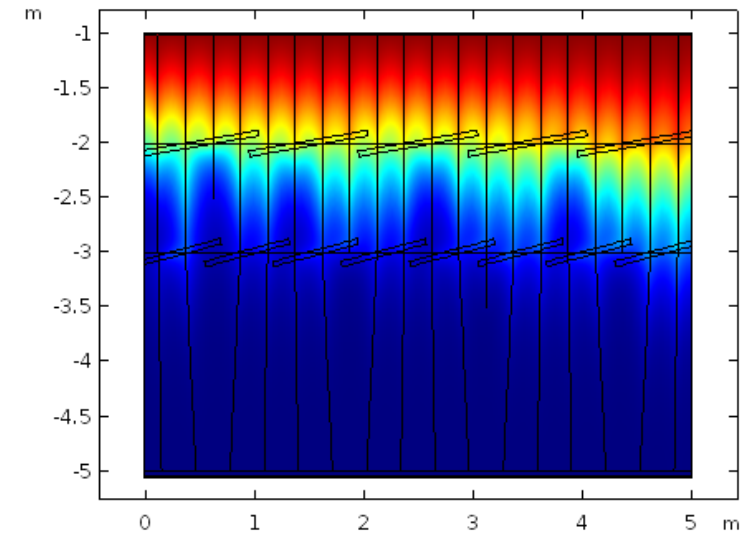
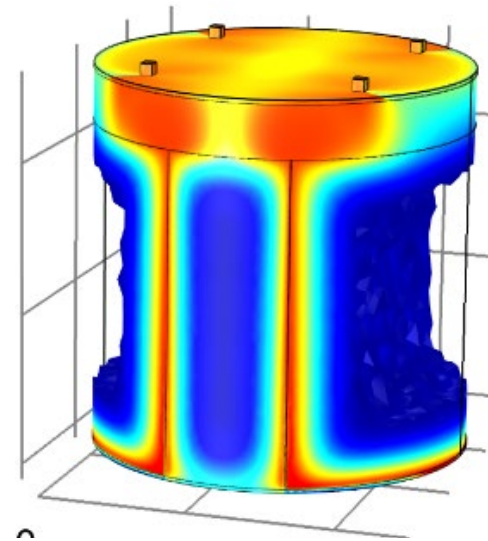
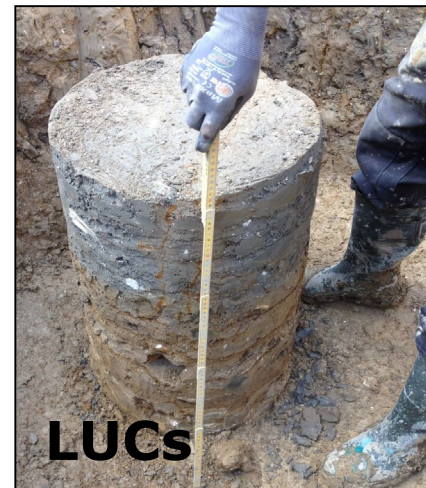


Modelbaserede indsigter i pesticidtransport gennem sprækket moræneler



Formål, processer og metoder

Undersøgelse af **transportveje** og **sårbarhed** af forskellige morænelerområder til pesticidudvaskning, **mættet zone** (> 1m dybde)



Processer

- Mættet flow
- Pesticidtransport

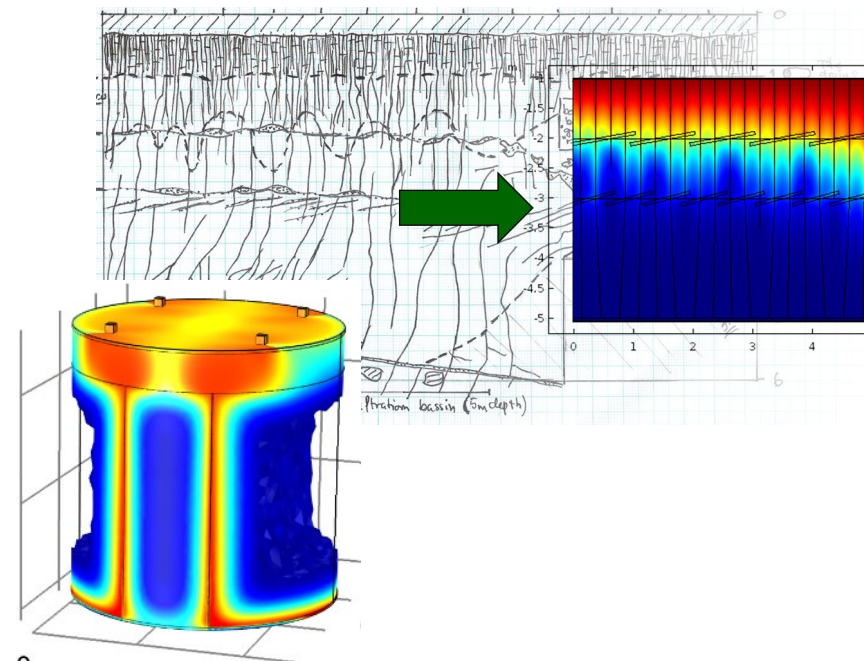
- Advektion (sprækker)
- Matrixdiffusion
- Sorption
- Nedbrydning

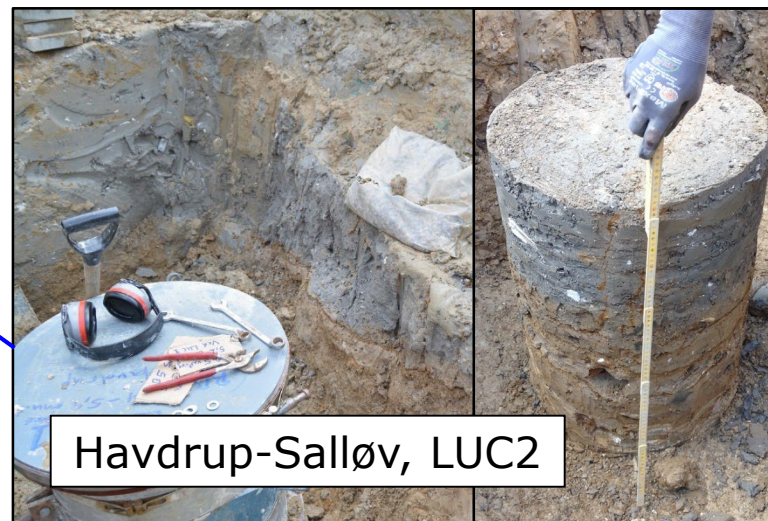
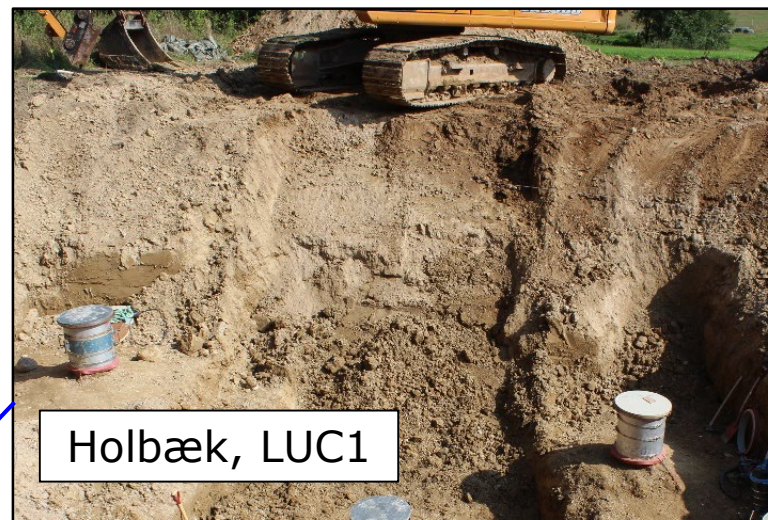
Metoder

- Felt og lab eksperimenter
- Large Undisturbed Columns (LUC)
- Tracer tests
- Geologiske karakterisering
- Sorption/nedbrydningsforsøg



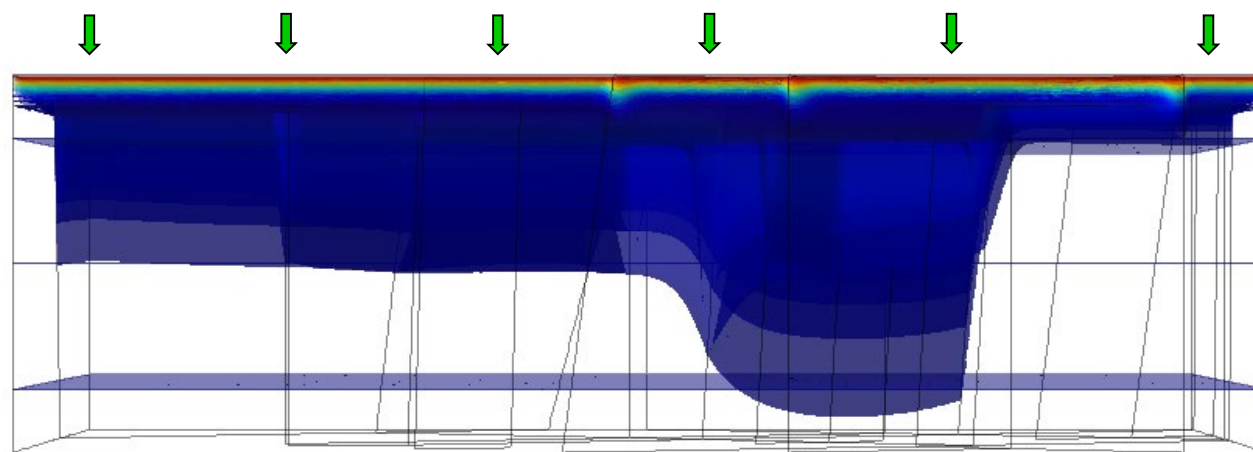
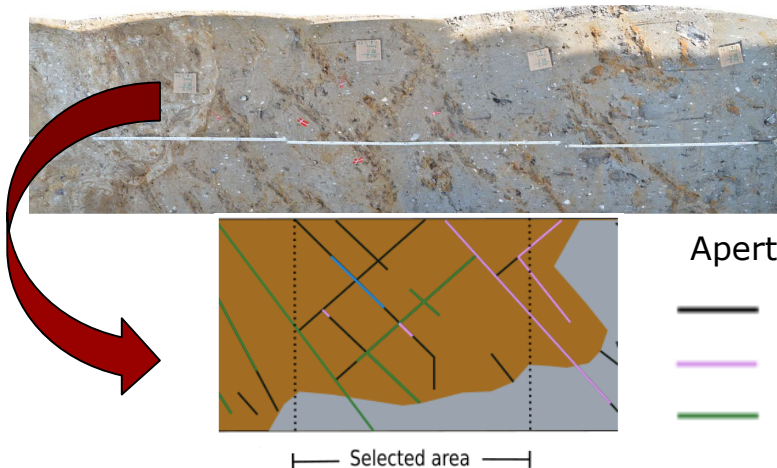
**Numerisk
modellering**





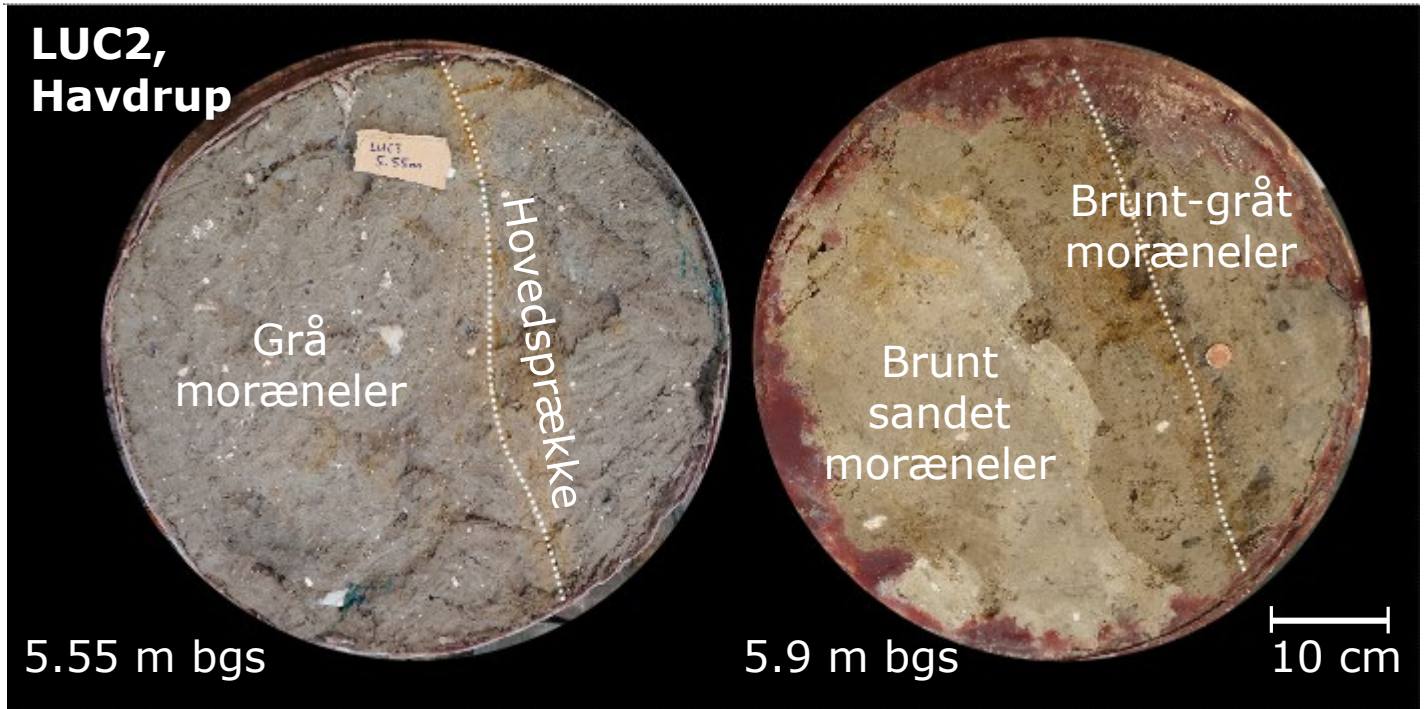
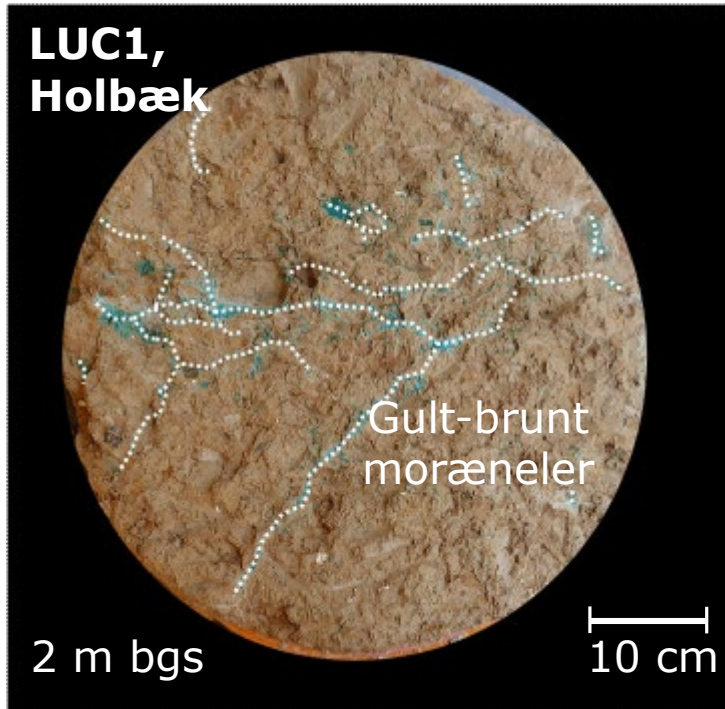
3-D modellering

Modelling af tracer infiltrationstests i Havdrup



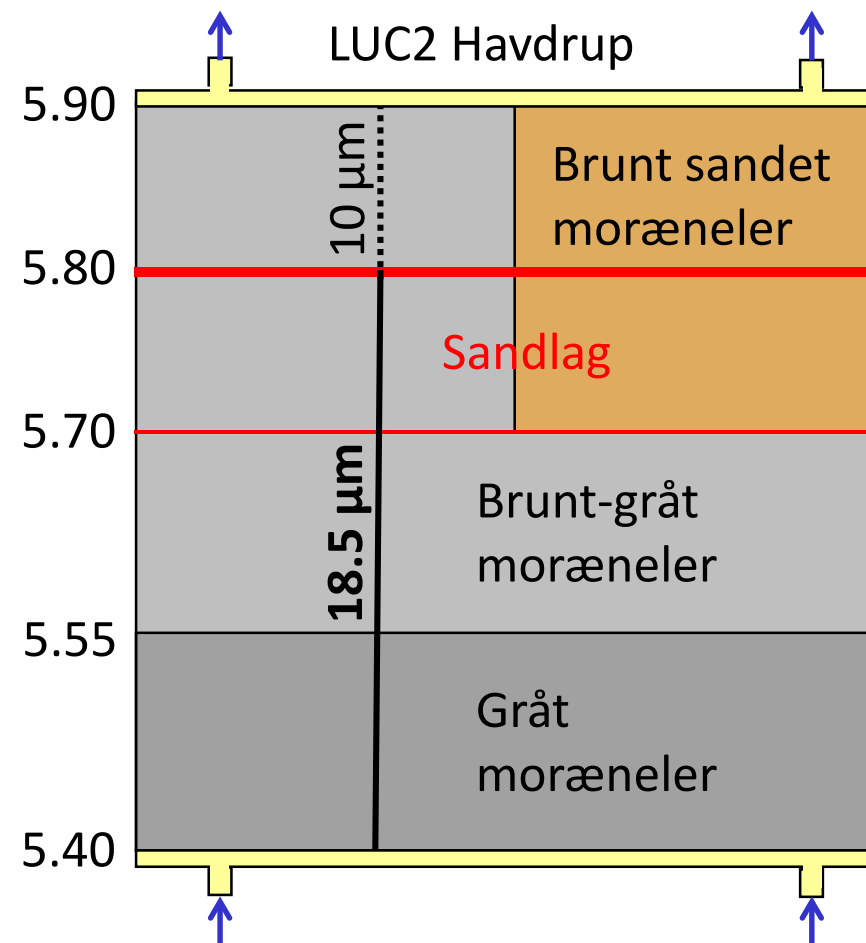
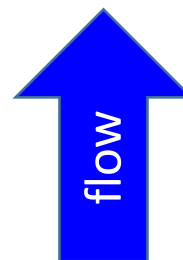
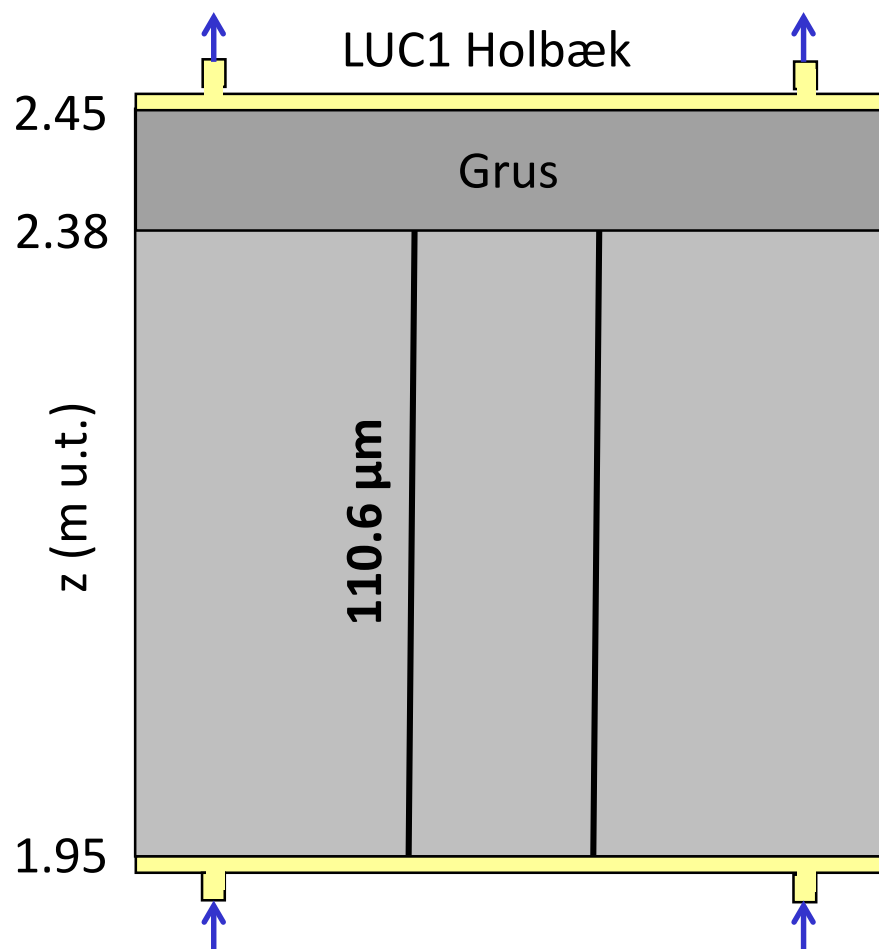
→ Master speciale Rasmus Thalund-Hansen

Top view af LUC1 og LUC2 slices

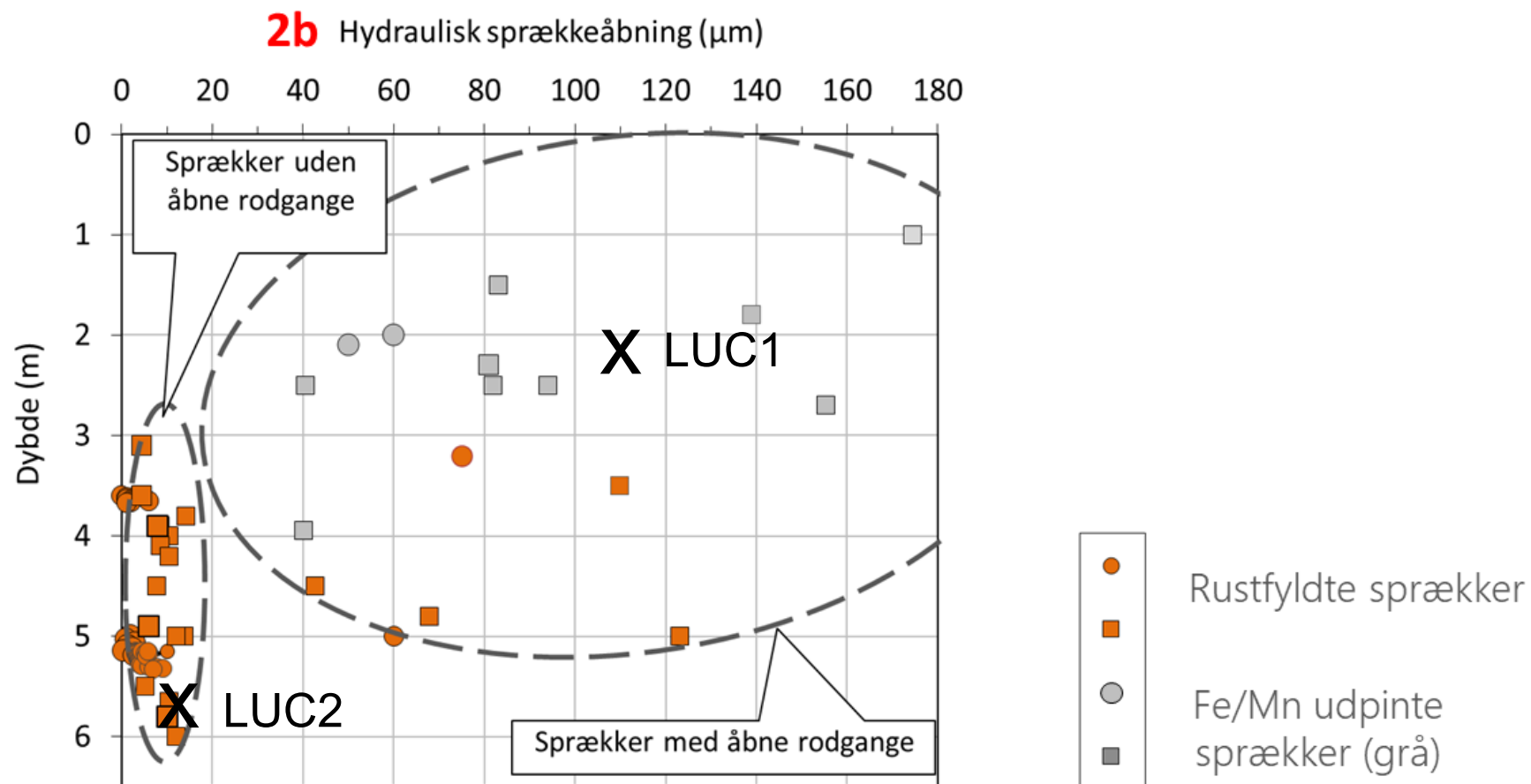


Makroporer (rodkanaler)
med jernudfældninger

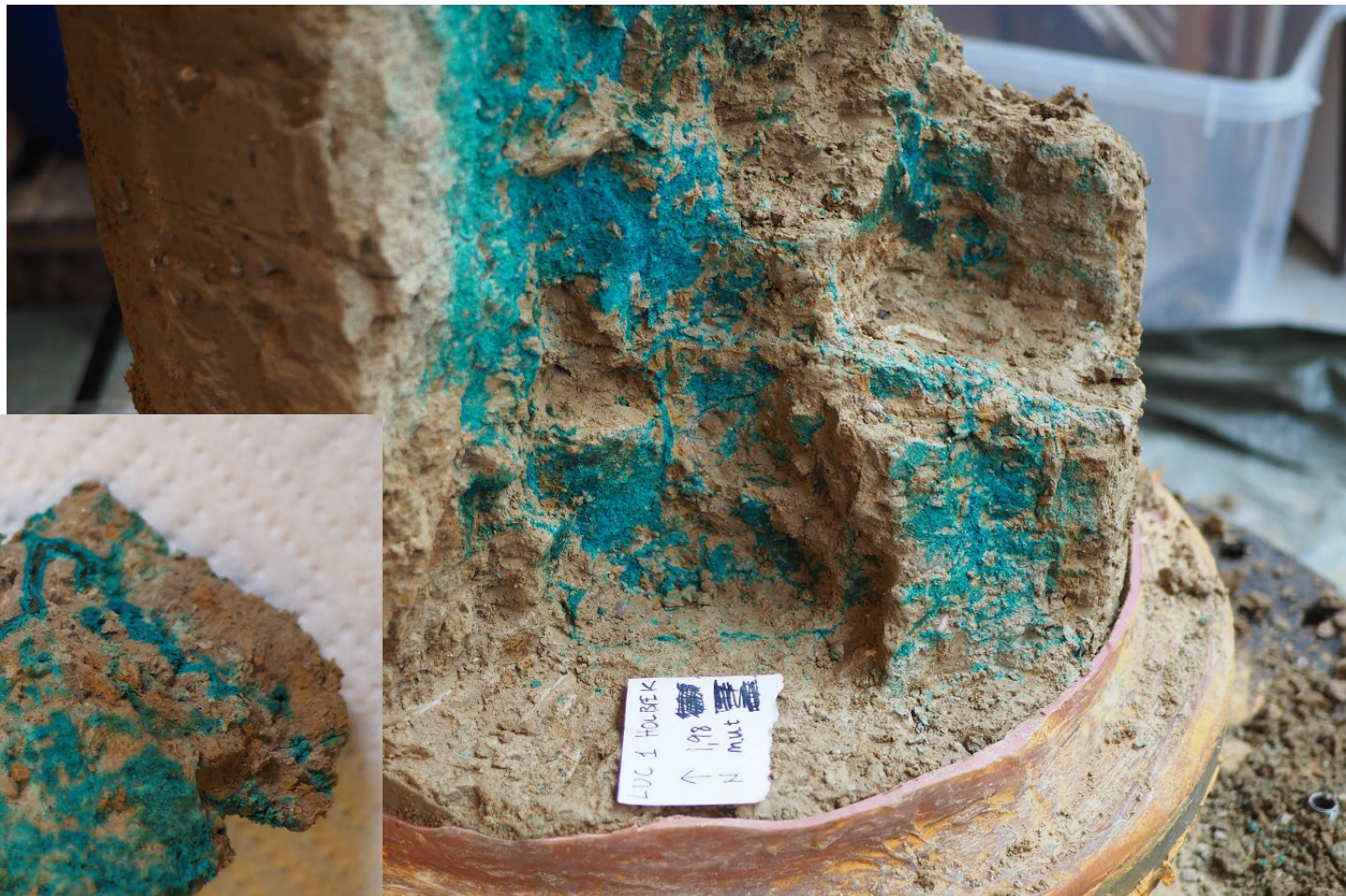
Konceptuelle opsætninger LUC1 og LUC2



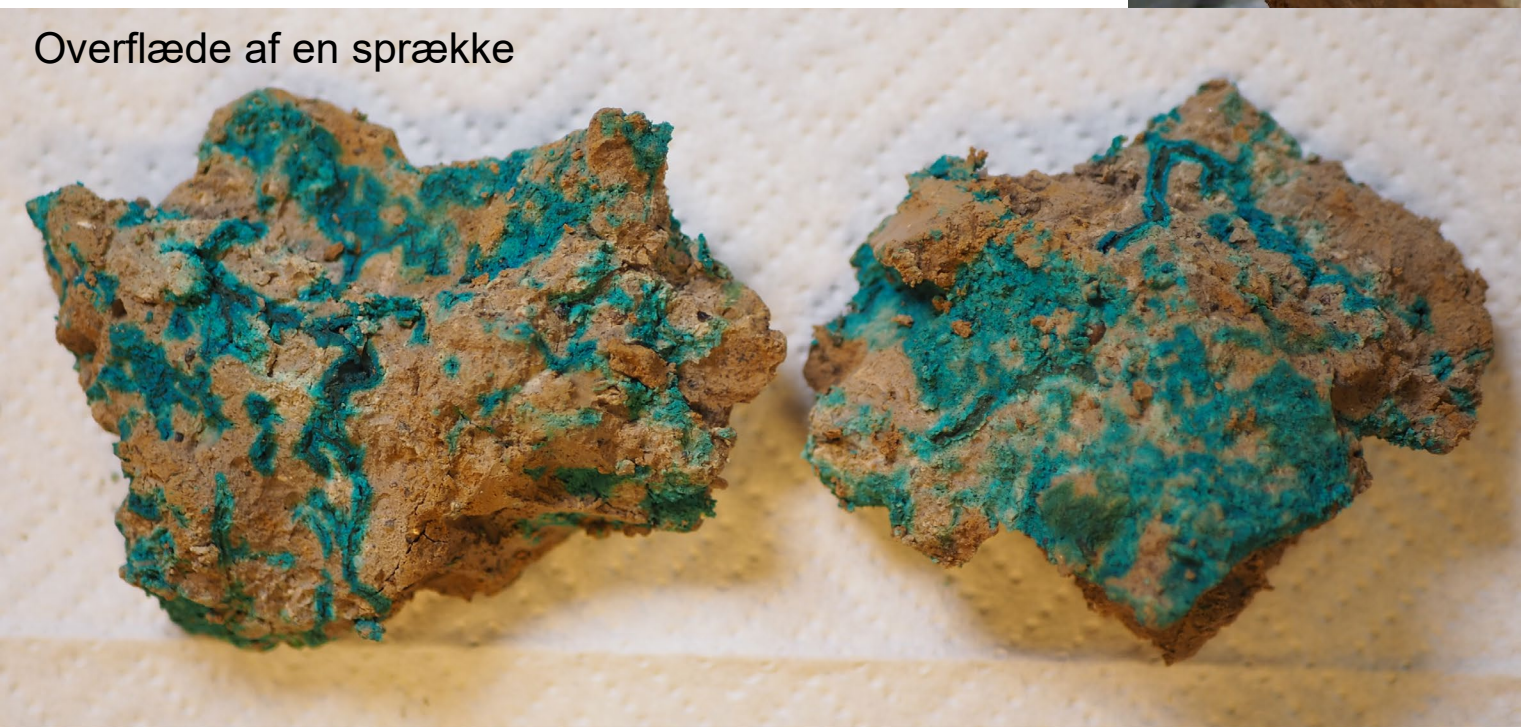
Konceptuelle opsætninger LUC1 og LUC2



Kanalisering i sprækker og makroporer (LUC1)



Overflåde af en sprække

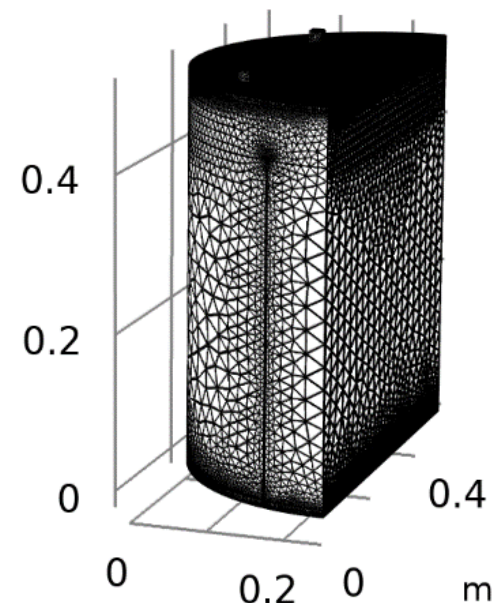
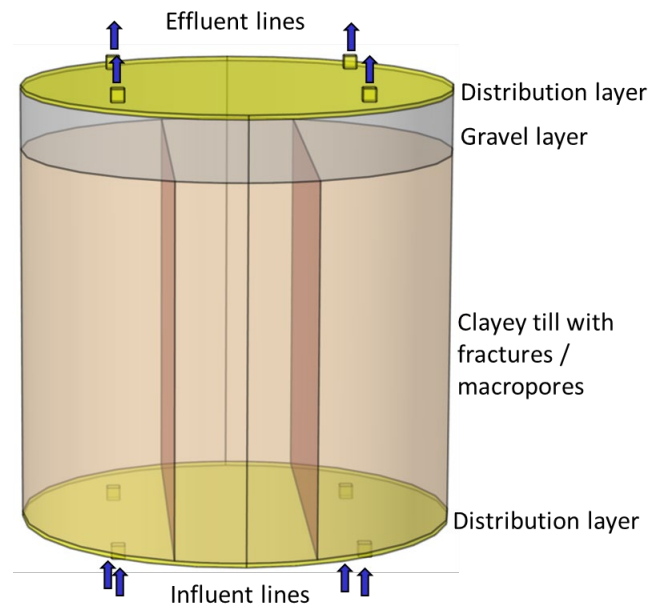


3D modellering af LUC eksperimenter

- Sprækkemodel (DFM) med idealiserede sprækker, samme sprækkelængder som i eksperiment
- Parametre fra hydraulisk karakterisering af søjler og jordprøver (matrixegenskaber)
- Hydraulisk sprækkeapertur kalibreret til vandflux og hydraulisk gradient i LUC eksperiment
- Transportparametre af sporstoffer og pesticider, input fra sorptionsforsøg
- Ingen nedbrydning i søjlerne påvist

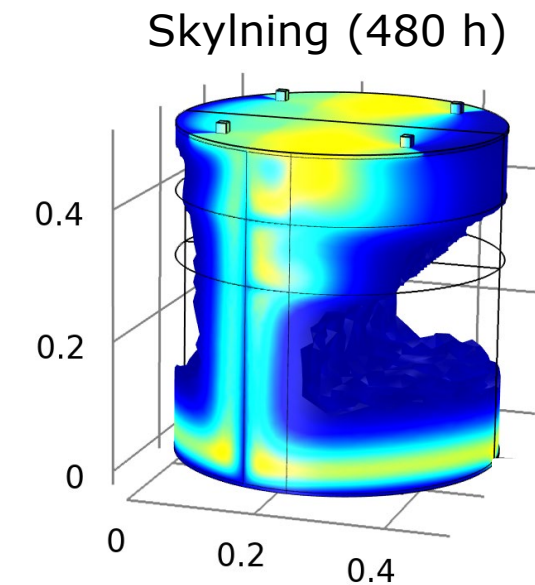
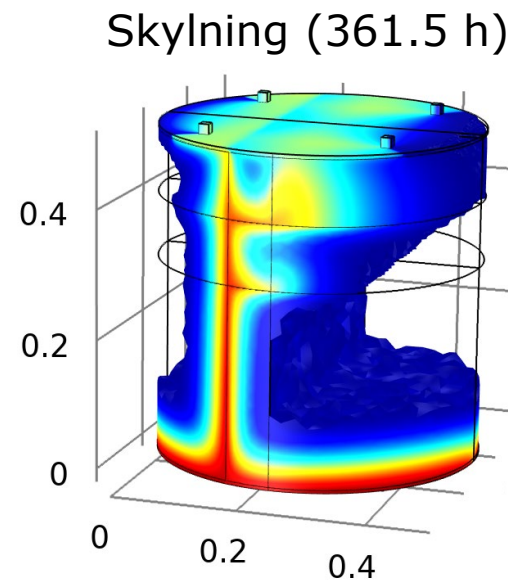
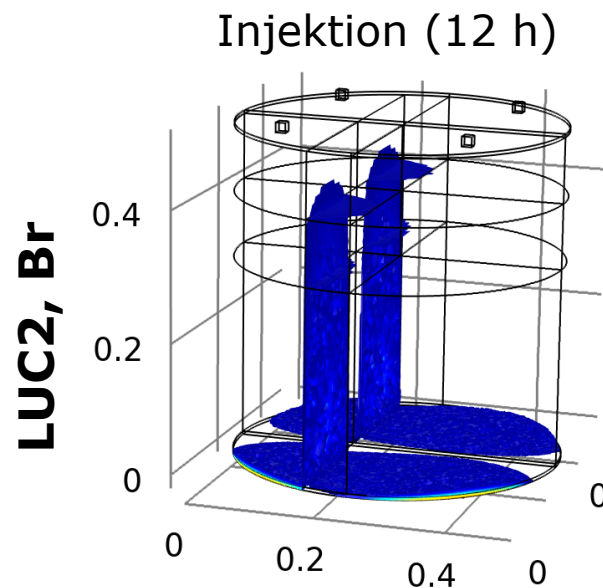
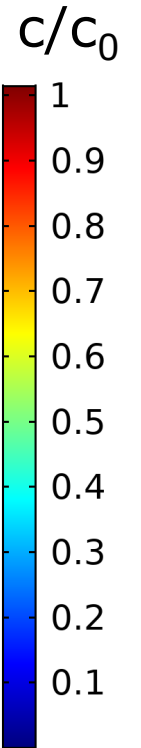
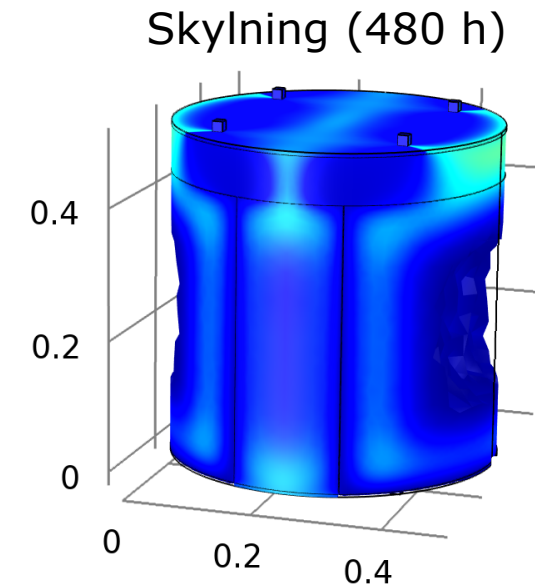
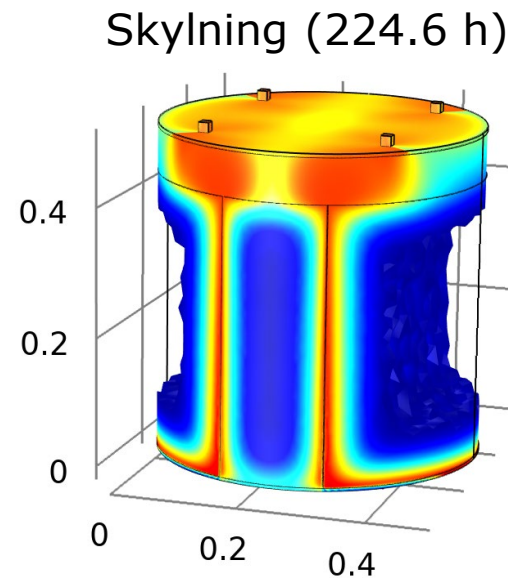
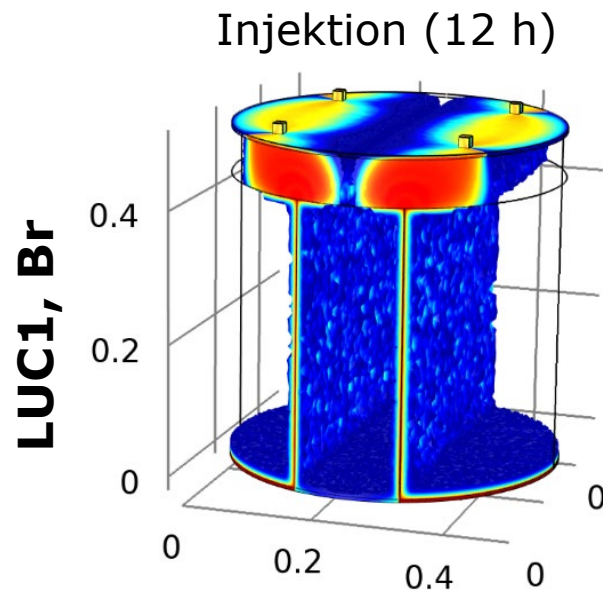


Jørgensen, Mosthaf, Rolle, Groundwater (2019)



Simulation af halv
søjle (symmetri)
Mesh med ca.
4.3 mio. elementer

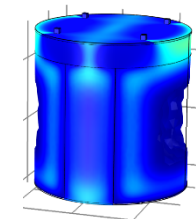
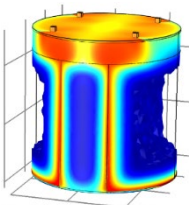
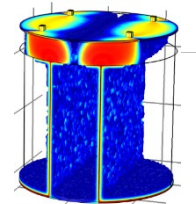
81 mm/dag for 29.6 h
grad $H = 0.23$
9.8 mm/dag bagefter
222 timer injektion,
så skylning



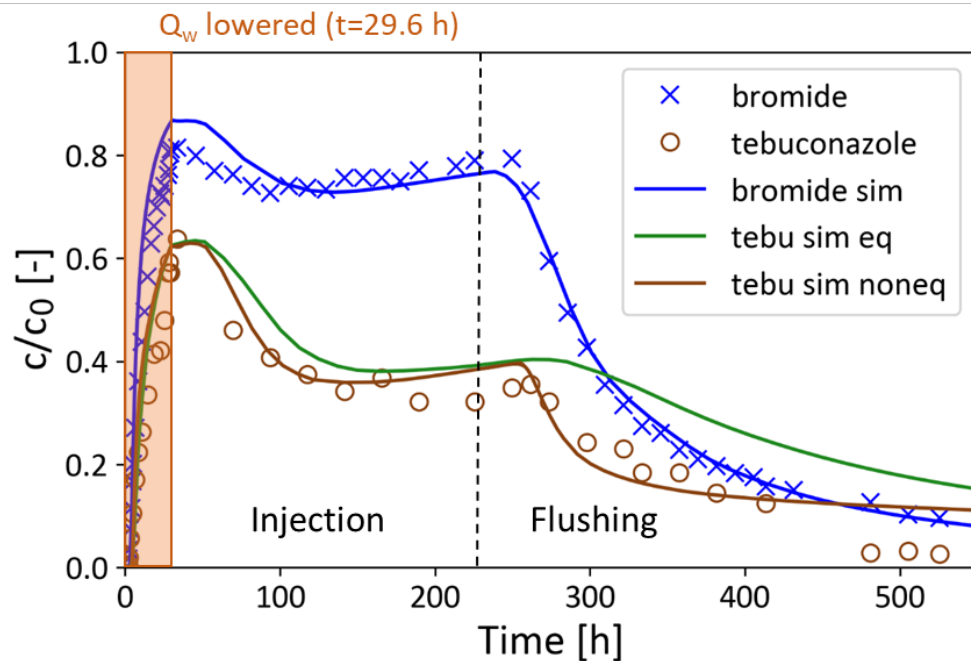
2.4 mm/dag
grad $H = 3$
Injektion i 360 timer,
så skylning

Mosthaf et al., WRR (2021)

Simulerede gennembrudskurver LUC1 og LUC2

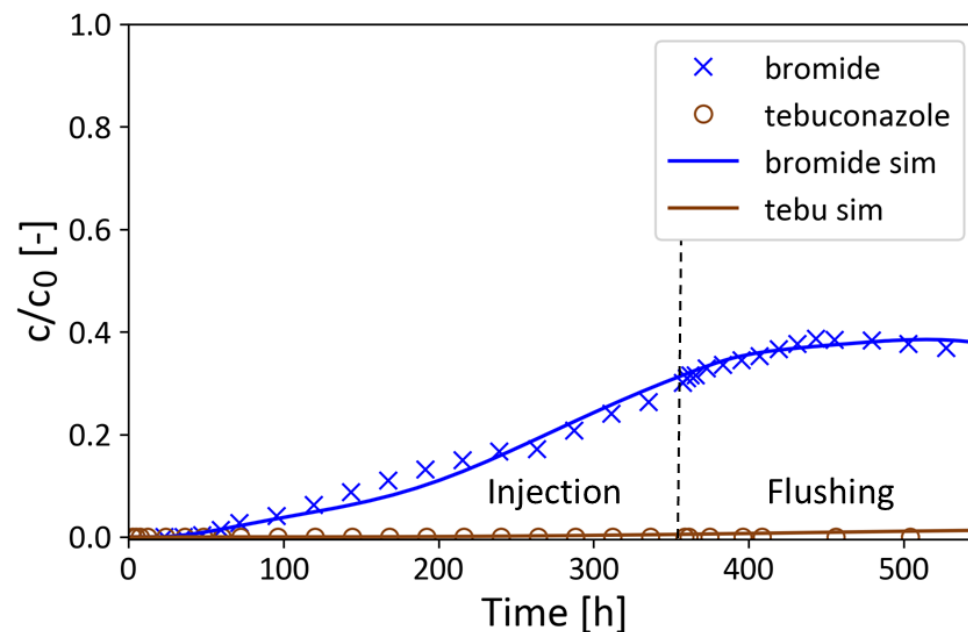


LUC1, 110.6 μm , hydr. grad. = 0.23

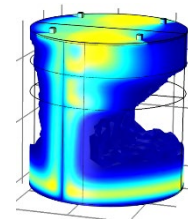
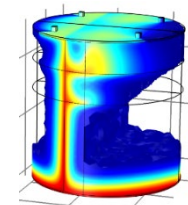
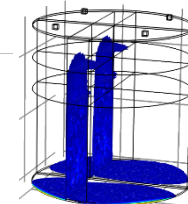


Hurtigt gennembrud, advektion i sprækker, uligevægts(de-)sorption for tebuconazol

LUC2, 18.5 μm , hydr. grad. = 3

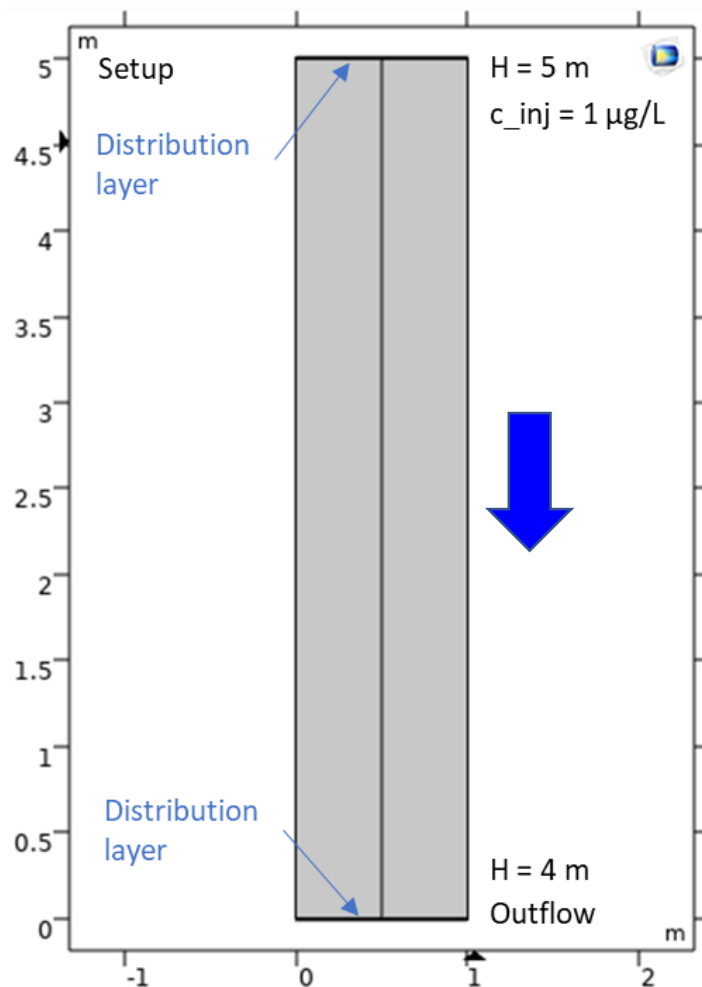


Langsommere gennembrud, mere kontakt med lermatrix og mere matrixdiffusion

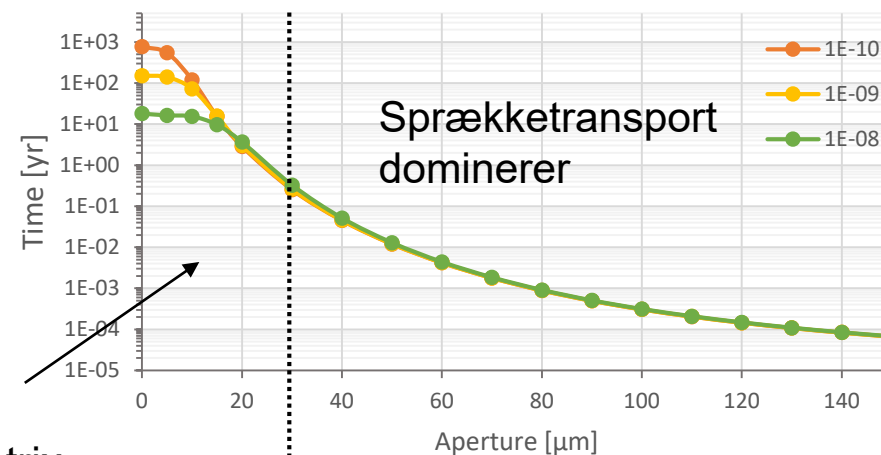


2-D studier af stoftransport

Ankomsttider, stoffflux og aperturer

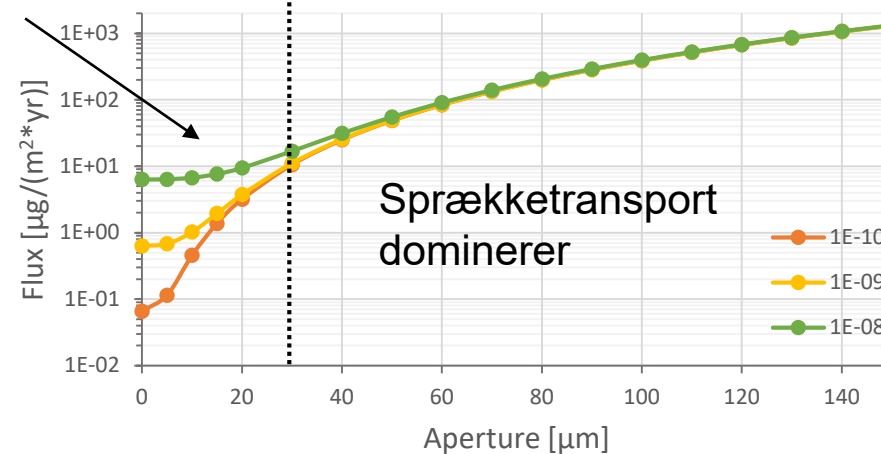


Ankomsttid af 10% of c_{inj}



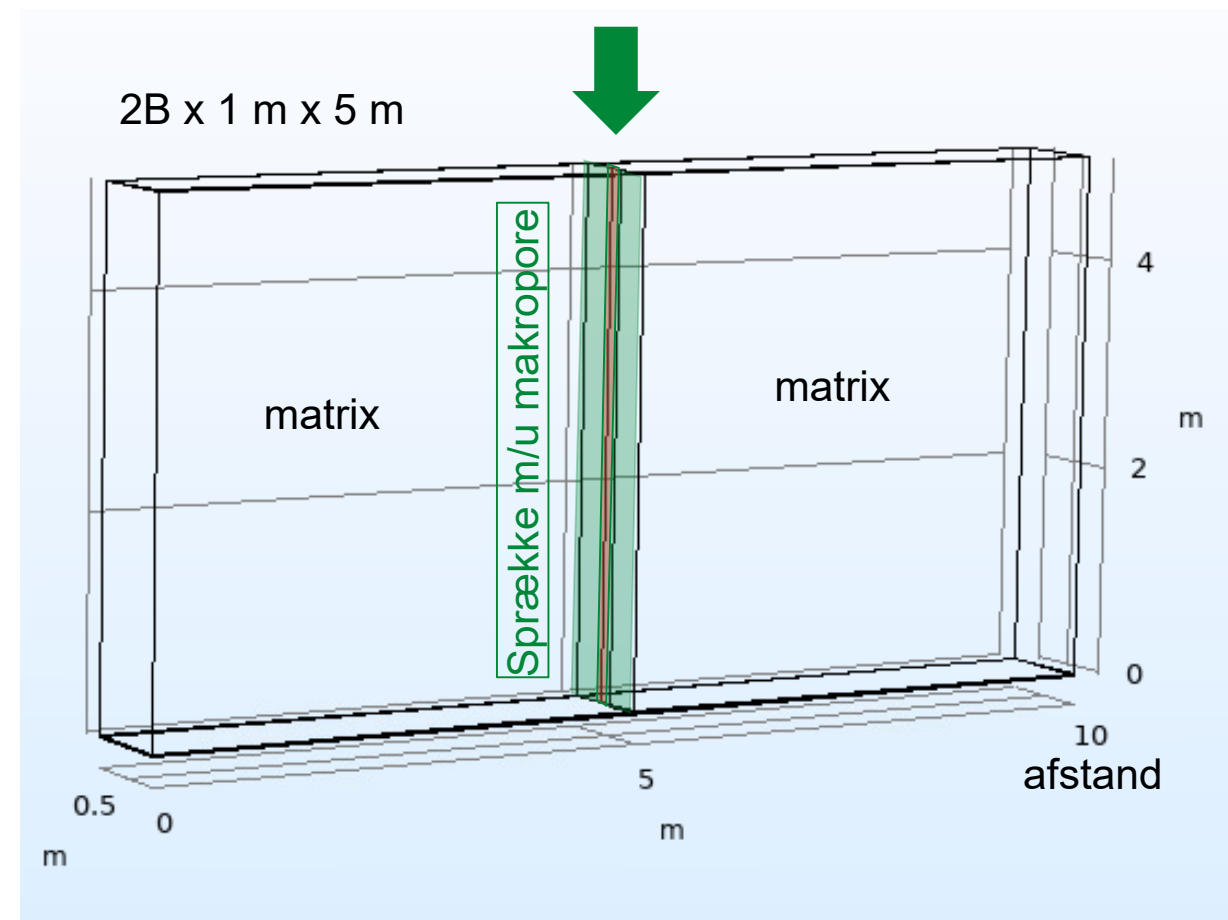
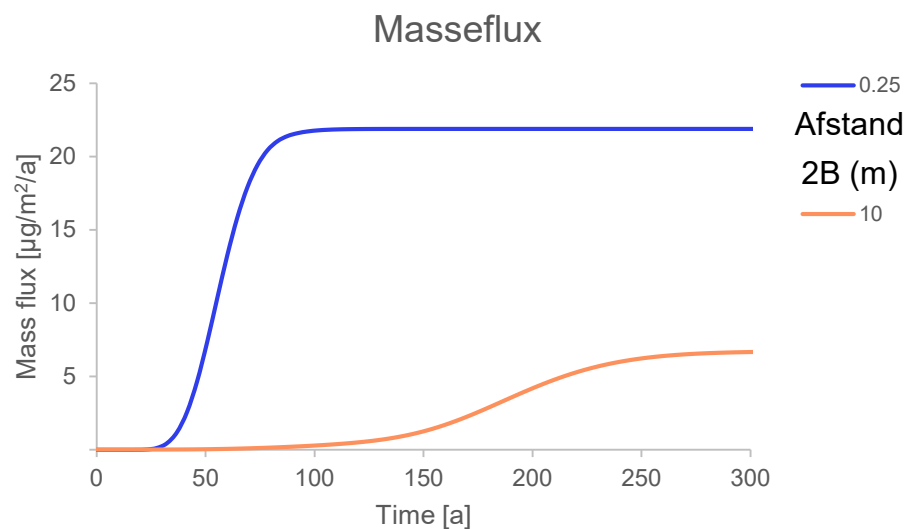
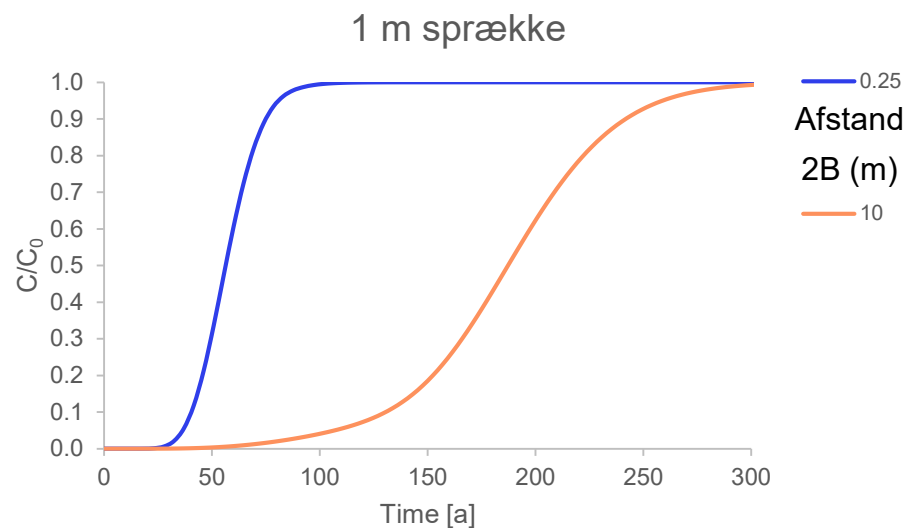
Effekt af matrix
konduktivitet

Flux på tidpunkt af 10% af c_{inj} i udløb



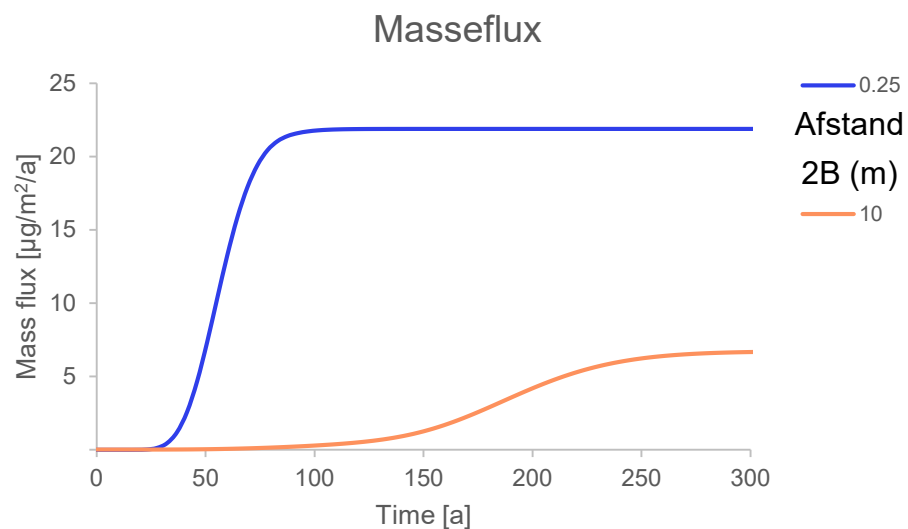
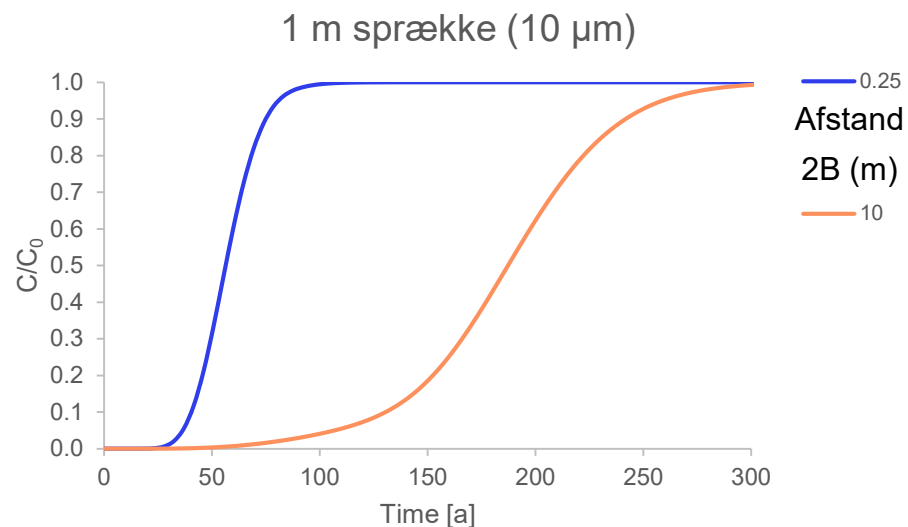
Indflydelse af sprækkeafstand med/uden makropore

1 m sprække, 10 μm

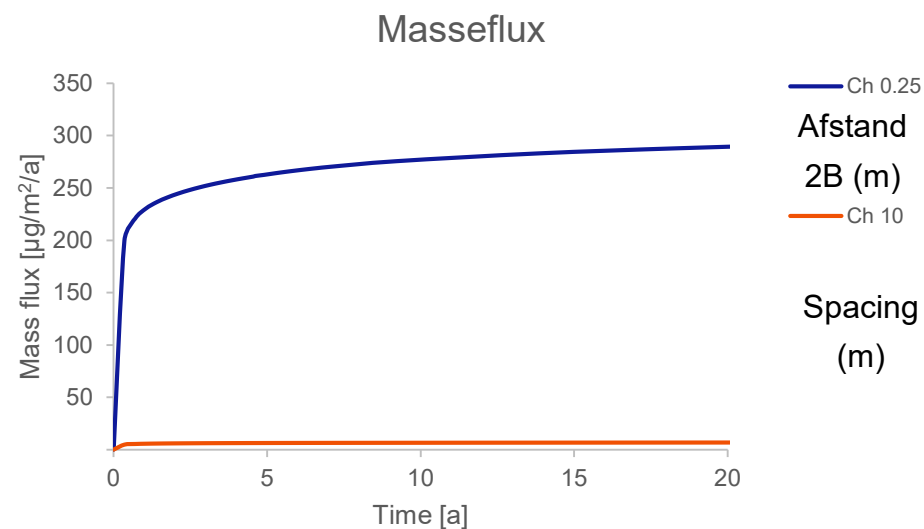
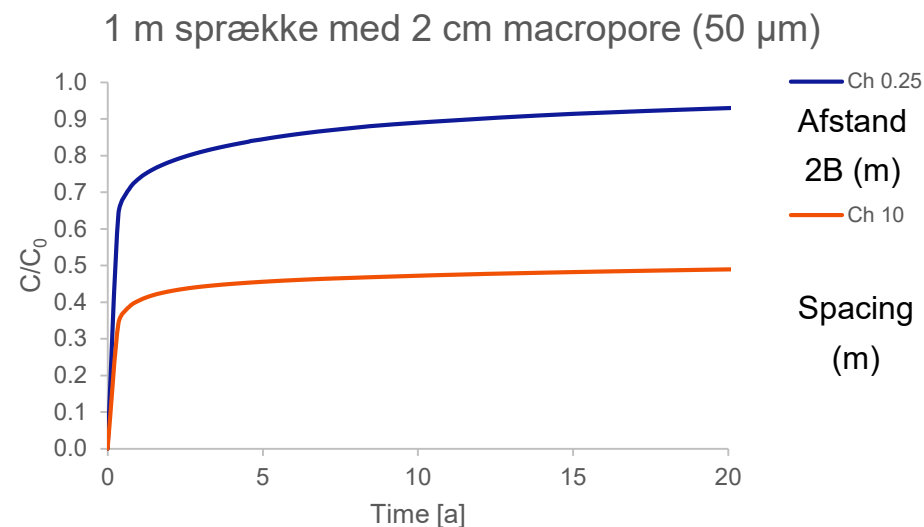


Indflydelse af sprækkeafstand m/u makropore

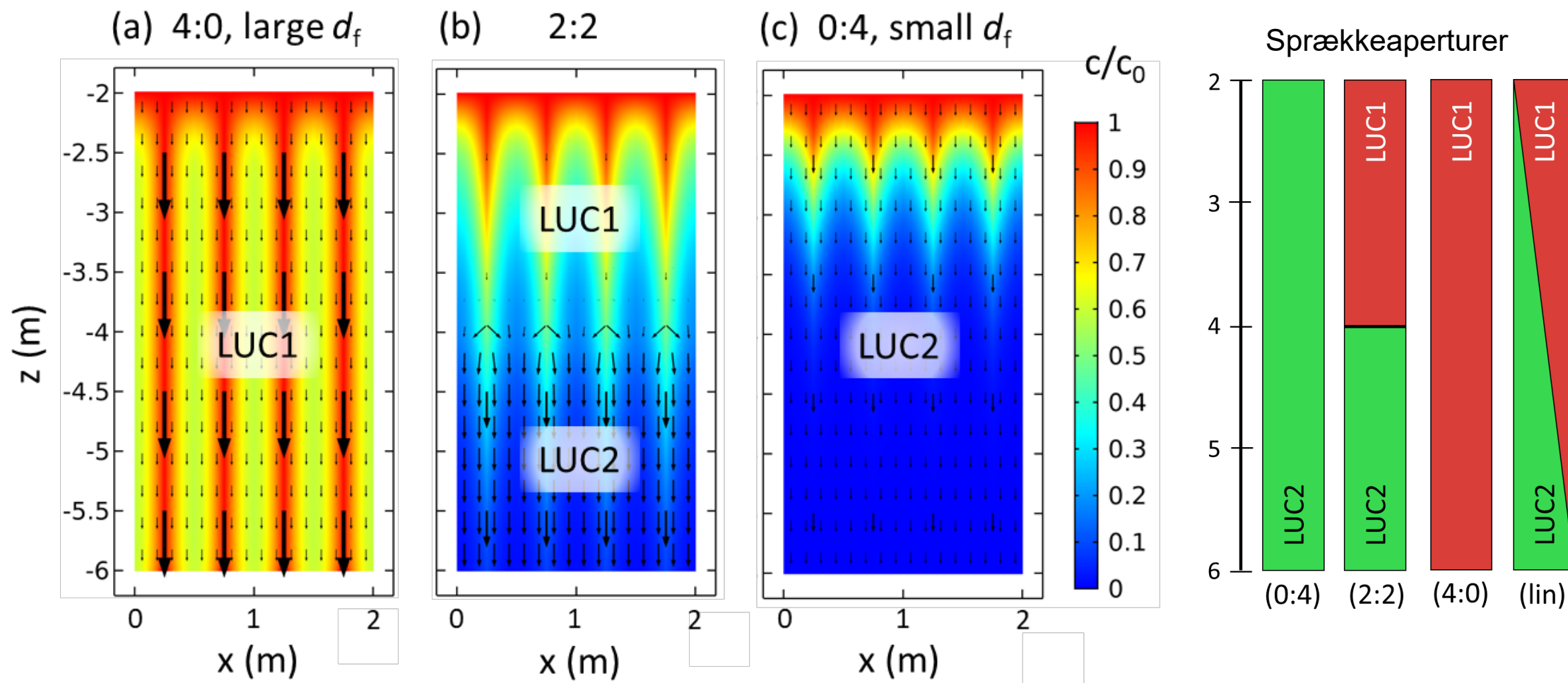
1 m sprække, 10 μm



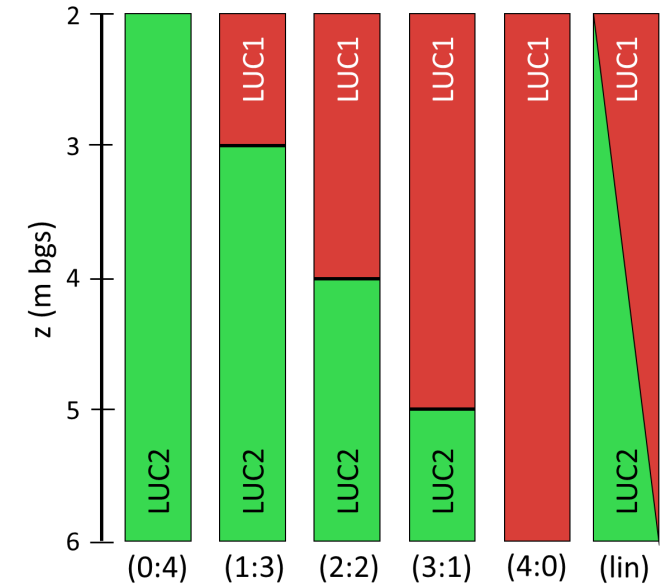
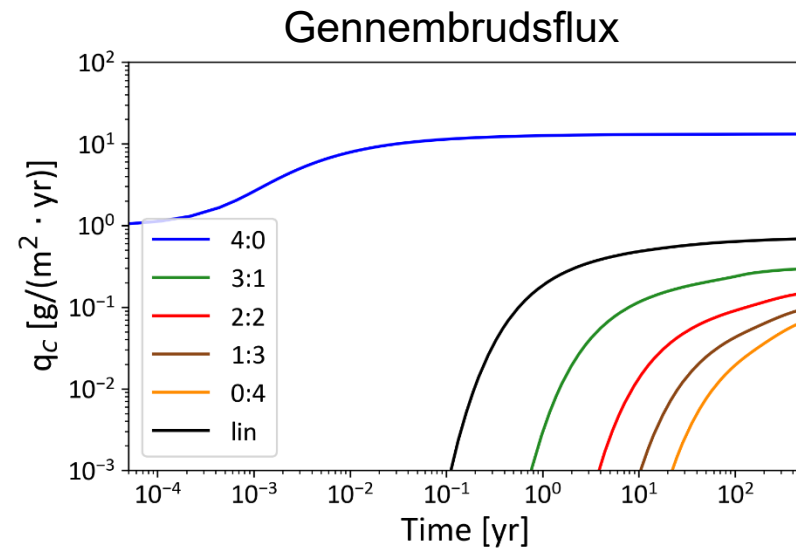
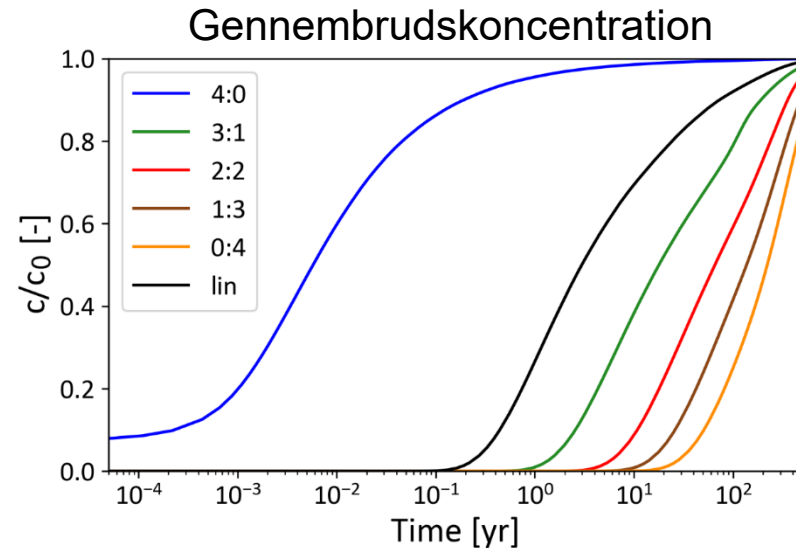
2 cm makropore på
1 m sprække, 10 μm



Variation af sprækkeapertur med dybden

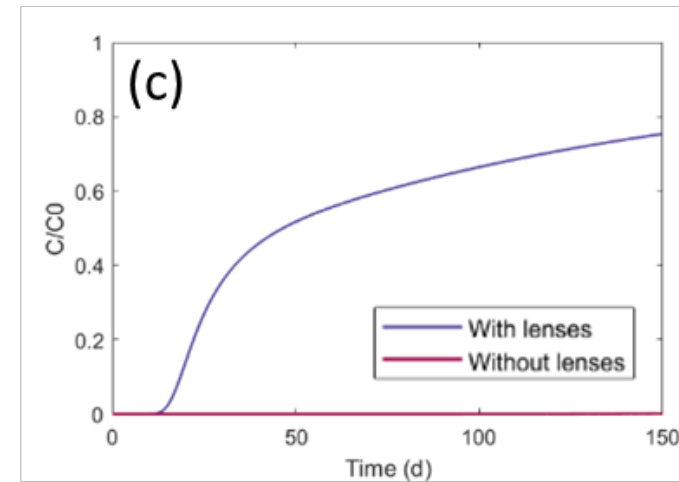
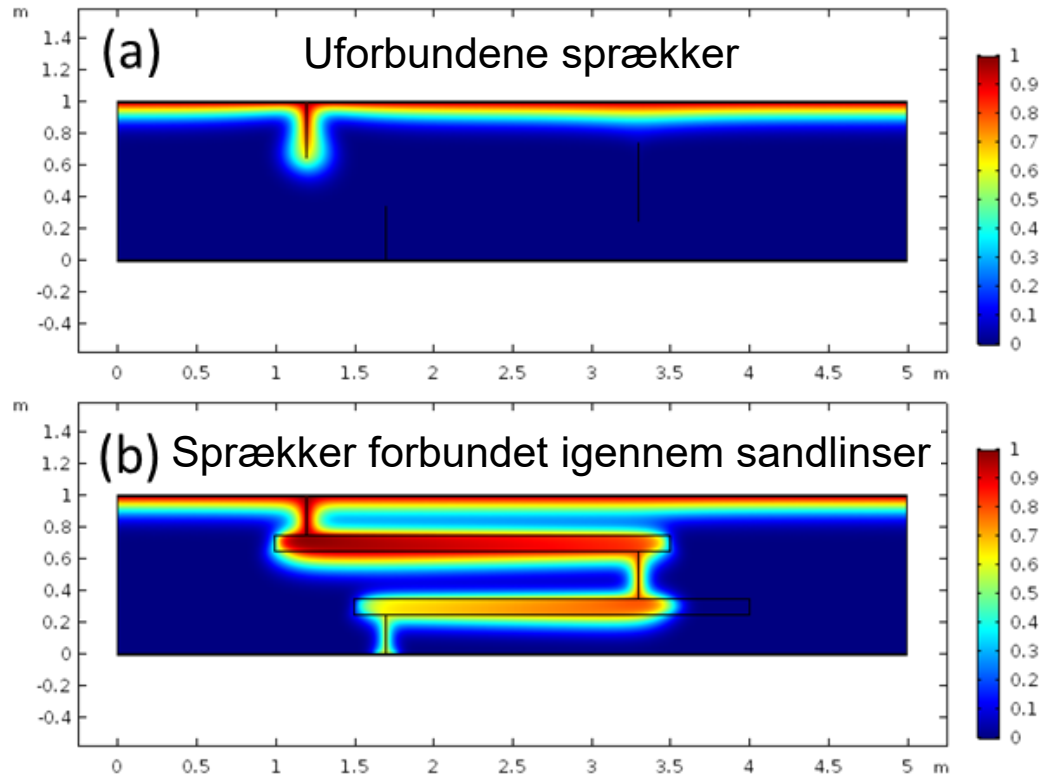


Variation af sprækkeapertur med dybden



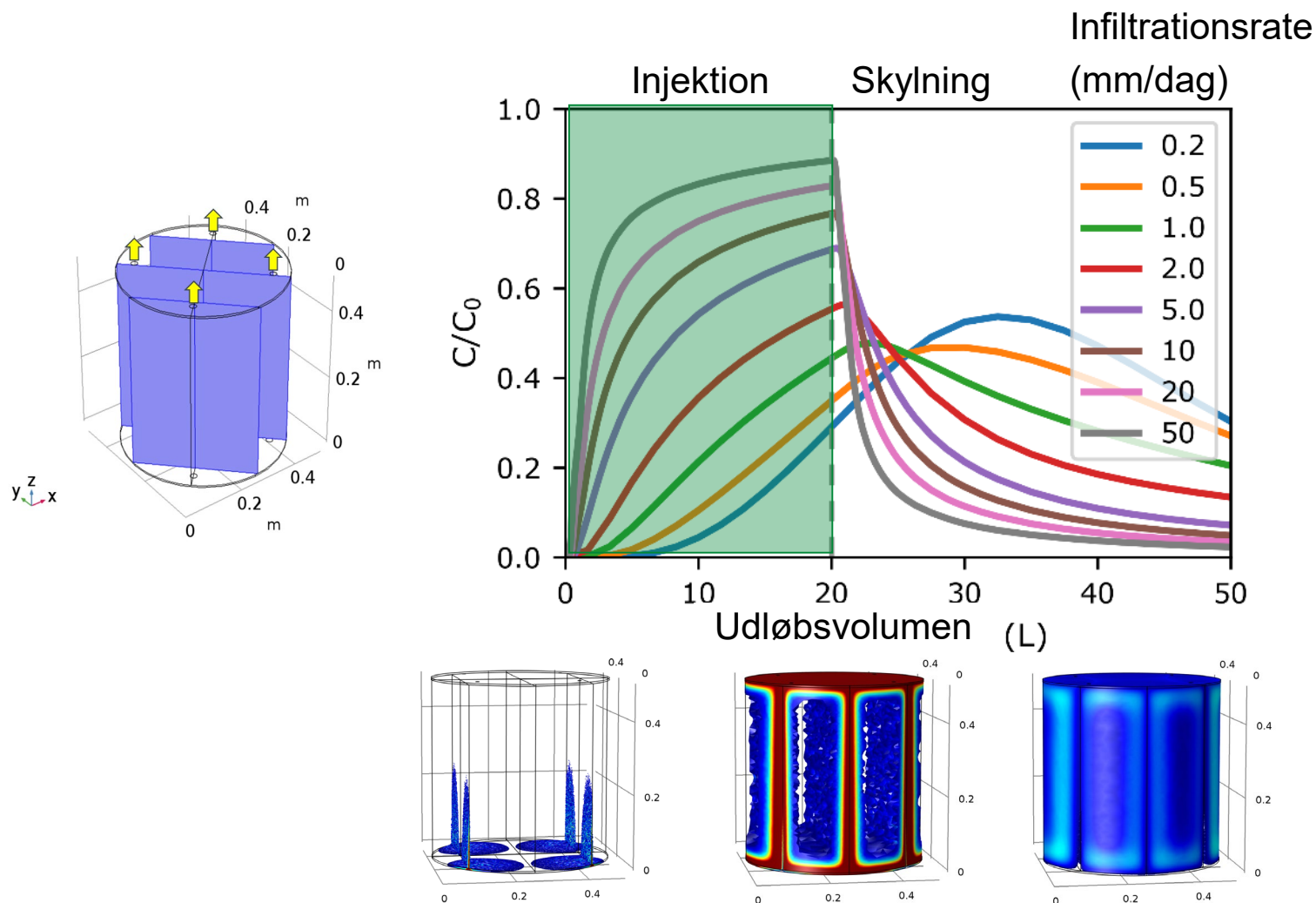
- Hurtig transport igennem højpermeable lag med store sprækker (LUC1)
- Mindre aperturer i dybden pga. healing eller udfældninger kan begrænse fluxen
- Lag med en mindre konduktivitet har en stærk indflydelse på gennembrugsfluxer og -tider (dage – årtier)

Sprækker forbundet igennem sandlinser



- Sprækker som ender i ler bidrager meget begrænset til transporten
- Sandlag eller linser kan forbinde sprækker og føre til mere vertikal transport

Gennembrudskurver fra en LUC med forskellige infiltrationsrater



- Hurtigere ankomsttider, højere maks koncentrationer med mere grundvandddannelsen
- Større indflydelse af matrixdiffusion for lave infiltrationsrater
- Forskellen i infiltrationsraten (grundvandsdannelsen) giver en forskel til sårbarheden selvom lertykkelsen er konstant i et opland

Take-home messages

- Moræner kan vise en **stor variation på en lille skala** (f.eks., på en mark med en lertype)
 - Bulk hydrauliske konduktiviteter mellem 10^{-9} m/s og 10^{-5} m/s (>1 m dybde)
 - Rodkanaler, makroporer, åbne sprækker og forbundene sandlag kan have stor indflydelse på bulk hydrauliske konduktiviteter, grundvandsdannelsen og nedsivningen
 - Variation overskygger forskellene mellem undersøgte morænelerstyper
 - En generel rangordning i sårbarhed for pesticidnedsivning til grundvandet baseret på lertype ikke mulig på basis af projektets resultater
- **Forskellen i grundvandsdannelsen** giver en stor forskel for sårbarheden selvom lertykkelsen og –typen er konstant i et opland
- Typisk findes en **lavere hydraulisk konduktivitet i større dybder** (pga. mindre aperturer, lukkede sprækker, større sprækkeafstand) → begrænser stoftransport

Den sidste slide... Tak!

Miljøstyrelsen for finansiering, CLAYFRAC projektgruppen (Jens Aamand, Massimo Rolle, Peter Jørgensen, Nora Badawi, Peter R. Jakobsen, Lars Trolborg, Bertel Nilsson), og de studerende Rasmus Thalund-Hansen, Una Petursdottir, Chloe Lanfers og Mariam Ouf



Ministry of Environment
and Food of Denmark
Environmental
Protection Agency

Mapping groundwater water vulnerability to pesticide contamination through fractured clays

CLAYFRAC

[Serietype og nummer]

[Måned og år]

Groundwater

Methods Note

A Large Undisturbed Column Method to Study Flow and Transport in Macropores and Fractured Media

by Peter R. Jørgensen^{1,2}, Klaus Moshfegh^{1,2}, and Massimo Rolle^{1,2}

Abstract
Exact soil columns can bridge the gap between field studies and idealized laboratory investigations of flow and transport in macropores and fractured media. However, the value of intact column studies is often hampered by shortcomings such as lack of column structures, small column size, and column run flow, which can cause serious uniform and longer system understanding. The flexible wall pressurized large undisturbed column (LUC) method overcomes these limitations and is a valuable approach to analyze fluid flow and solute transport in macropores and fractured geological formations. The method investigates subsurface processes in complex media, mimicking in situ conditions and facilitating the control of system boundary conditions including effective stress. In recent years, considerable experience has been gained through different applications of the LUC approach. Modeling tools have also been developed for a detailed interpretation of flow and transport processes in LUC systems. This paper describes the steps of the LUC method from column excavation in the field to experimental setup in the laboratory. The description encompasses the key features of the sampling of LUCs in field excavations, the laboratory setup, the procedure for hydraulic and transport experiments, as well as practical challenges and potential issues during operation of an LUC system. Application examples with a fully three-dimensional numerical model of LUC tracer experiments are also presented to illustrate the quantitative interpretation of transport processes in macropores/clay till.

Introduction
Controlled laboratory experiments in porous media are essential to investigate flow and contaminant transport in the subsurface (Wirth et al. 2010; Rolle et al. 2013a; Hubner et al. 2014, 2015; Ye et al. 2015). Such experiments often need to include natural geological heterogeneity and preferential flow pathways, for example, fractures, carbonate beds, and root channels, because these often control contaminant transport in otherwise low permeability geological units such as clay till, and limestone (Gruik et al. 1980; Hartono et al. 1992; Parker et al. 1997; Kilar and Gossens 1999; Berkowitz 2002; Jørgensen et al. 2006b; Cherry et al. 2006; Kosterhede et al. 2008; Kosterhede et al. 2012, 2013; Libby and Rabbitt 2014; Baulou et al. 2016). Well-controlled laboratory studies are essential to complement field investigations, because in the latter it can be difficult or even impossible to establish, control, and manipulate boundary conditions. This typically leads to large degrees of freedom for the evaluation of obtained contaminant transport data and, consequently, to large uncertainties of derived key-values for the description of mass-transport processes.

Conclusions
The LUC method is a valuable approach to investigate flow and transport in macropores and fractured media. The method overcomes the limitations of intact column studies and facilitates the control of system boundary conditions including effective stress. In recent years, considerable experience has been gained through different applications of the LUC approach. Modeling tools have also been developed for a detailed interpretation of flow and transport processes in LUC systems. This paper describes the steps of the LUC method from column excavation in the field to experimental setup in the laboratory. The description encompasses the key features of the sampling of LUCs in field excavations, the laboratory setup, the procedure for hydraulic and transport experiments, as well as practical challenges and potential issues during operation of an LUC system. Application examples with a fully three-dimensional numerical model of LUC tracer experiments are also presented to illustrate the quantitative interpretation of transport processes in macropores/clay till.

Water Resources Research

RESEARCH ARTICLE

Transport of Tracers and Pesticides Through Fractured Clayey Till: Large Undisturbed Column Experiments and Model-Based Interpretation

K. Moshfegh^{1,2}, M. Rolle^{1,2}, U. Petursdottir^{1,2}, J. Aamand^{1,2}, and P. R. Jørgensen^{1,2}

Abstract
Leaching of contaminants through fractured aquifers such as clayey till may occur due to typically slow matrix advection and diffusion, or it can be drastically enhanced in the presence of preferential flow through fractures and macropores. Despite the large critical role that it can significantly impact contaminant leaching and residence time, these different mass-transfer mechanisms largely exhibit contrasting behavior and very different time scales for contaminant leaching toward underlying aquifer systems. However, the prevalent controls on contaminant transport and their effects are difficult to assess. This paper shows a detailed characterization of flow and transport processes under water-saturated conditions in two large undisturbed columns (LUCs) collected from two visually similar fractured limestone-clayey till typical for the Northern hemisphere. Flow-through tracer and pesticide experiments revealed a contrasting transport behavior. In one column, transport through fractures/macropores was dominant, whereas matrix advection and diffusion had a different influence on solute transport in the other column. Detailed 3D discrete-fracture-matrix models were developed to illustrate prevalent controls on contaminant transport and to quantitatively interpret the flow-through experiments with a minimal number of fitting parameters. Nonprelaminar sorption kinetics were included to reproduce the transport behavior of the controlled pesticides. The parameters estimated from the two LUC experiments were integrated in a vertical cross-section model to investigate the influence of varying fracture properties on vertical solute transport through surficial clayey till aquifers. The results showed that small fracture apertures in deeper parts of the aquifer could substantially prolong solute migration times and control solute fluxes.

1. Introduction
Glacial deposits such as clayey tills are often found in the upper geological layers in many countries of the Northern hemisphere (Jørgensen et al. 2010; Jørgensen et al. 2010; Kim et al. 2017; McGee, Gillman, et al. 1993; Parker et al. 1996; Yeung et al. 2013). Usually, clayey tills have a low hydraulic conductivity and can slow down solute migration, or even act as a barrier for contaminant leaching toward groundwater bodies (Jørgensen et al. 2010). However, pesticides have frequently been found in aquifers underlying agricultural regions, such as clayey tills (Bradbury et al. 1995; Cherry et al. 2006; Hultine et al. 2005; Jørgensen & Pedersen 1992; Jørgensen et al. 2010; Møller et al. 2016). This is due to the specific pesticides and their degradation products can threaten groundwater quality and may even sequester drinking water supply wells. The pesticides and their metabolites were found in about 40% of 2,500 monitored drinking water wells in 2010 in Denmark, with more than 11% exceeding the EU limit value of 0.1 µg/l for pesticides in drinking water (Council of the European Union, 1998; Thieling et al. 2016), causing the shutdowns of many water supply wells.

Flow patterns in glacial clayey tills are often very heterogeneous and complex (Jørgensen et al. 2010; Borchert et al. 2005). In addition to matrix heterogeneity, the soil layers and sand lenses (Zander et al. 2012), fractures and macropores can act as preferential transport pathways for contaminants and considerably shorten travel times and increase solute fluxes (Borchert et al. 2010; Pothoff et al. 2017; Thornton et al. 2012; Lørensen et al. 2013). Due to the low hydraulic conductivity of the clayey till matrix, there is often a strong contrast between fracture and matrix conductivity. Hence, solute transport in open macropores and major fractures happens relatively fast compared to transport in the clayey till matrix where diffusion

Technische Universität Berlin

DTU

Master's Thesis

Modeling Transport and Retardation of Tracers and Pesticides in Fractured Clayey till

Mariam Ouf
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Technical University of Denmark
March 2022

DTU Environment
Master's Thesis

21 January 2018

Rasmus Thalund-Hansen, s123066

DTU Environment
Department of Environmental Engineering

Master's Thesis

Model-based investigation of solute transport in macropores and heterogeneous fractured clay till

Chloe Annelies Lanfers (s141003)

Kongens Lyngby 2019

DTU

Master's Thesis

Transport of tracers and pesticides
in fractured clayey till:
LUC flow-through experiments
and model-based interpretation

Una Petursdottir
s130207

Technical University of Denmark
June 2019

DTU Environment
Department of Environmental Engineering