Role of tree-roots for groundwater contamination beneath glacial aquitards

Part 1

DTU Course “Groundwater Quality” (2025)

Peter R. Jørgensen

peterjoergensen.com

Peter R. Jørgensen

- 1986: Hydrogeologist from Univ. Of Copenhagen
- 1986-1995: Researcher at Danish Geotechnical Inst.
- 1995: Ph.D. in Contaminant Hydrology
- 1995-2001: Ass./Assoc. prof. Univ. Of Copenhagen/DTU
- 2001-2009: Research/Consulting at Orbicon/GEO
- 2010 – now: Leader of multidisciplinary research platform ”pjbluetech”.

Content

Part 1:

1. Glacial aquitards: What are they and why should we care?
2. Geological characterization of glacial aquitards
3. Fractures, deep tree roots and root macropores
4. Historical interpretations of flow and transport in glacial tills based on traditional indirect hydraulic techniques
5. State-of-art quantitative determination of flow and transport in fractures and root-macropores
6. Identification of groundwater vulnurability by multidisciplinary approach.

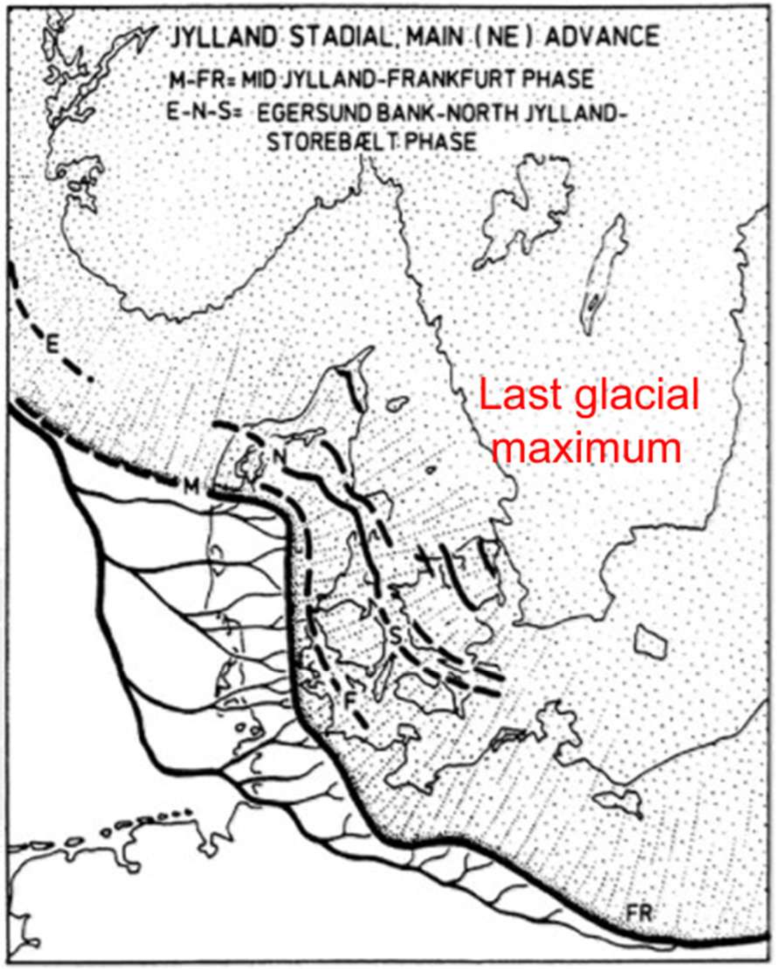
Glacial aquitards in millions of km^2

Heterogeneous, low-permeability deposits that share similar lithological and overall hydrogeological characteristics across large distances and continents.

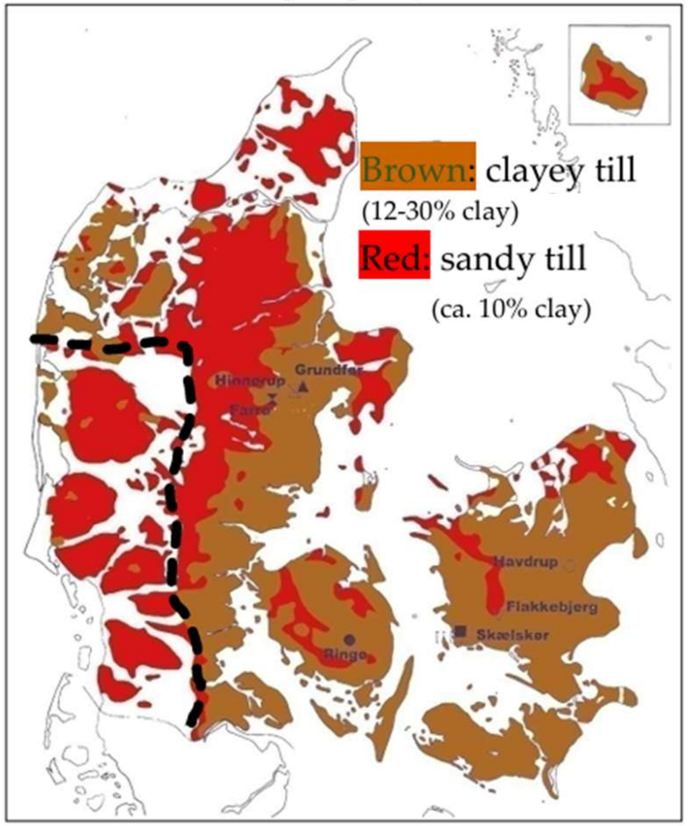
Vast areas occupied by indigenous forests in past Holocene time.

(Adapted from Ferris et al. 2020)

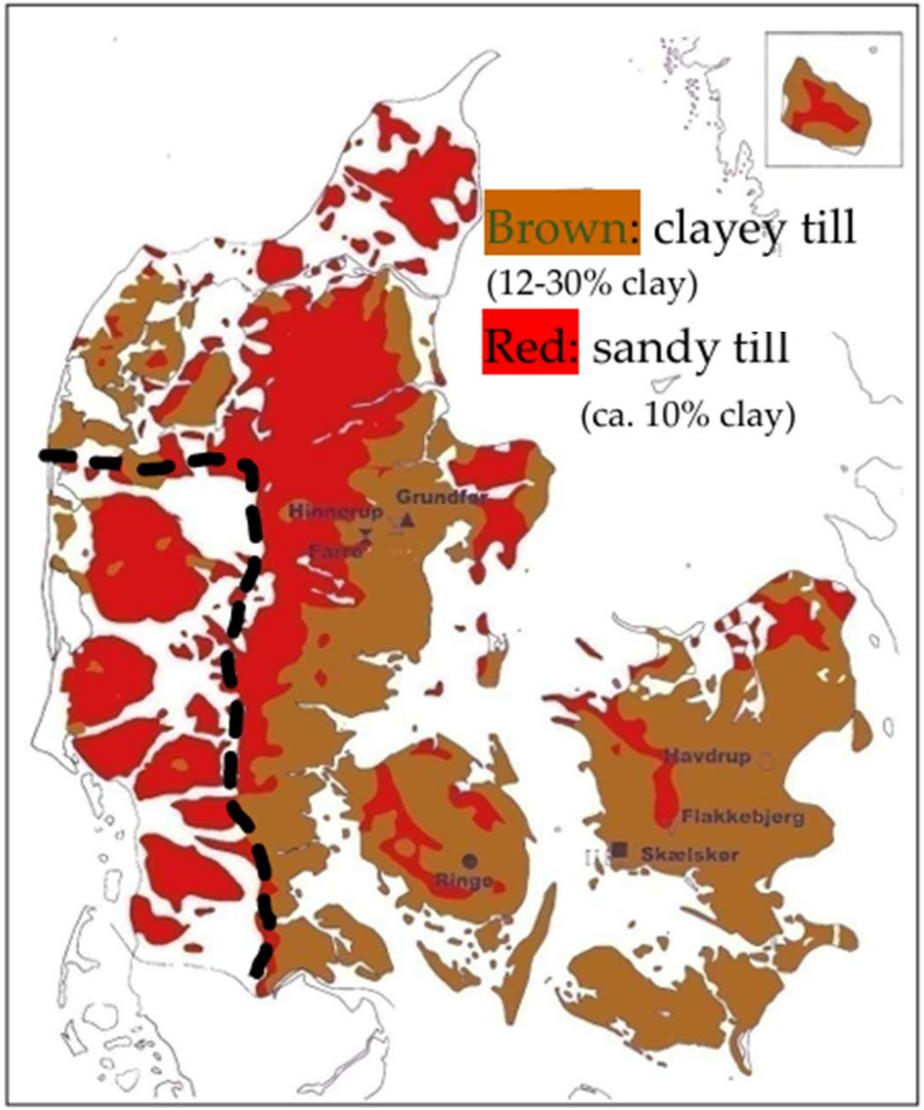
Moraines of glacial till: clayey till, sandy till (i.e., glacial aquitards)

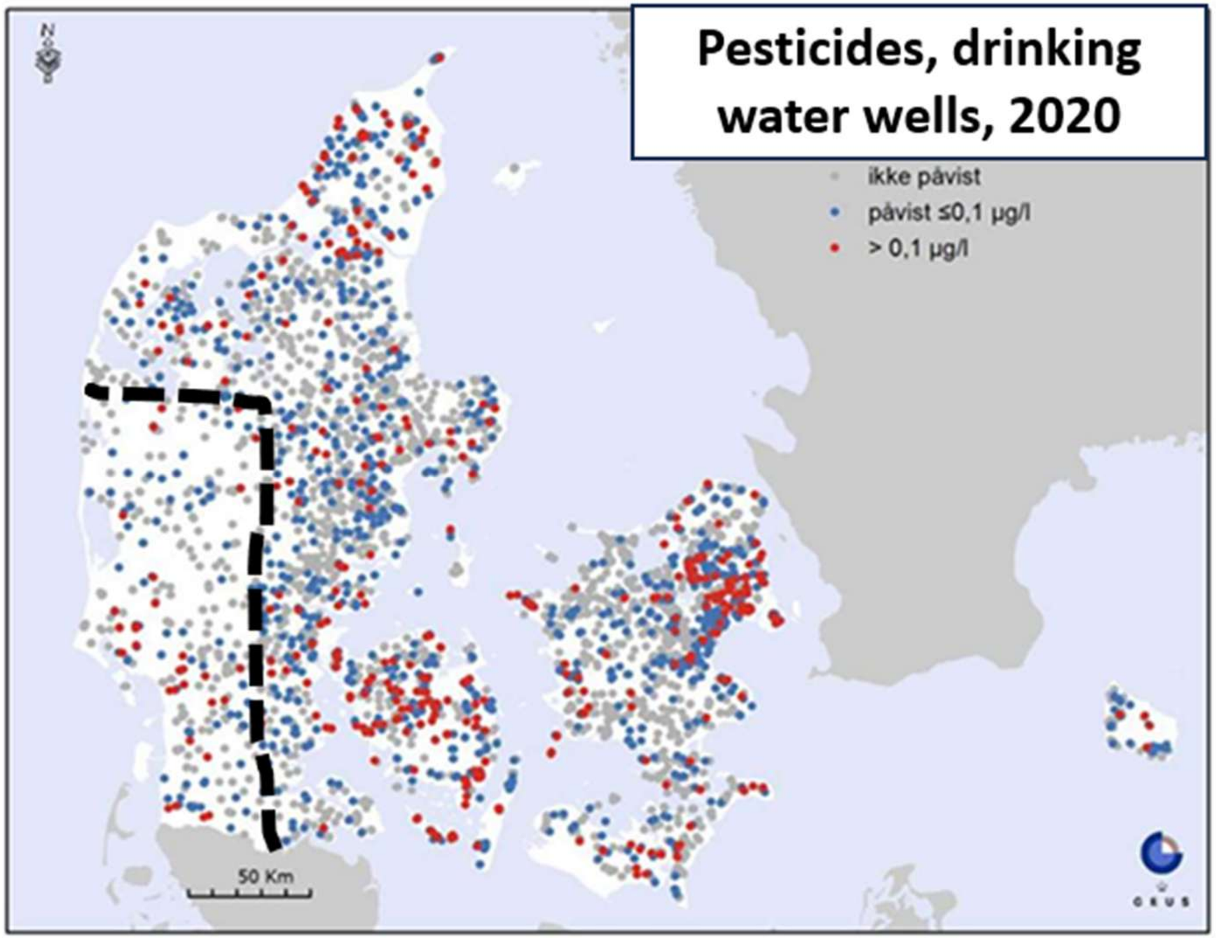


Clayey till form aquitards and is often the only natural protection of underlying aquifers

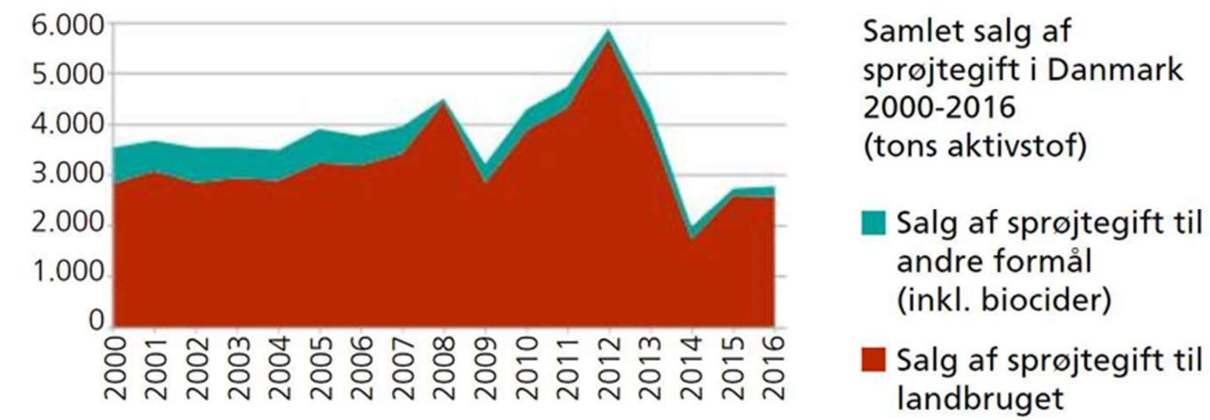


Integrity of glacial tills compromised



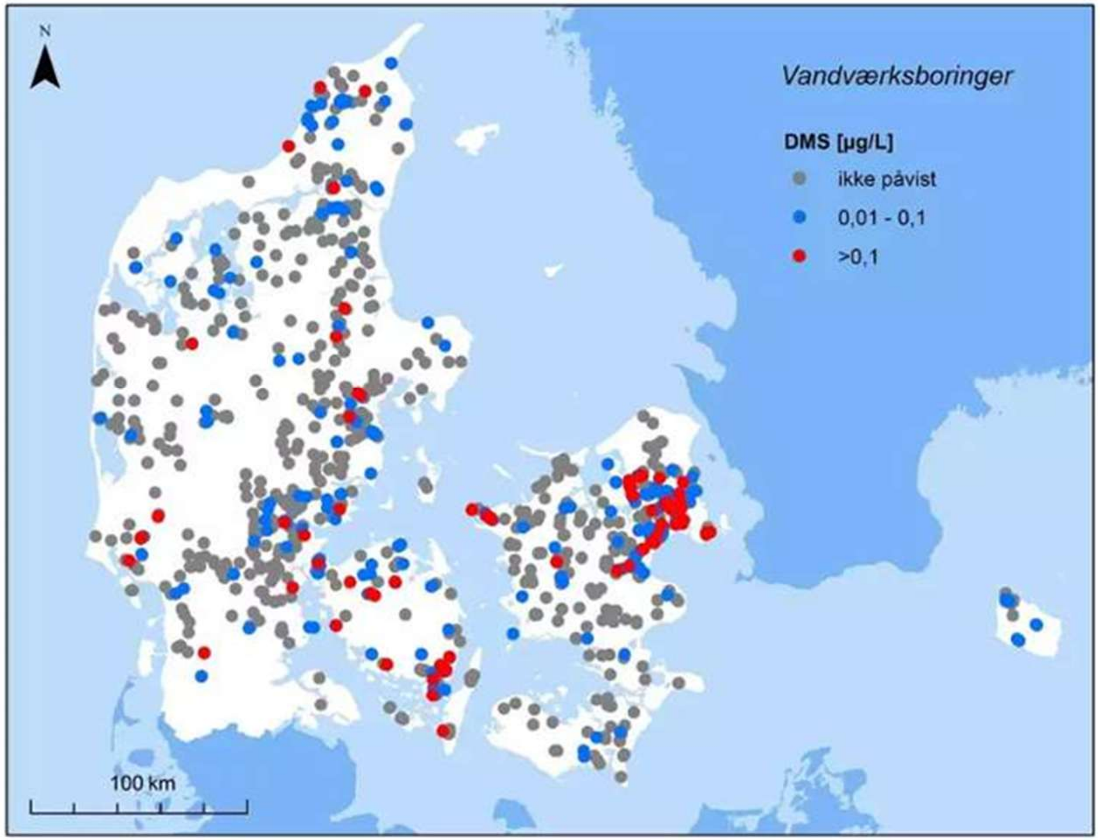


Total sale pesticides (tons a.i.)



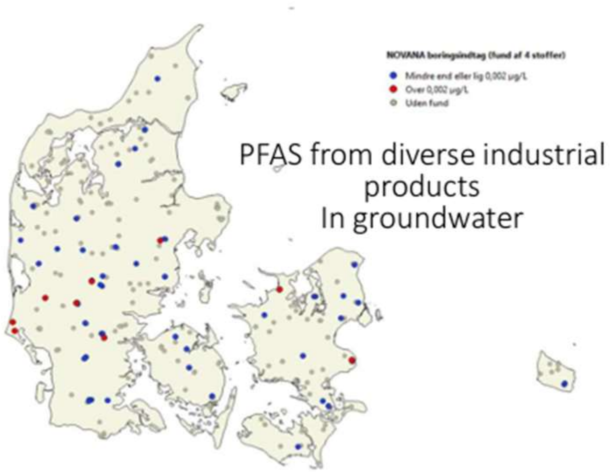
Referencer: Danmarks Statistik – Statistikbanken (2017), Miljøstyrelsen (2004), (2007), (2010), (2012), (2013), (2014a), (2016) og (2017a)

Persistent mobile organic compounds (PMOC)
Forever-chemicals



Biocide metabolite DMS from
agriculture and urban areas
(paint and building materials)
found in more than
30% of wells

PFAS



PFAS found in surface water, groundwater, and rain

Drinking water standard based on toxicological criteria = 0,002 µg/L

Helbredseffekter af PFAS

PFAS-stoffer kan være sundhedsskadelige og medføre:

*Forøget risiko for nyrekræft og testikelkræft

*Nedsat vaccineeffekt hos børn

*Forhøjede kolesteroltal

*Forandringer i leverenzymer

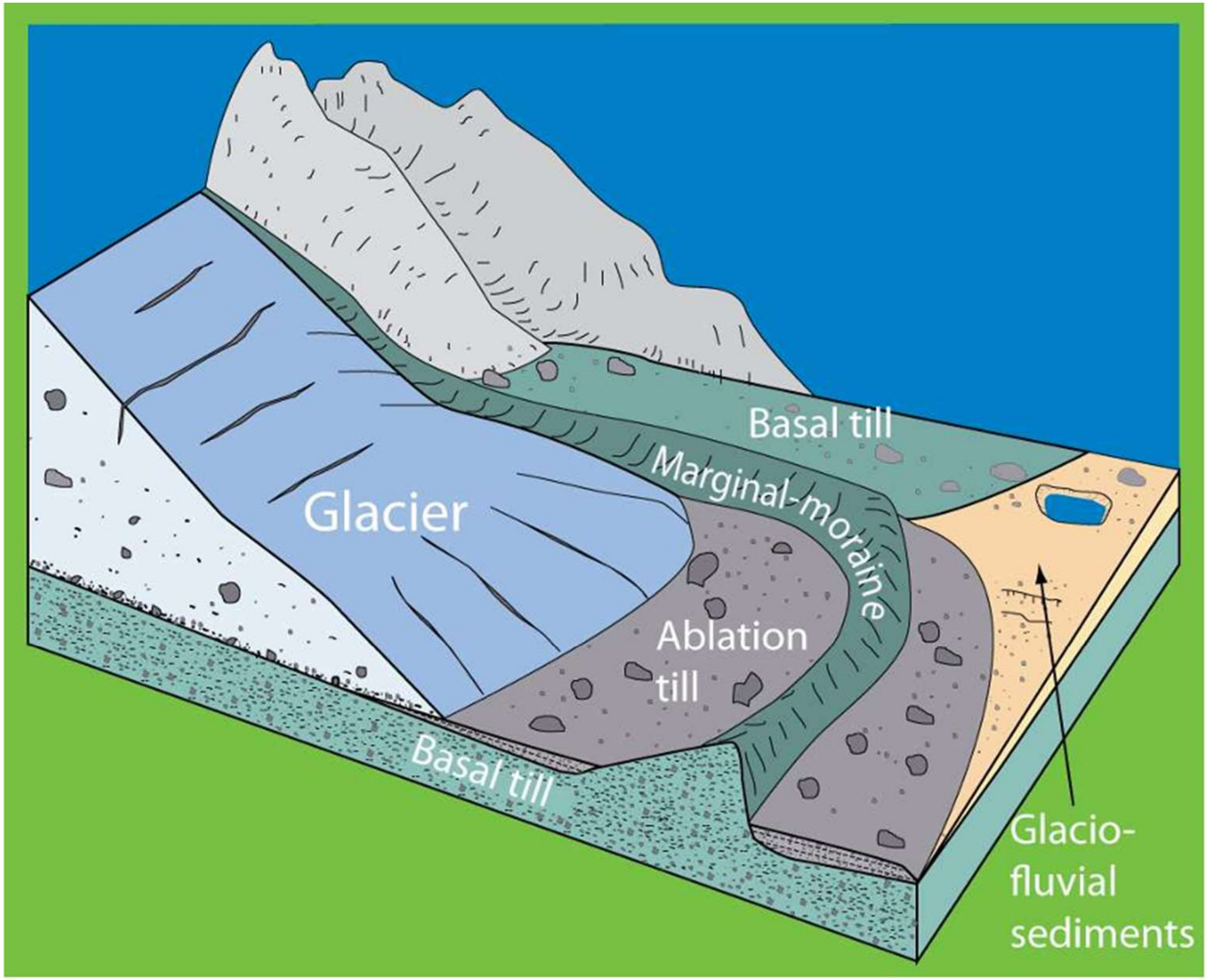
*Mindre fald i fødselsvægt

*Øget risiko for højt blodtryk hos gravide

Kilde: CDC

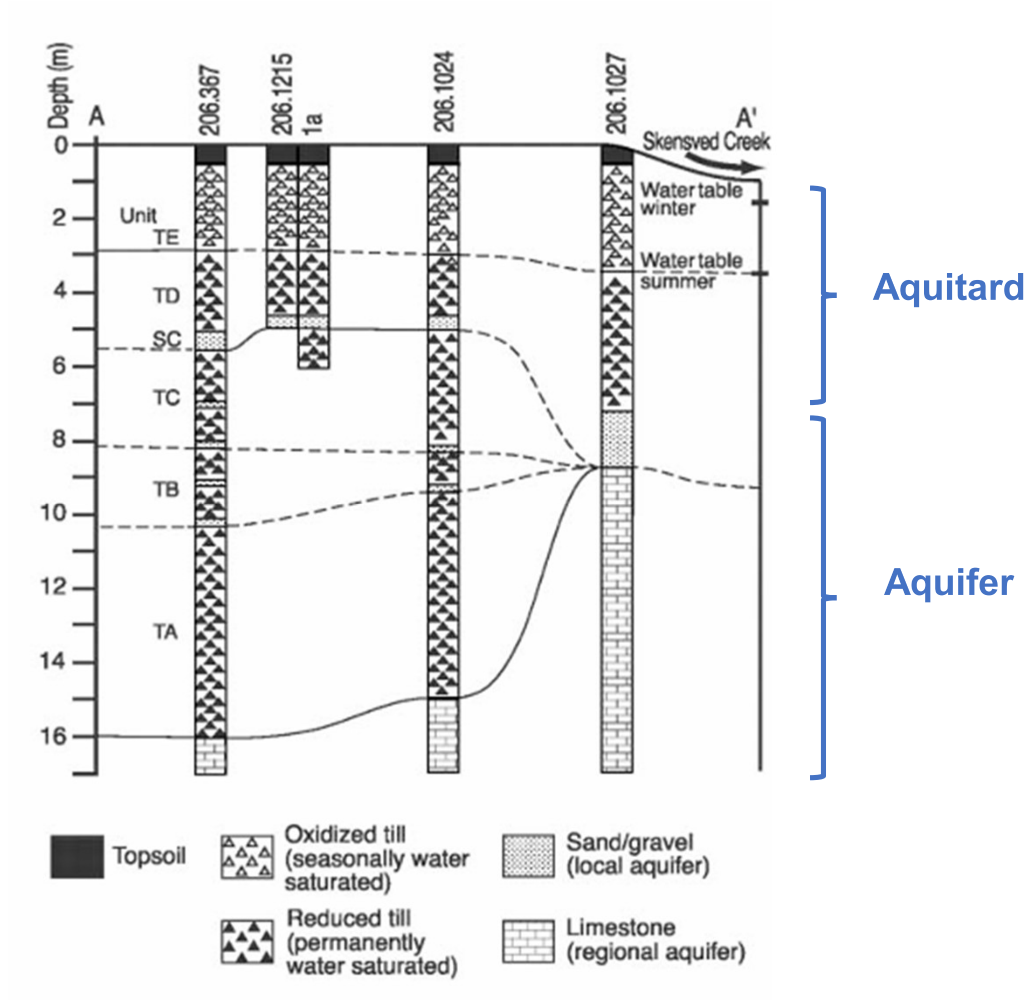
Geology
&
Hydrogeology
of glacial till landscapes

Glacial till types



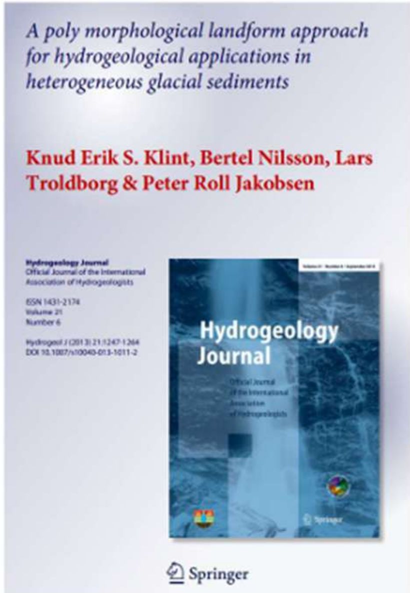
More than 5 major ice-advances have occured across Denmark in the last ice-age (Weichsel ice-age)

Vertical succession of glacial till units (TA-TE) each typically less than 5 m thick



(Jørgensen et al. 2004)

Distribution of different till types



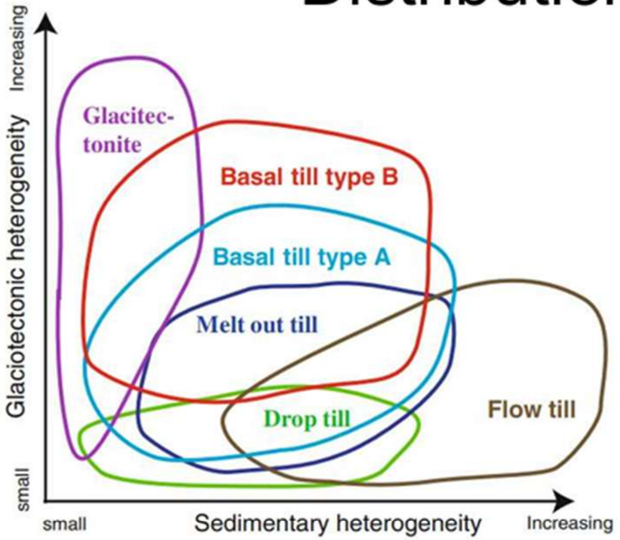


Fig. 2 Principal diagram of the relative geological heterogeneity of different till types (see Table 1) as a result of combined sedimentary and glaciotectonic heterogeneity

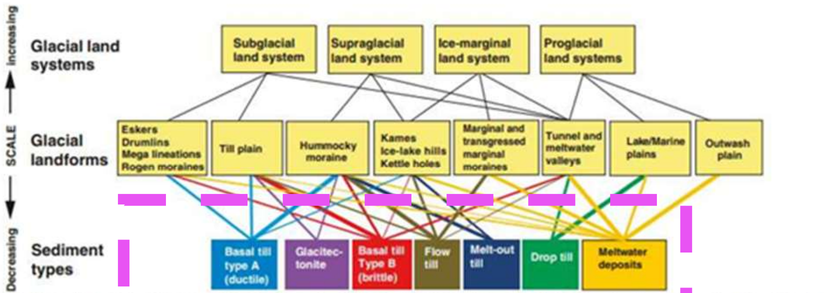


Fig. 1 Scale hierarchy and classification of land systems, landforms and sediment types in glacial deposits. The *connection lines* between glacial landforms and sediment types represent which till types are represented in the individual glacial landforms and the line thickness indicates the importance of the sediment types in the individual landforms

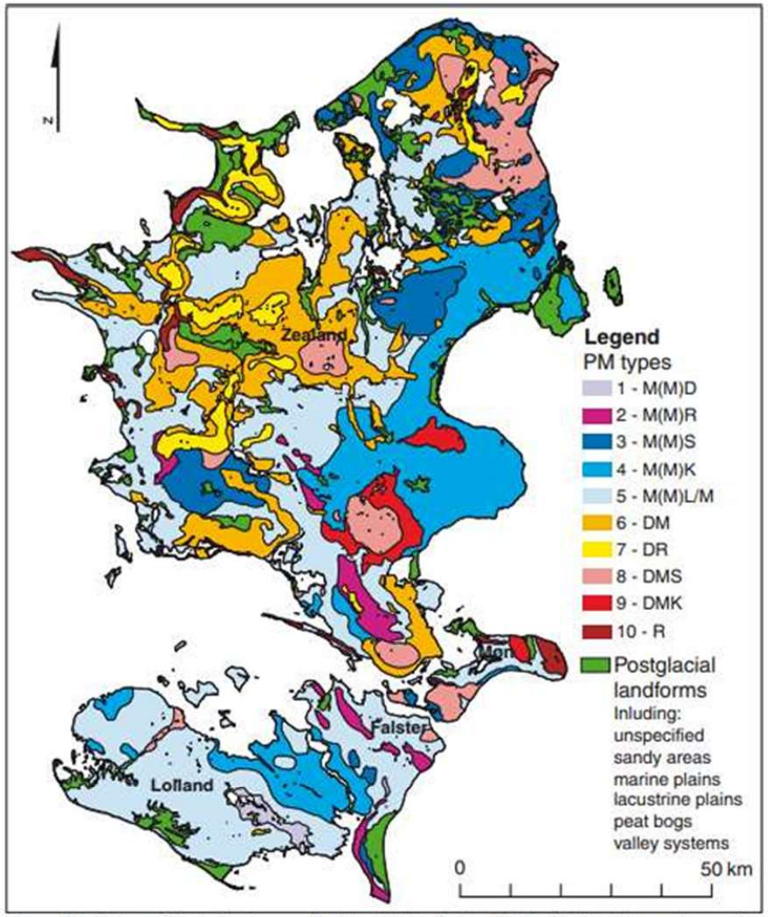
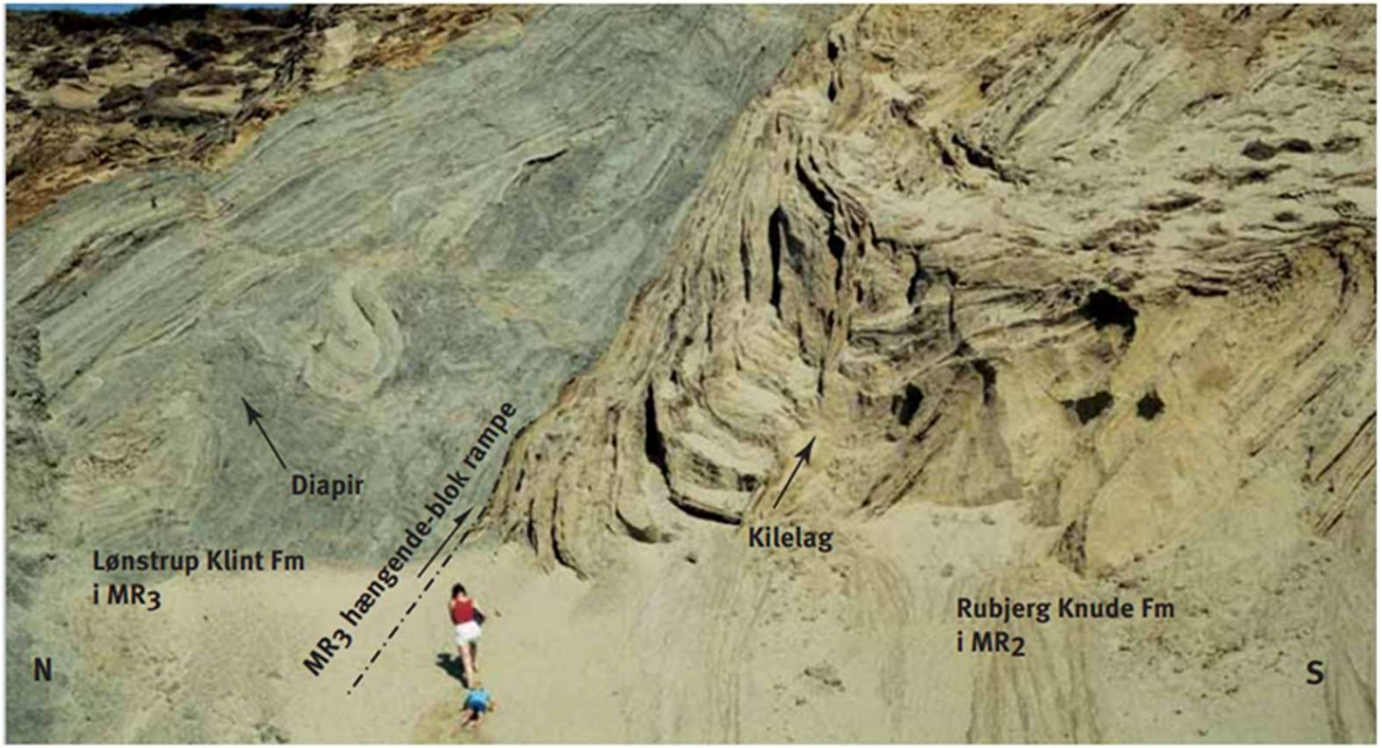
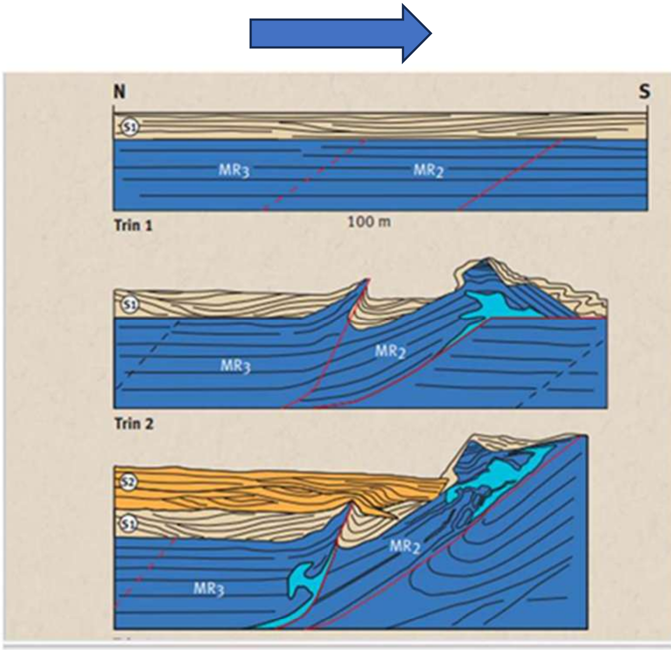


Fig. 4 Poly morphological map of Zealand and surrounding islands. PM units: *M* undulating till plain, *D* hummocky moraine, *S* outwash plain, *R* marginal moraine, *K* basement limestone, *L* basement marine clay

The force of the ice-cap glaciers has created extreme geological heterogeneity in glacial tills…..

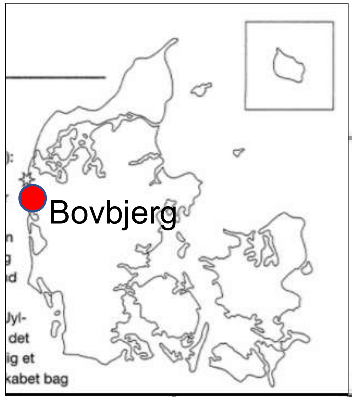


Movement of ice sheet/glacier



(S.A.S. Pedersen 2006)

Heterogenity of glacial tills



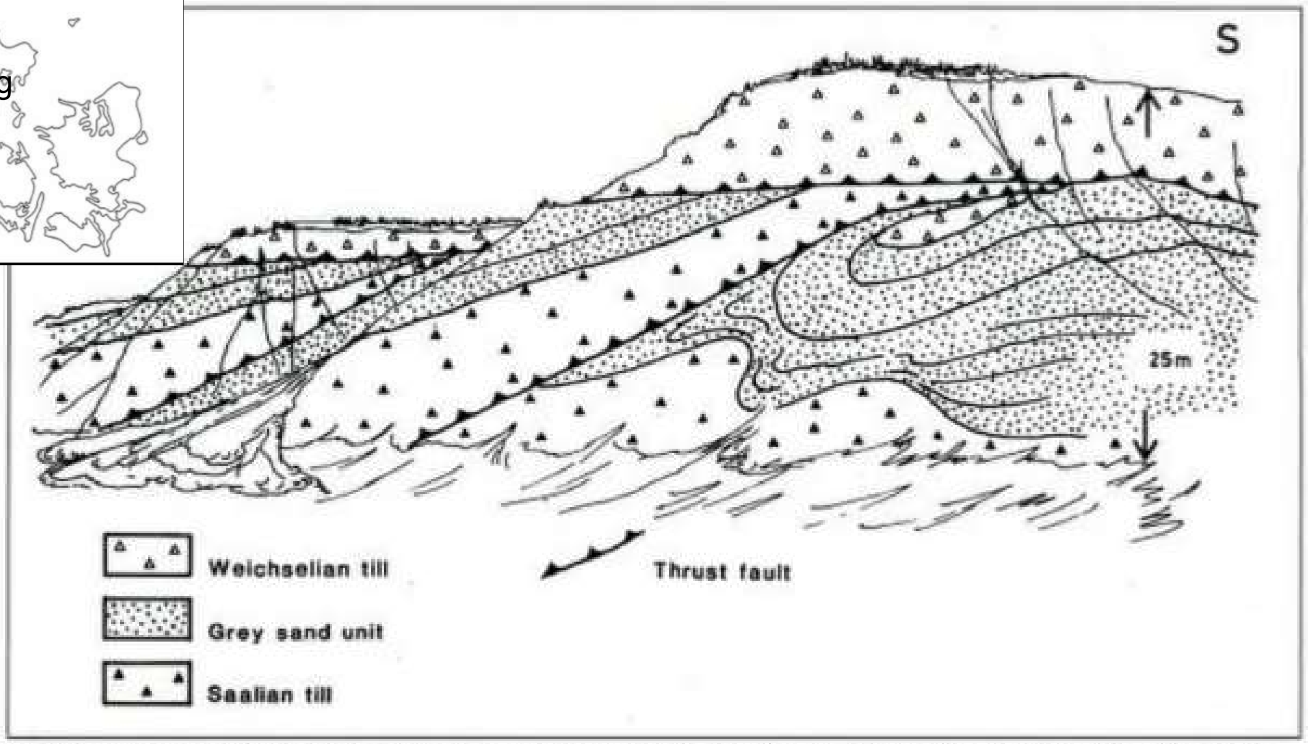
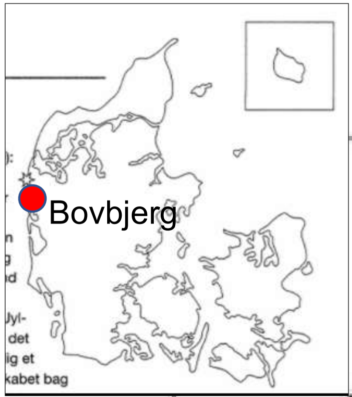


Fig. D1:3. Flage-opskydning i den stærkt deformerede centrale del af Bovbjerg profilet. I det nedre stokværk ses stejlt nordhældende overskydninger, langs hvilke moræneler fra Saale samt den nederste del af lagfølgen fra Weichsel er skudt op. Det øvre stokværk består af en diskordant bænk af moræneler fra Weichsel. Efter Pedersen m. fl. (1988).

Heterogenity of glacial tills



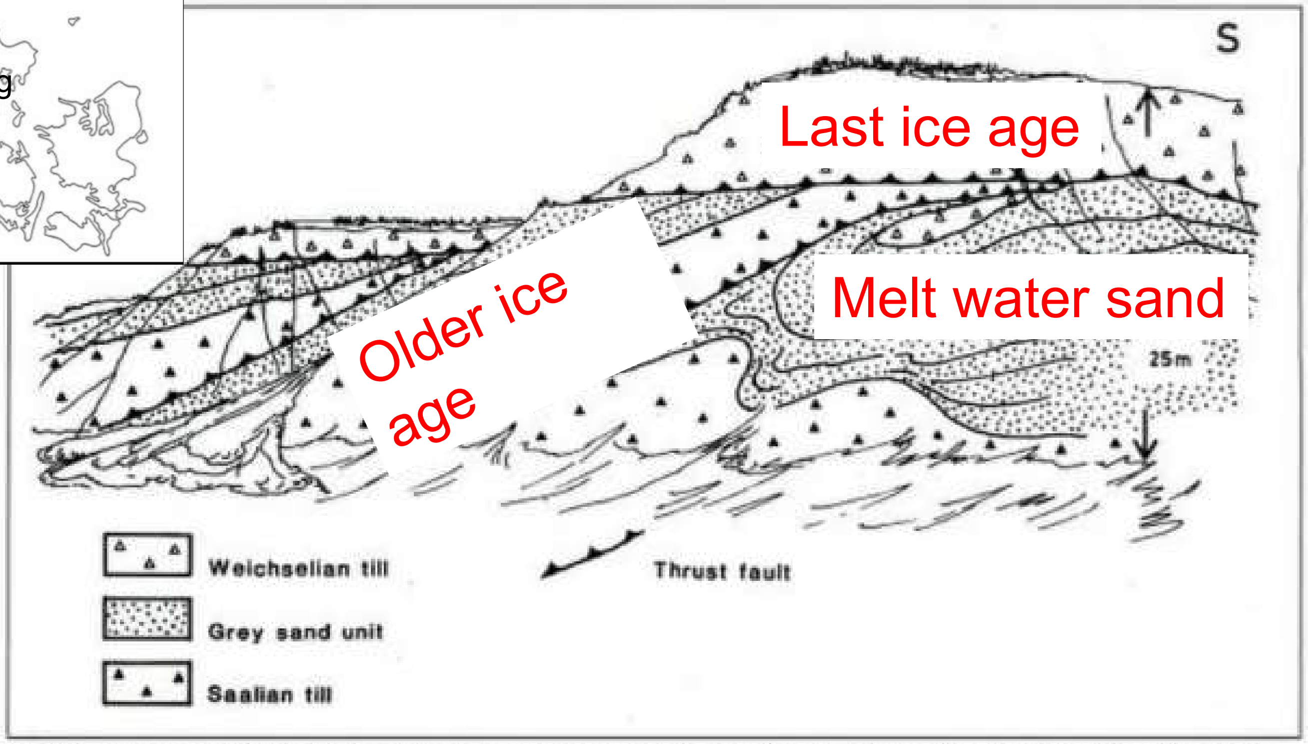


Fig. D1:3. Flage-opskydning i den stærkt deformerede centrale del af Bovbjerg profilet. I det nedre stokværk ses stejlt nord-hældende overskydninger, langs hvilke moræneler fra Saale samt den nederste del af lagfølgen fra Weichsel er skudt op. Det øvre stokværk består af en diskordant bænk af moræneler fra Weichsel. Efter Pedersen m. fl. (1988).

Heterogenity of glacial tills

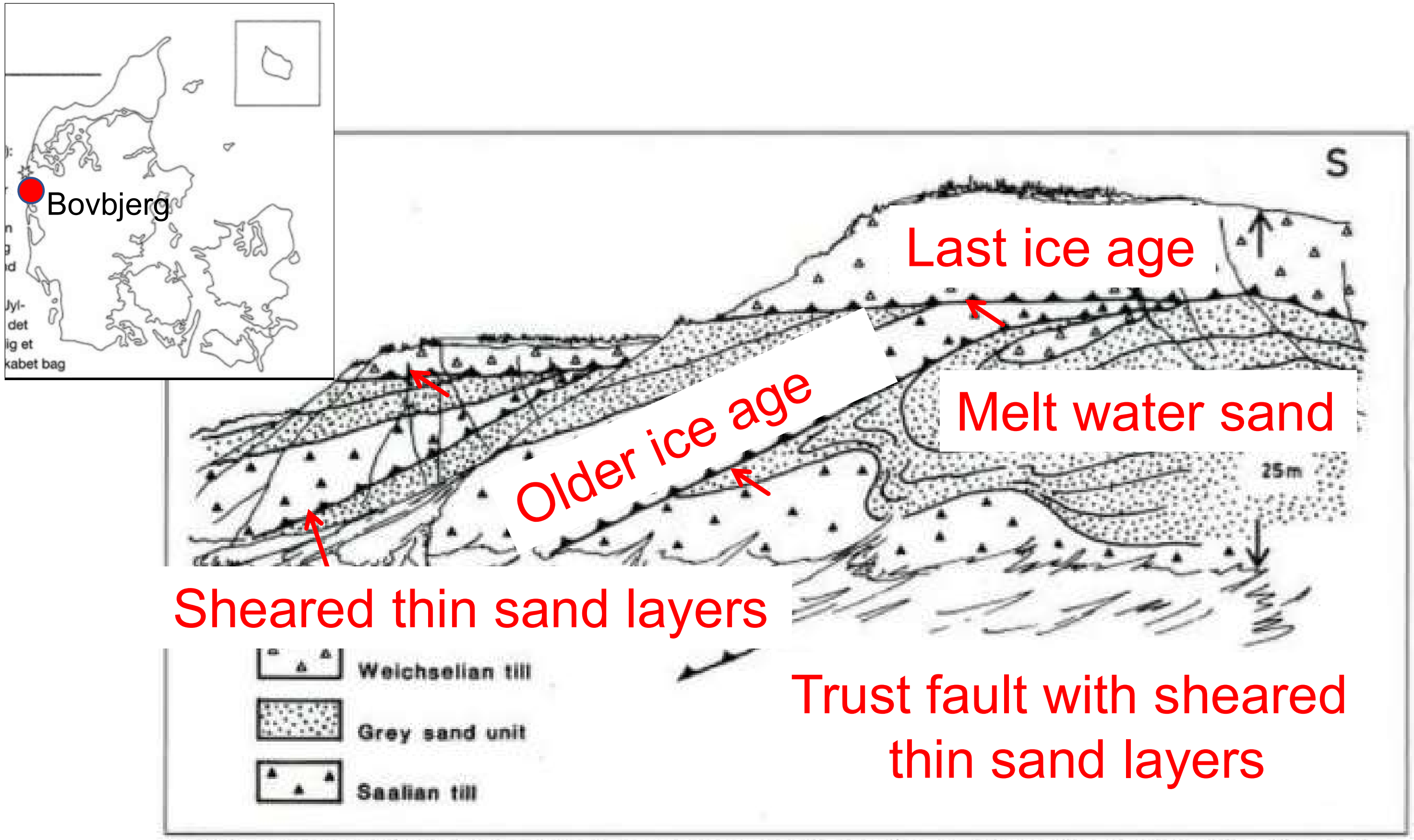
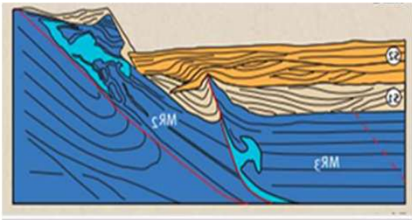
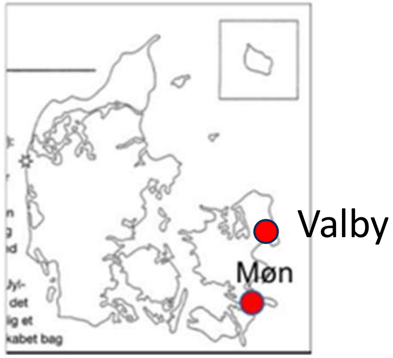
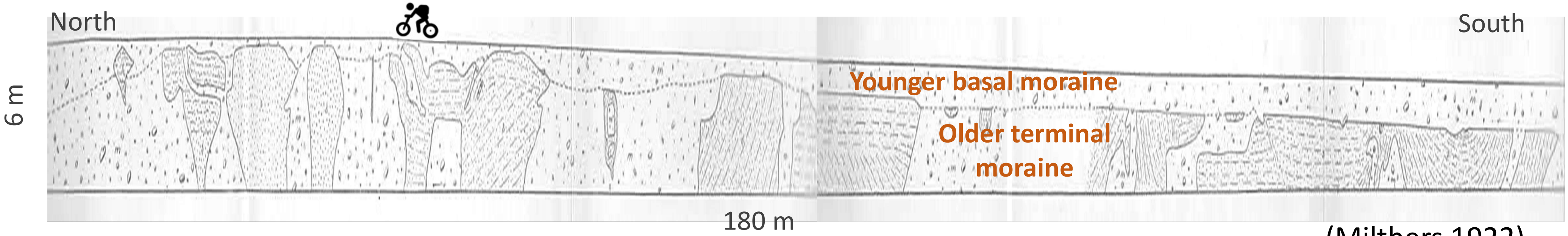


Fig. D1:3. Flage-opskydning i den stærkt deformerede centrale del af Bovbjerg profilet. I det nedre stokværk ses stejlt nordhældende overskydninger, langs hvilke moræneler fra Saale samt den nederste del af lagfølgen fra Weichsel er skudt op. Det øvre stokværk består af en diskordant bænk af moræneler fra Weichsel. Efter Pedersen m. fl. (1988).

Cross-section through Valby Bakke in Copenhagen





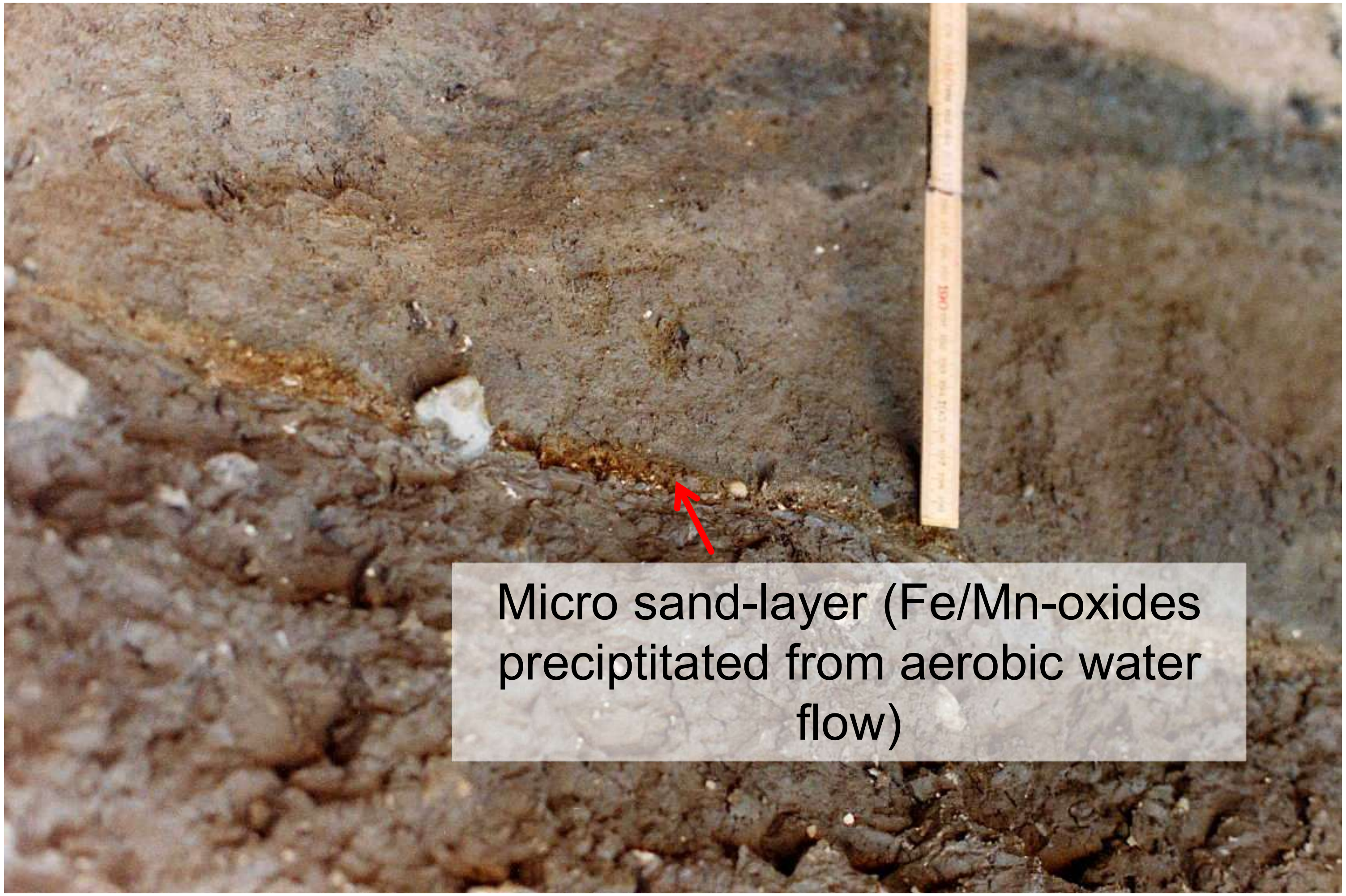


(Milthers 1922)

Heterogenity of glacial tills

Heterogeneity of glacial till

Heterogenity of glacial tills



Fractures is a common feature for most glacial till types across the continents

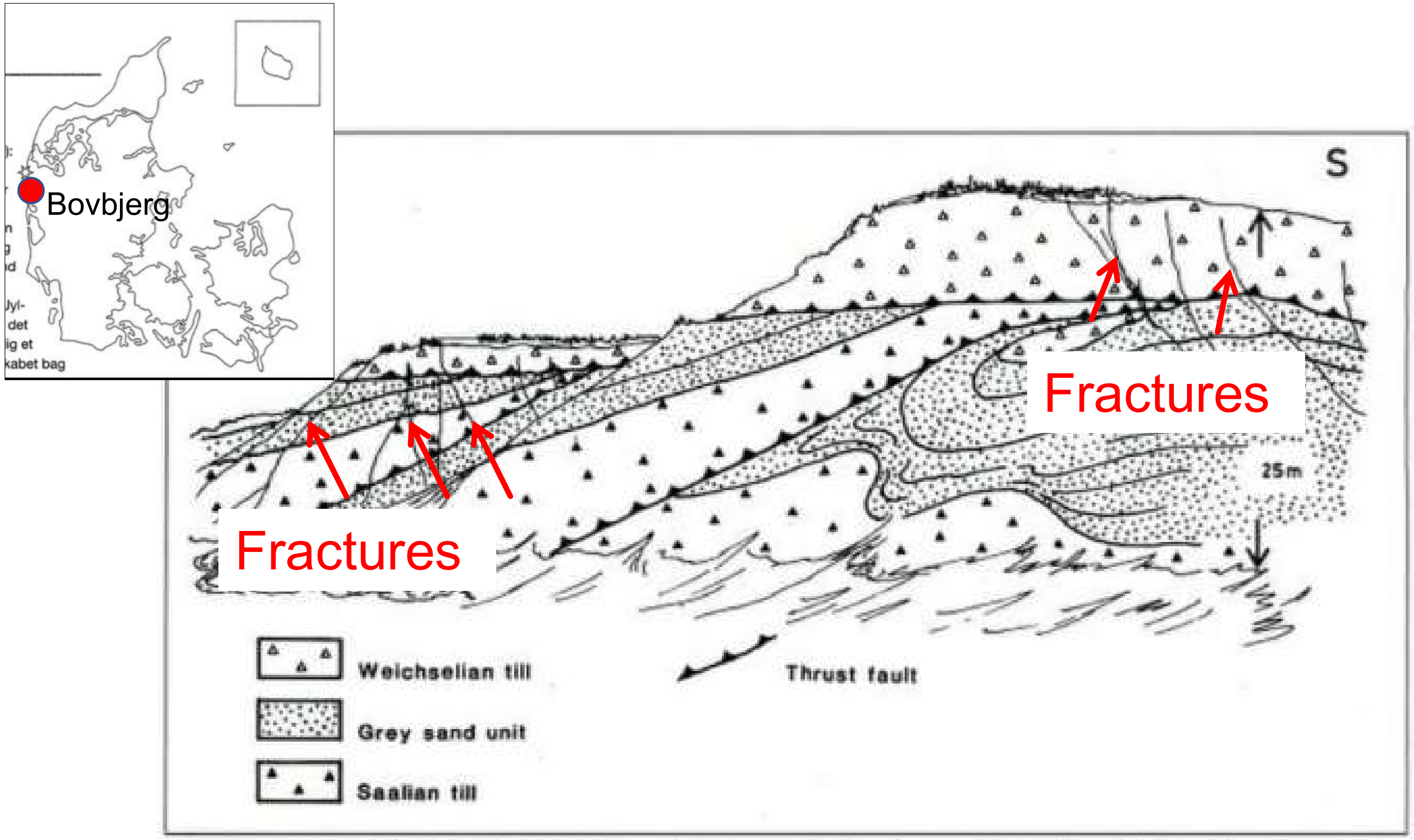


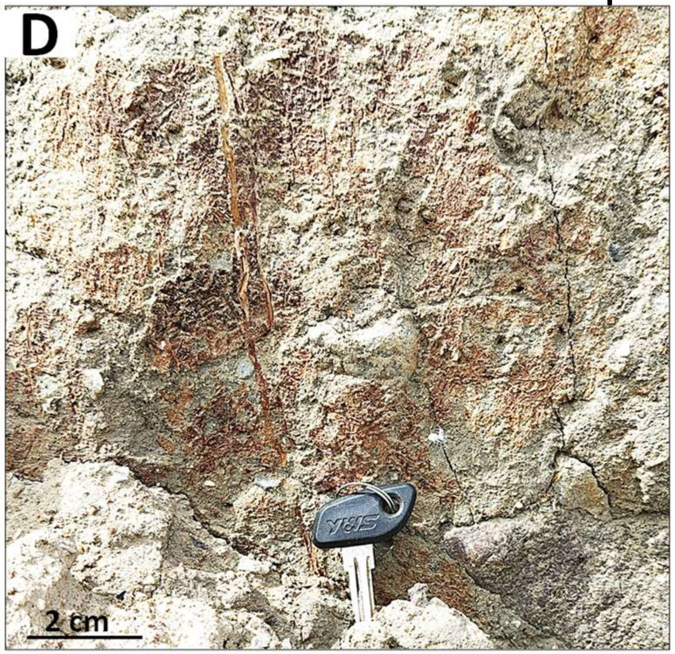
Fig. D1:3. Flage-opskydning i den stærkt deformerede centrale del af Bovbjerg profilet. I det nedre stokværk ses stejlt nordhældende overskydninger, langs hvilke moræneler fra Saale samt den nederste del af lagfølgen fra Weichsel er skudt op. Det øvre stokværk består af en diskordant bænk af moræneler fra Weichsel. Efter Pedersen m. fl. (1988).

Glacial tills are typically intensively fractured (dessiccation, glacial tectonic forces, uplift etc.)

Root casts/macropores are widespread features on fracture surfaces

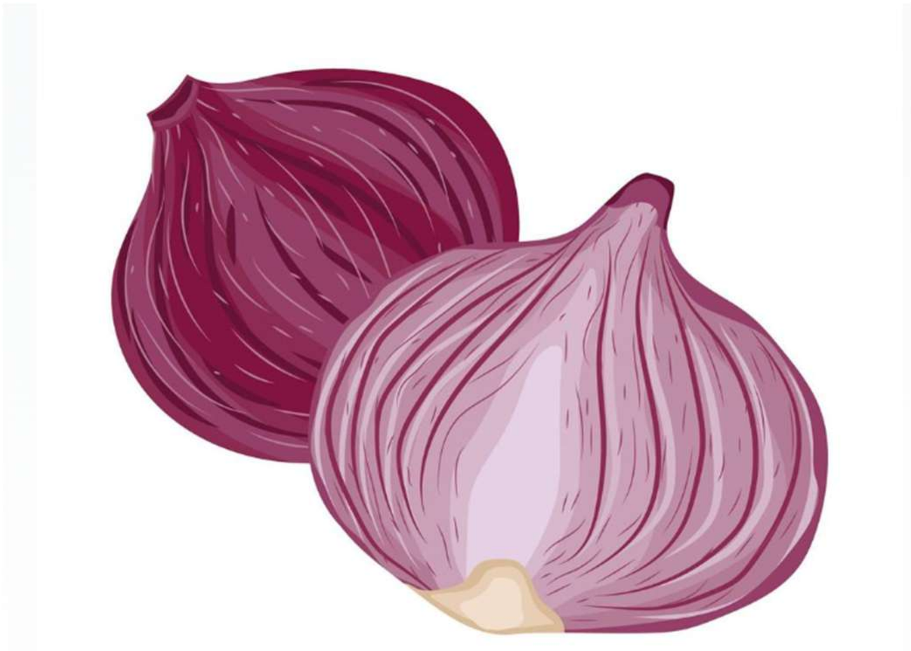
2.5-2.8 m depth

4 m depth

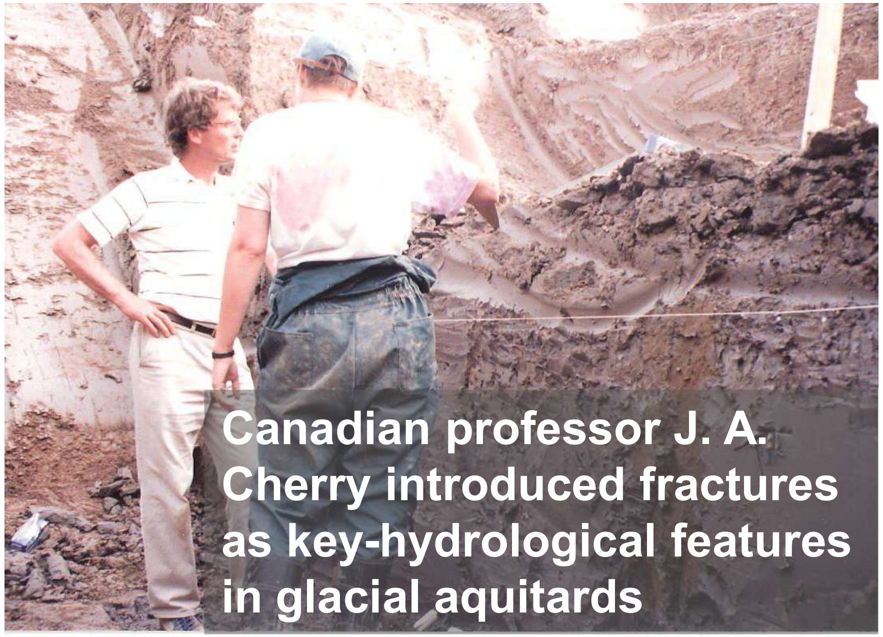


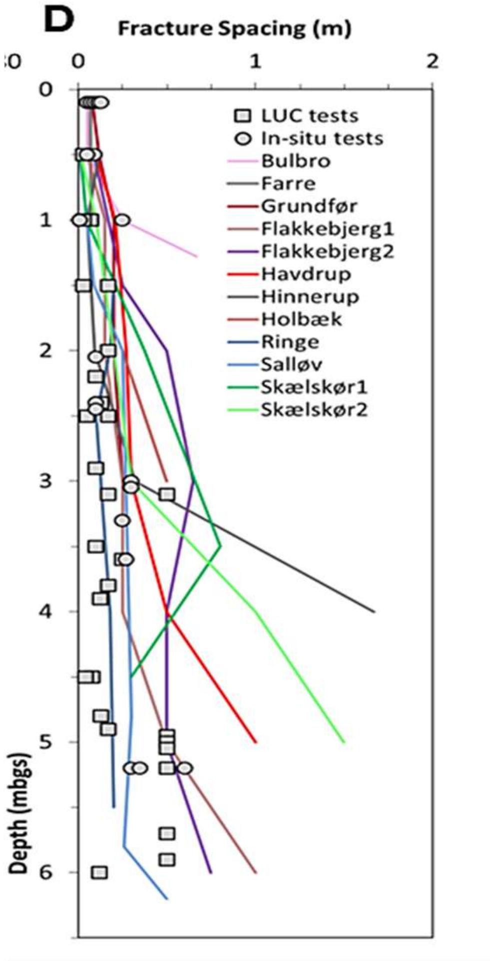
5.2 m depth

All together
- a nightmare of complexity and chaos

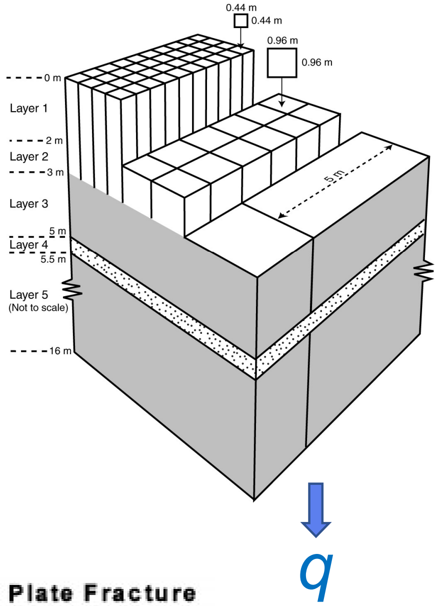


In the past 3-4 decades focus in hydrogeological research has been on the hydraulic role of fractures

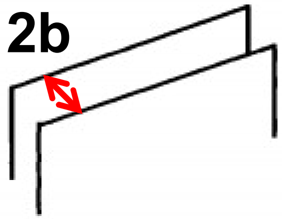

Canadian professor J. A. Cherry introduced fractures as key-hydrological features in glacial aquitards



Saturated flow in fractures



Continuous Parallel Plate Fracture
Constant Aperture



$$q = (2b)^3 \cdot \frac{\rho g}{12\mu} \cdot i$$

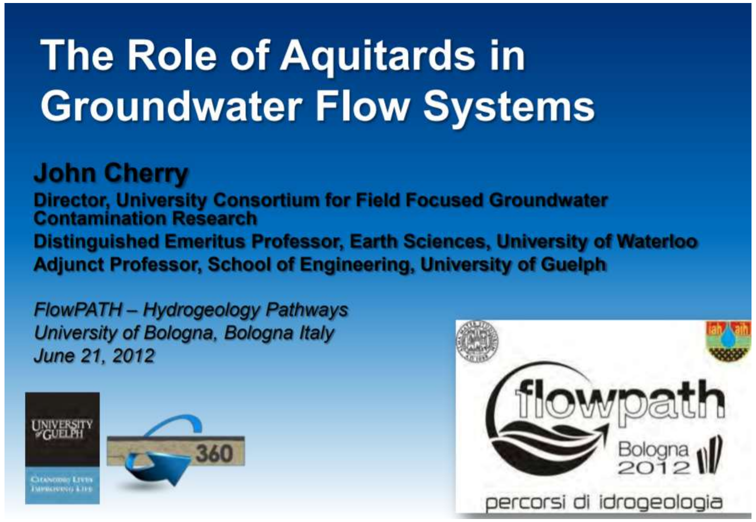
(Snow 1968)

Flow along fractures

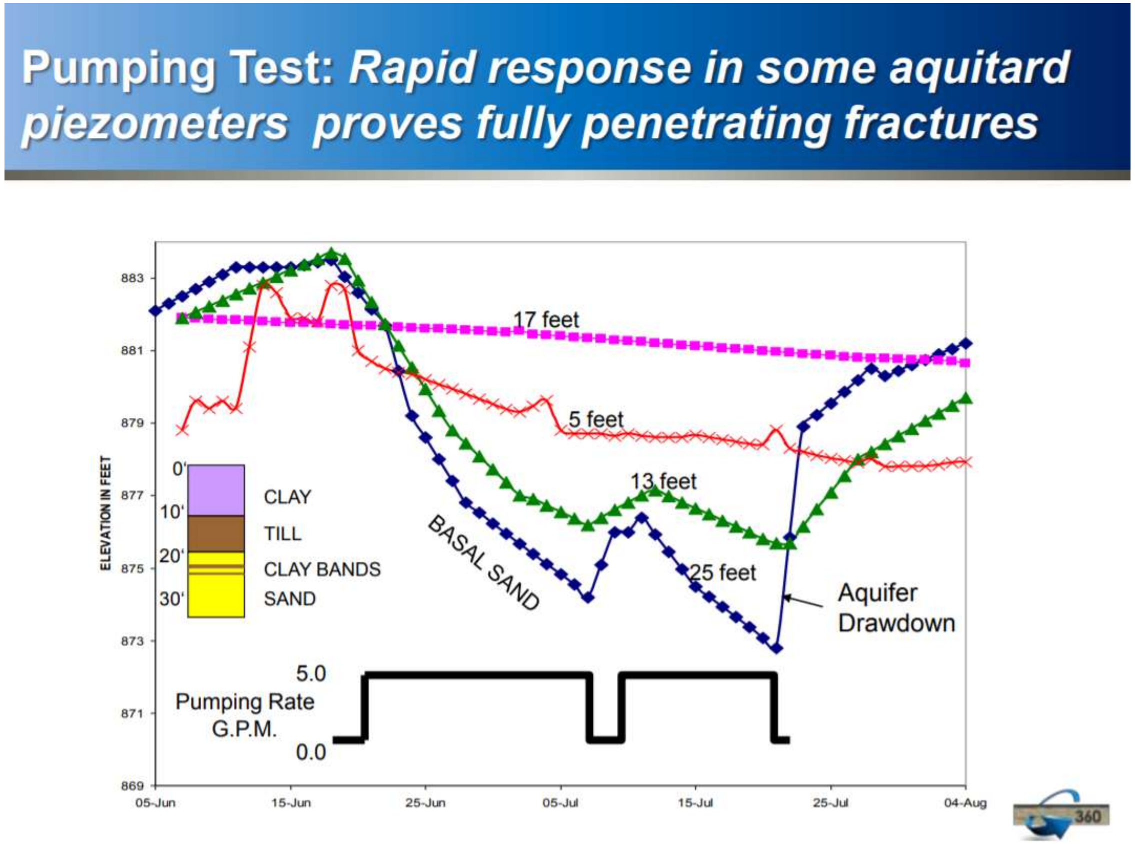
No reliable in-situ or lab methods were available to directly determine flow in fractures

Investigators used indirect techniques and interpretation to evaluate hydrogeological role of fractures

Evidence for widespread occurrence of deep pathways for rapid water movement attributed to flow in fractures (Canada)



(Cherry 2012)



10 – 20 m deep hydraulic active zone in glacial aquitards attributed to fractures (Canada)

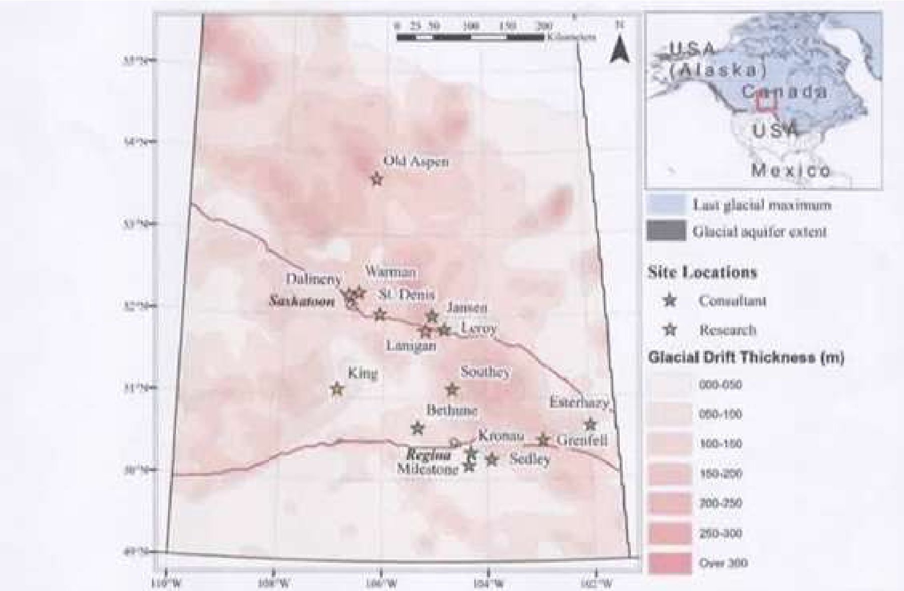


Fig. 2 Location of sites included in the study (Layers from Ehlers et al. 2010; Mossop and Shetsen 1994)

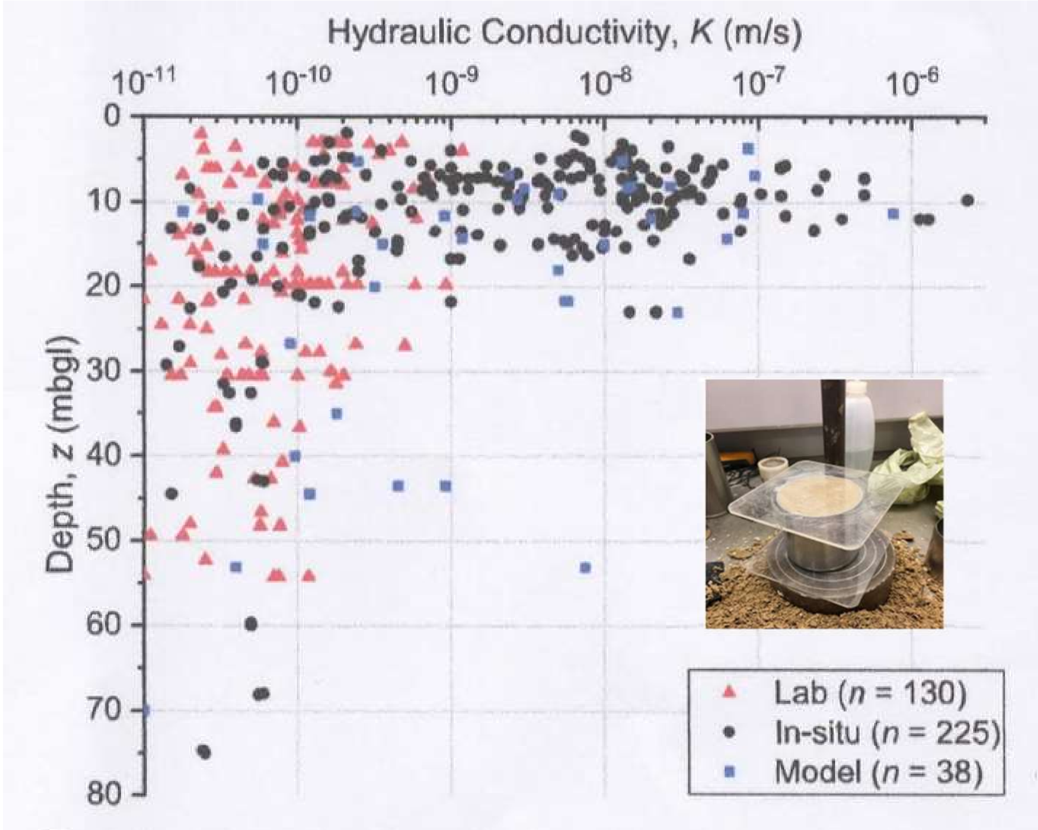
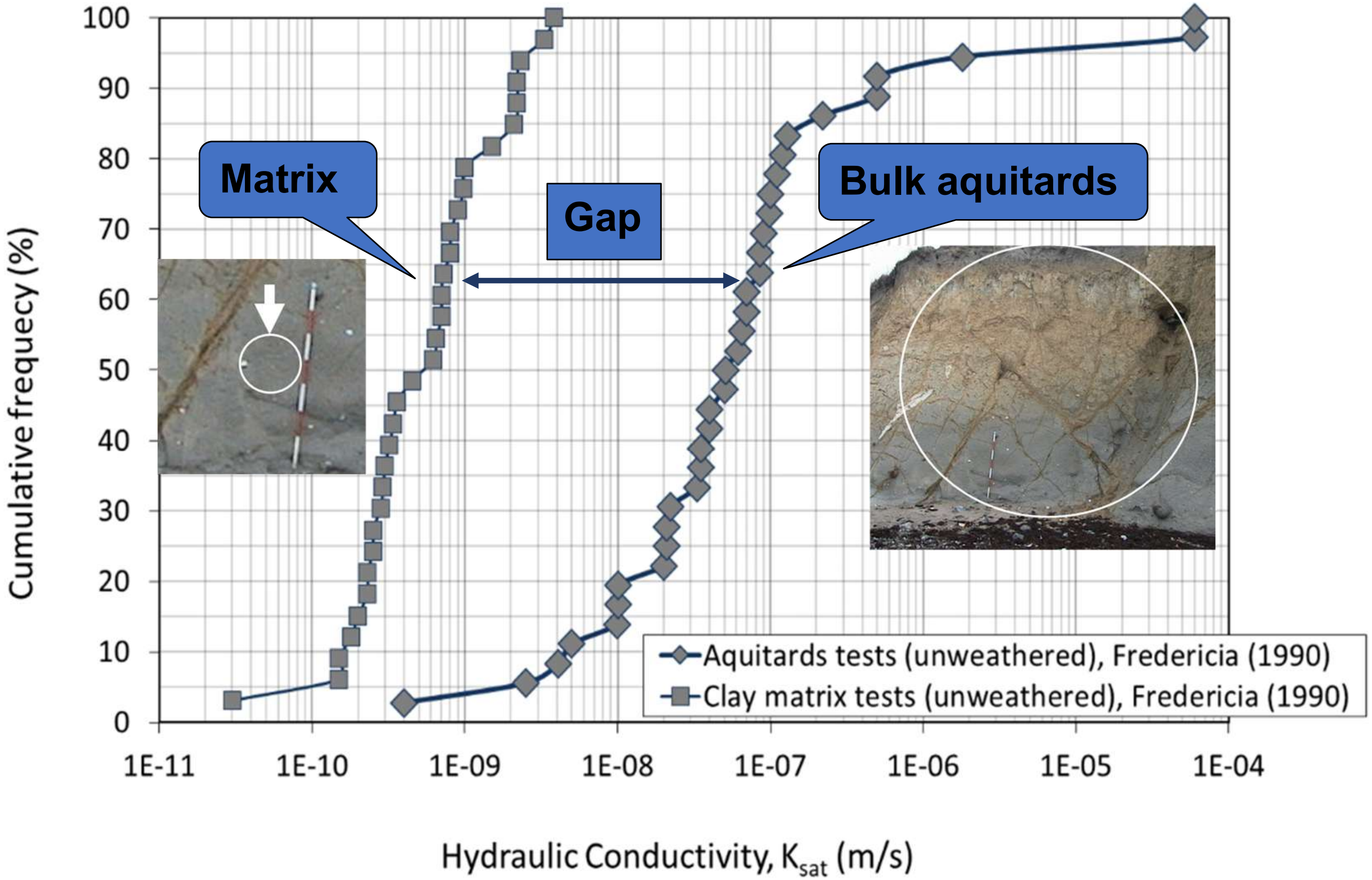


Fig. 4 Aggregate hydraulic conductivity with depth, data classed by test group

(Ferris et al.2020)

Similar observations in Denmark attributed to flow in fractures



Root macropores/imprints are widespread inside fractures

Canadian test pit

Test Pit Beside Disposal Area

Root Imprints on Gray Fracture Surface

Root macropores/imprints are widespread inside fractures

Canadian test pit

Test Pit Beside Disposal Area

Root Imprints on Gray Fracture Surface

NB: Quantitative studies of flow in deep natural fractures and root macropores have not been possible due to lacking techniques for representation of in-situ soil-stress in laboratory

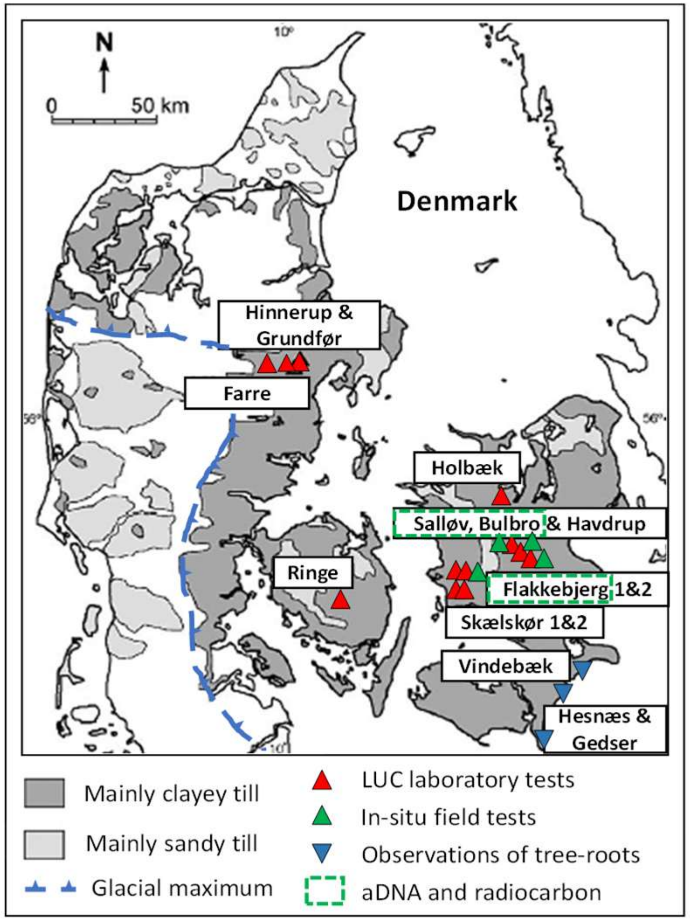
Narrow focus on fractures

Root casts/macropores (primarily located within the fractures) have been considered of minor importance and have been disregarded

Reseach gap about the fundamental mechanisms of groundwater vulnerability

NB: Uncertainty about biological versus geological mechanisms controlling groundwater vulnerability to surface pollution

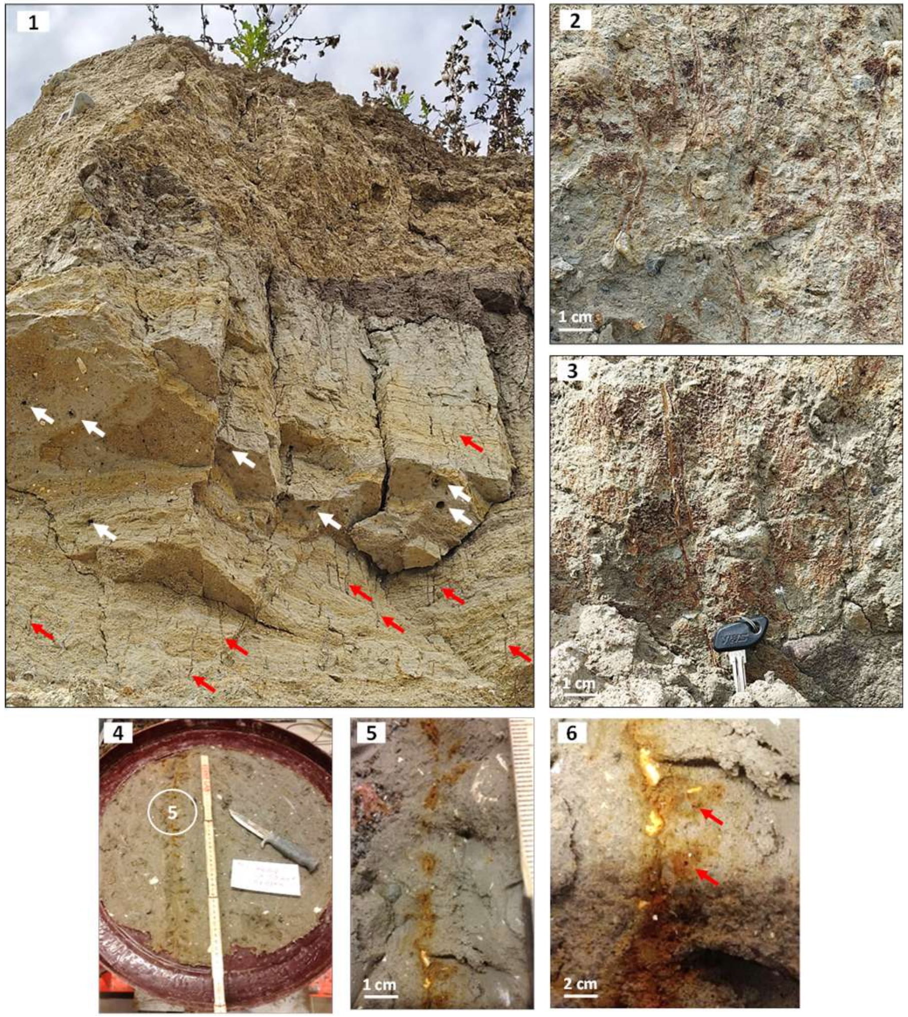
Techniques to distinguish flow in fractures and root macropores inside fractures



Jørgensen et al. (1993, 2019)

Ouf et al. (2025)

Multidisciplinary approach



We used:

- ancient DNA (aDNA),
- radiometric dating,
- X-ray imaging,
- geochemistry,
- glacial geology
- flow and transport experiments
- mathematical modeling

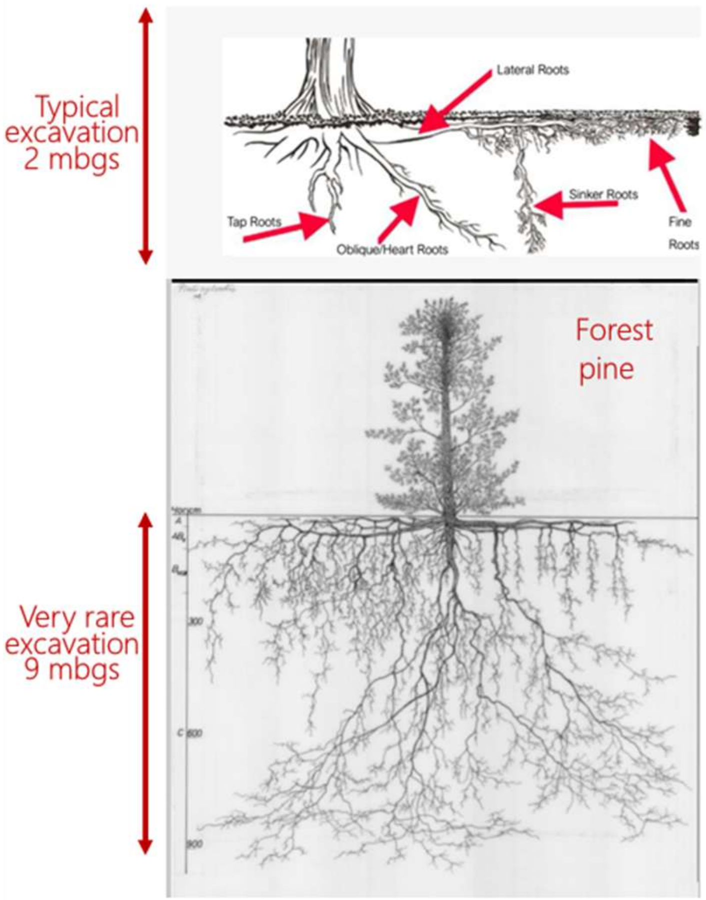
to identify and evaluate the hydrological impact of root macropores introduced by reforestation on groundwater vulnerability

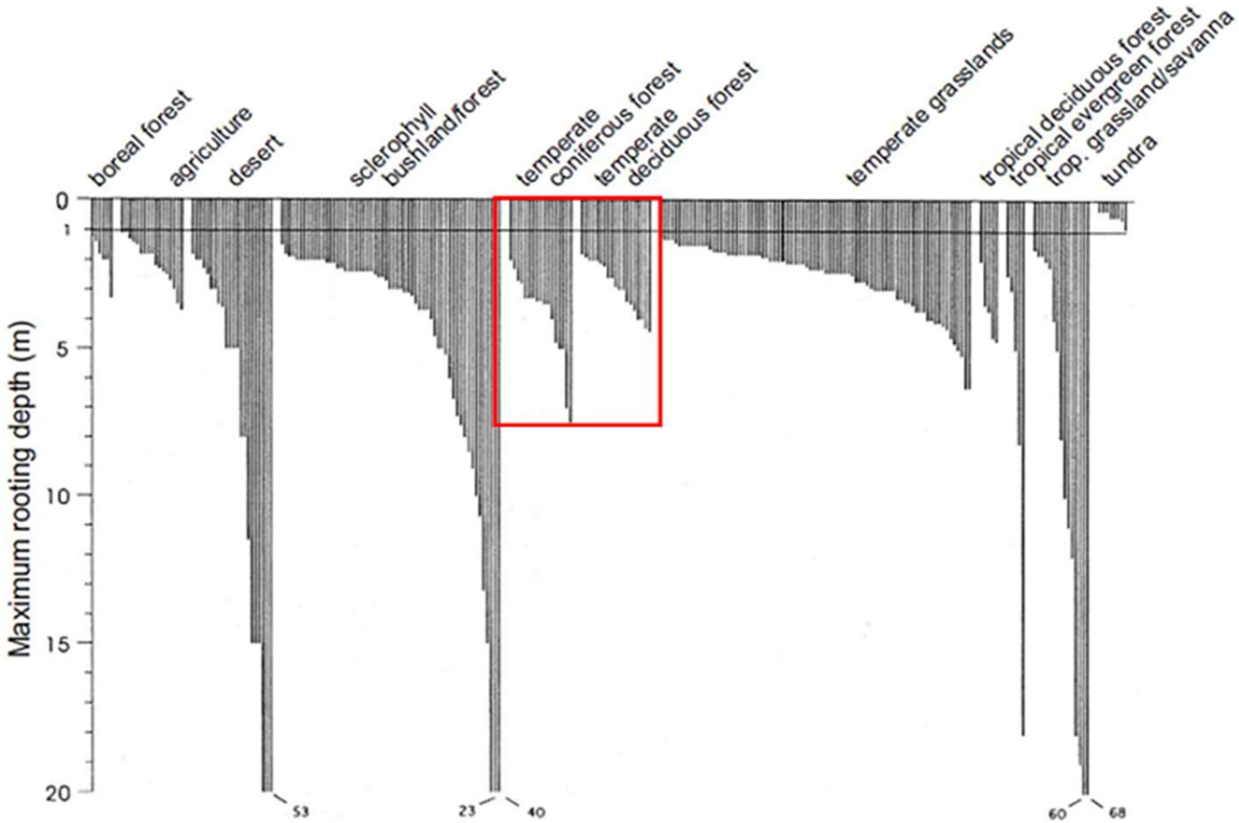
Why address root macropores:

- Tree roots can penetrate much deeper than previously assumed (and much deeper than most agricultural crops)
- abandoned deep root macropores are found widespread in glacial aquitards and similar fine-grained aquitards
- roots from trees and shrubs can increase infiltration in soils
- reforesting is declared global UN strategy for mitigating global warming.

Data are sparse on the maximum depth of tree roots

Statistics biased by shallow excavations and difficult acces

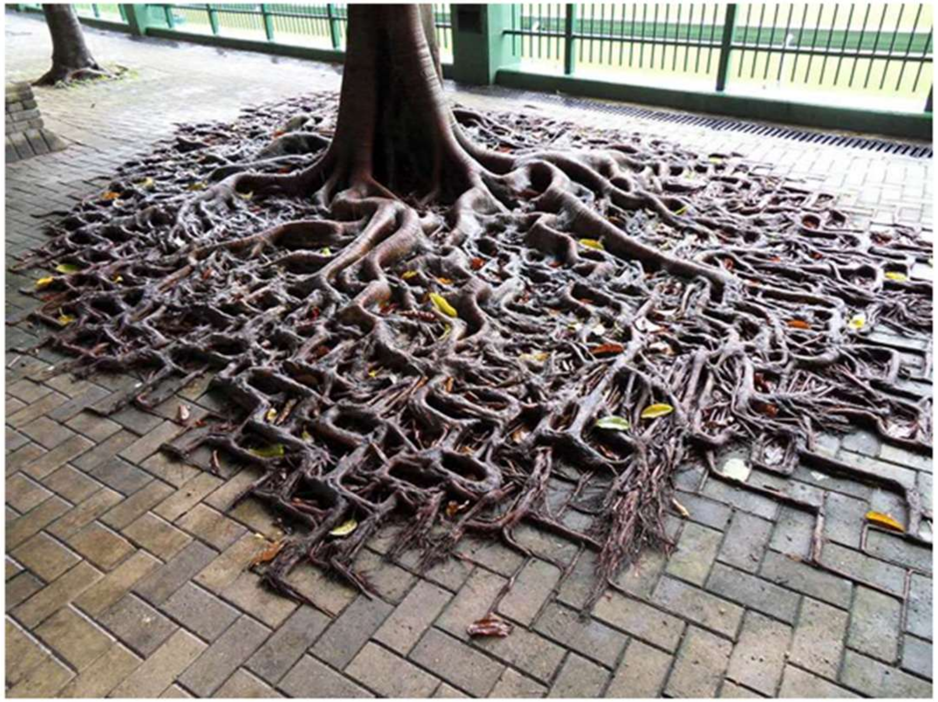


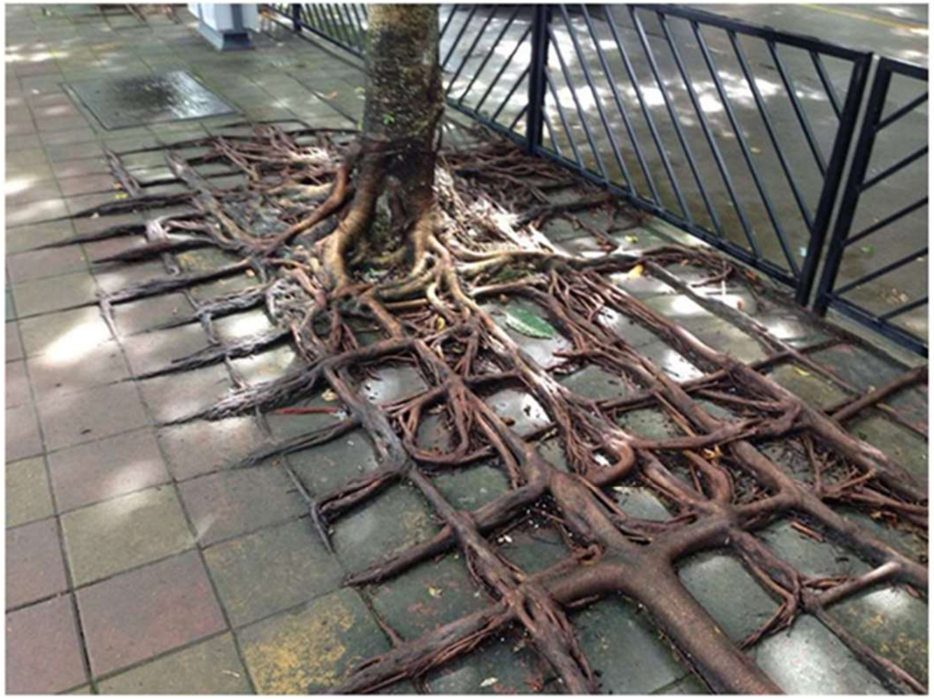


(Canadell et al. 1994)

Tree roots and tree-root behavior

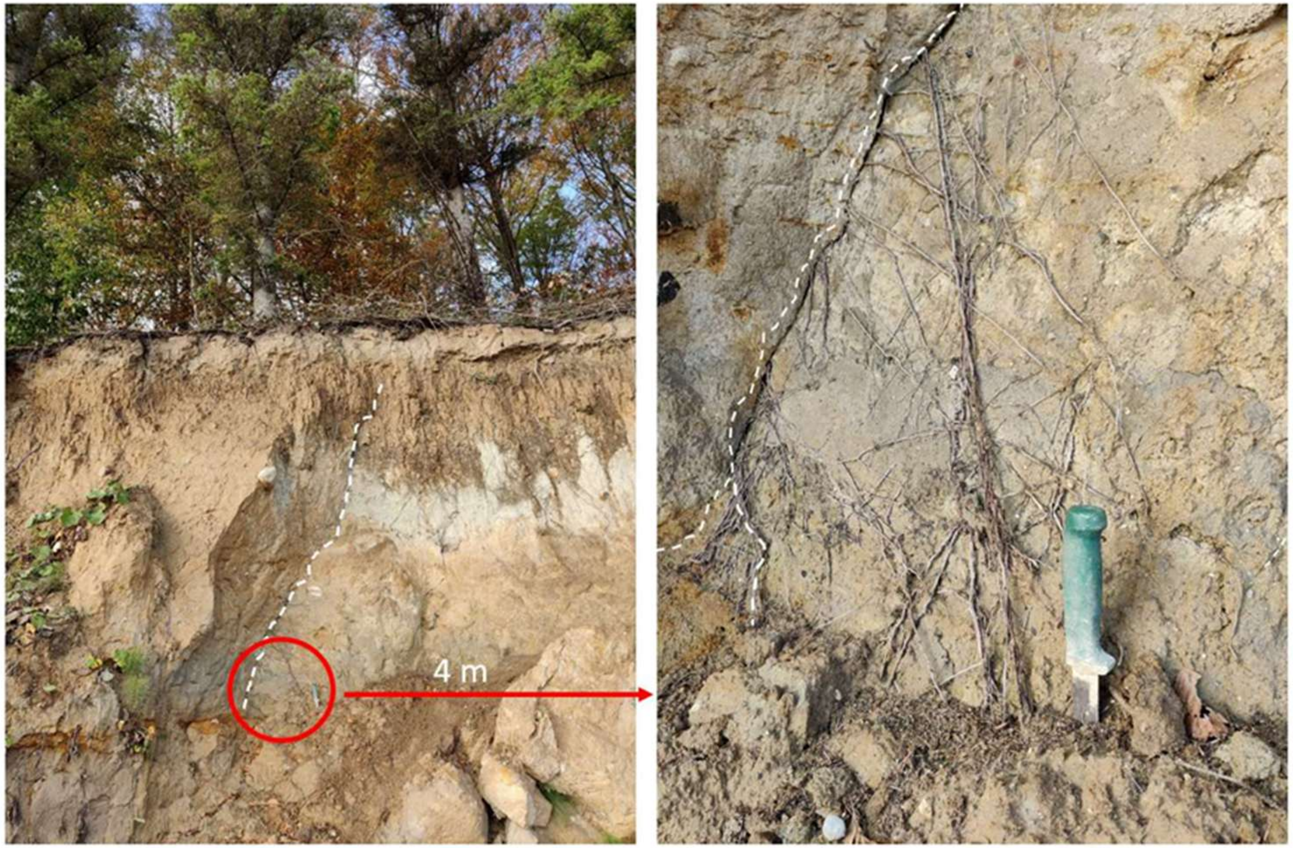
1. Extreme plasticity within and between tree species
2. Can sense gravity, gradients of moisture, and nutrients - and manage growth accordingly
3. Can sense fractures to ease penetration in dense geological materials
4. Can take on different shapes as respons to subsoil conditions and environment.





Tree roots in glacial aquitards

1. Can sense and prefer to grow along fractures and pre-exsisting root-holes
2. Can take different shapes to opimize water-uptake (e.g. root dimorphism)
3. Can grow several meters per year.



”Pull and push” by water tables (hydrotrophism)

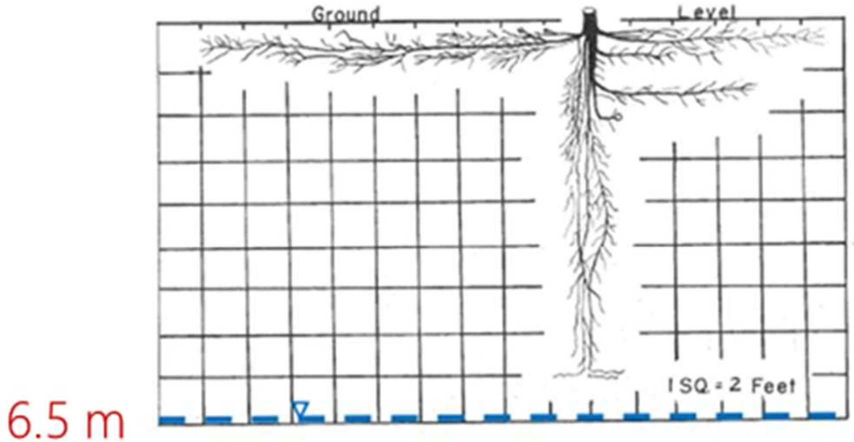


Fig. 37. Siberian elm: 11 years, 29 feet tall, water table 16 feet. Sarpy very fine sandy loam, Dakota County. Roots penetrated directly to the water table at 16 feet; lateral development was limited mostly to the surface 2 feet of soil.

Root systems from trees can grow several meters per year as repose to WTD.

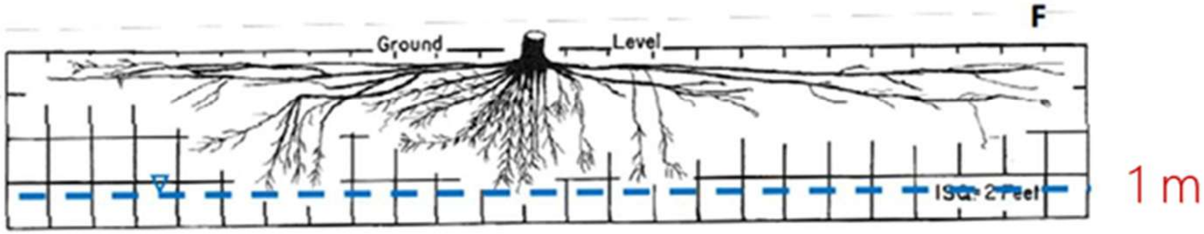


Fig. 36. Siberian elm: 9 years, 30 feet tall, water table 6.5 feet. Cass sandy loam, Merrick County. The high water table typically results in a shallow but very wide-spreading root system. The rate of lateral growth was nearly 3 feet a year.

(Yocum 1937 & Fan et al. 2017)

Water table (WT) depths controls:

- Precipitation
- Topography
- Aquitard leakage into aquifers
- Pumping in aquifers (drinking-water abstraction). Can increase rooting depth as a positive feed-back mechanism.

Recorded maximum depths of tree roots in glacial aquitards are random and difficult to obtain:

- **9 mbgs (Ruland et al. 1991)**
- **10 mbgs (Yocum 1937)**
- **15-20 mbgs (McMahoon 2001)**

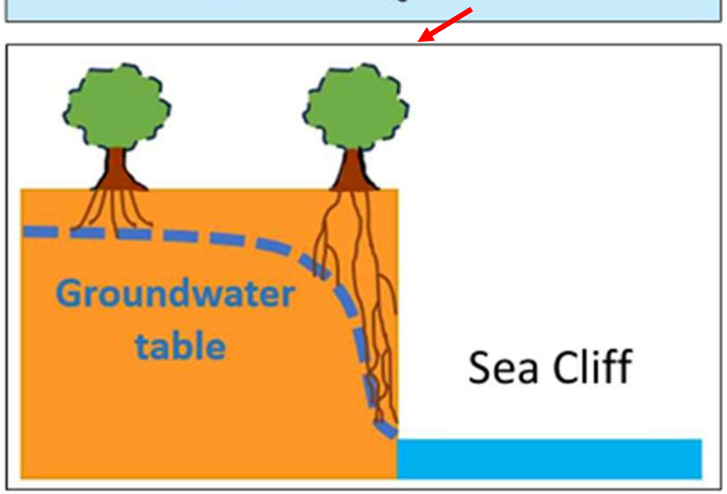
- **Missing roots in widely spaced fractures**
- **Missing roots controlled by random deep WT´s**
- **Destruction of fracture pathways**

Observations of tree roots in landslides

Once in every 100 year storm flod event

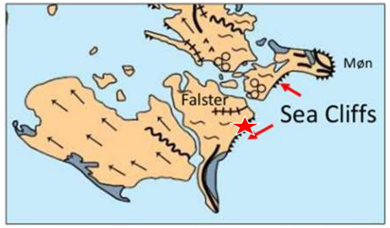
(Dr.dk 20. Oct. 23)

Sea cliffs

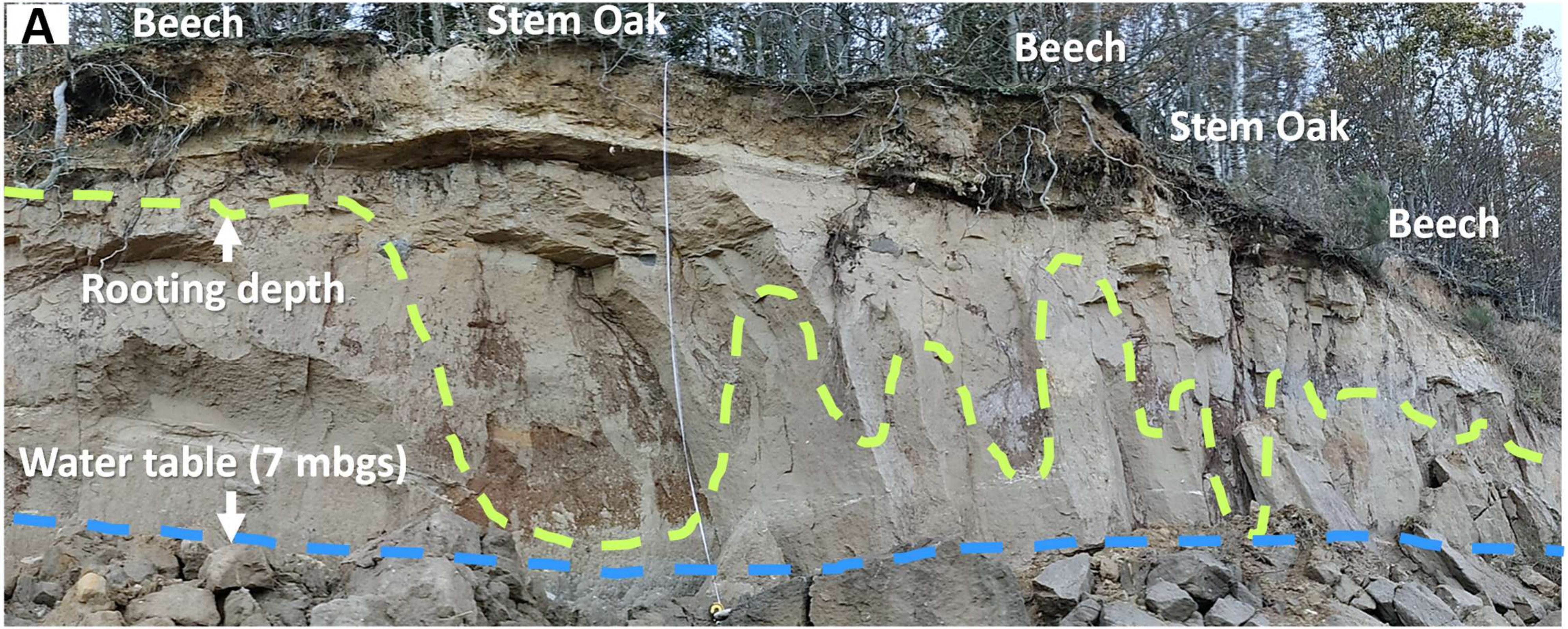


Occurrence and depths of root macropores in fractures

Tree rooting depths controlled by tree species and water table depth



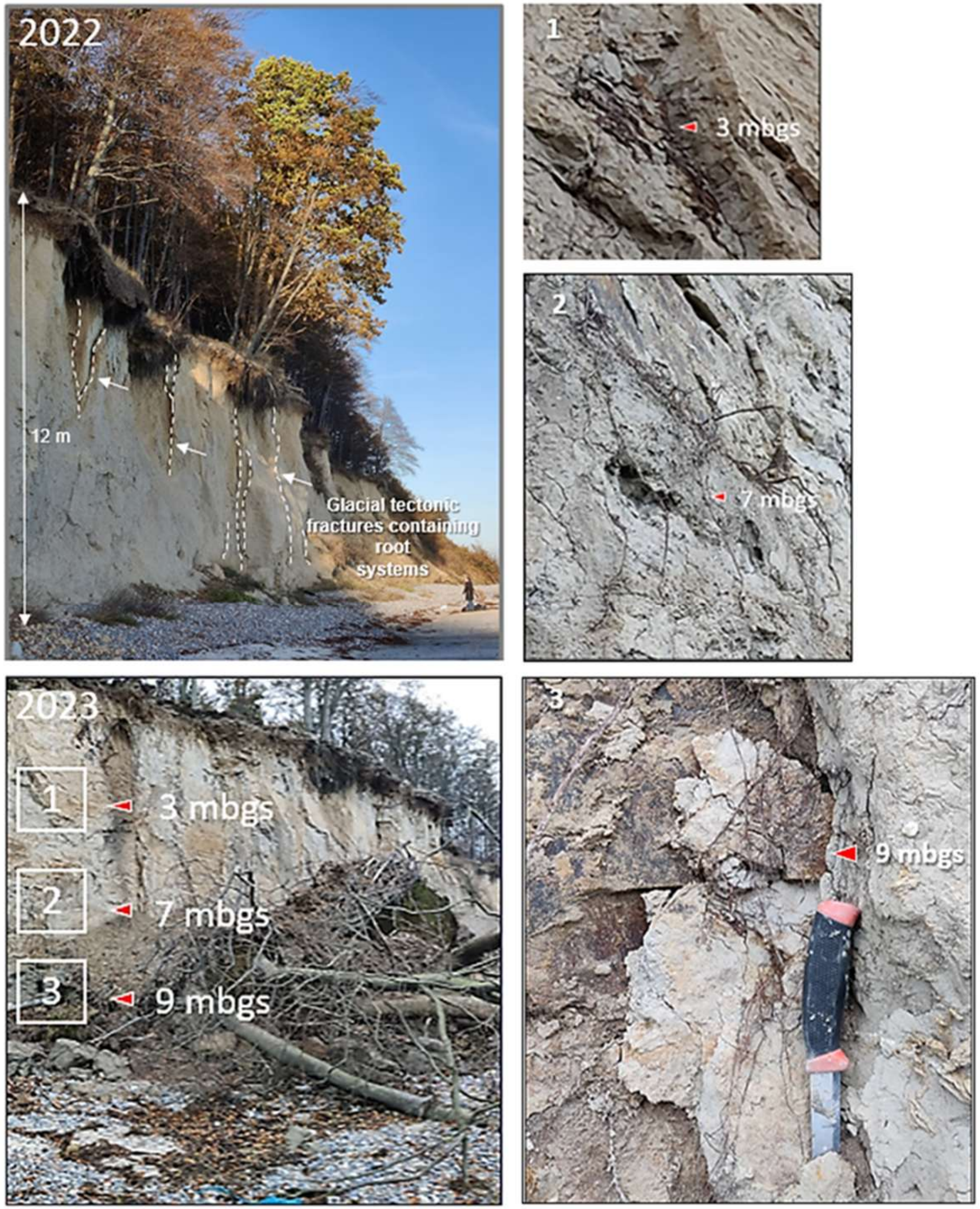
A



Rooting of Stem Oak (10-14 years in age)
(most abundant tree species in Danish reforestation projects)

coarse roots dividing into bundles of fine roots

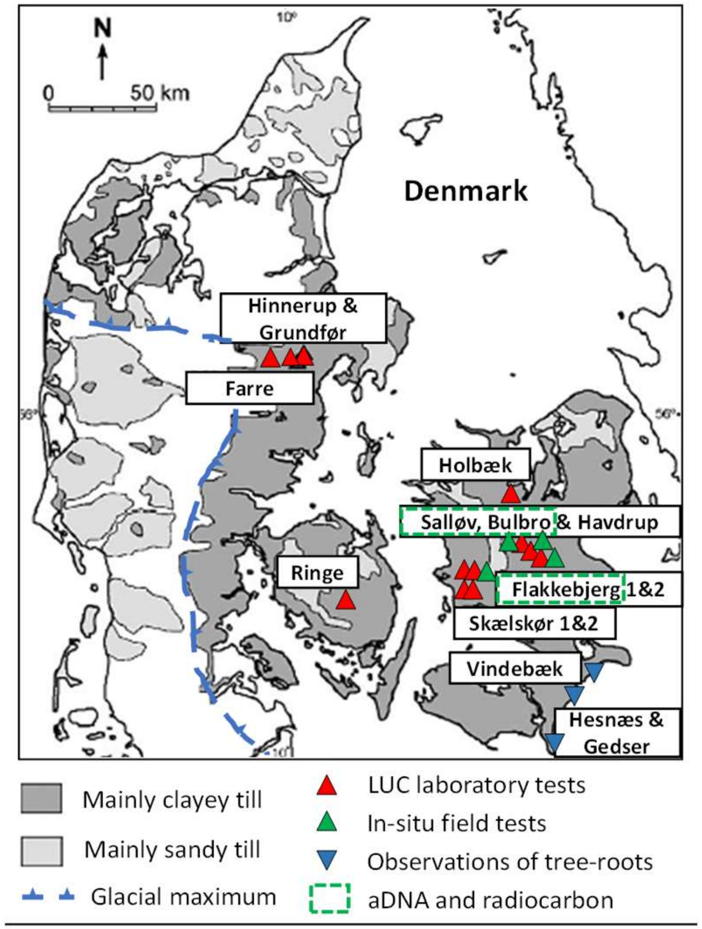
development of root dimorphism to optimized water up-take

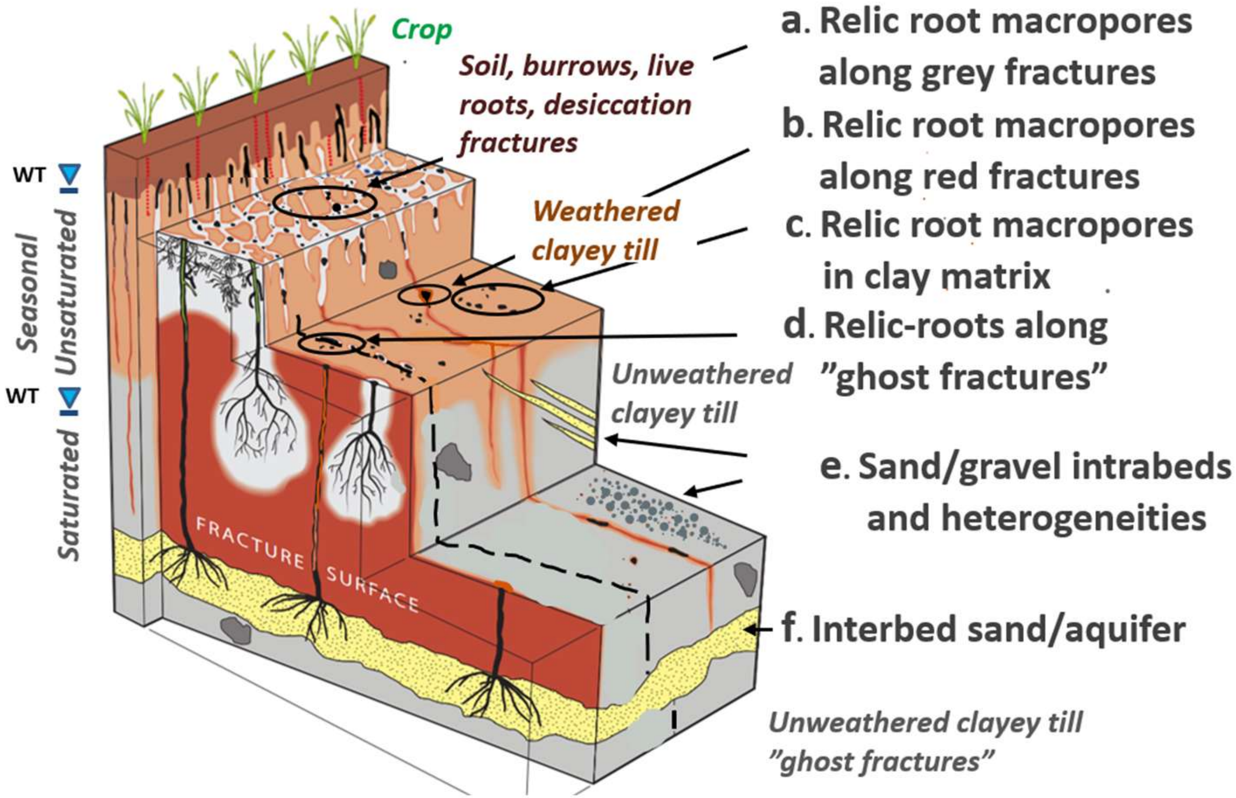


fine roots from stem oak to more than 10 m depth

Occurrence and depths of root macropores in fractures

Deep relic root macropores were found in all study sites



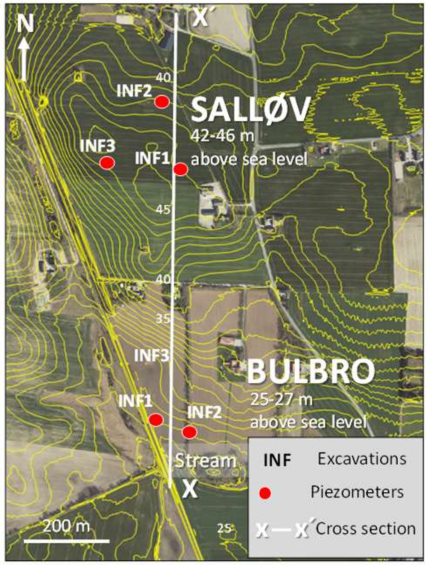


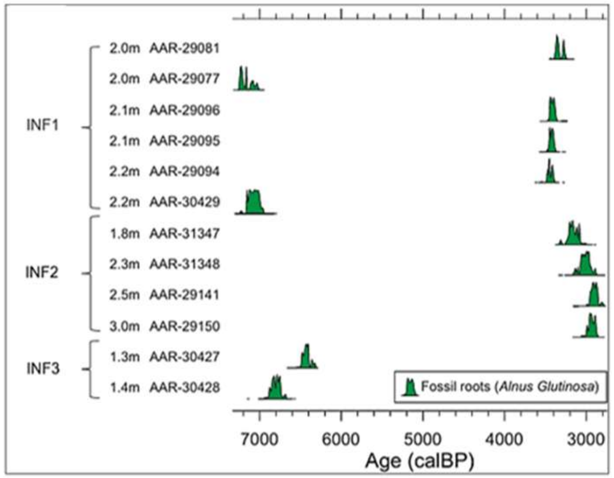
Research questions

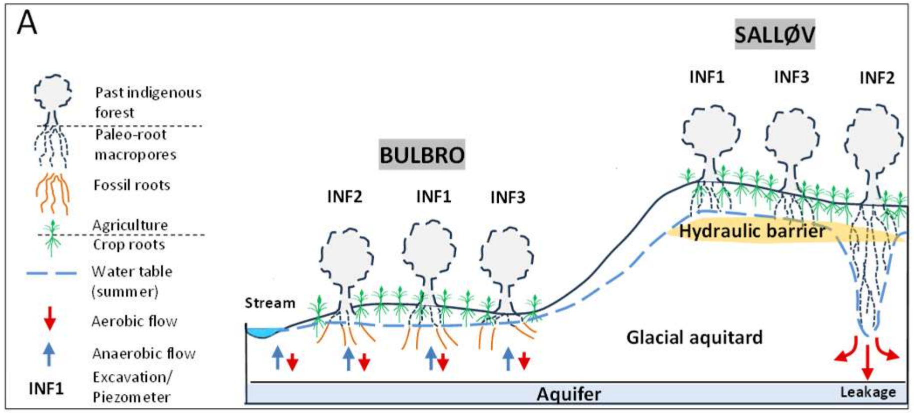
- Origin, extent, and depths of roots and root macropores in fractures
- Role of flow in fractures versus in root macropores along fractures
- Hydraulic role of deep root macropores at geographical scale

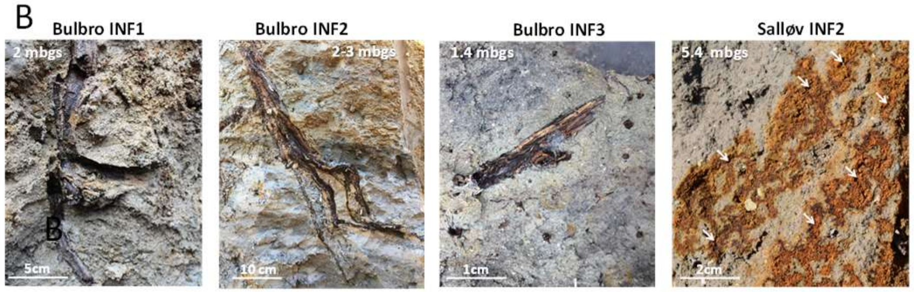
Salløv-Bulbro hill-slope

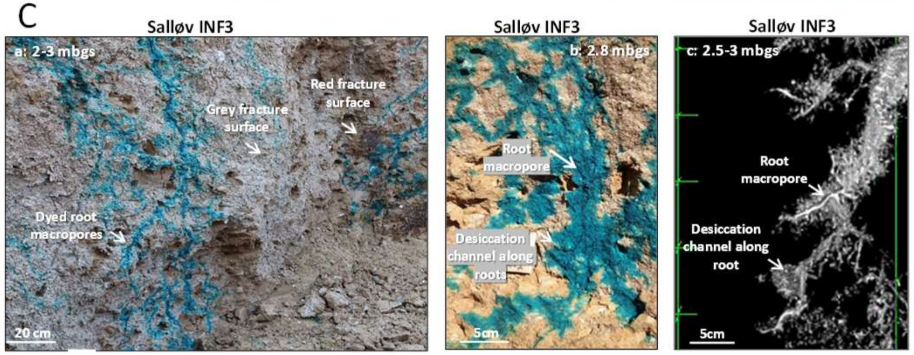
Absence of forest vegetation for more than 1,000 years





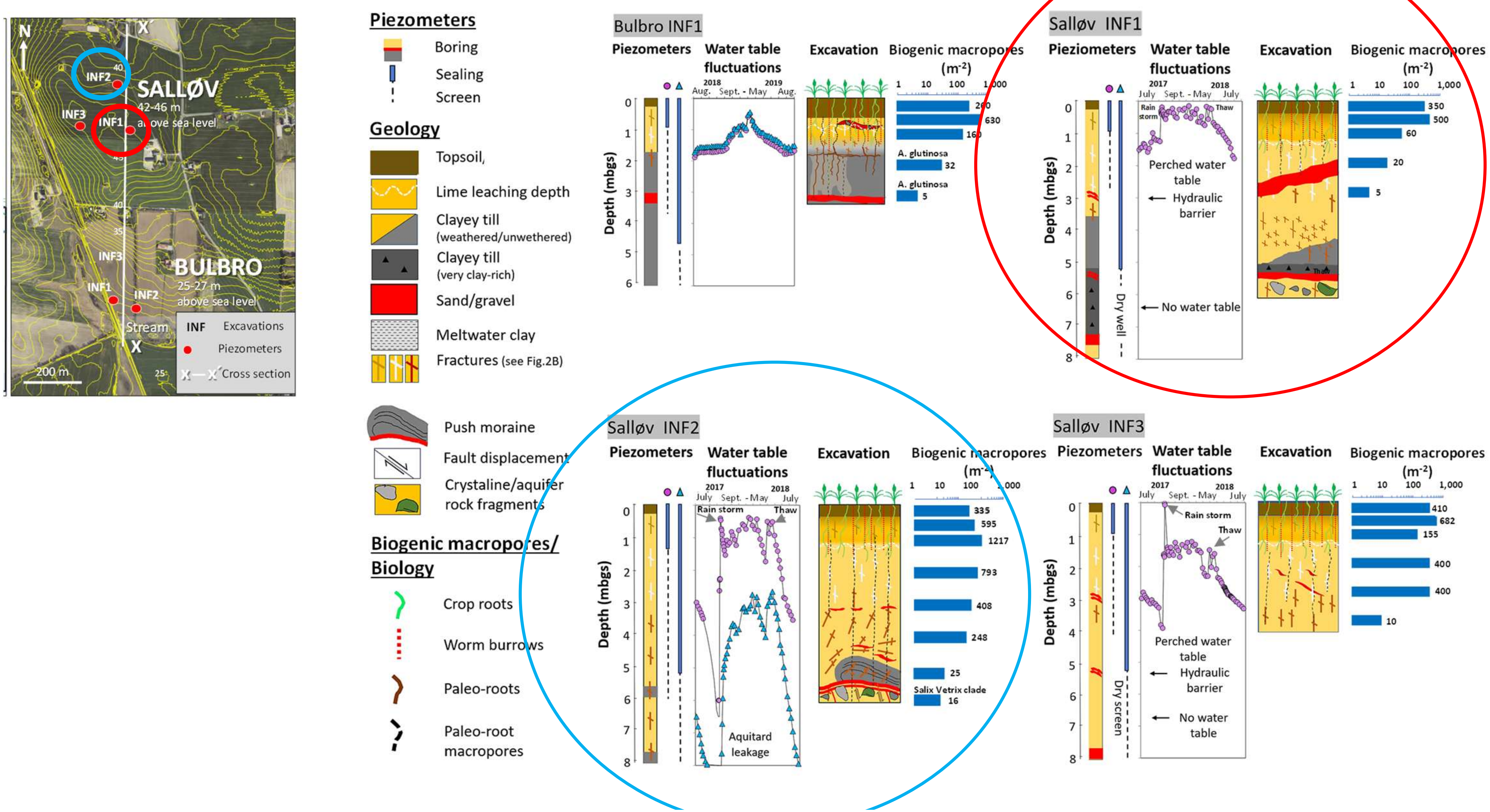






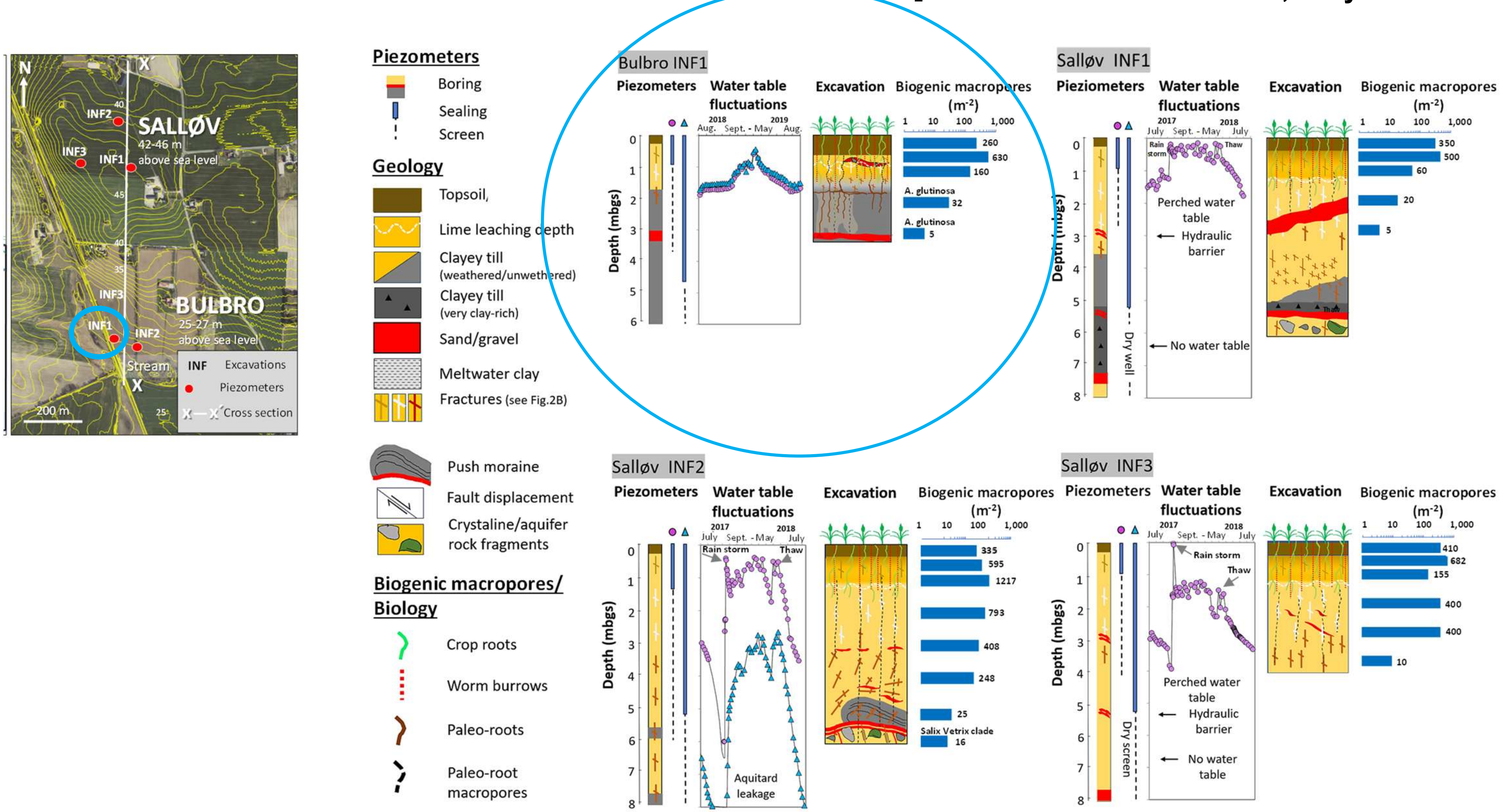
Salløv-Bulbro hill-slope

Absence of forest vegetation for more than 1,000 years



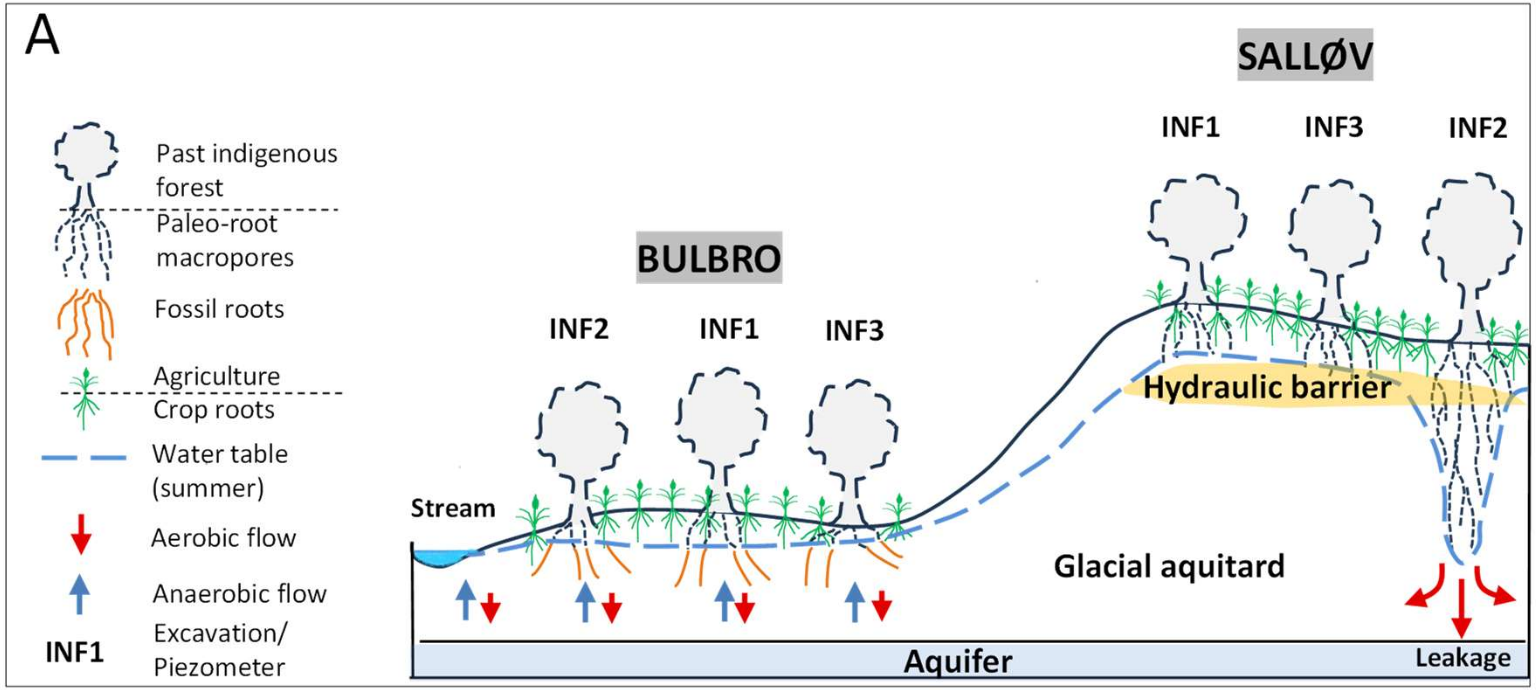
Salløv-Bulbro hill-slope

Absence of forest vegetation for more than 1,000 years



Salløv- Bulbro hill-slope

Absence of forest vegetation for more than 1,000 years



- Dense root macropore system across sites are from indigenous stone-age forests
- Show long-term persistence and widespread occurrence of ancient relic root macropores mixed with modern root macropores

Identification of flow system pattern using dye tracer infiltration

Dye tracer flow in tree root macropores along exposed fracture surfaces

Summary of active flow paths

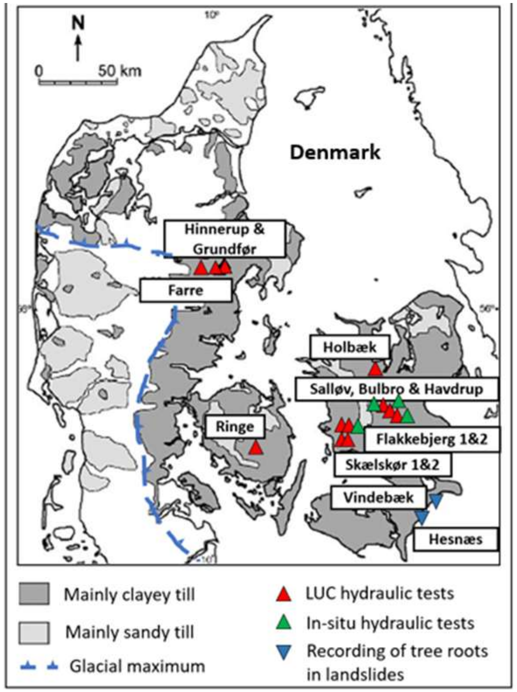
- Dyed relic root macropores provided rapid connected major flow paths in all study sites sometimes throughout the vadose zone and 1 - 2 m into water-saturated zone.

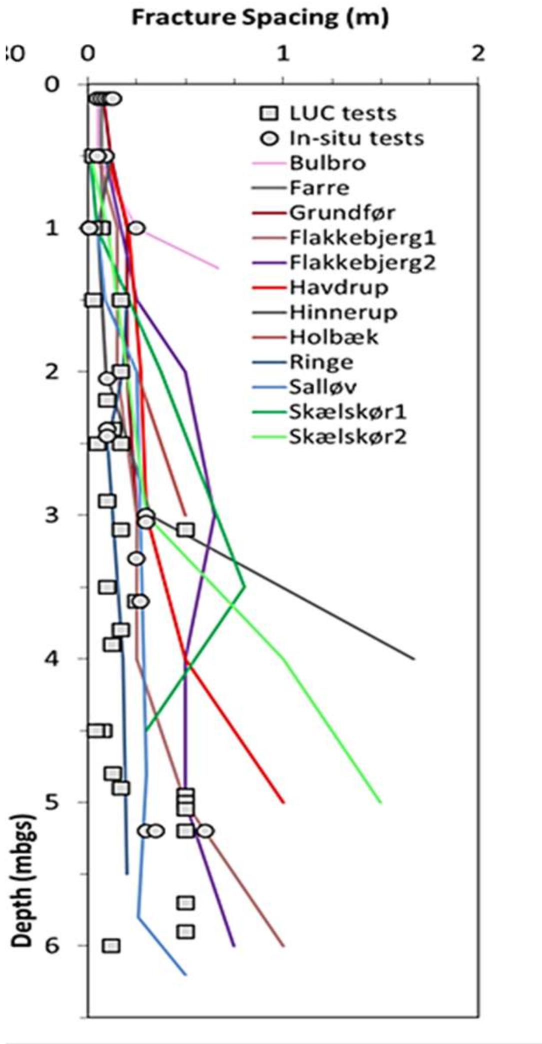
- Dyed root macropores interconnected with water-bearing coarse-grained lithological heterogeneities, some of which provided aquitard leakage into underlying aquifers.

- Fractures per se (i.e., without root macropores inside) were consistently occluded or formed very narrow flow paths from approximately 1 - 2 mbgs at the study sites.

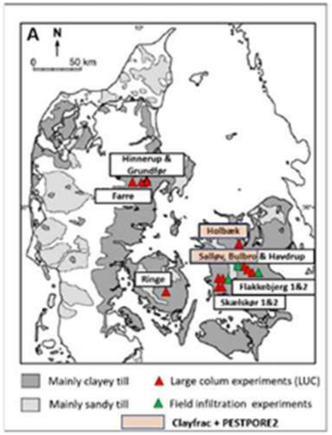
Quantification of flow in fractures and relic root macropores

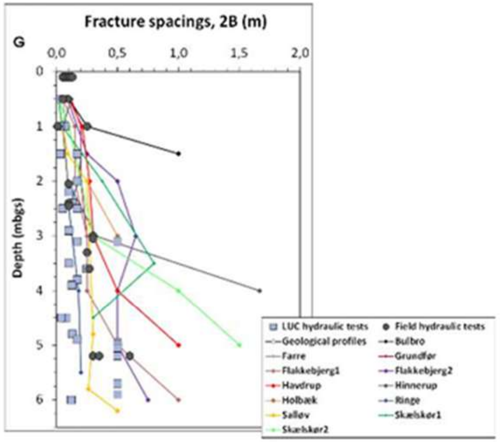
Next-level techniques developed and applied in Denmark





Integrated quantification of flow with contaminant migration behavior



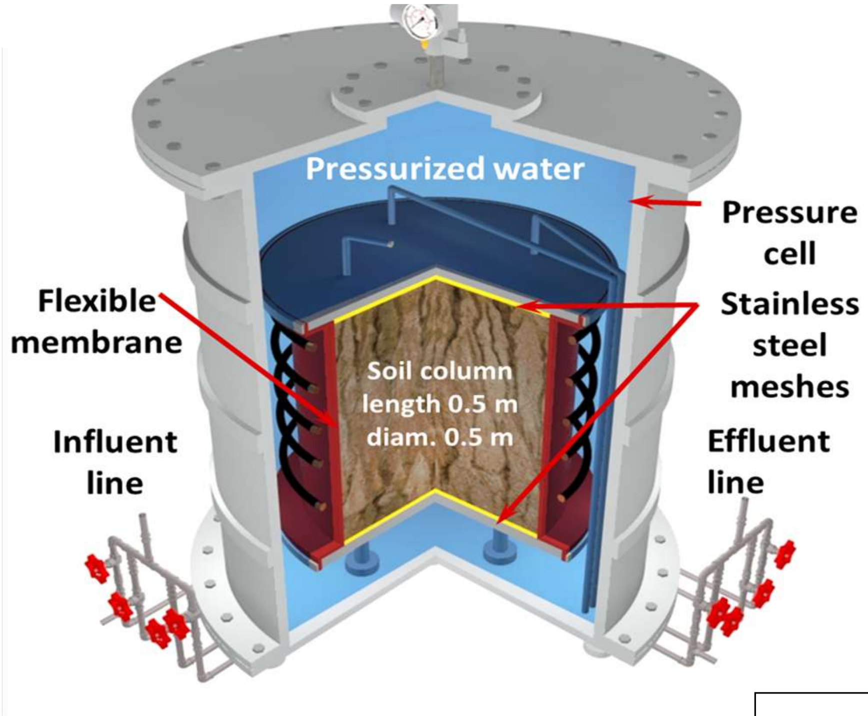


12 study sites across Denmark

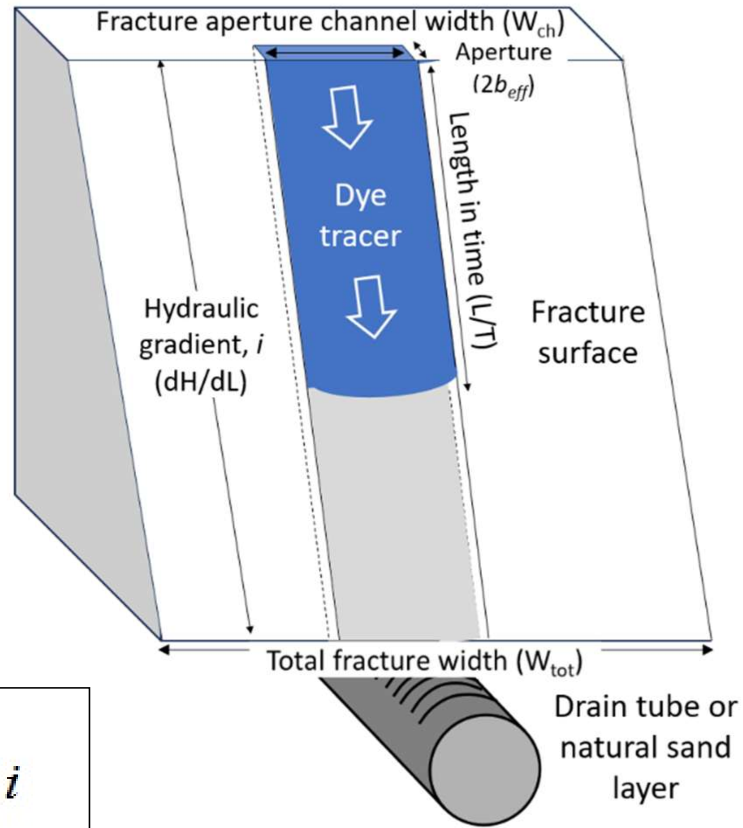
Study site, land use, and source of data A = Arable land, F = Forest/Orchard, O = Other	**Number and type of hydraulic experiments**	**Contaminant and tracer flow-through in experiments**	**Type of glacial till [transition from oxidized to unoxidized till, mbgs]**
Bulbro (A) this study and (6)	3 field infiltration experiments	Brilliant Blue (BB) dye tracer	Basal till above Paleocene clay and limestone aquifer [1.5 - 1.8]
Farre (A) this study and (38–40)	4 LUC experiments	PFAS (PFBA), Mecoprop (MCPP), orthophosphate, BB	Basal till above sandy aquifer [> 4]
Flakkebjerg1 (A) this study and (41)	3 LUC experiments	Ni, Zn, Cd, Cu, Pb, bromide, BB	Basal till over sandy aquifer [4.5]
Flakkebjerg2 (A) this study and (25)	5 Field infiltration experiments	Glyphosate, AMPA, MCPP, MCPA, bentazon, pendimethalin, propyzamide, azoxystrobin, bromide and BB and Uranine	Melt-out sandy till above lodgement clayey till above sand aquifer [3.8]
Grundfør (A) (27, 42)	2 LUC experiments	MCPP, MCPA, Nitrate, bromide and BB	Melt-out till above sandy aquifer (only oxidized) [>3]
Havdrup (A/F) this study and (43, 44)	6 LUC and 6 field infiltration experiments	MCPP, Simazine, prochloraz, metsulfuron-methyl, bromide, BB and Uranine	Basal till above sandy aquifer [2.5-3]
Hinnerup (F) (27, 42, 45)	2 LUC experiments	Nitrate, bromide, BB	Basal till above sandy aquifer [2.8]
Holbæk (A) this study and (44, 46)	3 LUC experiments	Bentazone, MCPA, tebuconazole, bromide, BB	Hummocky till above marginal till [>3]
Ringe (O) (47–49)	2 LUC experiments	Creosotes (DNAPL and solutes), nitrate bromide, BB	Basal till above sandy aquifer [>4]
Salløv (A) this study and (44, 50)	3 LUC and 9 field infiltration experiments	Bentazone, MCPA, tebuconazole, bromide, BB	Basal and terminal till above Paleocene clay and limestone aquifer [3 – 8]
Skælskør1 (F) this study and (51)	4 LUC experiments	DNAPL creosote, MCPP, dichlorprop, MCPA, 2.4D simazine, atrazine, terbuthylazine, bacteriophage, latex microspheres, BB and Uranine	Basal till above sandy aquifer [4.3]
Skælskør2 (O) this study and (52, 53)	3 LUC experiments	MCPP, dichlorprop, MCPA, 2.4D simazine, atrazine, terbuthylazine, BB and Uranine	Postglacial freshwater layers on top of basal till above sandy aquifer [3.5 – 4]

Techniques developed to distinguish flow and transport in fractures and root macropores

LUC lab. Tests (Jørgensen et al. 1993,2019)

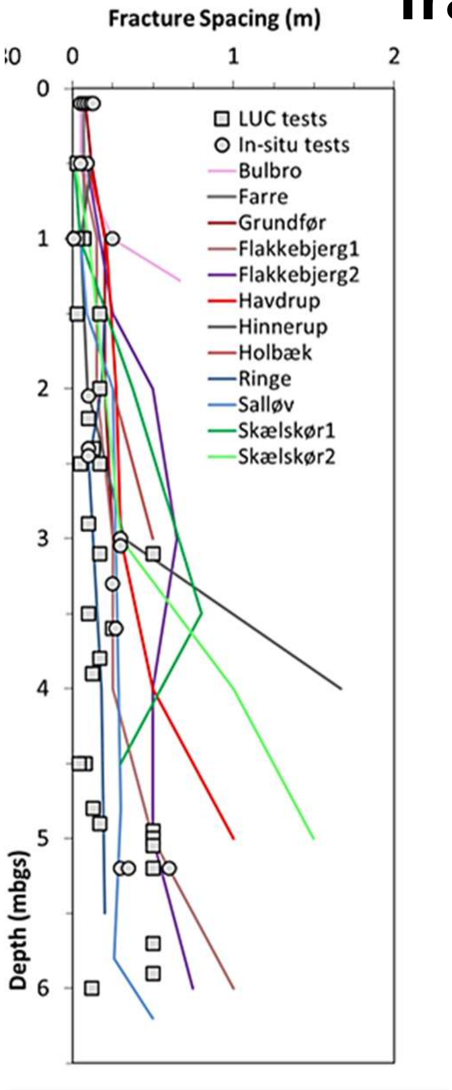


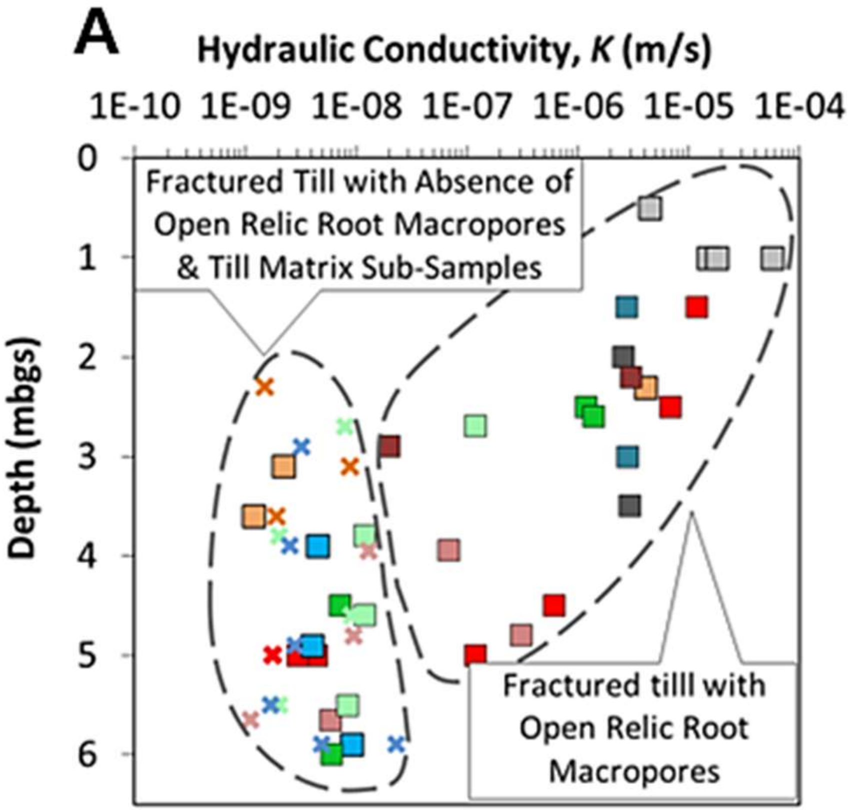
In-situ field tests (Ouf et al. 2025)

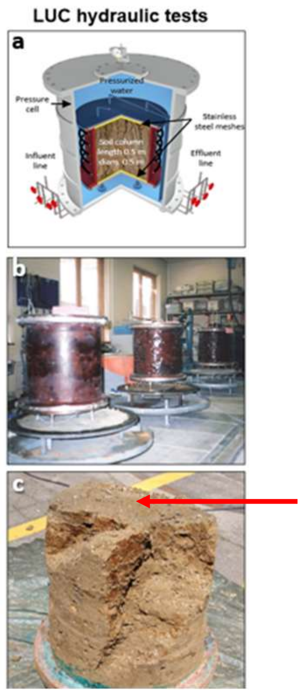


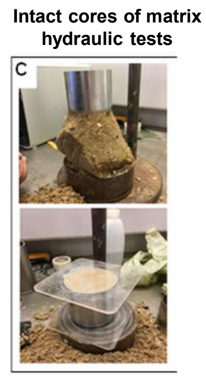
$$q = (2b)^3 \cdot \frac{\rho g}{12\mu} \cdot i$$

1 - 3 orders of magnitude higher *K*-values for fractures with root macropores inside than without

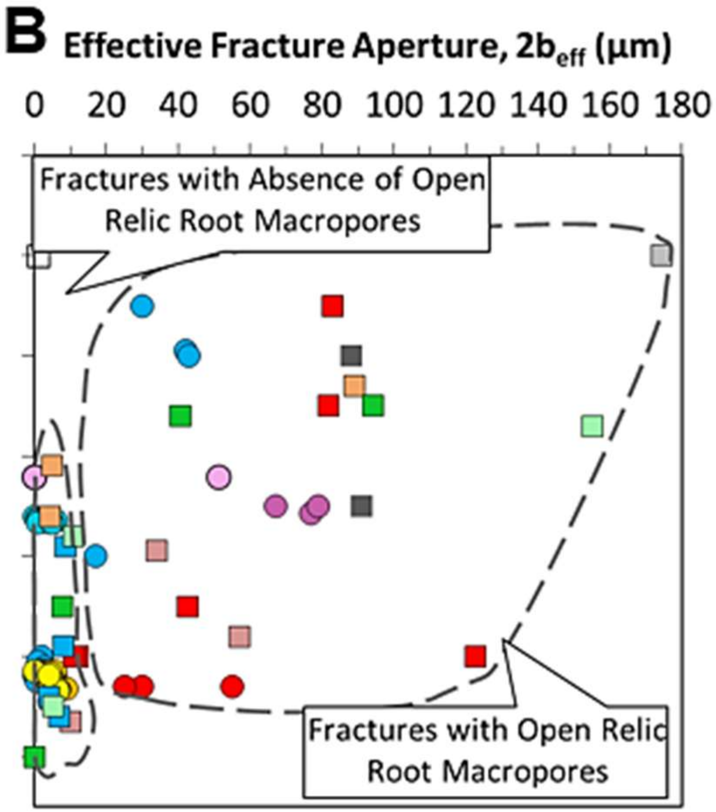








1 - 3 orders of magnitude higher water-fluxes in fractures with open root macropores inside than in fractures without



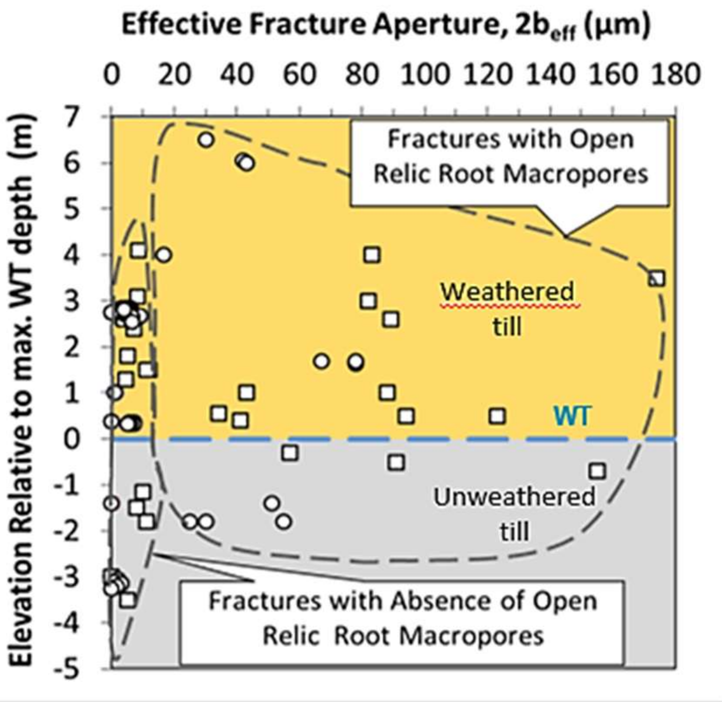
Cubic law for flow (*q*) in fractures

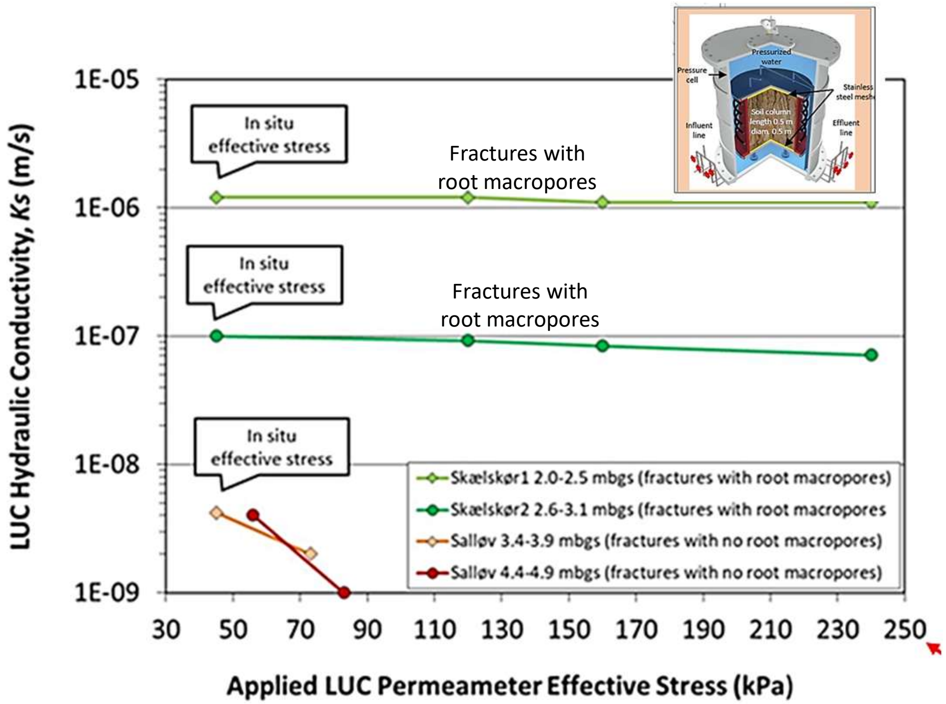
$$q = (2b)^3 \cdot \frac{\rho g}{12\mu} \cdot i$$

Results show:

1. **Consistent small apertures 0-10 µm for fractures**
2. **About 10 times larger apertures for fractures with root macropores**

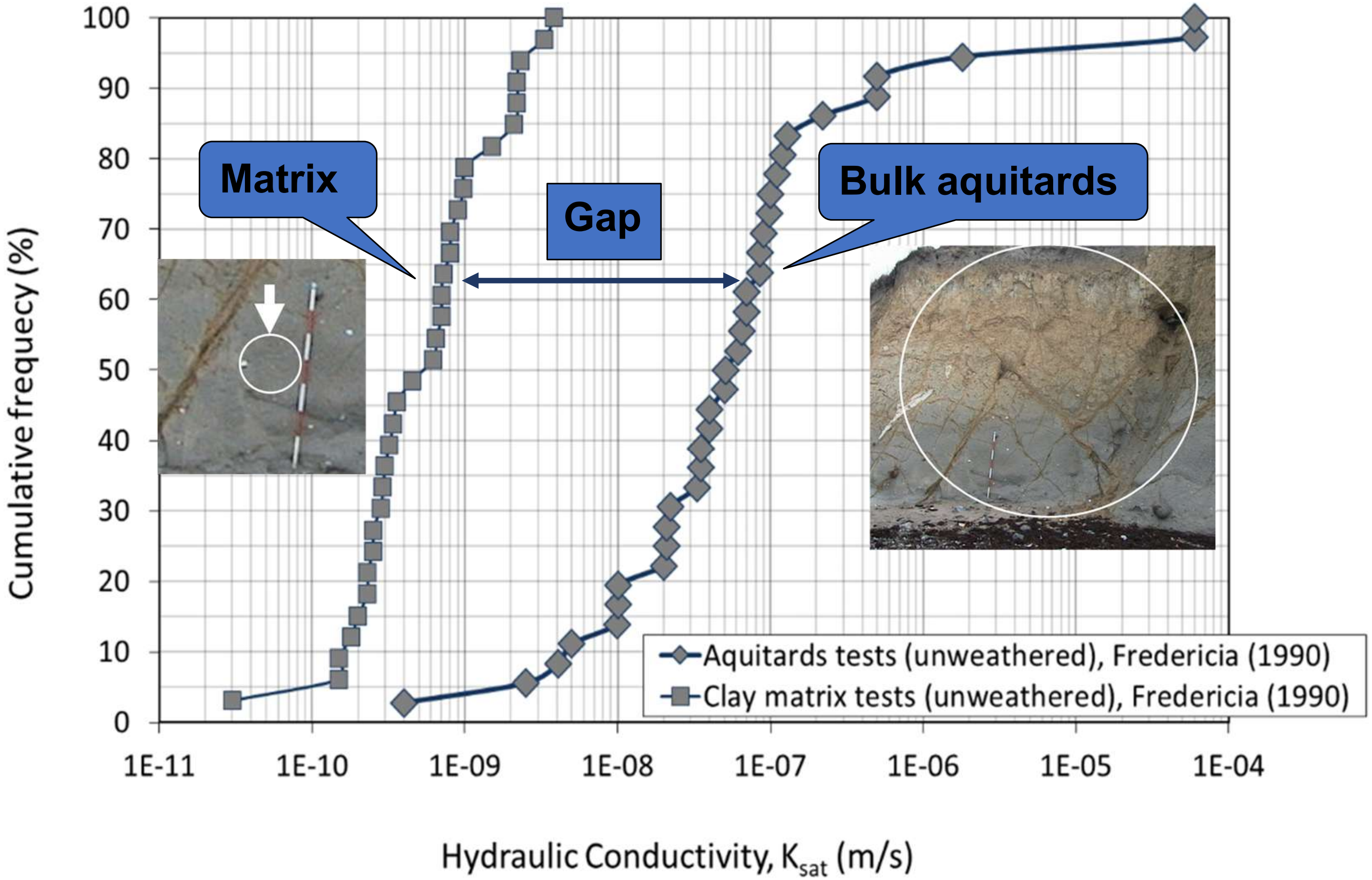
Fractures without root macropores inside occlude below water table depths in aquitards



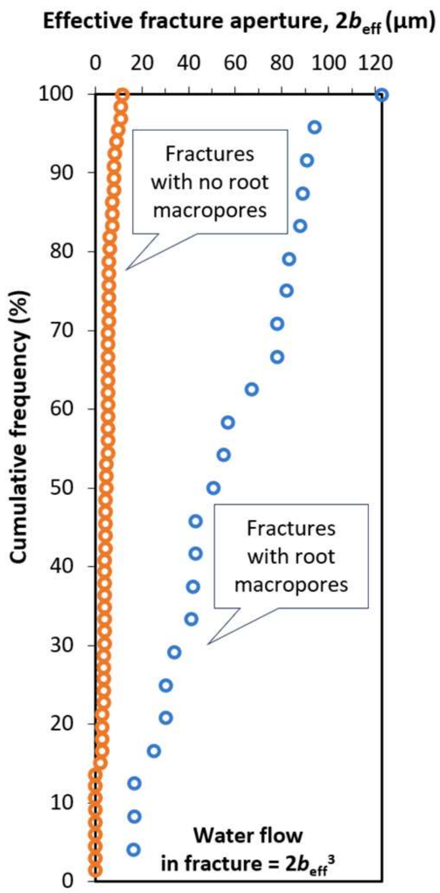


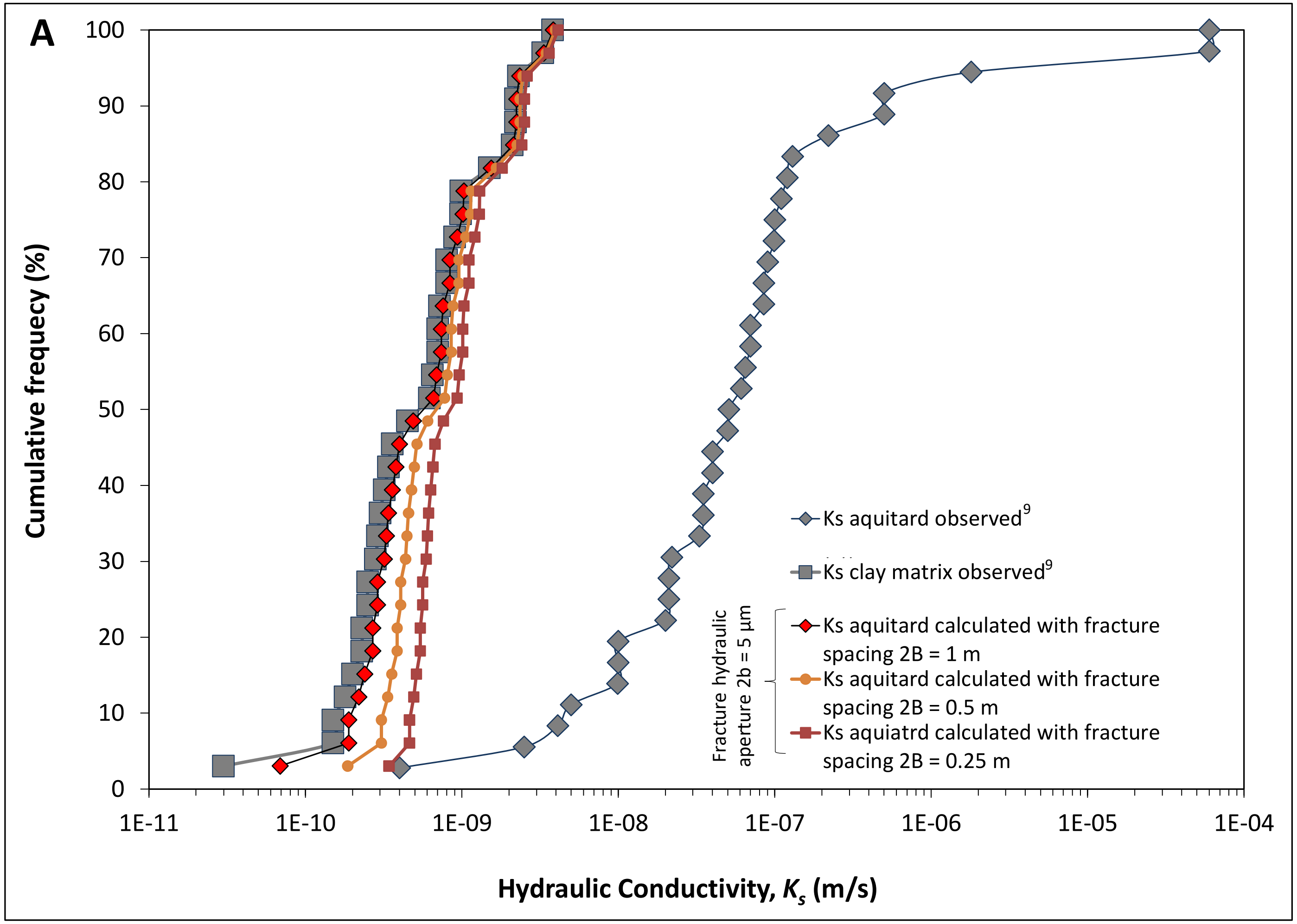
Equivalent with 15-20 m depth

Observations in Denmark attributed to flow in fractures

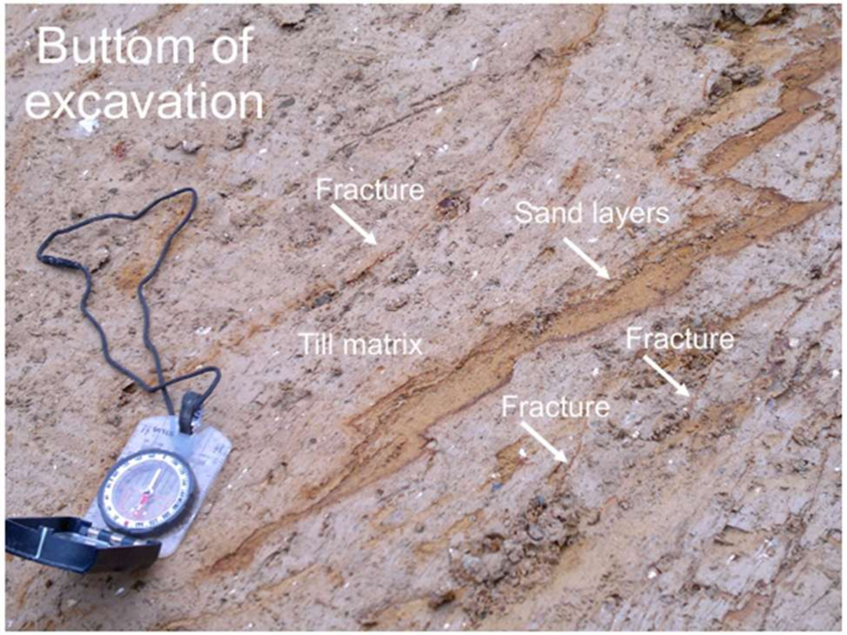


Fractures insufficient to explain high in-situ K values





Lithological heterogeneity in aquitards plays a larger role to flow than previously assumed



Conclusions

Part 1:

1. Depths of roots and relic root macropores span from 1 - 2 mbgs to potentially more than 10 mbgs (deep rooted tree species, such as Stem Oak in locations with deep water tables).

2. Open root macropores from trees are major controls of groundwater flow and contaminant transport in the vadose zone.

3. Flow in fractures with no relic root macropores inside is marginal below 1-2 mbgs in the vadose zone and negligible below aquitard water tables (saturated zone).

4. Coarse-grained lithological heterogeneities (matrix texture, sand lenses, and sand windows) represent major pathways of flow and transport into aquifers beneath current and historical rooting depths in aquitards.

Role of tree-roots for groundwater contamination beneath glacial aquitards

Part 2

DTU Course "Groundwater Quality" (2025)

Peter R. Jørgensen

peterjoergensen.com

Content

Part 2:

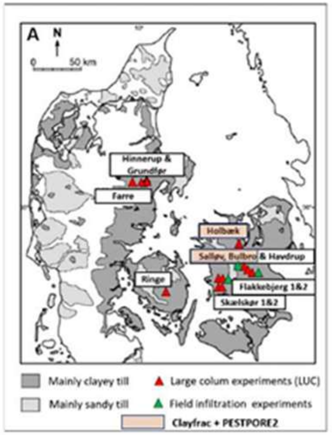
1. Solute contaminant behavior in glacial aquitards

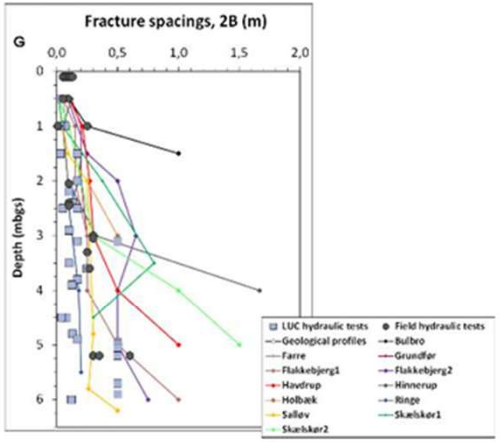
2. Contaminant fluxes in fractures versus root macropores

3. Cause-effect relationship between aquitard glacial geology and aquifer contamination

4. Accelleration of aquifer pollution by reforestation of agricultural land with legacy soil contamination

Integrated contaminant transport in hydraulic tests





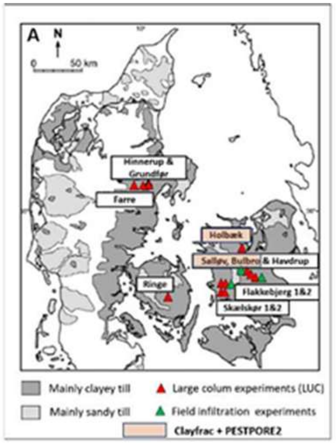
12 study sites across Denmark

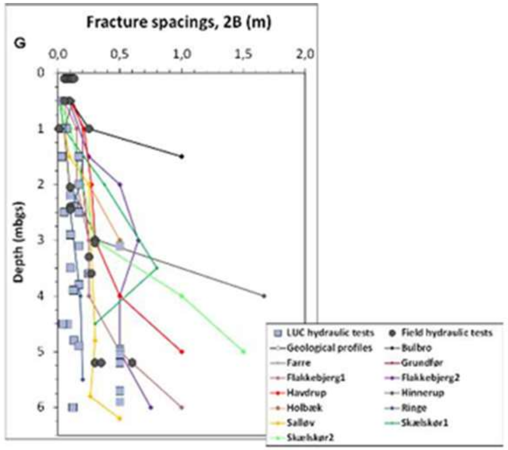
Study site, land use, and source of data A = Arable land, F = Forest/Orchard, O = Other	Number and type of hydraulic experiments	Contaminant and tracer flow-through in experiments	Type of glacial till [transition from oxidized to unoxidized till, mbgs]
Bulbro (A) this study and (6)	3 field infiltration experiments	Brilliant Blue (BB) dye tracer	Basal till above Paleocene clay and limestone aquifer [1.5 - 1.8]
Farre (A) this study and (38–40)	4 LUC experiments	PFAS (PFBA), Mecoprop (MCPP), orthophosphate, BB	Basal till above sandy aquifer [> 4]
Flakkebjerg1 (A) this study and (41)	3 LUC experiments	Ni, Zn, Cd, Cu, Pb, bromide, BB	Basal till over sandy aquifer [4.5]
Flakkebjerg2 (A) this study and (25)	5 Field infiltration experiments	Glyphosate, AMPA, MCPP, MCPA, bentazon, pendimethalin, propyzamide, azoxystrobin, bromide and BB and Uranine	Melt-out sandy till above lodgement clayey till above sand aquifer [3.8]
Grundfør (A) (27, 42)	2 LUC experiments	MCPP, MCPA, Nitrate, bromide and BB	Melt-out till above sandy aquifer (only oxidized) [>3]
Havdrup (A/F) this study and (43, 44)	6 LUC and 6 field infiltration experiments	MCPP, Simazine, prochloraz, metsulfuron-methyl, bromide, BB and Uranine	Basal till above sandy aquifer [2.5-3]
Hinnerup (F) (27, 42, 45)	2 LUC experiments	Nitrate, bromide, BB	Basal till above sandy aquifer [2.8]
Holbæk (A) this study and (44, 46)	3 LUC experiments	Bentazone, MCPA, tebuconazole, bromide, BB	Hummocky till above marginal till [>3]
Ringe (O) (47–49)	2 LUC experiments	Creosotes (DNAPL and solutes), nitrate bromide, BB	Basal till above sandy aquifer [>4]
Salløv (A) this study and (44, 50)	3 LUC and 9 field infiltration experiments	Bentazone, MCPA, tebuconazole, bromide, BB	Basal and terminal till above Paleocene clay and limestone aquifer [3 – 8]
Skælskør1 (F) this study and (51)	4 LUC experiments	DNAPL creosote, MCPP, dichlorprop, MCPA, 2.4D simazine, atrazine, terbuthylazine, bacteriophage, latex microspheres, BB and Uranine	Basal till above sandy aquifer [4.3]
Skælskør2 (O) this study and (52, 53)	3 LUC experiments	MCPP, dichlorprop, MCPA, 2.4D simazine, atrazine, terbuthylazine, BB and Uranine	Postglacial freshwater layers on top of basal till above sandy aquifer [3.5 – 4]

Integrated contaminant transport in hydraulic tests

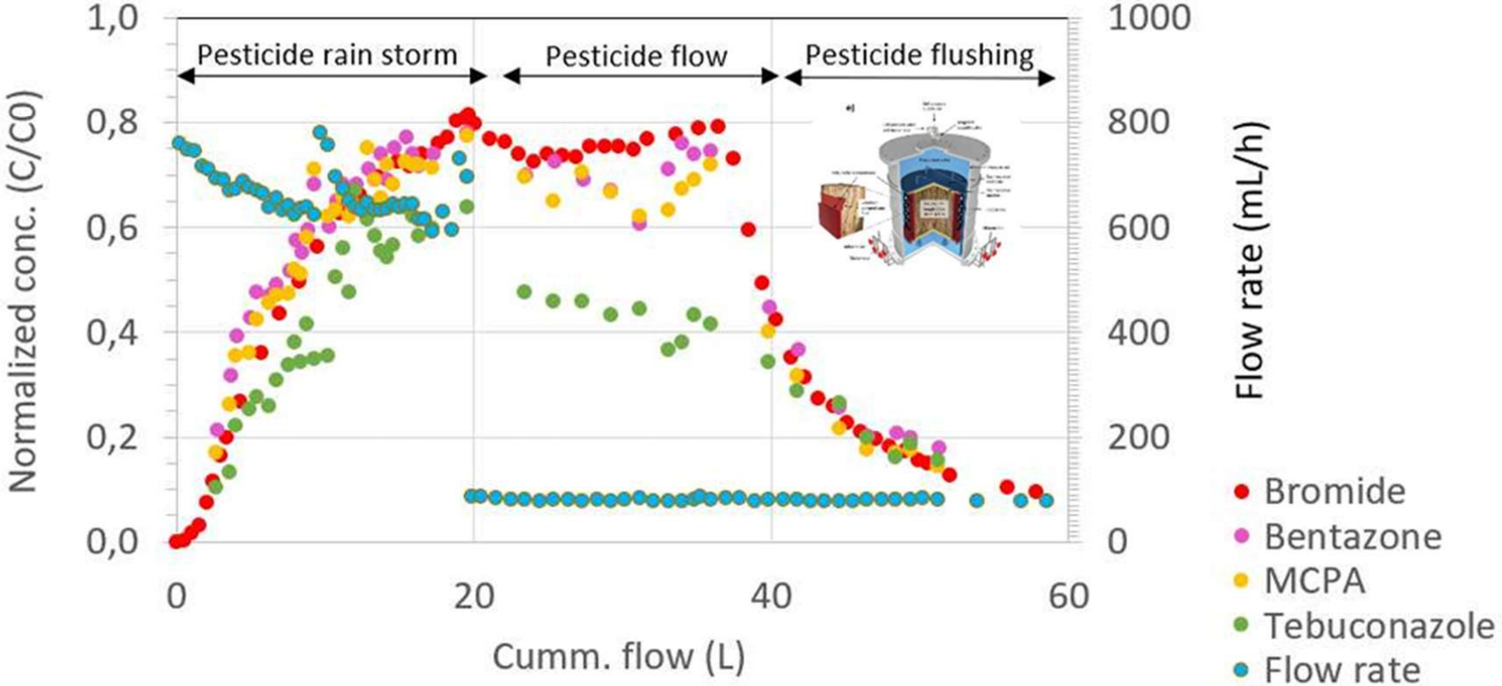
12 study sites across Denmark

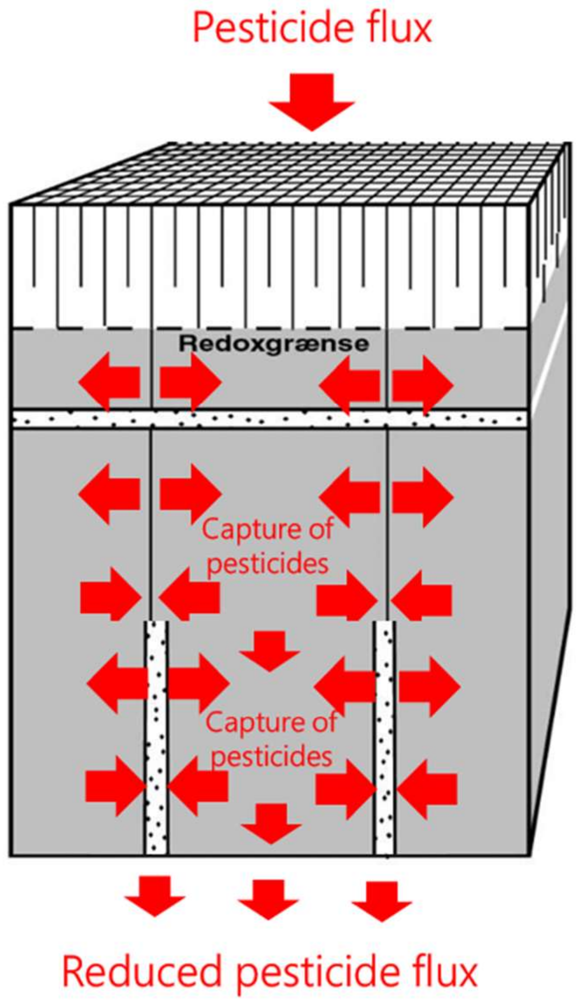
Study site, land use, and source of data A = Arable land, F = Forest/Orchard, O = Other	Number and type of hydraulic experiments	Contaminant and tracer flow-through in experiments	Type of glacial till [transition from oxidized to unoxidized till, mbgs]
Bulbro (A) this study and (6)	3 field infiltration experiments	Brilliant Blue (BB) dye tracer	Basal till above Paleocene clay and limestone aquifer [1.5 - 1.8]
Farre (A) this study and (38–40)	4 LUC experiments	PFAS (PFBA), Mecoprop (MCPP), orthophosphate, BB	Basal till above sandy aquifer [> 4]
Flakkebjerg1 (A) this study and (41)	3 LUC experiments	Ni, Zn, Cd, Cu, Pb, bromide, BB	Basal till over sandy aquifer [4.5]
Flakkebjerg2 (A) this study and (25)	5 Field infiltration experiments	Glyphosate, AMPA, MCPP, MCPA, bentazon, pendimethalin, propyzamide, azoxystrobin, bromide and BB and Uranine	Melt-out sandy till above lodgement clayey till above sand aquifer [3.8]
Grundfør (A) (27, 42)	2 LUC experiments	MCPP, MCPA, Nitrate, bromide and BB	Melt-out till above sandy aquifer (only oxidized) [>3]
Havdrup (A/F) this study and (43, 44)	6 LUC and 6 field infiltration experiments	MCPP, Simazine, prochloraz, metsulfuron-methyl, bromide, BB and Uranine	Basal till above sandy aquifer [2.5-3]
Hinnerup (F) (27, 42, 45)	2 LUC experiments	Nitrate, bromide, BB	Basal till above sandy aquifer [2.8]
Holbæk (A) this study and (44, 46)	3 LUC experiments	Bentazone, MCPA, tebuconazole, bromide, BB	Hummocky till above marginal till [>3]
Ringe (O) (47–49)	2 LUC experiments	Creosotes (DNAPL and solutes), nitrate bromide, BB	Basal till above sandy aquifer [>4]
Salløv (A) this study and (44, 50)	3 LUC and 9 field infiltration experiments	Bentazone, MCPA, tebuconazole, bromide, BB	Basal and terminal till above Paleocene clay and limestone aquifer [3 – 8]
Skælskør1 (F) this study and (51)	4 LUC experiments	DNAPL creosote, MCPP, dichlorprop, MCPA, 2.4D simazine, atrazine, terbuthylazine, bacteriophage, latex microspheres, BB and Uranine	Basal till above sandy aquifer [4.3]
Skælskør2 (O) this study and (52, 53)	3 LUC experiments	MCPP, dichlorprop, MCPA, 2.4D simazine, atrazine, terbuthylazine, BB and Uranine	Postglacial freshwater layers on top of basal till above sandy aquifer [3.5 – 4]





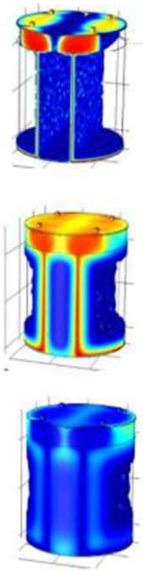
Integrated quantification of flow and contaminant behavior in LUC

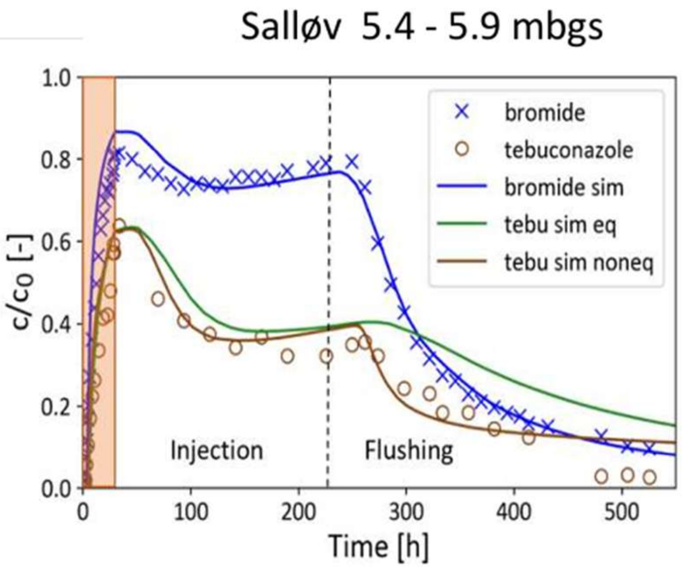




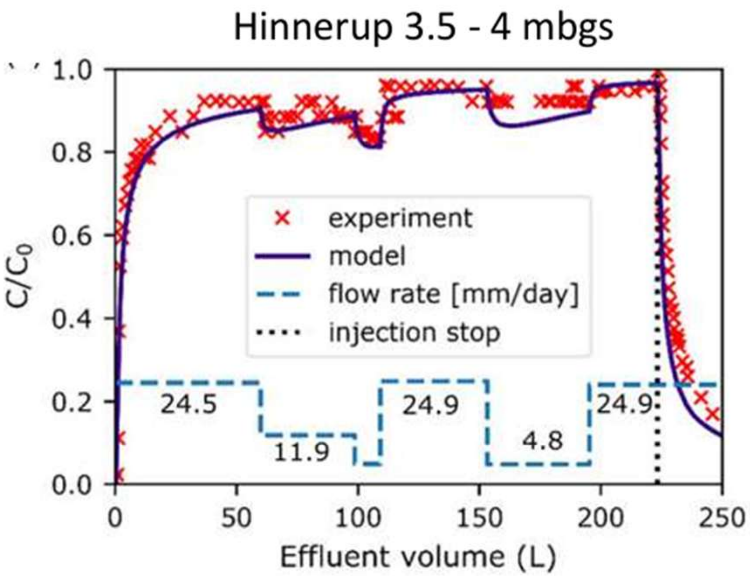
Integrated model studies of LUC experiments

- Dynamic assessment of model-transport parameters
- Testing of model descriptions under time variable flow (i.e. different groundwater recharge rates)

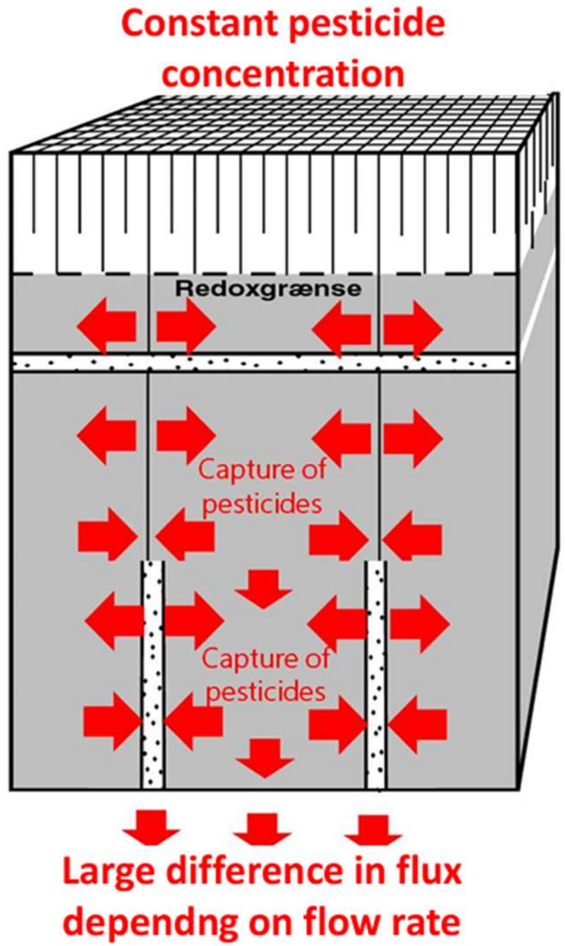




(Mosthaf et al. 2021 Groundwater)

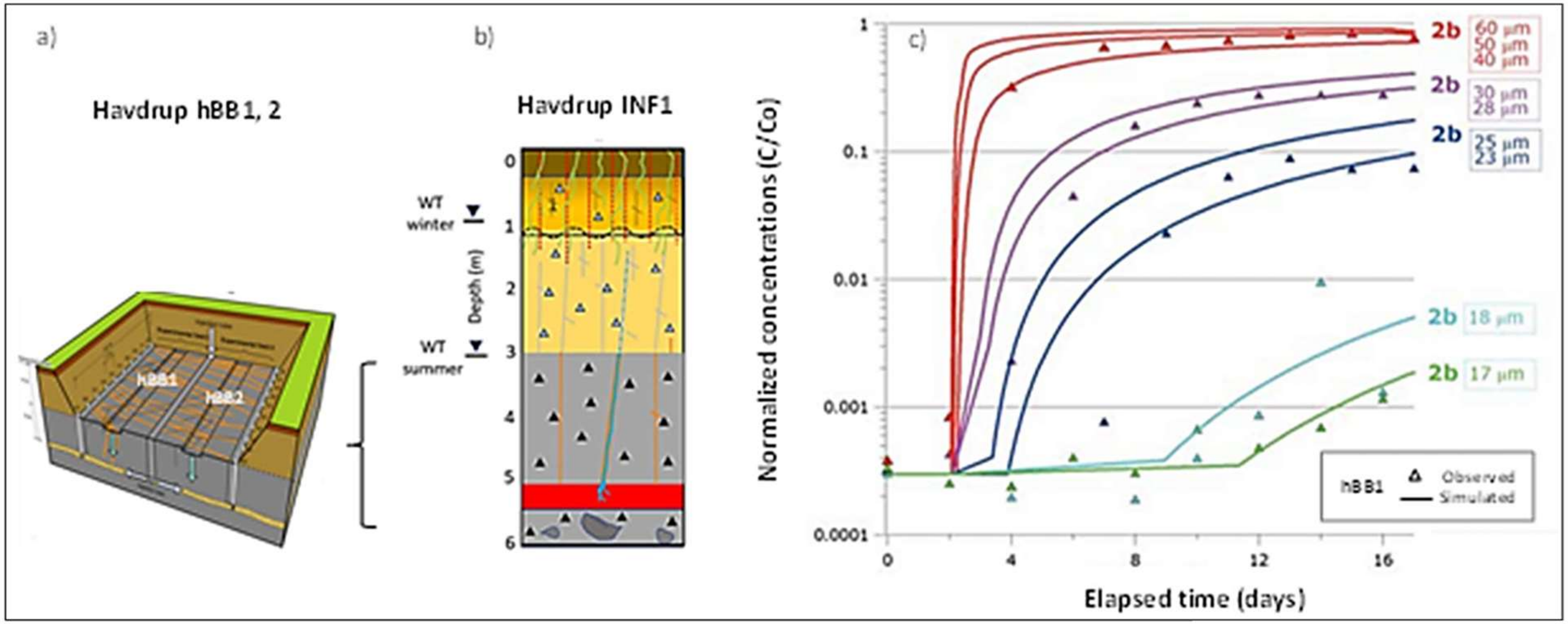


(Jørgensen et al. 2019 Groundwater)



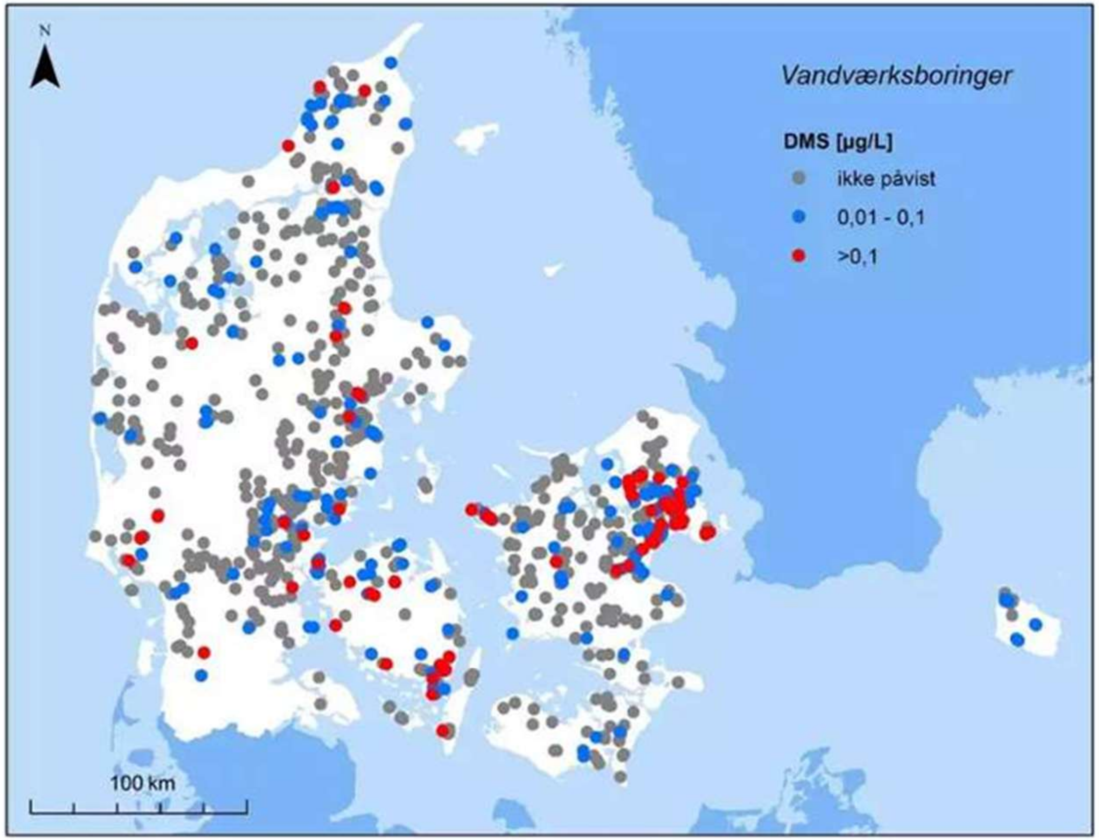
Pesticide field experiments

Testing of consistency between LUC and field model parameters and pesticide migration



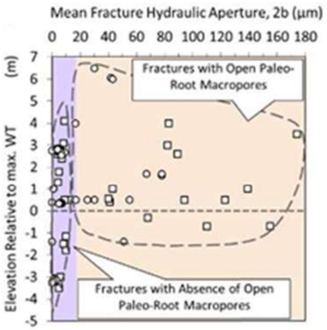
(Jørgensen et al. 2002 WRR)

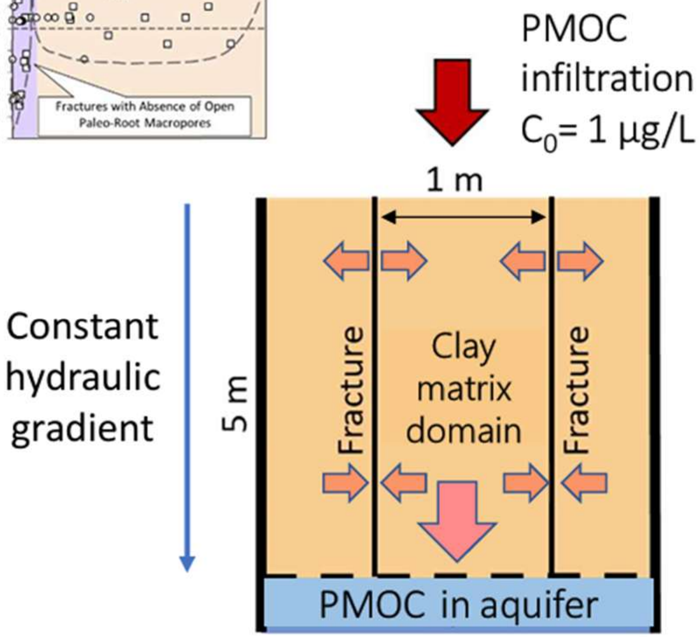
Modeling of DMS (PMOC) into aquifers

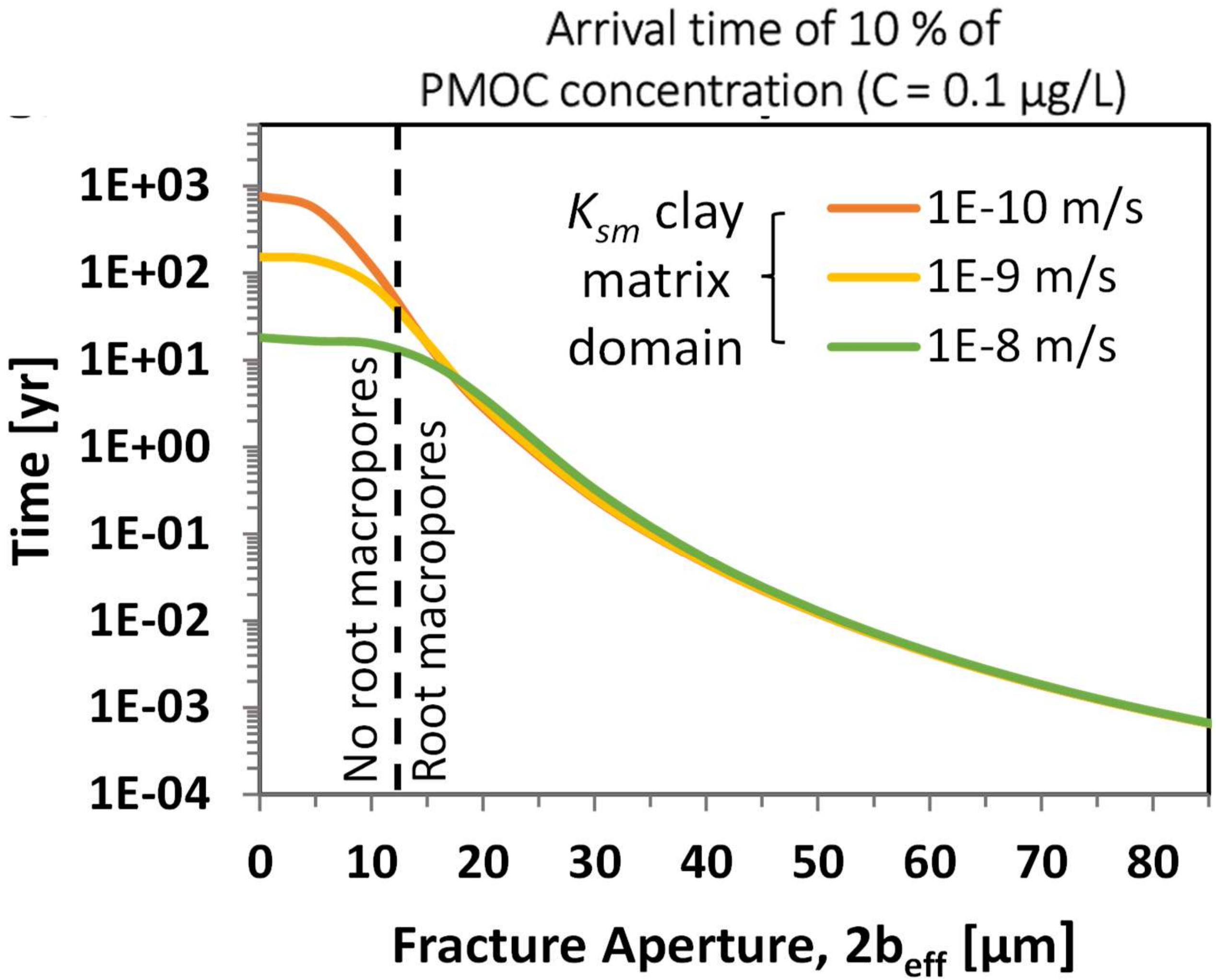


Biocide metabolite DMS from
agriculture and urban areas
(paint and building materials)
found in more than
30% of wells

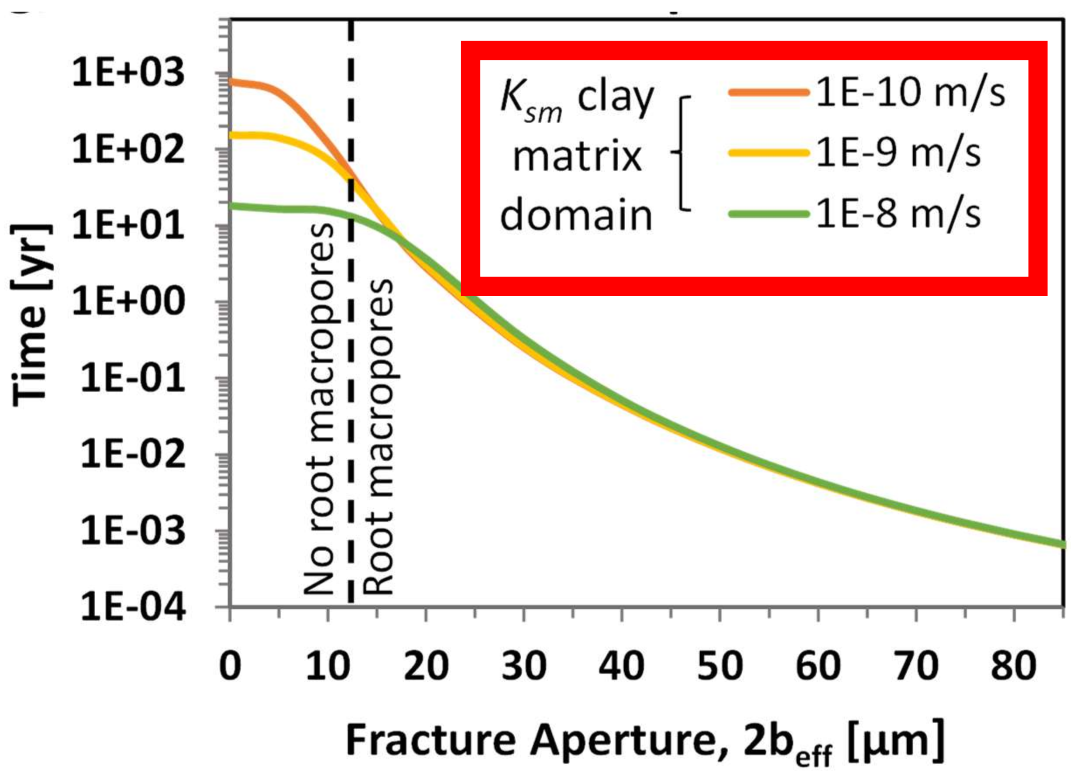
Assement of aquifer vulnerability to ”Persistent Mobile Organic Contaminants” (PMOC) ex. DMS, PFAS (PFBA), DPC, BAM

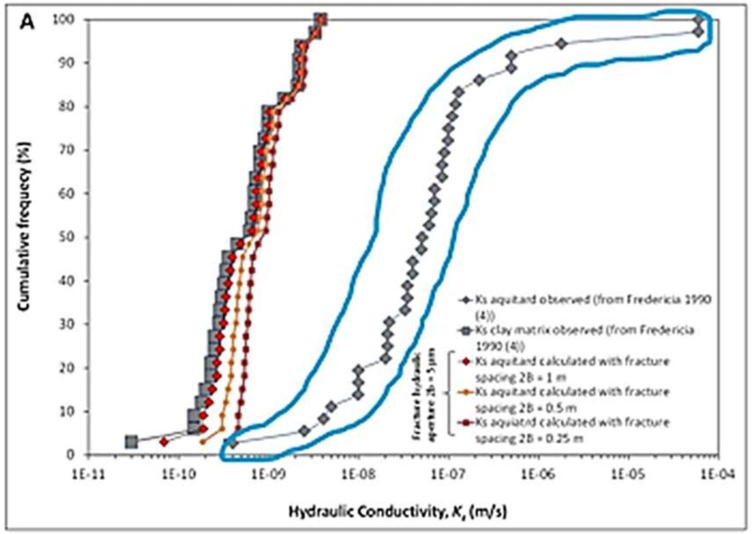




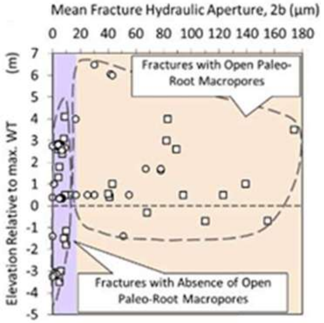


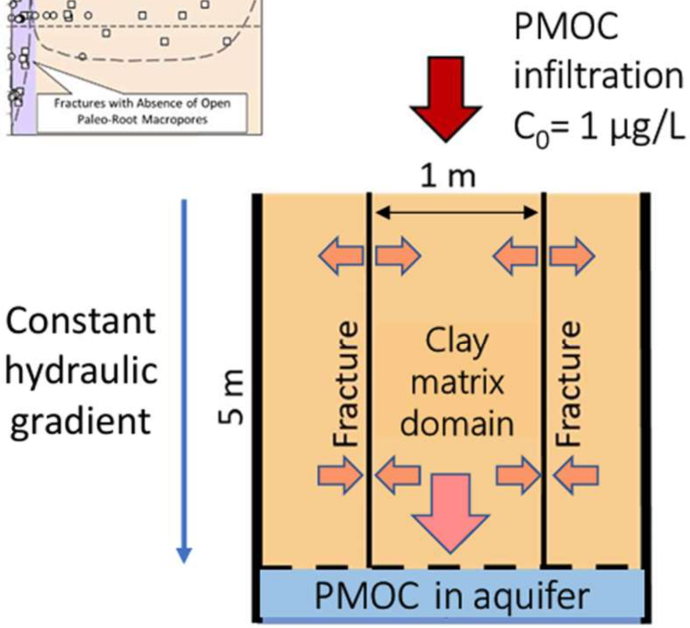
Ks clay matrix domain values describe different degrees of geological heterogenity in the bulk aquiatrd

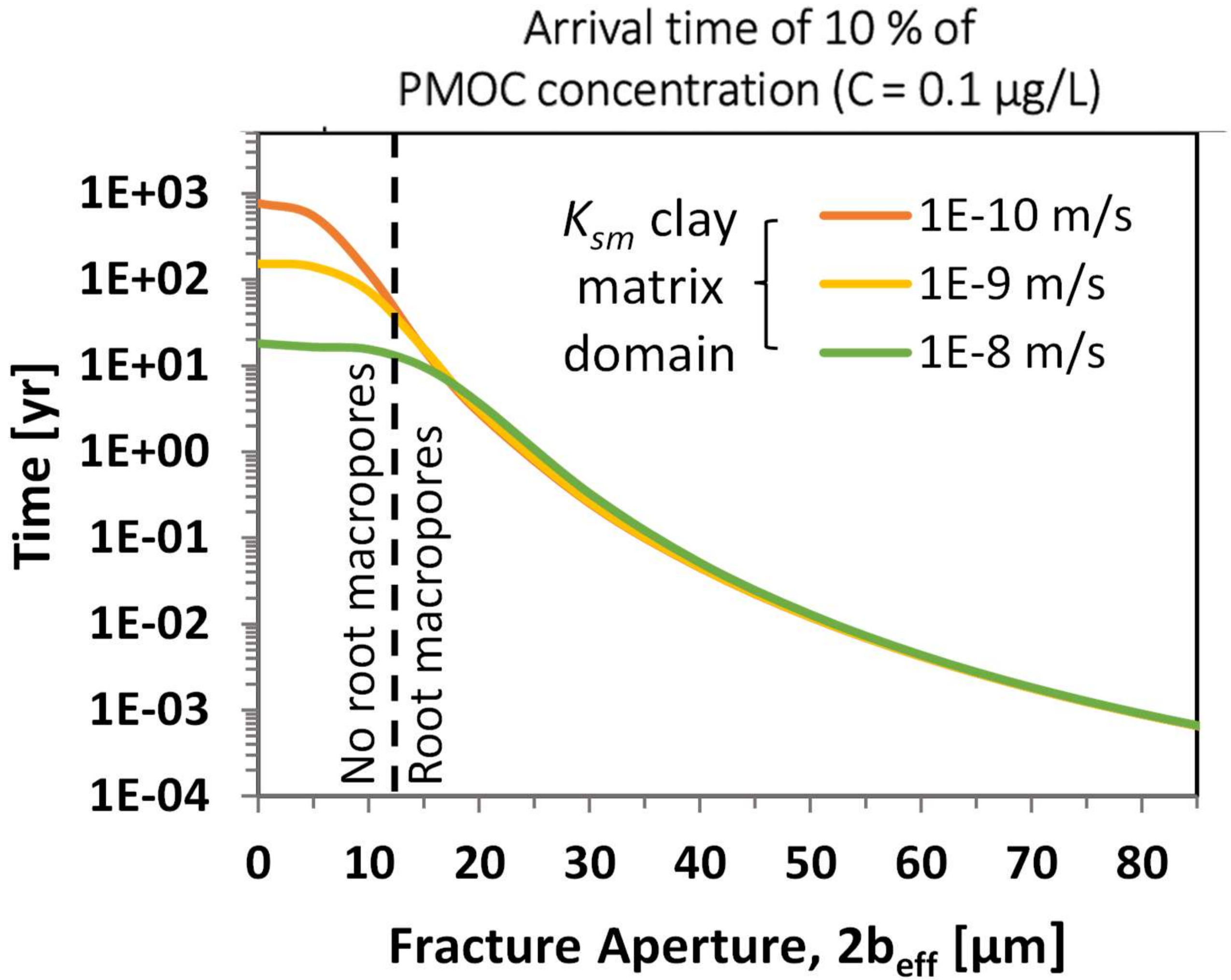




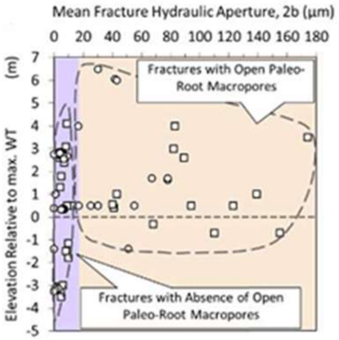
Assement of aquifer vulnerability to "Persistent Mobile Organic Contaminants" (PMOC) ex. DMS, PFAS (PFBA), DPC, BAM

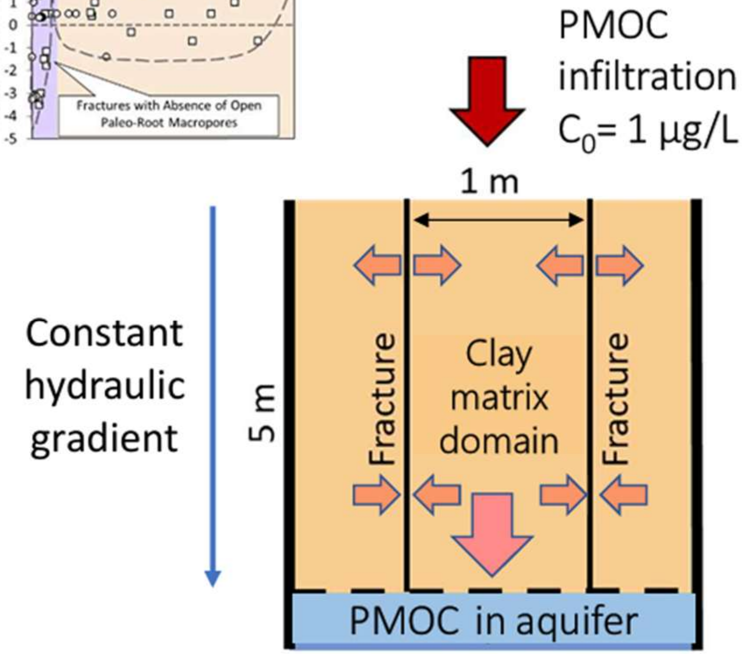


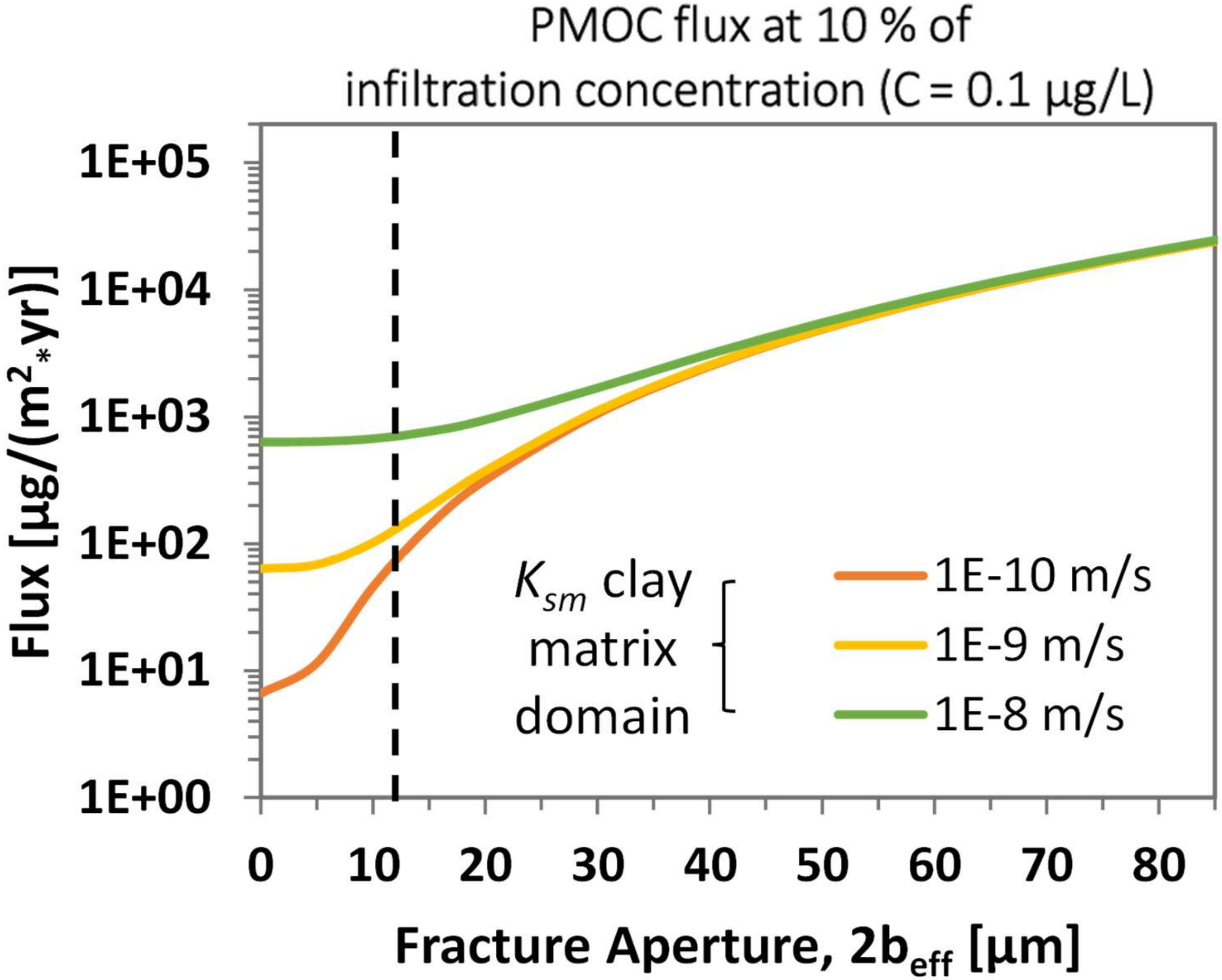




Assement of aquifer vulnerability to ”Persistent Mobile Organic Contaminants” (PMOC) ex. DMS, PFAS (PFBA), DPC, BAM







Distribution of different till types

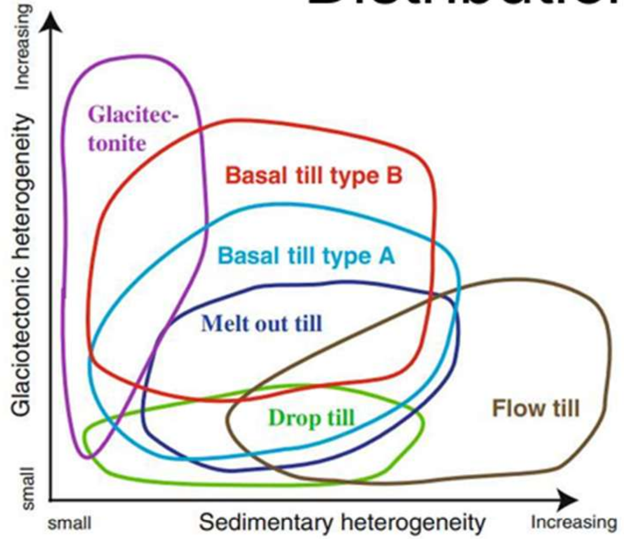


Fig. 2 Principal diagram of the relative geological heterogeneity of different till types (see Table 1) as a result of combined sedimentary and glaciotectonic heterogeneity

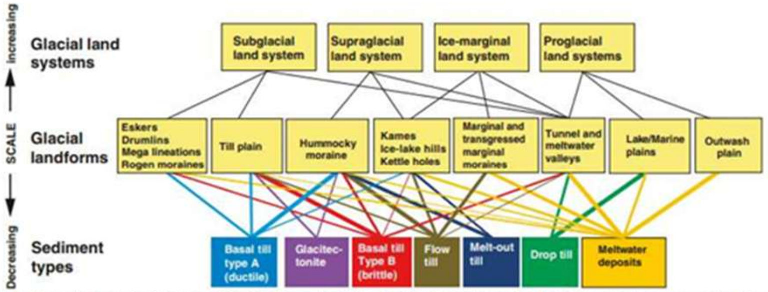


Fig. 1 Scale hierarchy and classification of land systems, landforms and sediment types in glacial deposits. The *connection lines* between glacial landforms and sediment types represent which till types are represented in the individual glacial landforms and the line thickness indicates the importance of the sediment types in the individual landforms

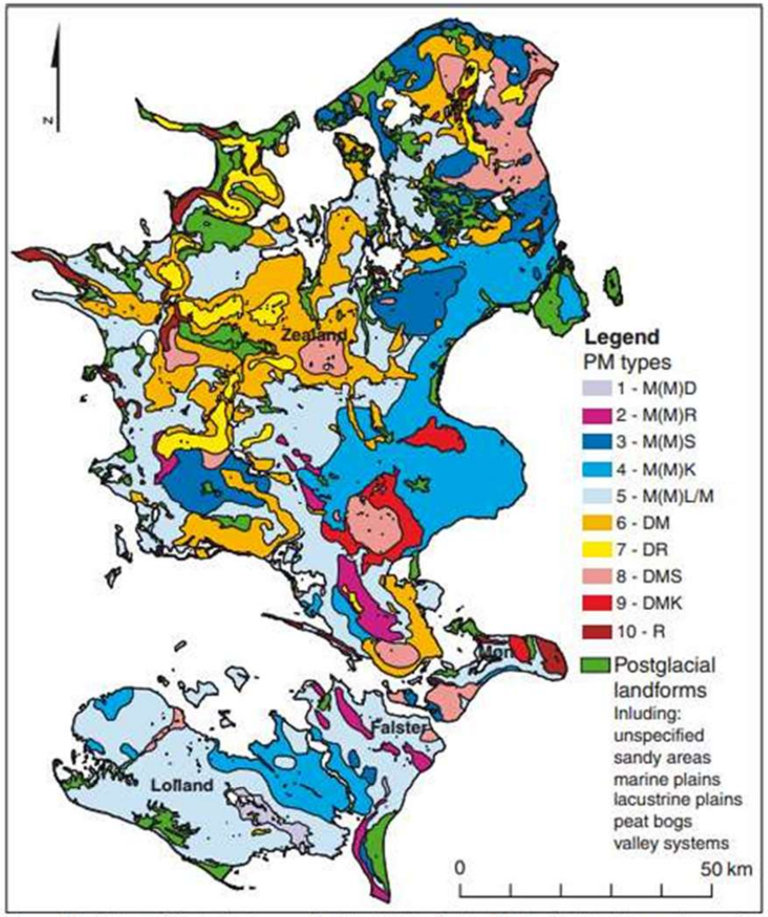


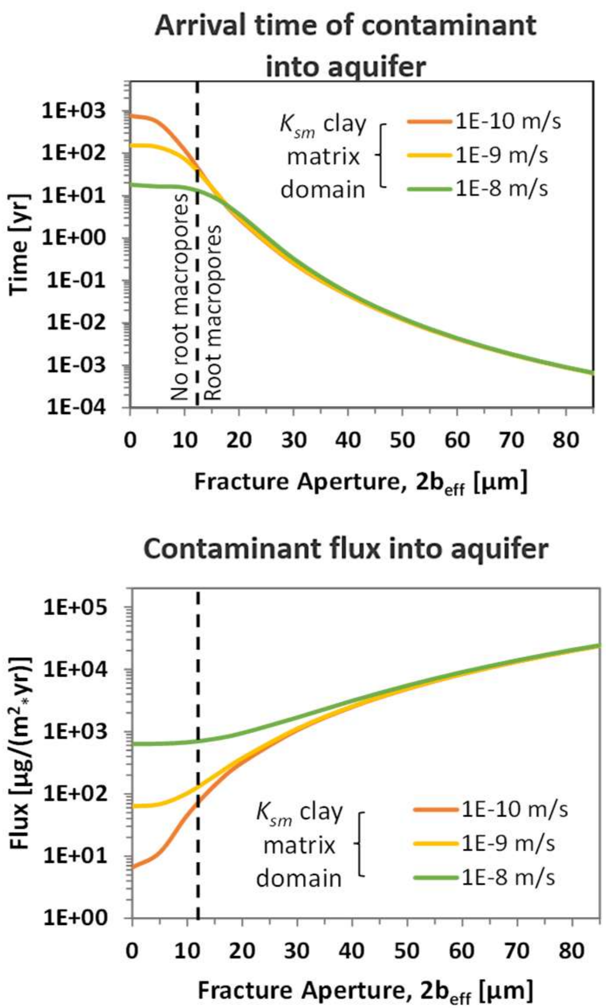
Fig. 4 Poly morphological map of Zealand and surrounding islands. PM units: *M* undulating till plain, *D* hummocky moraine, *S* outwash plain, *R* marginal moraine, *K* basement limestone, *L* basement marine clay

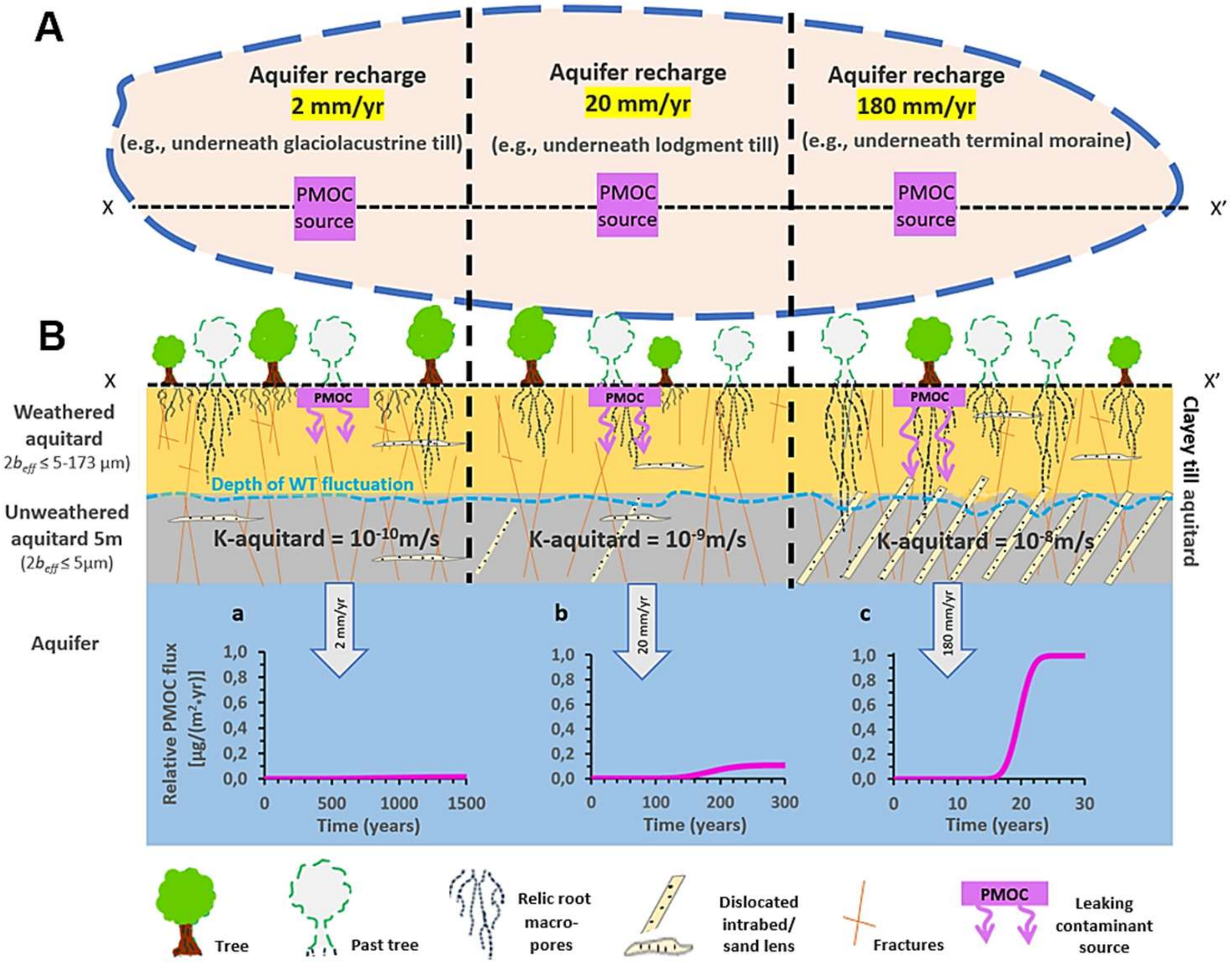
Groundwater protection by glacial till type (tendency only)

Increasing glaciotectonic deformation (dislocation and folding of layers) and lithological heterogeneity in the following order of till types:

- glaciolacustrine till
- lodgement till, hummocky till/flow tills
- terminal tills/push moraines (least protection).

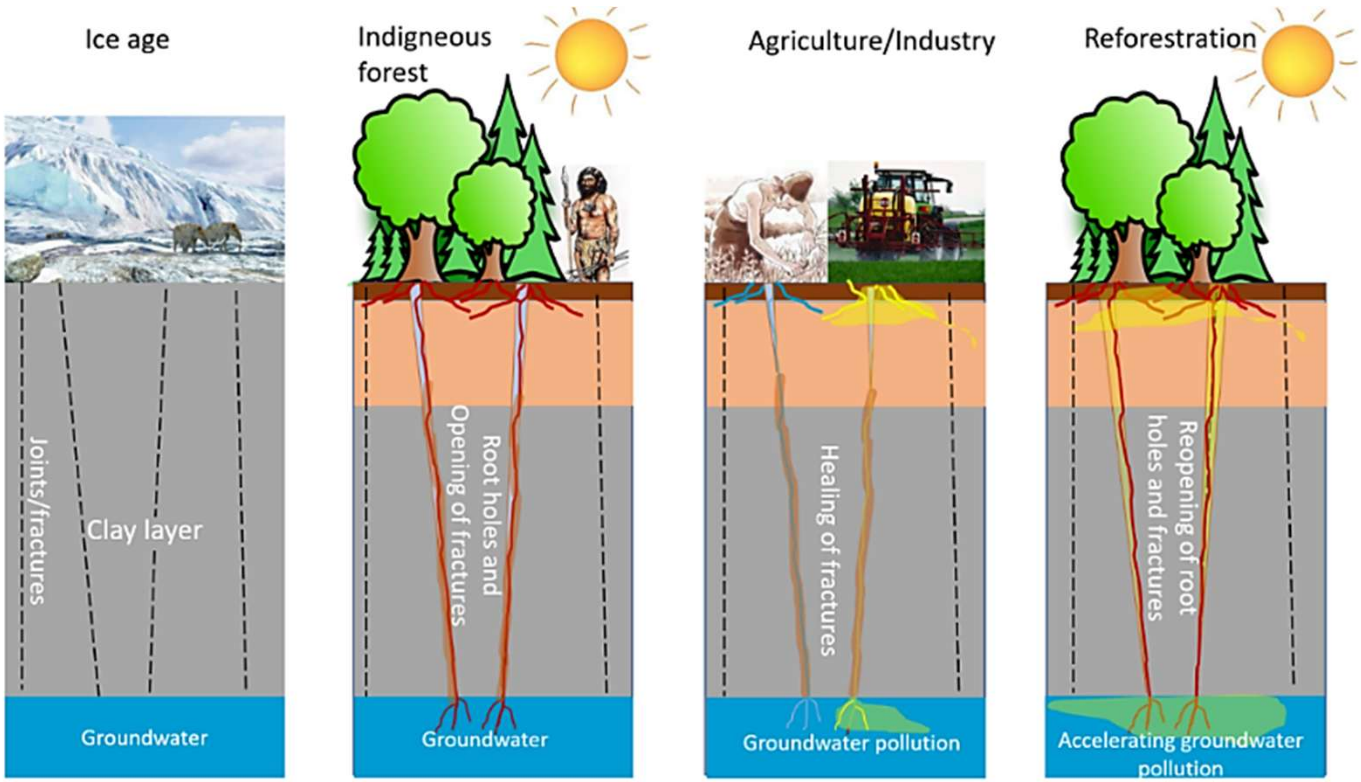
"Translated" to different aquitard leakage in schematic watershed



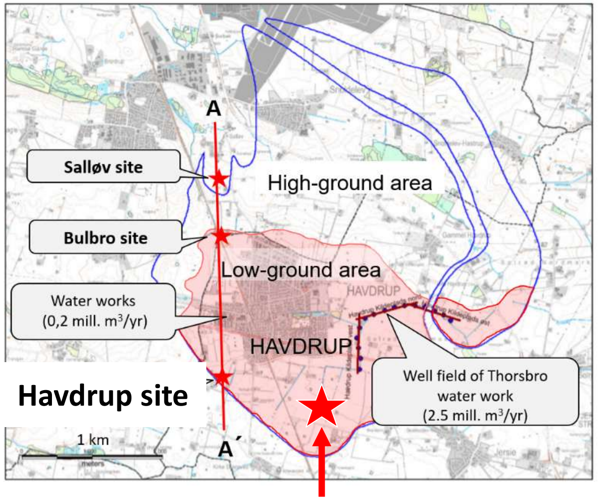


Danish goverment has decided that 250,000 hectars of mainly agricultural land shall be reforested

Groundwater pollution by reforestation land with legacy soil pollution??

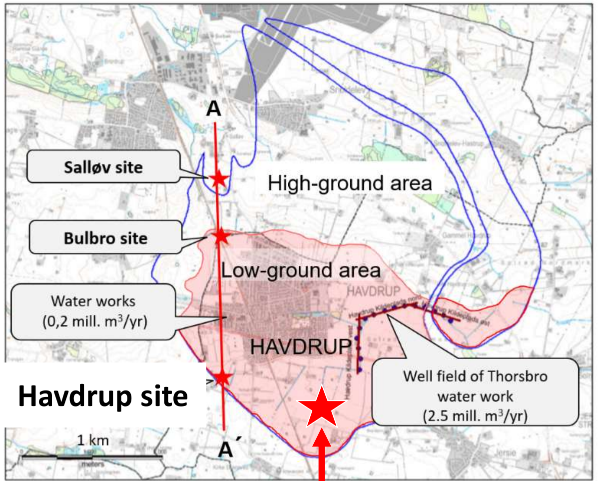


Model-scenario with groundwater pollution by reforestation of Salløv site with legacy DMS soil pollution



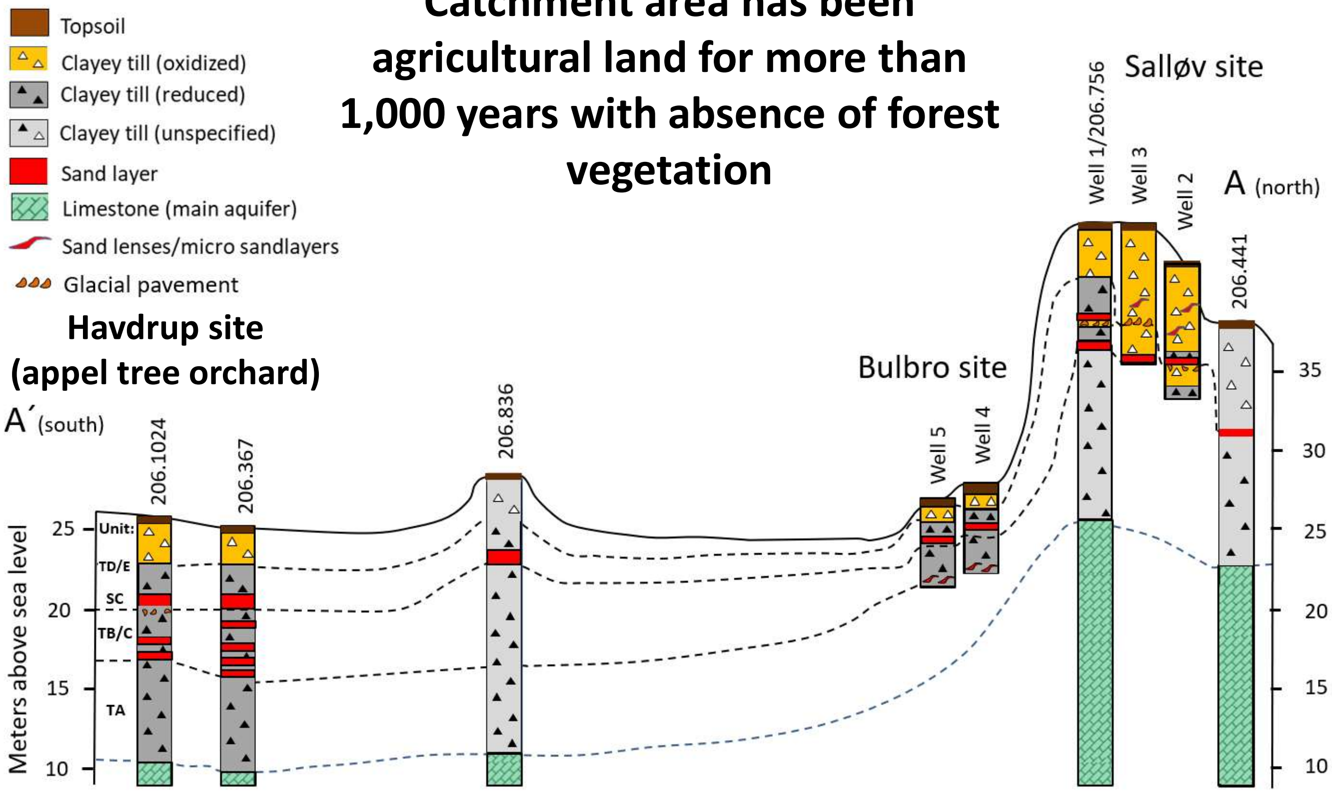
DMS contaminated strawberry fields

Model-scenario to assess groundwater pollution with legacy DMS soil pollution by reforestation of Salløv site

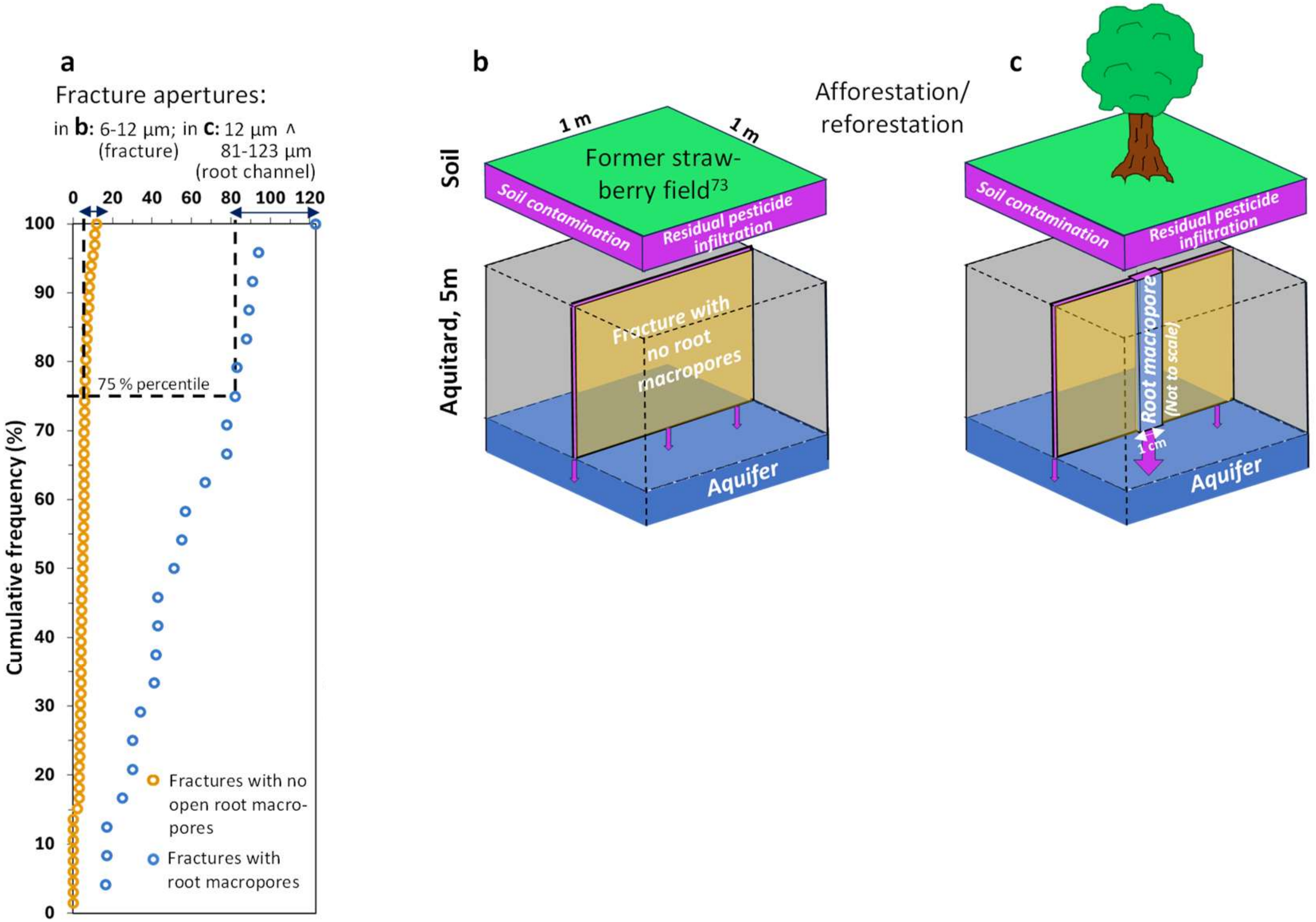


DMS contaminated strawberry fields

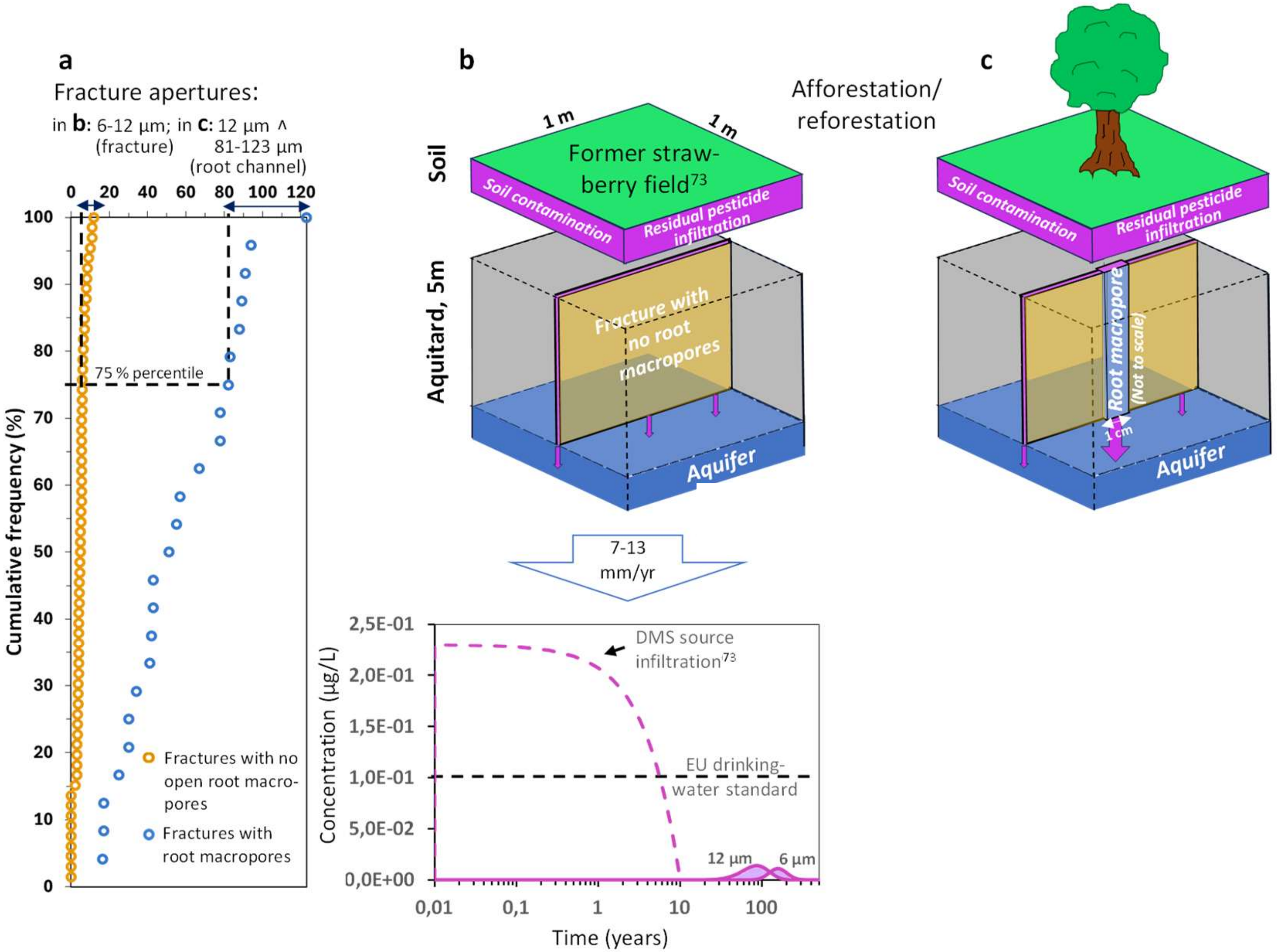
Catchment area has been agricultural land for more than 1,000 years with absence of forest vegetation



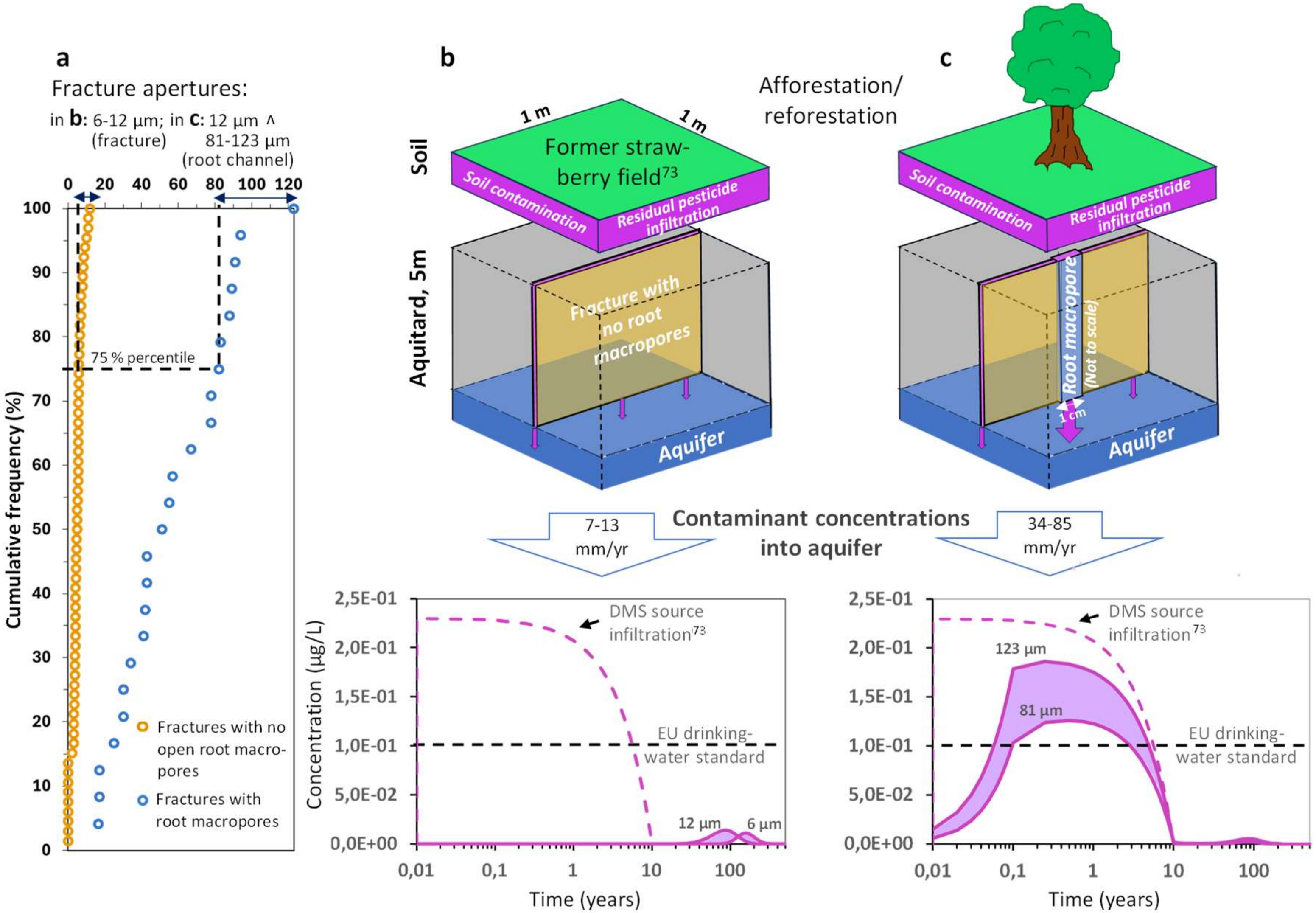
Reforestation of Salløv site with legacy DMS soil pollution



Reforestation of Salløv site with legacy DMS soil pollution



Reforestation of Salløv site with legacy DMS soil pollution

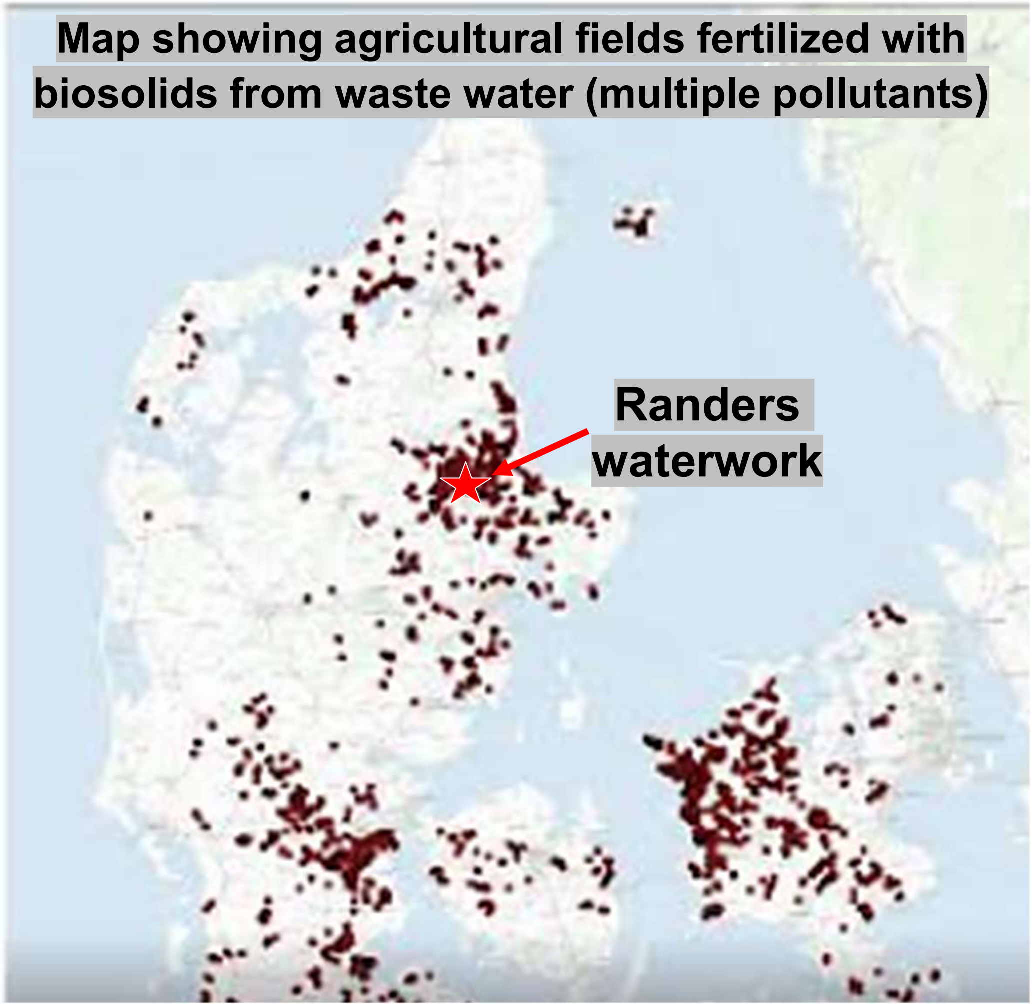


Announcement by Danish goverment of reforestation to protect drinking water aquifer against pollution


Ny bynær skov skal beskytte drikkevandet og skabe ny natur

Over 200 hektar jord syd for Randers Fjord er udpeget til ny skov i et samarbejde mellem Naturstyrelsen, Randers Kommune og Verdo Vand. Det er et af de første statslige skovrejsningsprojekter i regi af Grøn Trepart.

Randers waterwork



Conclusions

Part 2:

1. Deep of root macropores, thickness of aquitard, and lithological heterogeneity are major hydrogeological controls of aquitard leakage and vulnerability of underlaying groundwater.

2. Targeted regulation and remediation of surface pollution in areas with aquitard thickness less than rooting depths and leaky aquitards has potential to keep pesticide concentrations in water supply wells below drinking water standards.

3. Groundwater protection need to consider groundwater risk by introducing new deep root macropores from reforestation in areas with residual soil-pollution and abstraction of groundwater for water supply.