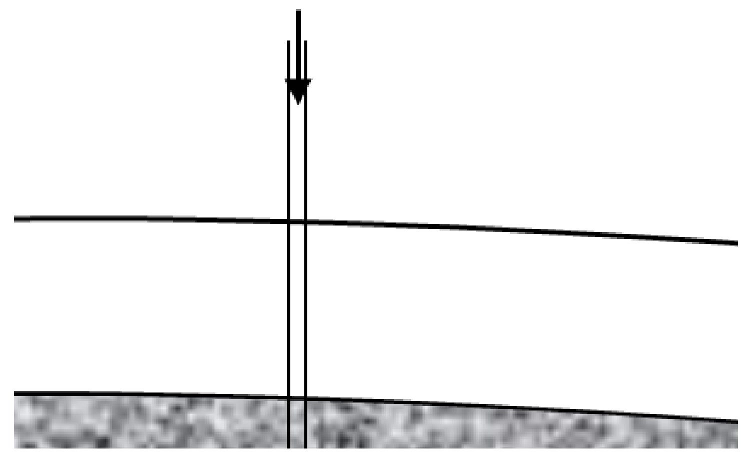
Similar work on faults: Leaky fault analytical model

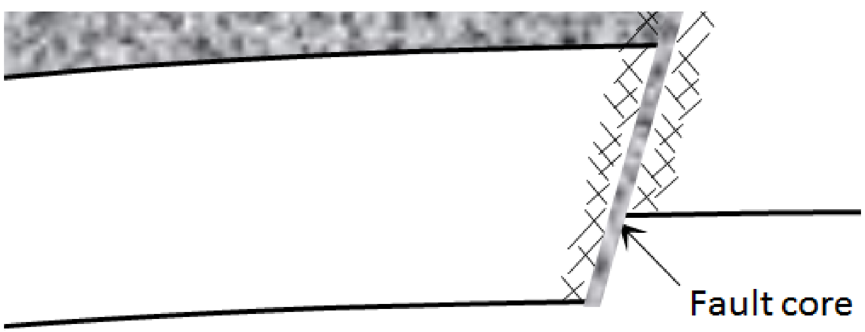


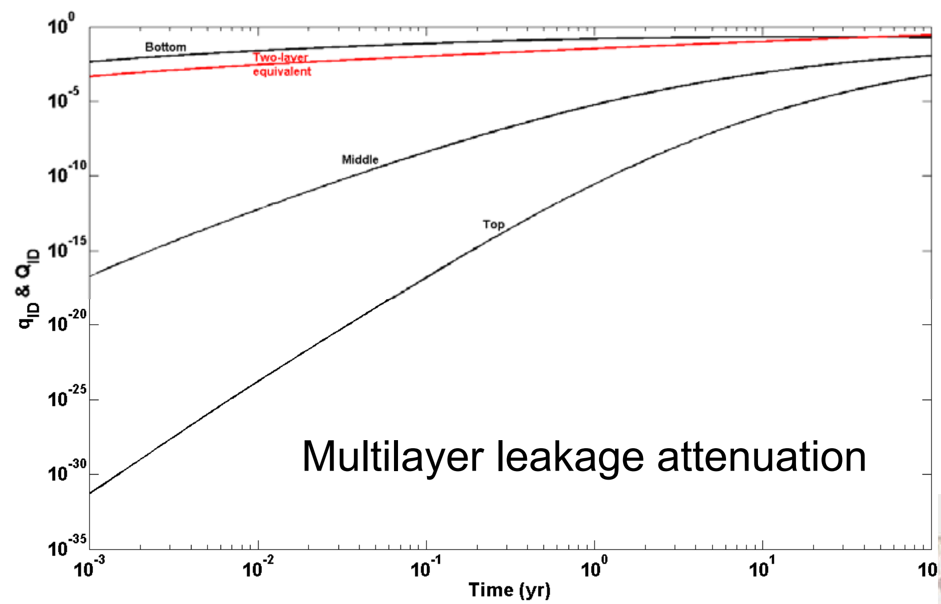
Zeidouni, WRR., 2012

Similar work on faults: Leaky fault analytical model





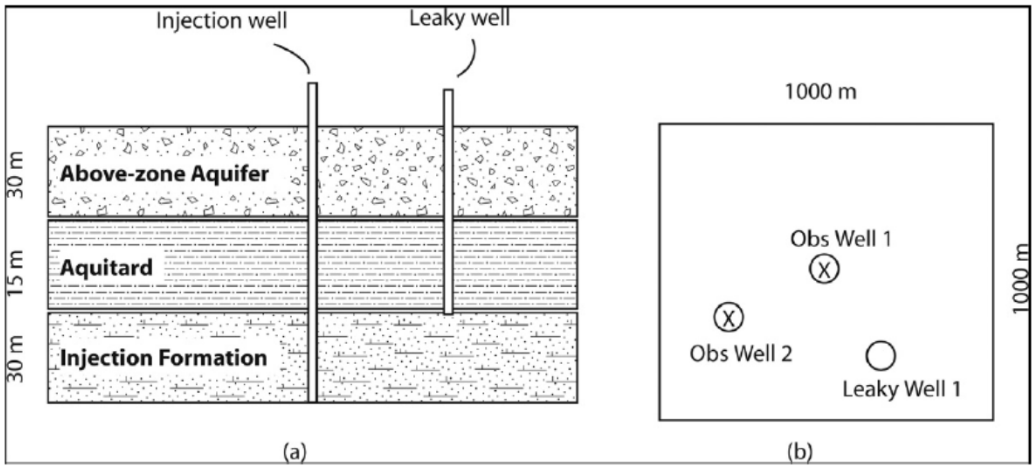




Zeidouni, WRR., 2012

Inversion of pressure anomaly data: "remediation"

- We observed "pressure anomaly": can we detect rate and location of source?

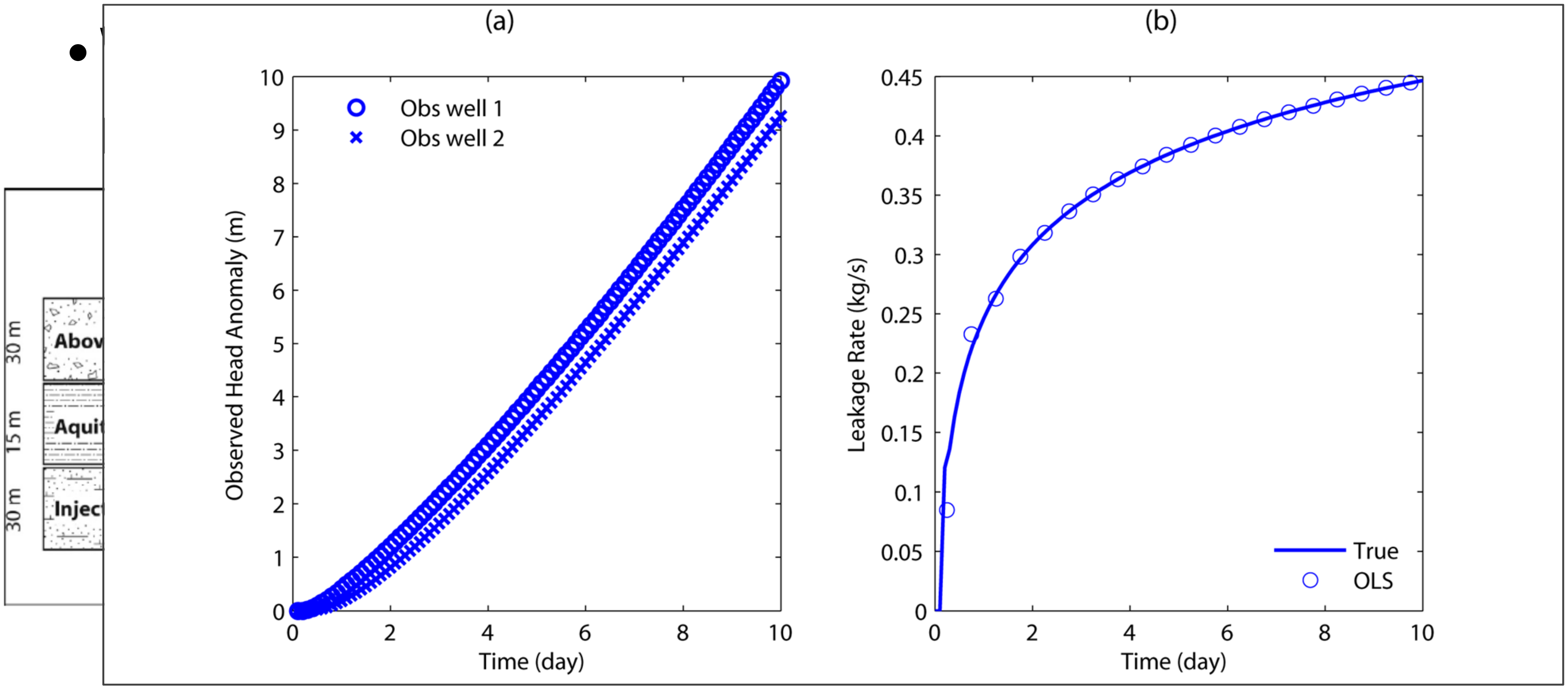


Simple homogeneous system

Given observation heads, ordinary least-square method can recover leakage rate history

Sun and Nicot, Adv.W.R., 2012

Inversion of pressure anomaly data: “remediation”

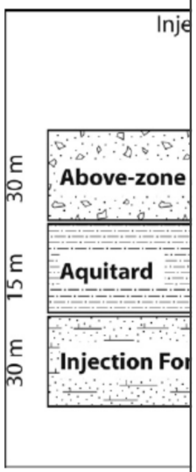


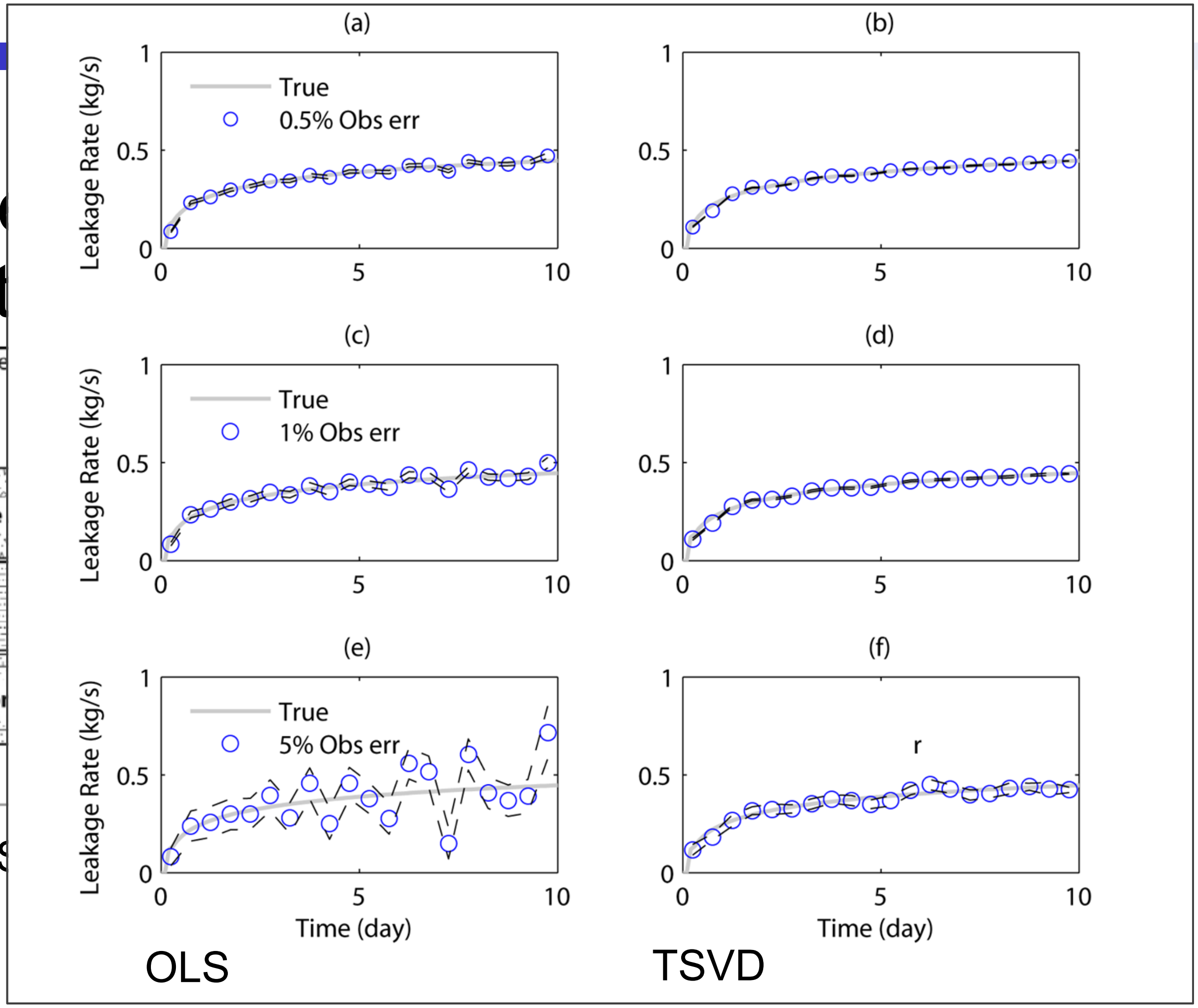
Given observation heads, ordinary least-square method can recover leakage rate history

Sun and Nicot, Adv.W.R., 2012

Inversion of pressure anomaly data: "remediation"

• W we detect
rat

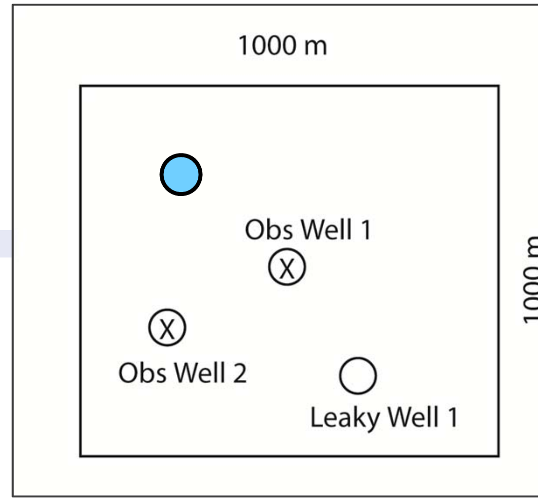


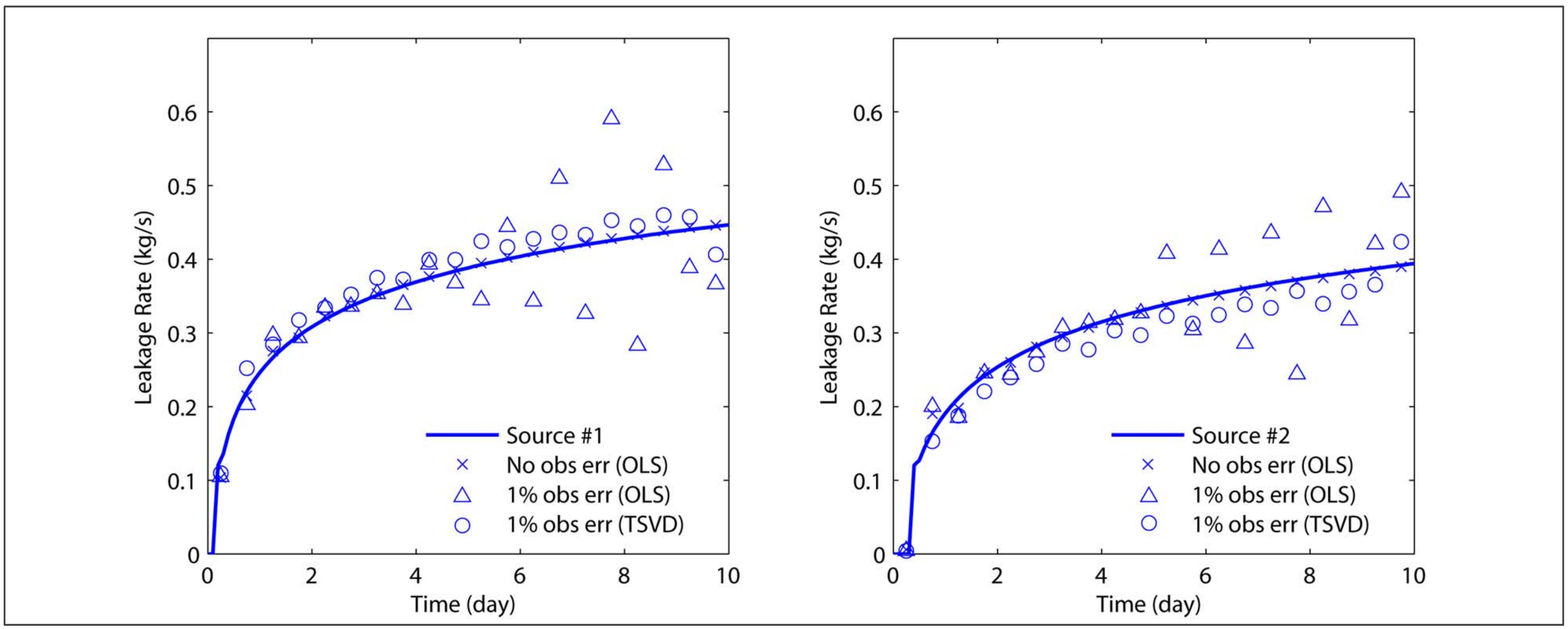


Effect of <u>observation errors</u>

Sun and Nicot, Adv.W.R., 2012

Inversion of pressure anomaly data: "remediation"





<u>Multiple</u> leaky wells

Sun and Nicot, Adv.W.R., 2012

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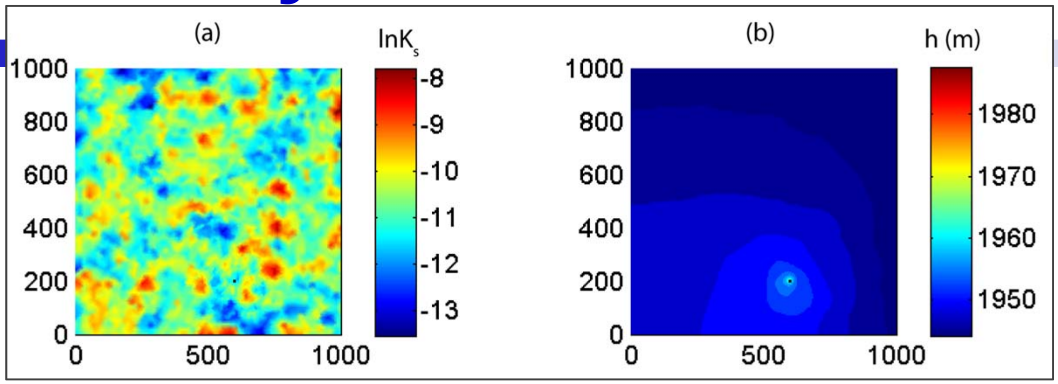
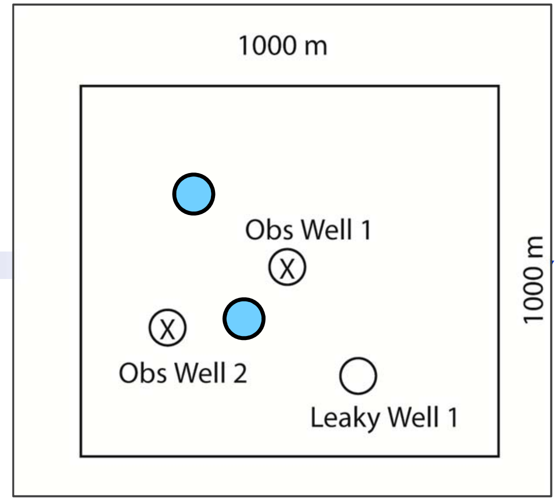
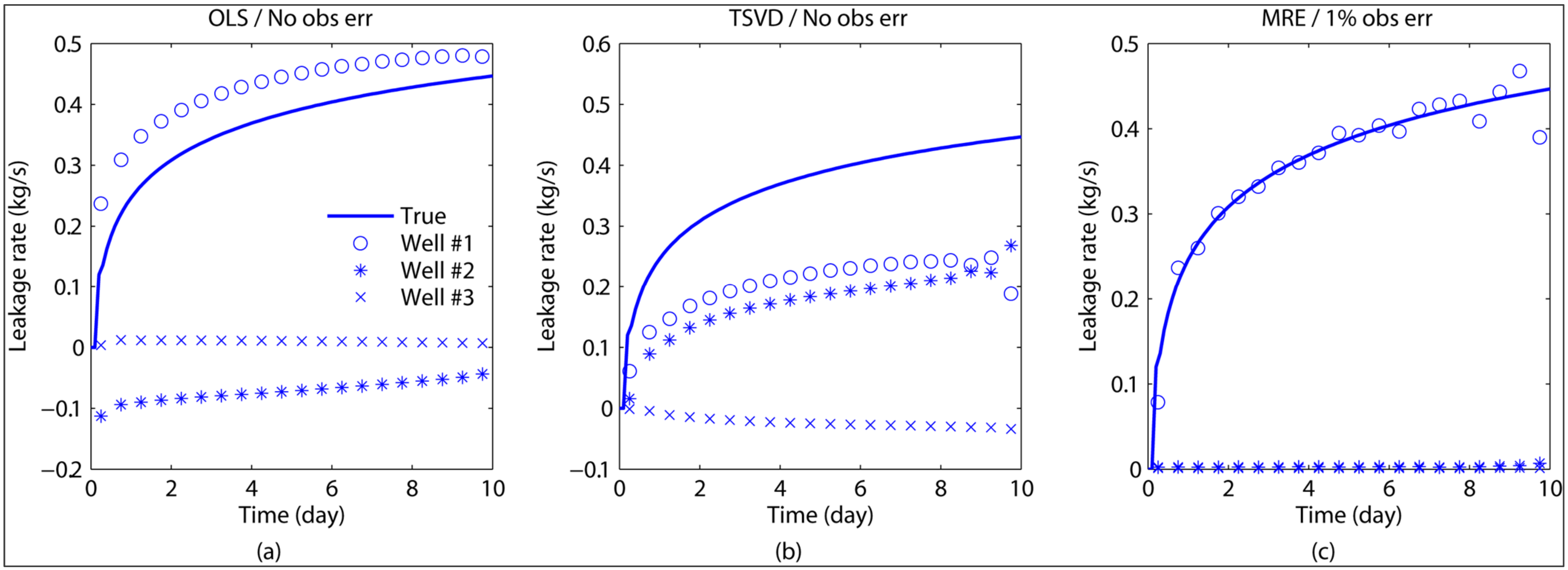
Inversion of pressure anomaly data: "remediation"





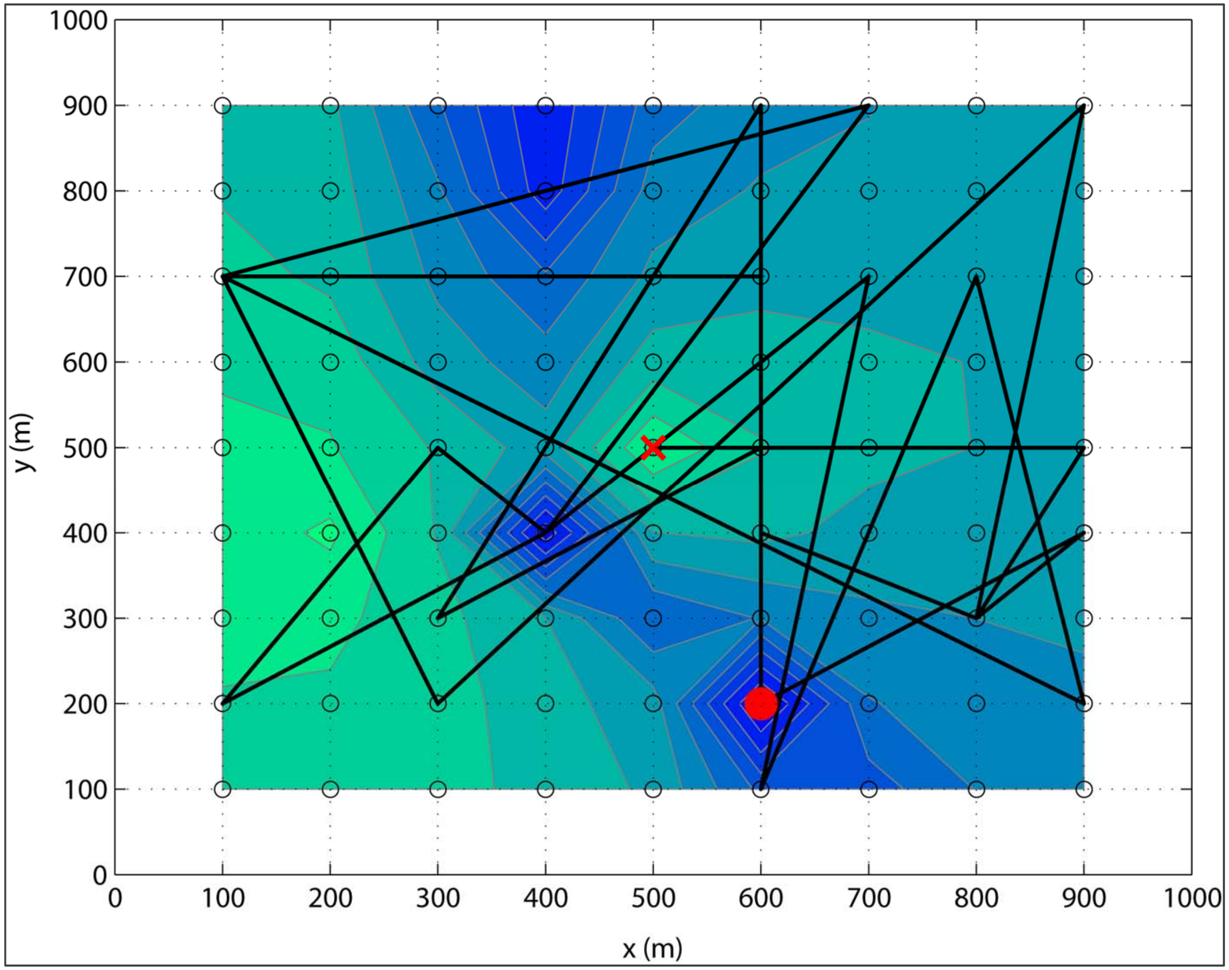
Now, heterogeneous K field



<u>Heterogeneous</u>; <u>multiple</u> leaky wells; locations known but rates unknown (could be 0)

Sun and Nicot, Adv.W.R., 2012

Inversion of pressure anomaly data: "remediation"



O: Well locations

X: Initial guess

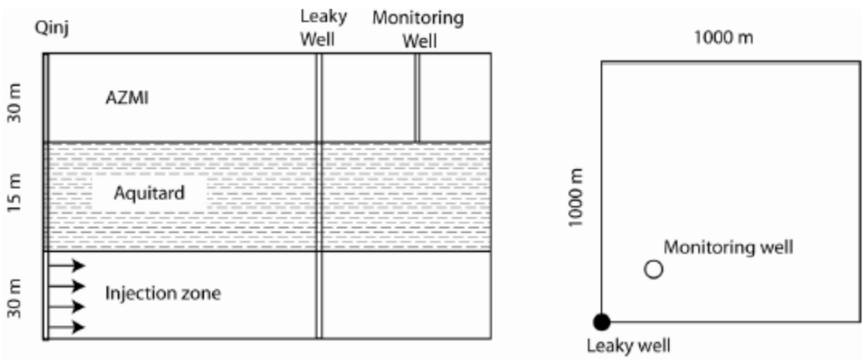
: Actual location

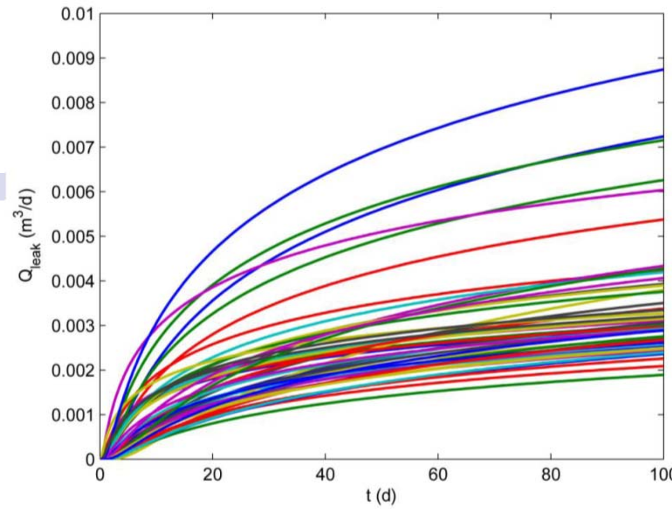
Conclusions:
Can detect leakage rates and locations
Try different solvers

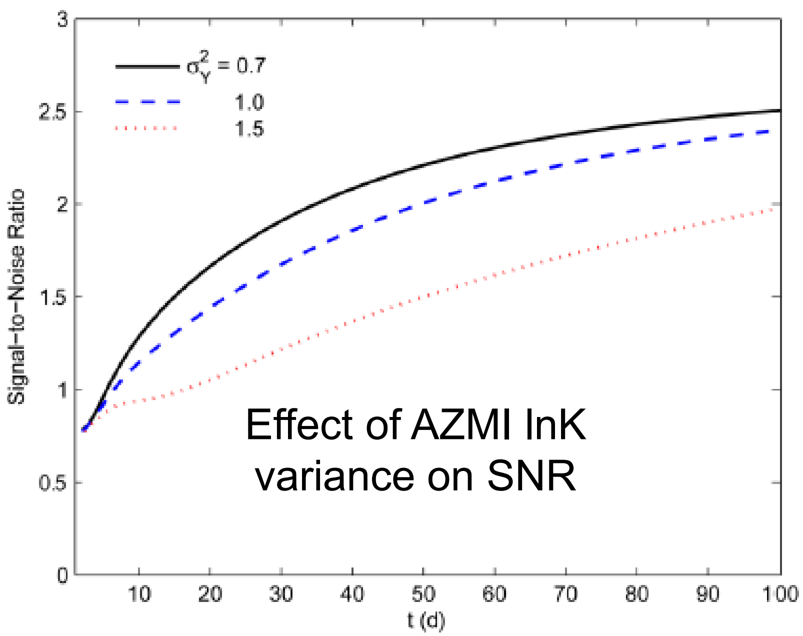
ONE leaky well but <u>location not known</u>: simulated annealing

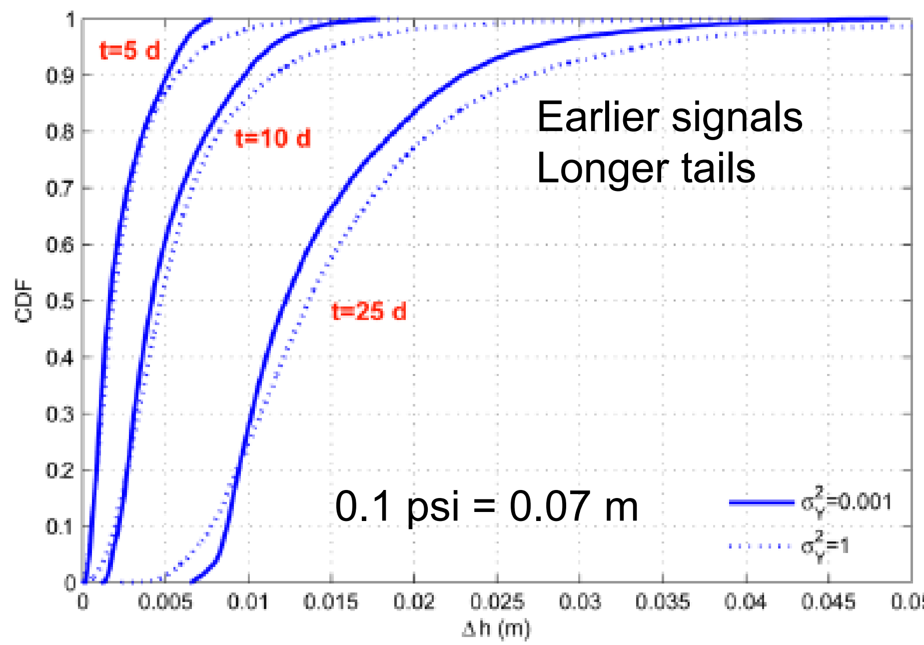
Sun and Nicot, 2012, Adv. WR

Leakage source detection: design perspective









Sun, Zeidouni, Nicot et al., accepted ms, Adv.W.R.

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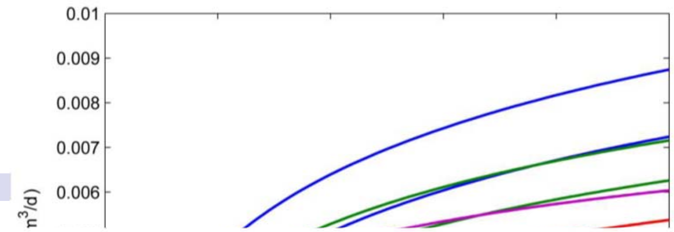
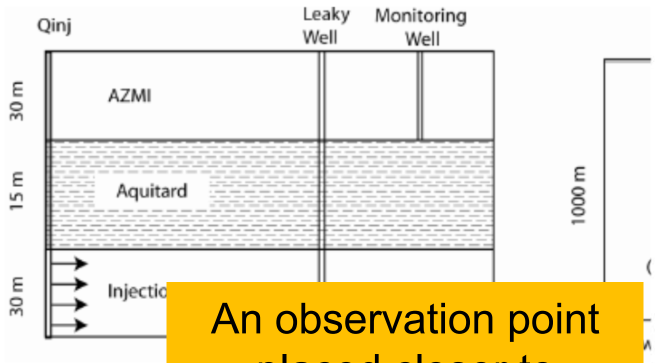
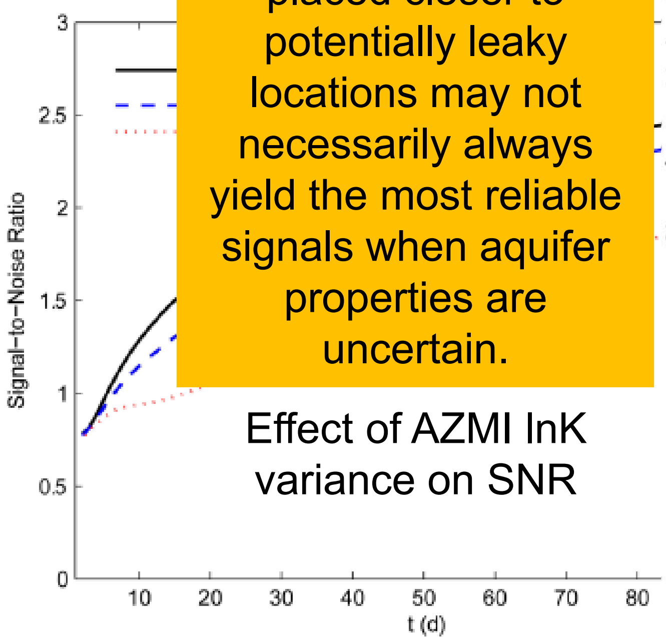
Leakage source detection: design perspective

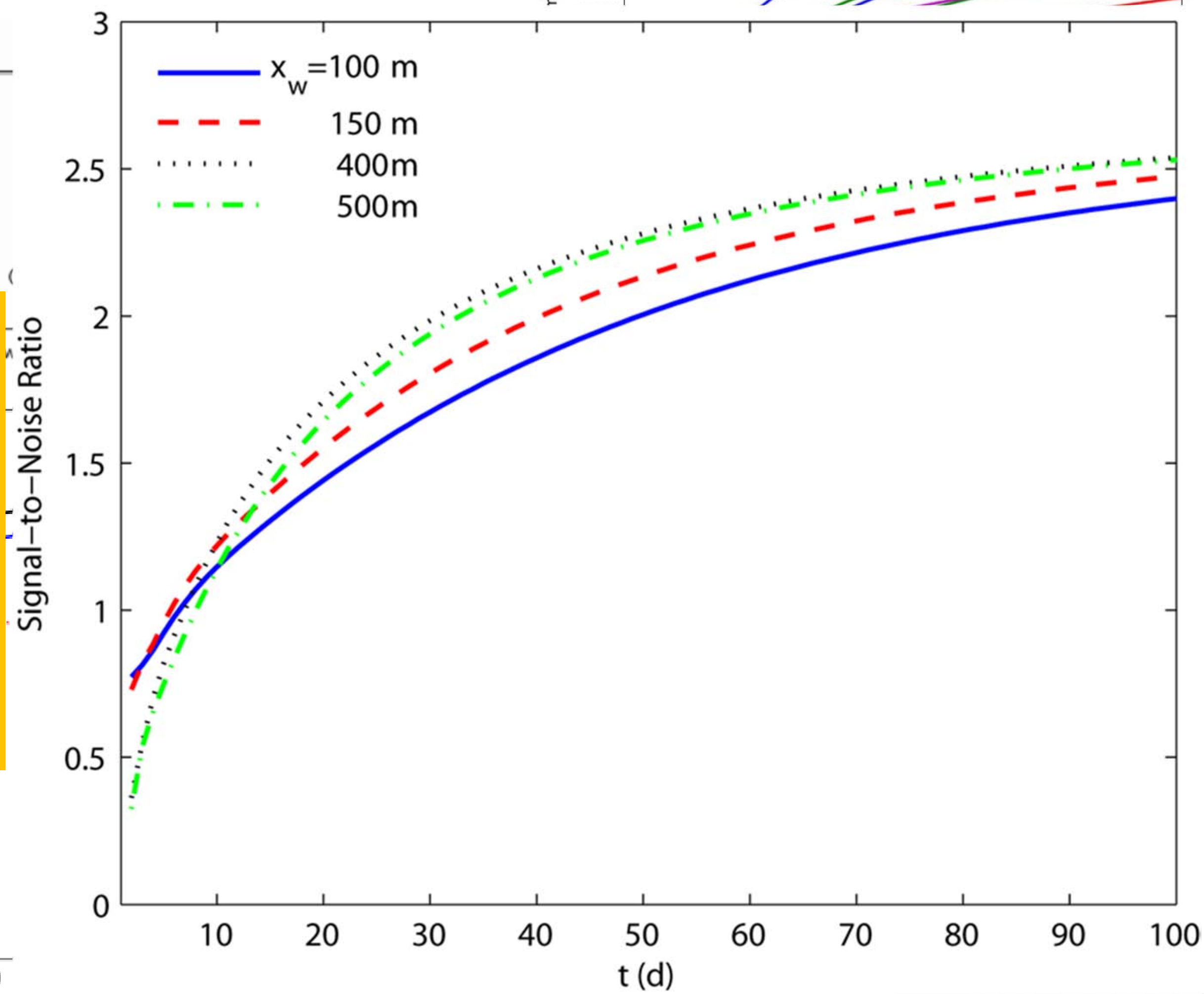




An observation point placed closer to potentially leaky locations may not necessarily always yield the most reliable signals when aquifer properties are uncertain.



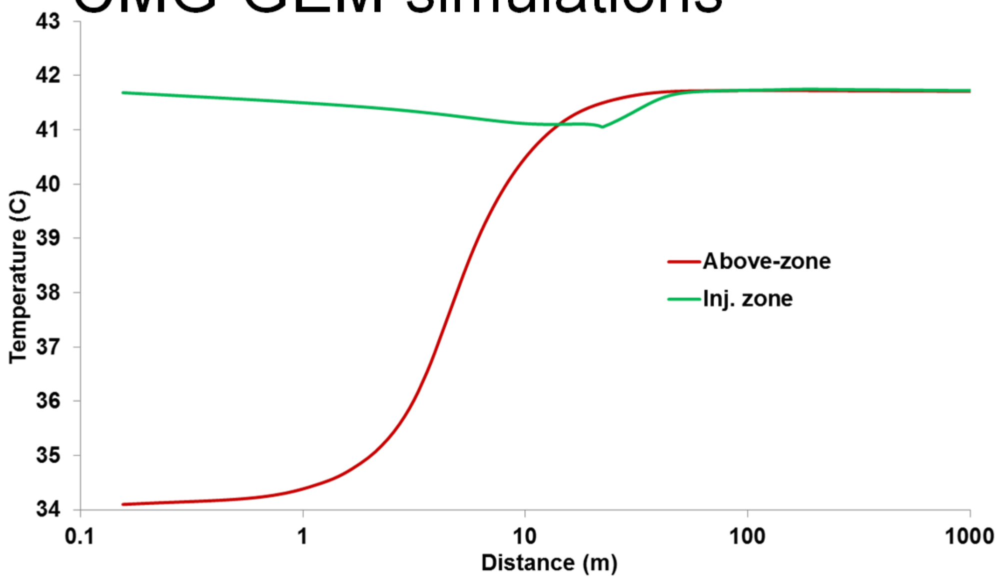
Effect of AZMI lnK variance on SNR



Sun, Zeidouni, Nicot et al., accepted ms, Adv.W.R.

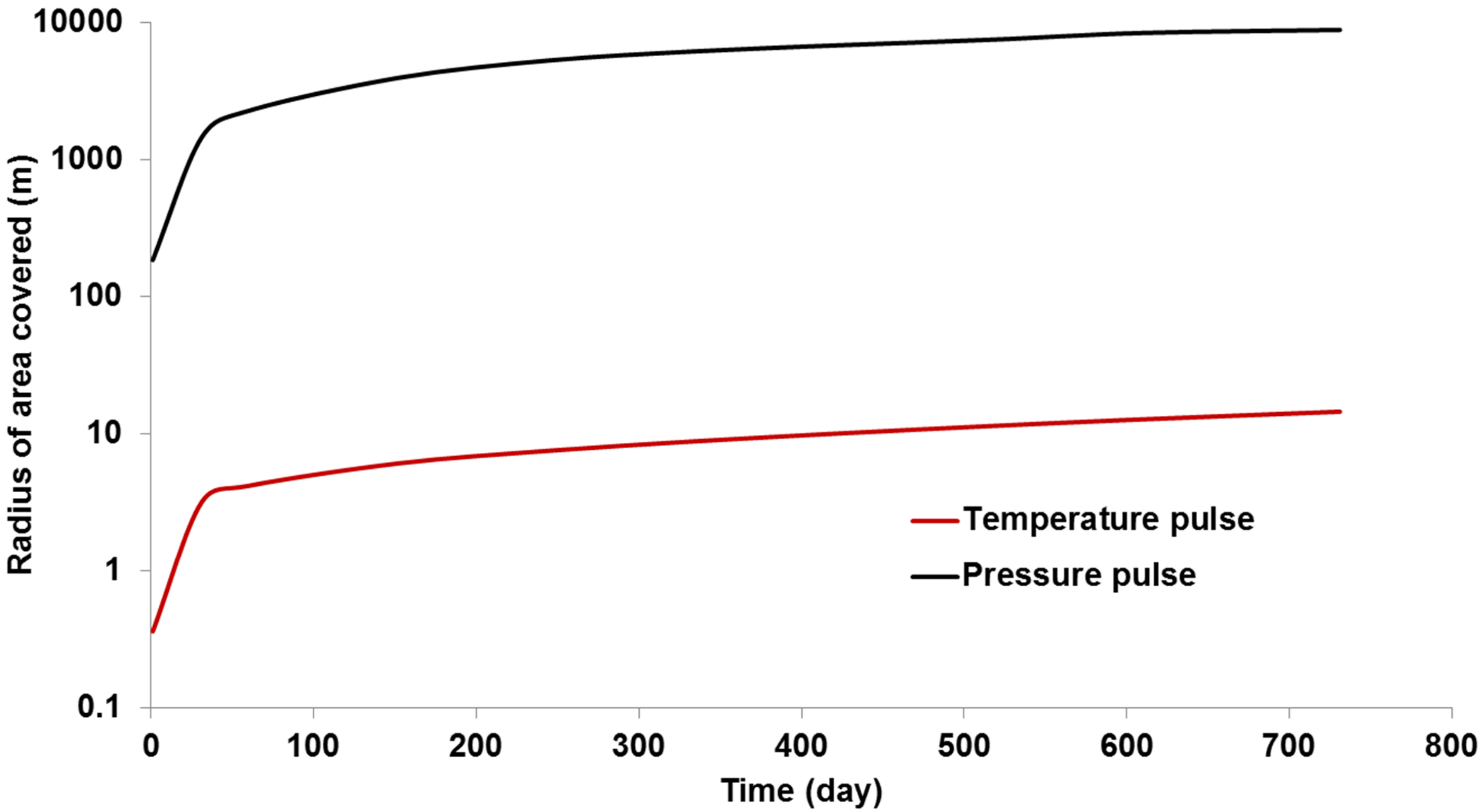
Pressure and temperature

- AZMI temperature changes because:
  - (1) Leak temperature; (2) Pressure changes (JT cooling); (3) Dissolution and vaporization (exothermic and endothermic processes)
- CMG-GEM simulations



Zeidouni et al., SPE, ms in progress

Above-zone temperature pulse



Temperature detection limit = 0.15°C; Pressure detection limit = 0.15 psi).

Zeidouni et al., SPE, ms in progress

- Chang, K.-W. M. A. Hesse, and J.-P. Nicot, 2013, Reduction of lateral pressure propagation due to dissipation into ambient mudrocks during geological carbon dioxide storage, in review WRR
- Sun, A. Y., and Nicot, J. -P., 2012, Inversion of pressure anomaly data for detecting leakage at geologic carbon sequestration sites: Advances in Water Resources, v. 44, p. 20–29.
- Sun, A.Y., Zeidouni, M., Nicot, J.-P., Lu, Z., and Zhang, D., Assessing leakage detectability at geologic CO_2 sequestration sites using the probabilistic collocation method : Advances in Water Resources, accepted
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- Zeidouni, M., 2012, Analytical model of leakage through fault to overlying formations, Water Resour. Res., 48, W00N02, doi:10.1029/2012WR012582.
- Zeidouni M. and Pooladi-Darvish M., Inter-aquifer flow through leakage conduits: analytical solutions for leakage rate and pressure change evaluation, in review for Journal of Petroleum Science and Engineering.
- Zeidouni M., Hosseini S.A., and Nicot J.-P., Above-zone temperature variations due to CO_2 leakage from the storage aquifer, in preparation for SPE 2013
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