STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

Modelling the Thermal Impact of a Repository for High-Level Radioactive Waste in a Clay Host Formation

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Thermal impact of the disposal of radioactive waste in clay

- **Geological disposal** & problem specification
  - General Context
  - Typical repository layout
  - The thermal issues associated with the disposal of heat-emitting wastes
- **T**: Thermal evolution of a typical repository ⬅ **Simple, thermal model**
  - Typical temperature evolution
  - Model equation, implementation, results
- **T-H**: Effect of / on groundwater flow ⬅ **Multiphysics model**
  - Thermo-hydraulic modelling of the far field
  - Model equations, implementation, results
- Basic **T-H-M**: Uplift ⬅ **Multiphysics model**
  - Thermo-hydro-mechanical modelling of the far field
  - Model equations, implementation, results
- **Conclusions**

Geological disposal
of long-lived, highly radioactive wastes

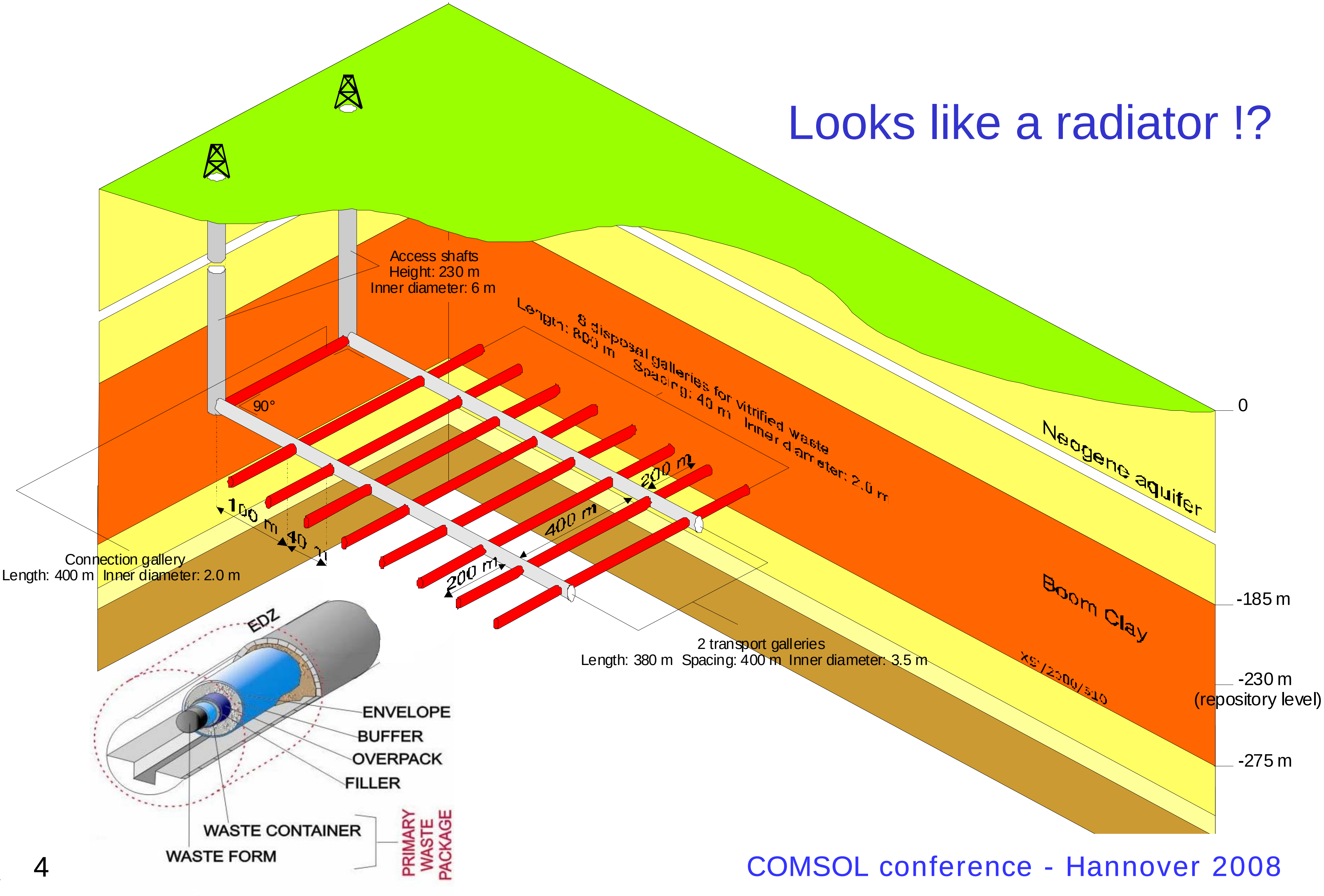
- **What can we do with our radioactive waste ?**
  - From nuclear power plants, medical, industrial activities
  - Main challenge = protection of men/environment
    during a **very long period of time** (**10^4** …**10^5** …**10^6** years…)

- **Geological Disposal of high-level waste**
  - Accepted in a wide range of countries and by the EC
  - Engineered barriers + **geological barrier** : compatible with time scales associated with long-lived radioactive wastes:
    - Vitrified high-level waste (VHLW, reprocessed, COGEMA)
    - Spent fuel

- **Clays as potential hosts for a repository**
  - Very **low permeability** ➔ solute transport by molecular diffusion
  - **Sorption** ➔ delay and spread releases of radionuclides in time
  - If plastic clay: **self-sealing**, self-healing
  - Not a resource

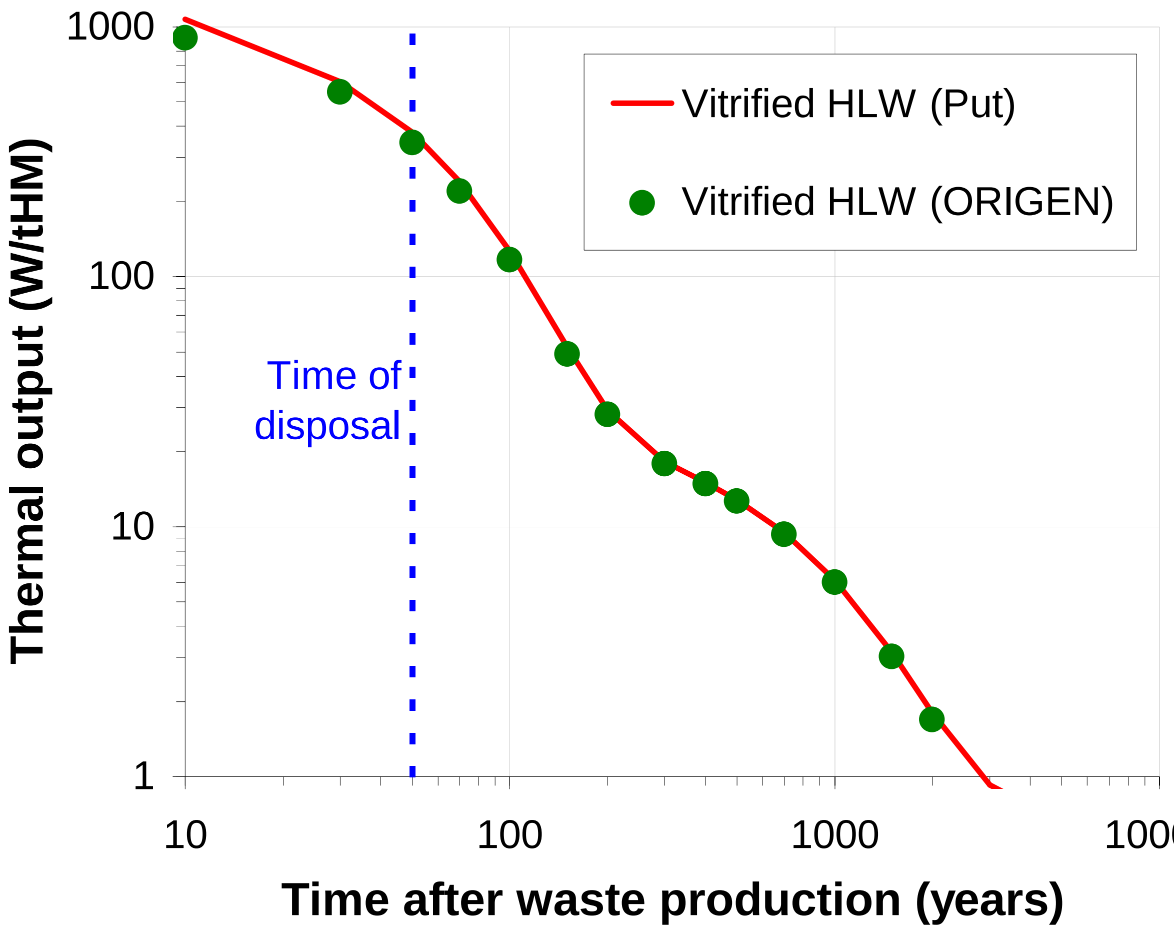
Typical repository design

Looks like a radiator !?



Some radioactive wastes can release considerable amounts of heat !

- Some radioactive wastes generate **a considerable amount of heat** due to radioactive decay, **even after interim storage** (50-80 years)
- Example: vitrified high-level waste (COGEMA)



Thermal issues

associated with the disposal of heat-emitting waste

- How **hot** will it be ?
  - Depends on waste type (radionuclide inventory)
  - Engineered barriers & rock thermal properties
  - Repository **design parameters**
    - Disposal **galleries spacing**
    - Waste **package pitch** within disposal galleries
- What could be the **consequences** of **ΔT** ?
  - Chemical/geochemical ?
    - Thermal degradation of engineered barriers & waste forms ?
    - Solubility & migration parameters of radionuclides,... ?
    - Thermal decomposition of organic matter in Boom Clay, CO_2 ?
  - Hydrogeology ?
    - Far field: **thermal impact on the aquifer** ?
  - Mechanical ?
    - Near field: Thermo-Hydro-Mechanics of EBS, host rock ?
    - Far field: **uplift** ?

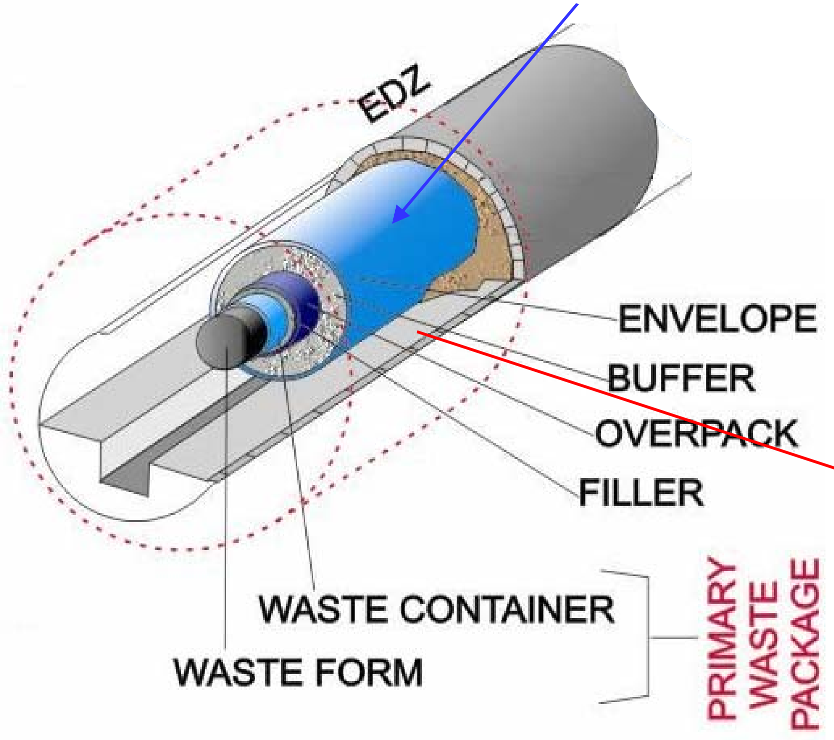
T: Thermal evolution
of a typical repository (Belgian repository design)

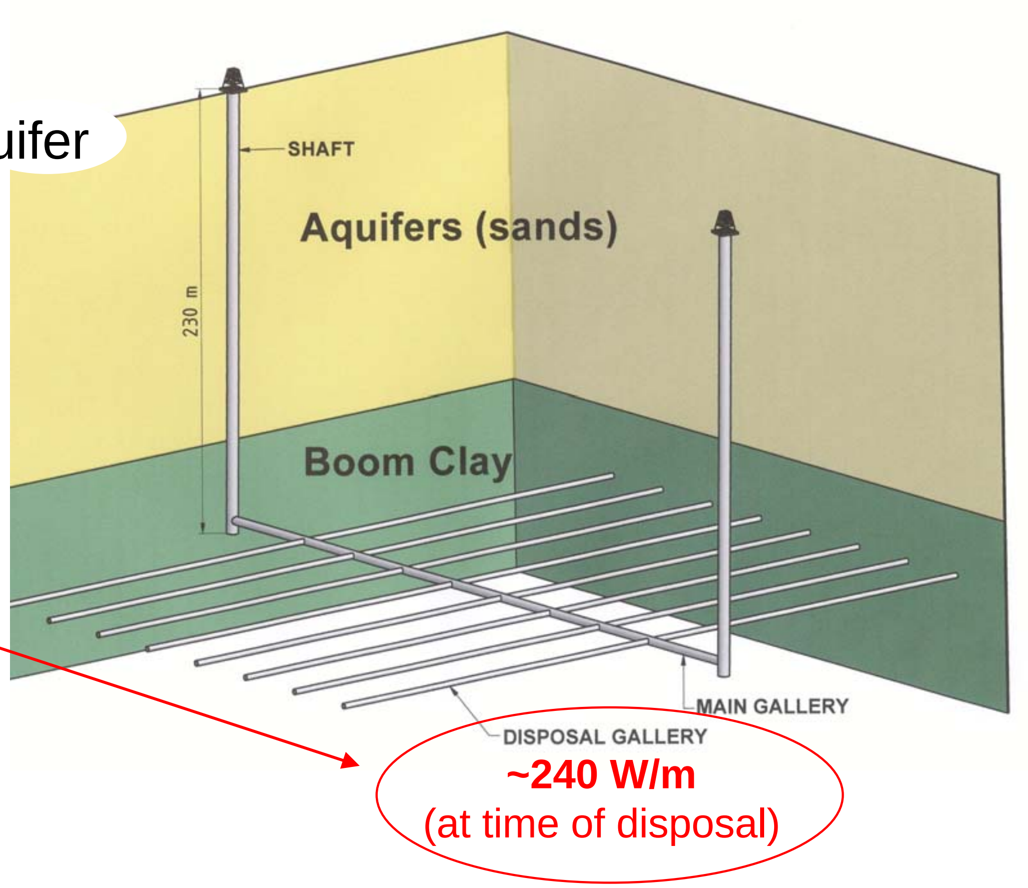
Typical thermal loading for a disposal system:

- VHLW: ~ **1 kW** per **supercontainer** after 60 years interim storage
- Supercontainer length = **4.2 m** (= package pitch: no spacing)
- Gallery spacing = **50 m**

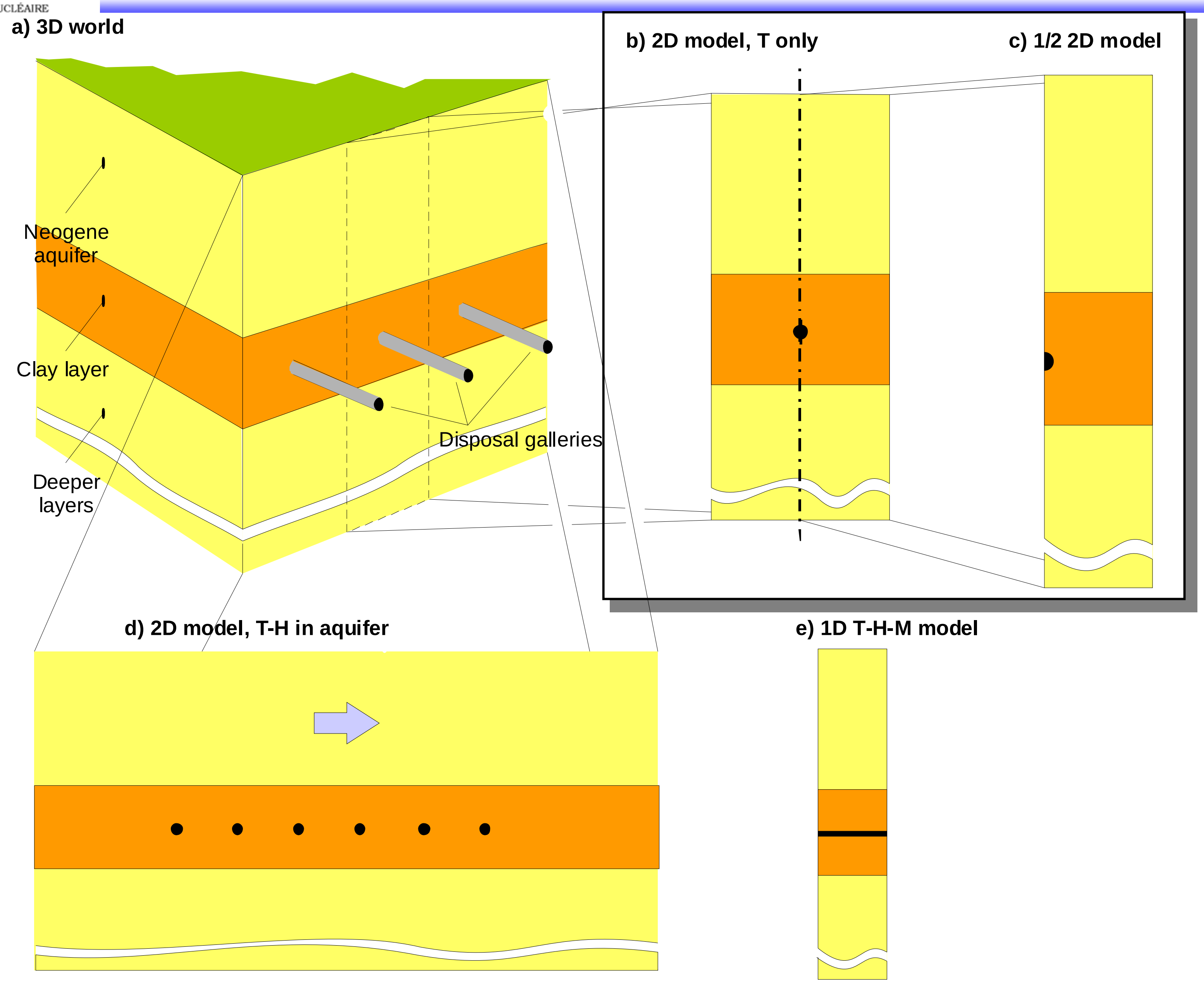
Peak temperatures ?

- Conservative : no flow in aquifer





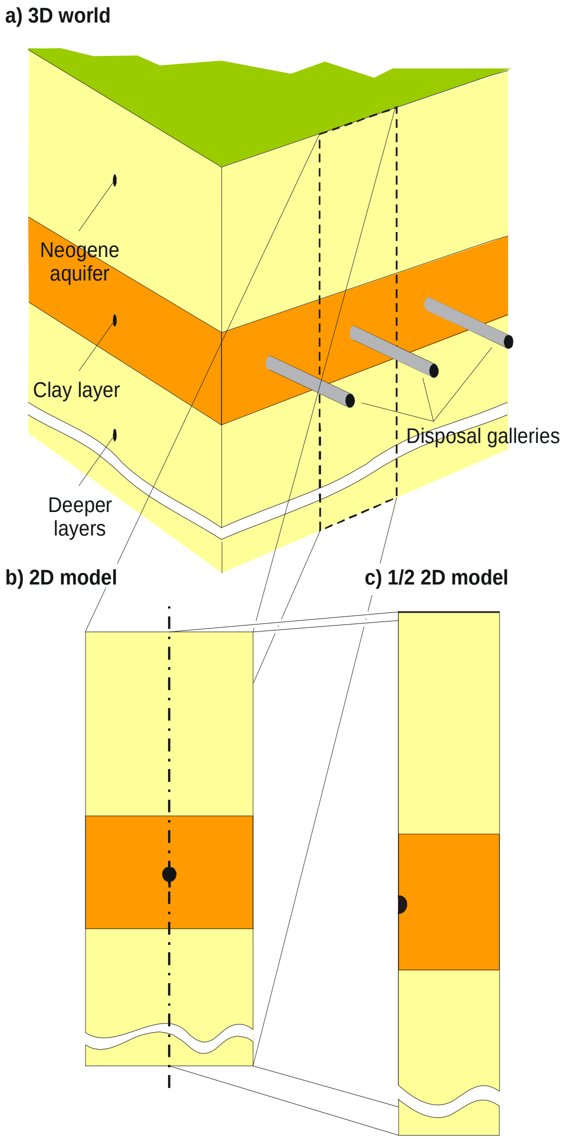
Reference geometry
T, T-H & T-H-M model reduction

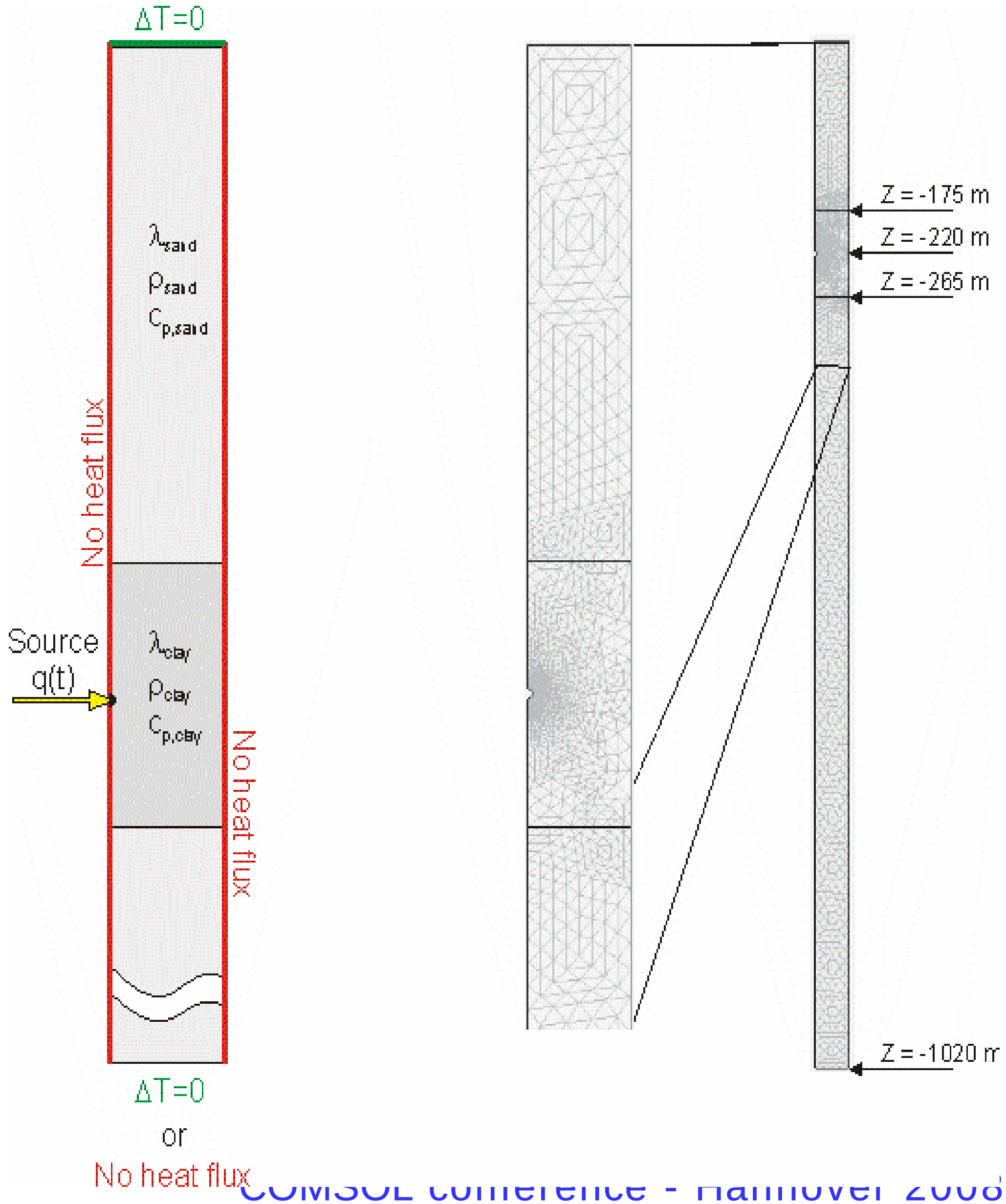


Model equations: T

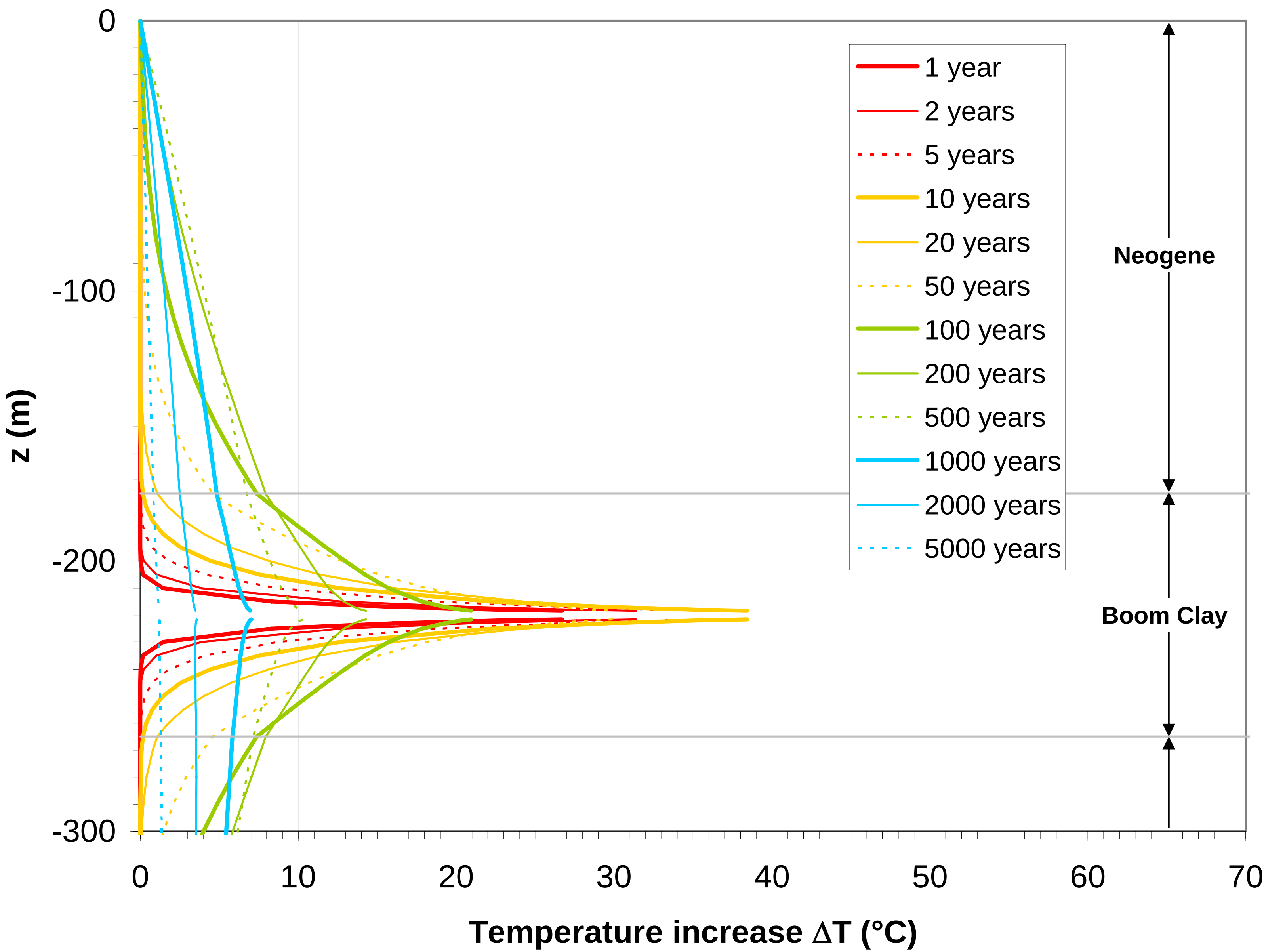
	Clay	Aquifer (sand)
T (thermal)	$\frac{\partial}{\partial t}\left(\rho_b c_{p,b} T\right) = \nabla\cdot\left(\lambda \nabla T\right) + q$ $\rho_b c_{p,b} = \eta \rho_w c_{p,w} + (1-\eta)\rho_s c_{p,s}$	$\frac{\partial}{\partial t}\left(\rho_b c_{p,b} T\right) + \cancel{\nabla\cdot\left(\rho_w c_{p,w} T \mathbf{u}\right)} = \nabla\cdot\left(\lambda \nabla T\right)$ $\mathbf{u} = \mathbf{0}$
H (hydro)	$\frac{\partial p}{\partial t} = \alpha_H \frac{\partial^2 p}{\partial z^2} + \Lambda \frac{\partial T}{\partial t}$ $\Lambda = \left(\frac{\partial p}{\partial T}\right)_{undrained,oedometer}$	$\frac{\partial}{\partial t}\left(\eta \rho_w\right) = \nabla\cdot\left(\rho_w \mathbf{u}\right)$ with $\mathbf{u} = \frac{k}{\mu}\left(\nabla p - \rho_w \mathbf{g}\right)$ (Darcy)
M (mech)	$\varepsilon_z = \frac{\Delta p + \beta_d K_d \Delta T}{\lambda_d + 2G}$	$\varepsilon_z = \frac{\beta_d K_d \Delta T}{\lambda_d + 2G}$

Thermal evolution, boundary conditions & mesh





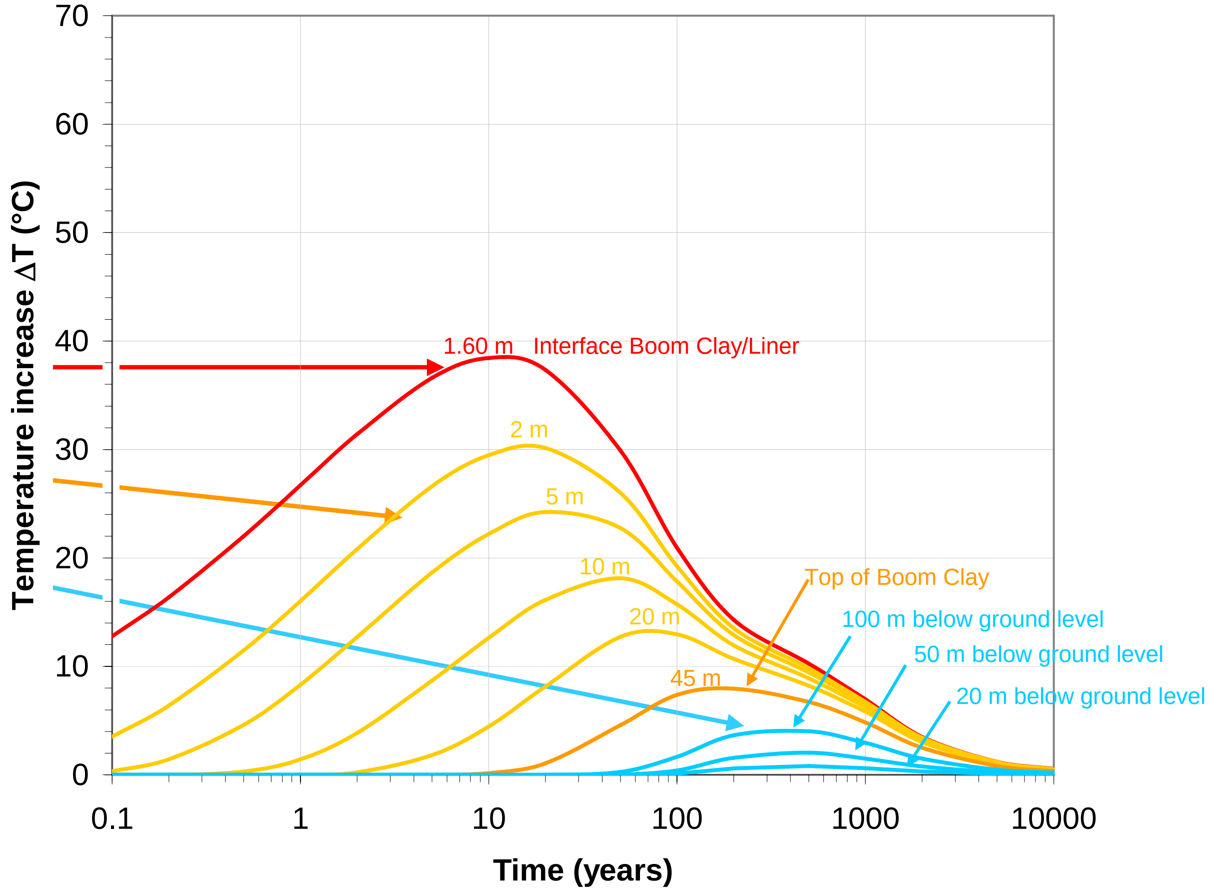
Thermal evolution, Vertical ΔT profiles



Thermal evolution, History of temperature increase ΔT

How **hot** will it be ?

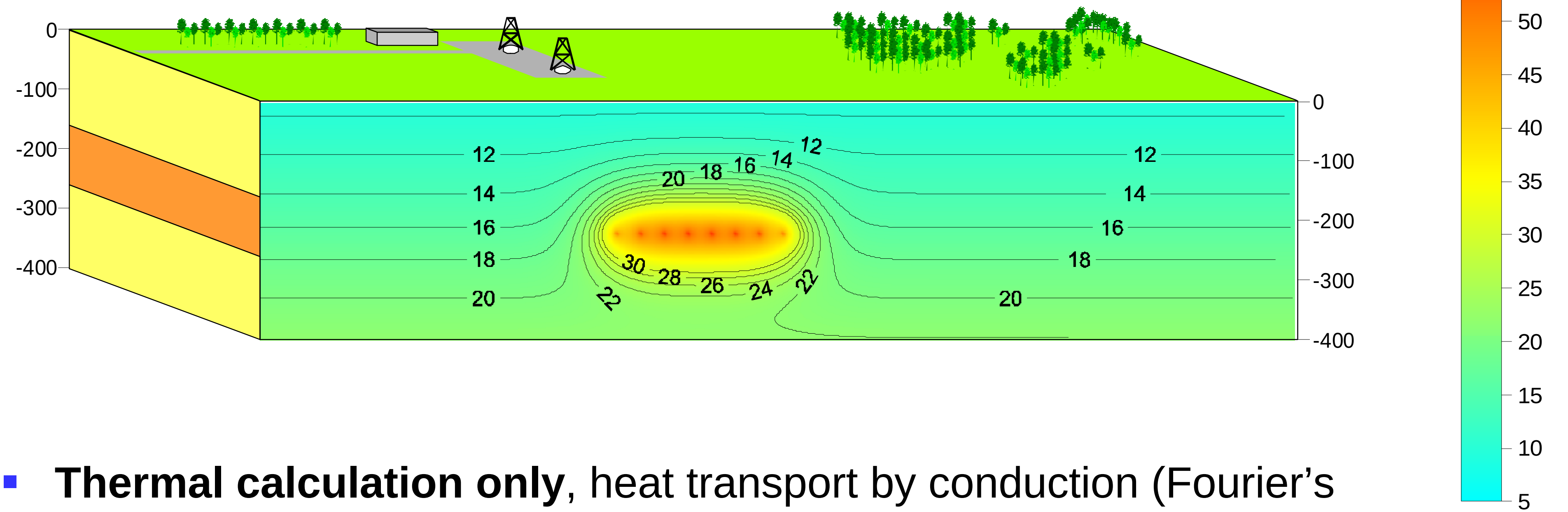
- Waste
- Engineered Barriers System (EBS)
- **Clay**
- **Aquifers**



Thermal evolution, full repository
Typical results, T contours

How **hot** will it be ?

- Example: calculated thermal field around a repository for vitrified waste



- **Thermal calculation only**, heat transport by conduction (Fourier's law). **Temperature field 100 years after disposal**

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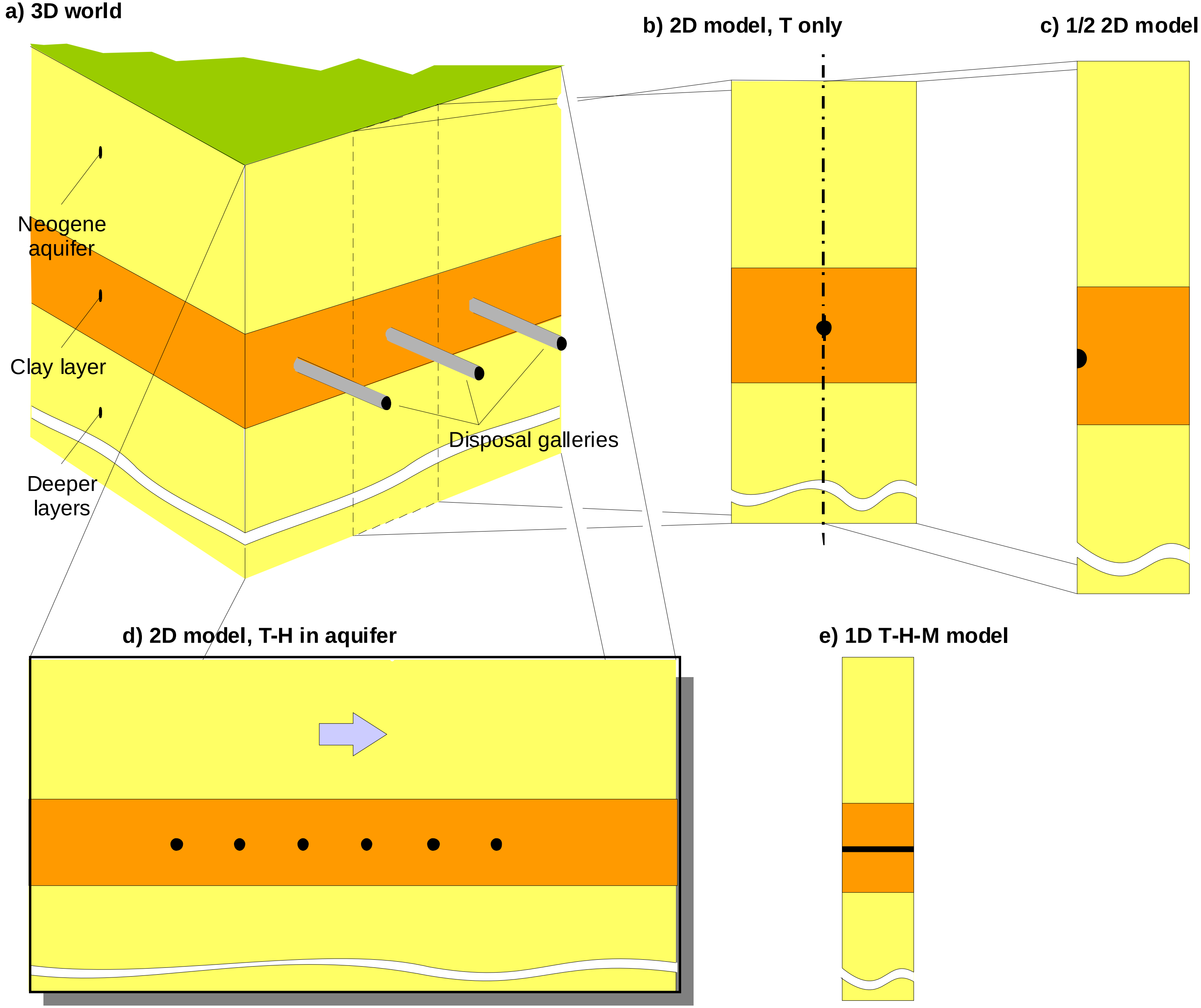
T, T-H & T-H-M model reduction

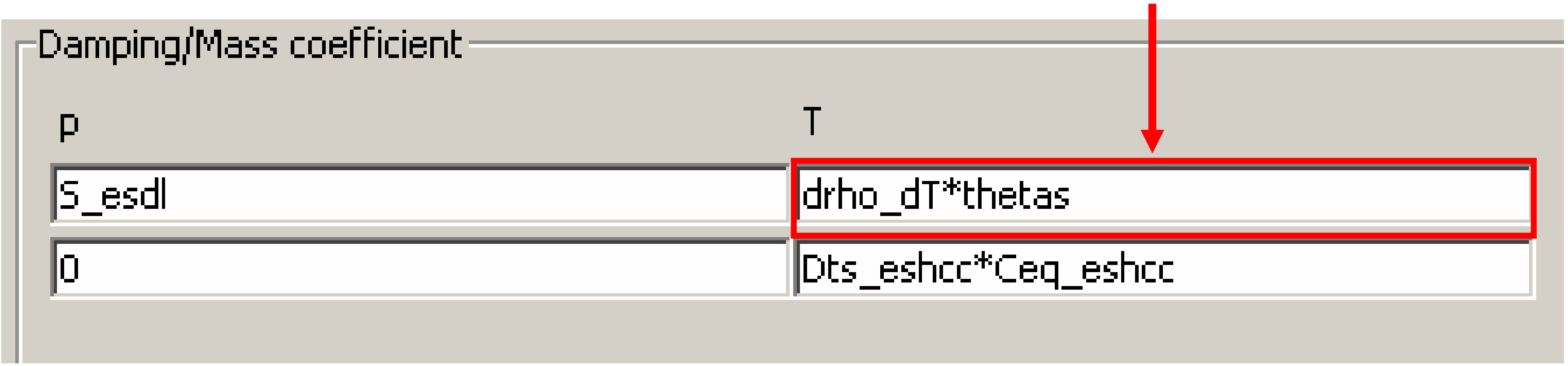


Model equations: T-H

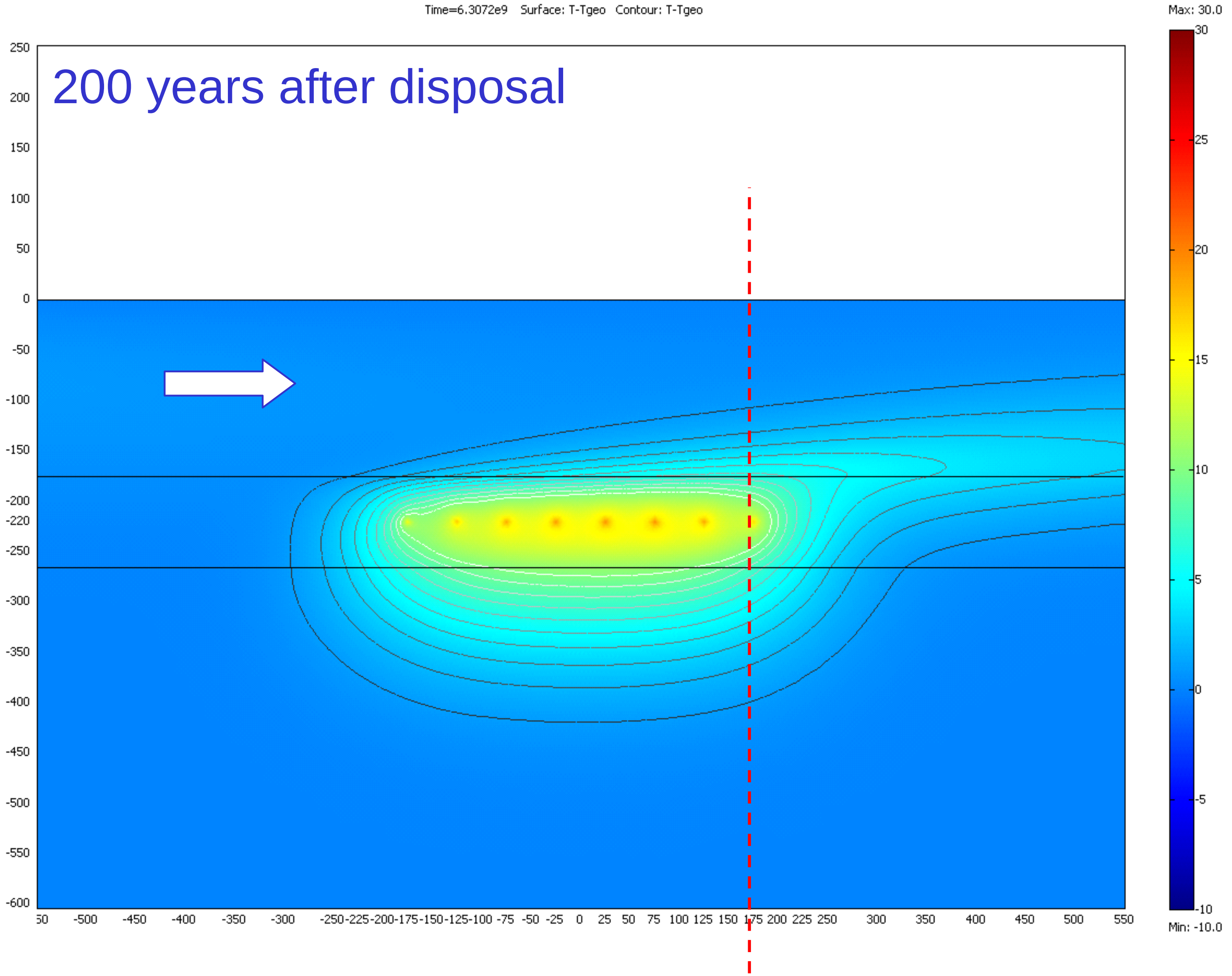
	Clay	Aquifer (sand)
T (thermal)	$\frac{\partial}{\partial t}\left(\rho_b c_{p,b} T\right) = \nabla \cdot \left(\lambda \nabla T\right) + q$ $\rho_b c_{p,b} = \eta \rho_w c_{p,w} + (1-\eta)\rho_s c_{p,s}$	$\frac{\partial}{\partial t}\left(\rho_b c_{p,b} T\right) + \nabla \cdot \left(\rho_w c_{p,w} T \mathbf{u}\right) = \nabla \cdot \left(\lambda \nabla T\right)$
H (hydro)	$\frac{\partial p}{\partial t} = \alpha_H \frac{\partial^2 p}{\partial z^2} + \Lambda \frac{\partial T}{\partial t}$ $\Lambda = \left(\frac{\partial p}{\partial T}\right)_{undrained,oedometer}$ **Very low k, no convective heat transport**	$\frac{\partial}{\partial t}\left(\eta \rho_w\right) = \nabla \cdot \left(\rho_w \mathbf{u}\right)$ with $\mathbf{u} = \frac{k}{\mu}\left(\nabla p - \rho_w \mathbf{g}\right)$ (Darcy)
M (mech)	$\varepsilon_z = \frac{\Delta p + \beta_d K_d \Delta T}{\lambda_d + 2G}$	$\varepsilon_z = \frac{\beta_d K_d \Delta T}{\lambda_d + 2G}$

COMSOL Multiphysics implementation and auxiliary equations

- Use of Earth Science Module (convenient, but not required)
  - **H**: Darcy's law (**esdl**)
  - **T**: Conduction & convection in porous media (**eshcc**)
  - Water density: $\rho = 1000.2 - 0.005 \times T^2$ [kg/m³] (T in °C)
  - Water viscosity: $\mu = \rho \cdot 9.2 \times 10^{-7} \cdot \exp(2050/(273.15+T))$ [Pa·s]
- No convection in low-permeability clay & geological layers below
  - Simply do not solve for flow in these subdomains ☺
- Coupling of heat and flow equations:
  - **H➔T**: Use velocities from **esdl** in **eshcc**
  - **T➔H**: COMSOL > Physics > Equation system > Subdomain settings



T-H evolution, effect of local flow pattern



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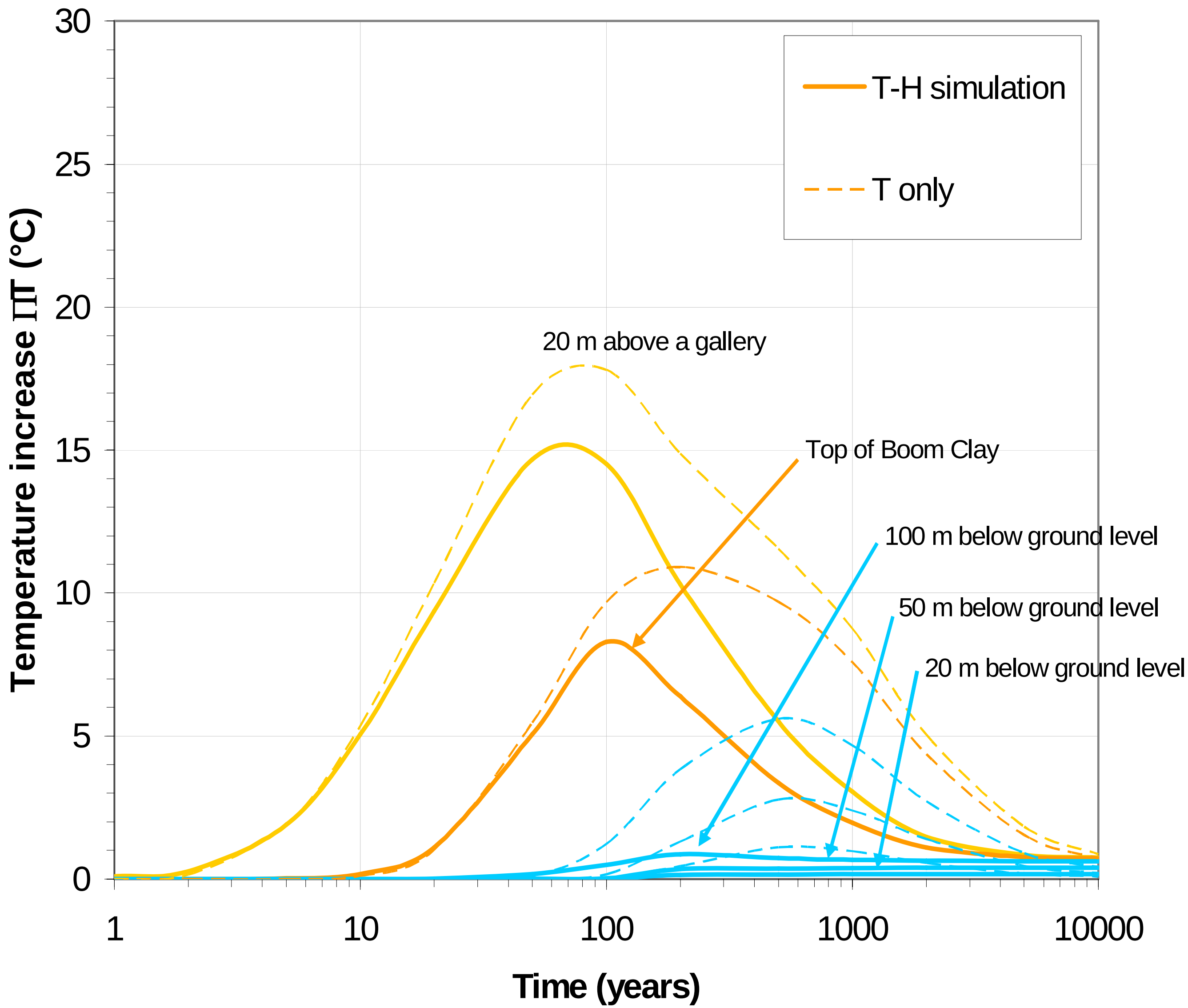
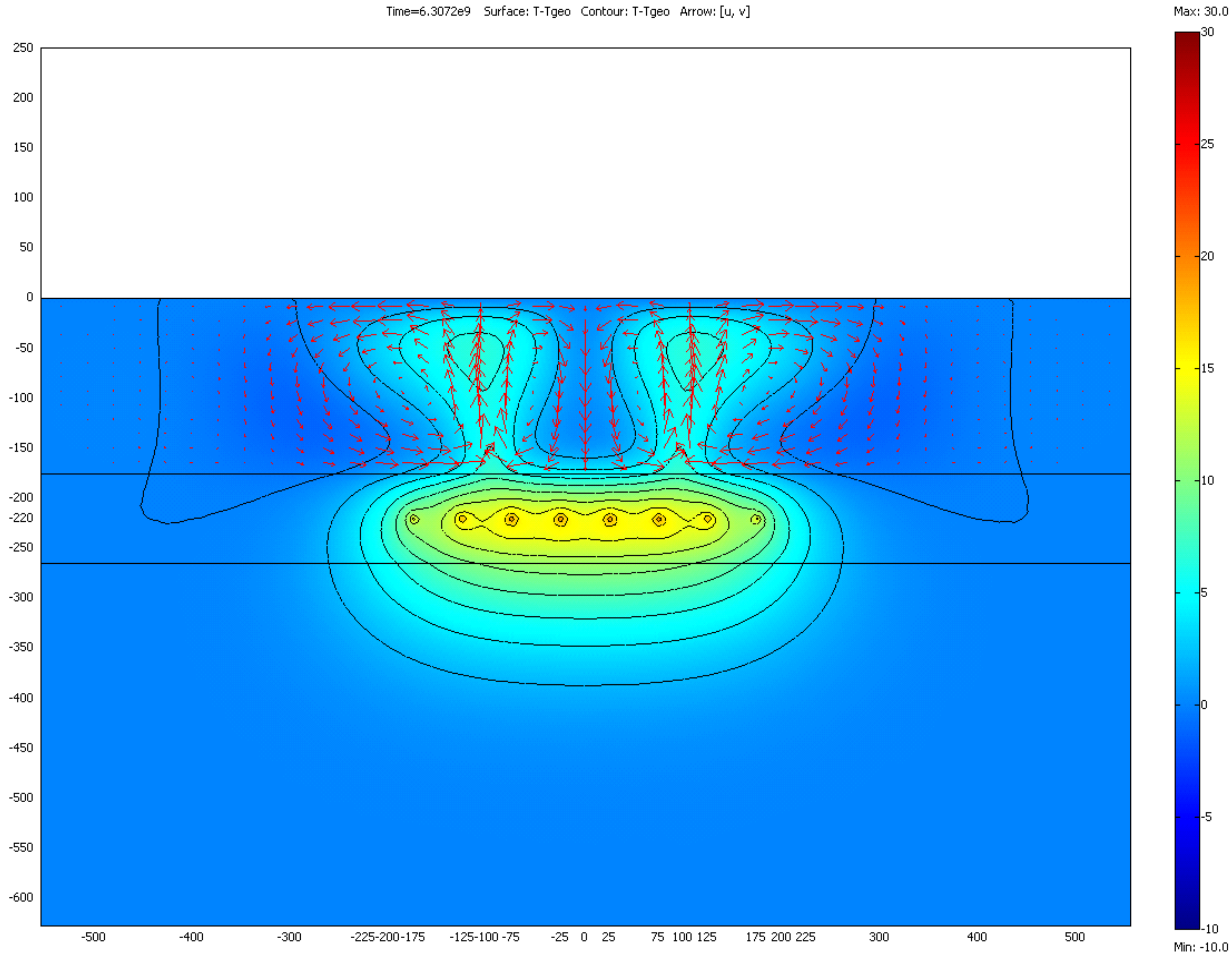


T-H evolution, convection cells
only in the absence of base flow !



T-H-M evolution, far field consequence: **uplift**

- Cause of uplift: **thermal expansion**

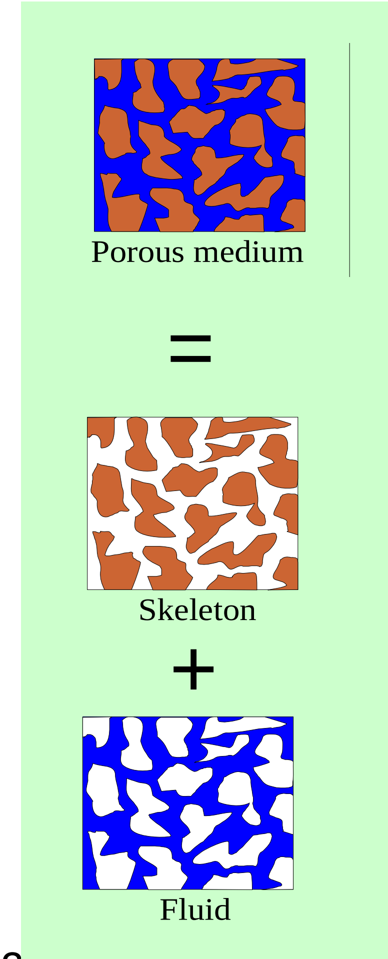
Material	Expansion coeff. (m^3/m^3 °C^{-1})	Symbol
Clay, drained	3×10^{-5}	β_d
Clay, undrained	13×10^{-5}	β_u
Water	21×10^{-5}	β_w
Sand, drained	3×10^{-5}	β_d

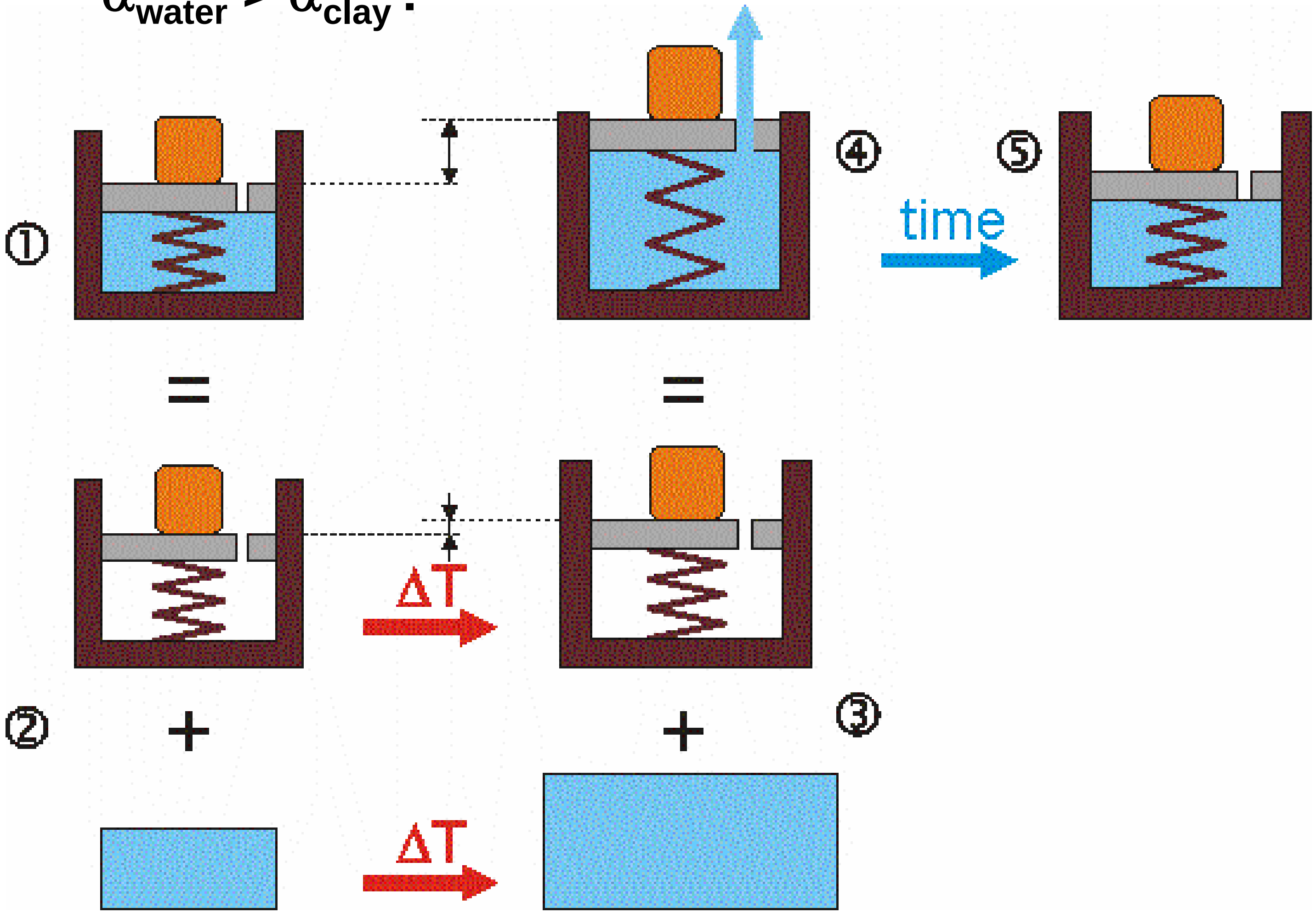
- Aquifers: excess water volume can quickly be accommodated
- Clay: overpressures, which slowly dissipate

T➔HM coupling

Terzaghi's analogy adapted to T➔HM

- ΔT ➔ thermal expansion (α)
- $\alpha_{water} > \alpha_{clay}$!





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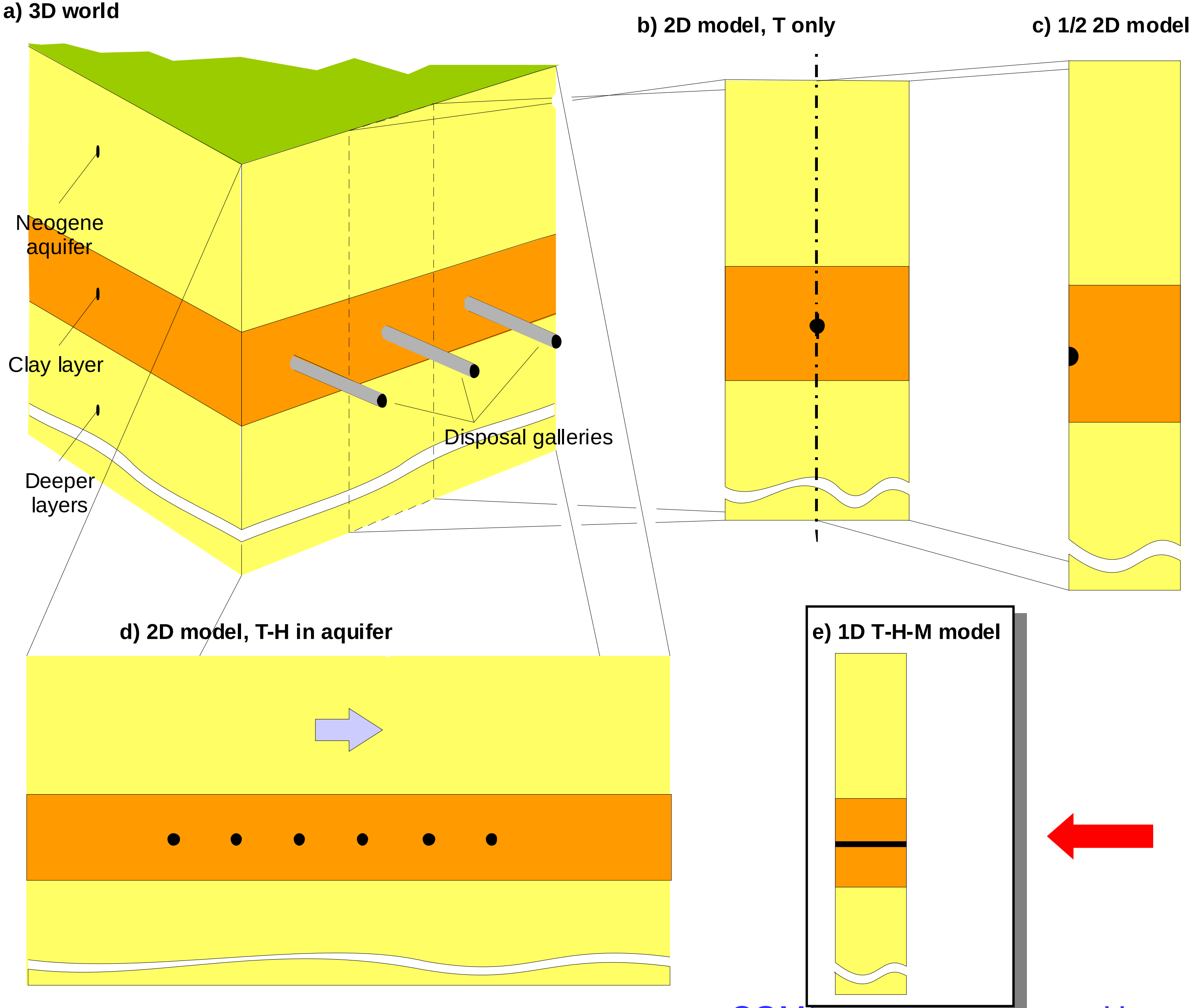

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Model equations: T-H-M

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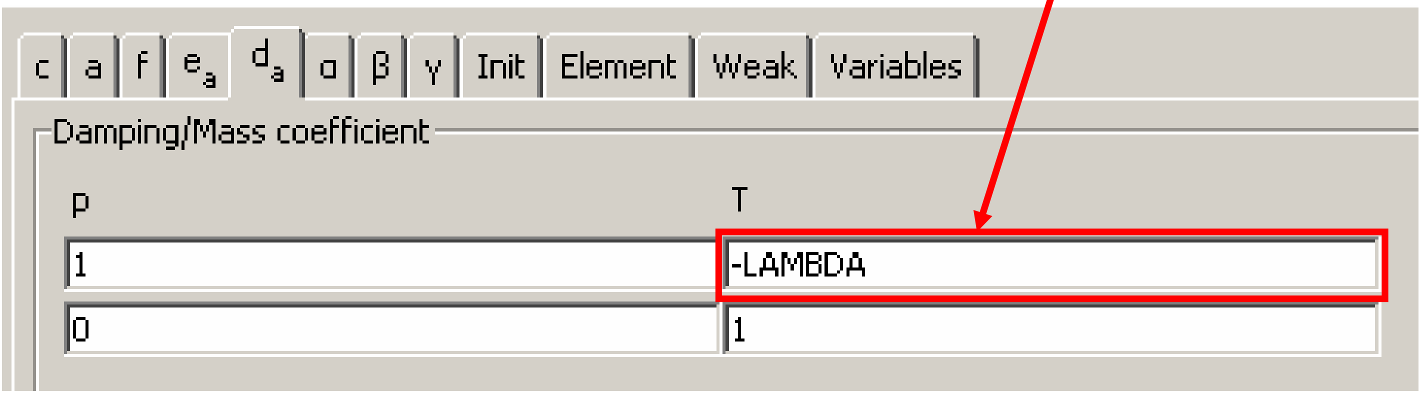
H (hydro)	$\frac{\partial p}{\partial t} = \alpha_H \frac{\partial^2 p}{\partial z^2} + \Lambda \frac{\partial T}{\partial t}$ $\Lambda = \left(\frac{\partial p}{\partial T}\right)_{undrained, oedometer}$	$\frac{\partial}{\partial t}\left(\eta \rho_w\right) = \nabla\cdot\left(\rho_w \mathbf{u}\right)$ with $\mathbf{u} = -\frac{k}{\mu}\left(\nabla p - \rho_w \mathbf{g}\right)$ (Darcy) **1D, heat transport by conduction**
M (mech)	$\varepsilon_z = \frac{\Delta p + \beta_d K_d \Delta T}{\lambda_d + 2G}$	$\varepsilon_z = \frac{\beta_d K_d \Delta T}{\lambda_d + 2G}$

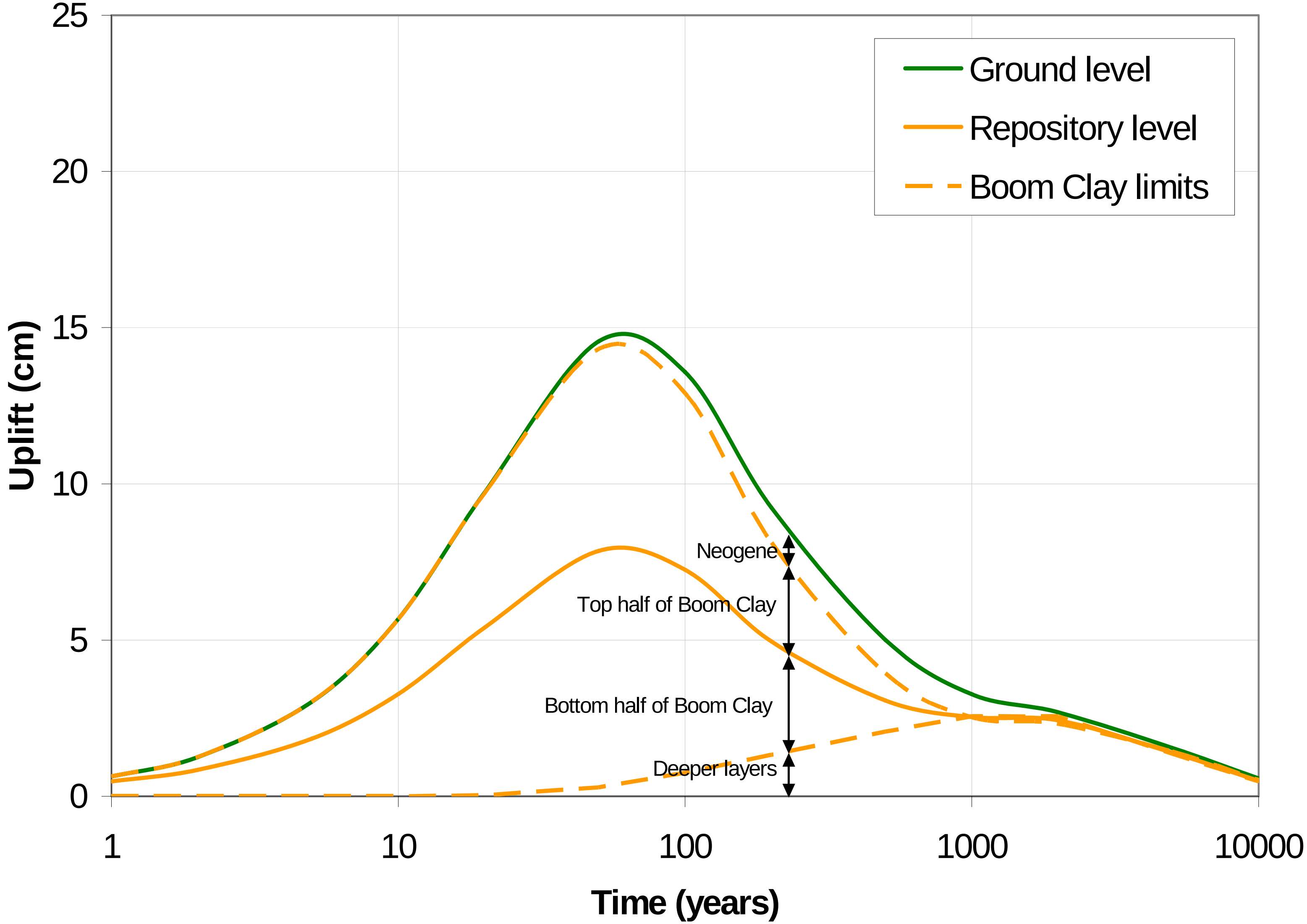
COMSOL Multiphysics implementation

- Summary of model equations (details in Picard & Giraud, 1995)
  - Heat transport: $\frac{\partial T}{\partial t} = \alpha_T \frac{\partial^2 T}{\partial z^2} + \frac{q}{\rho_b c_{p,b}}$
  - Porewater pressure dissipation: $\frac{\partial p}{\partial t} = \alpha_H \frac{\partial^2 p}{\partial z^2} + \Lambda \frac{\partial T}{\partial t}$
  - Vertical deformation: $\varepsilon_z = \frac{\Delta p + \beta_d K_d \Delta T}{\lambda_d + 2G}$
- Solve two 1D diffusion equations, then integrate ε_z over depth
- "Coupling" in COMSOL Multiphysics:
  - COMSOL > Physics > Equation system > Subdomain settings



Uplift evolution

note that most of the uplift is due to thermal expansion of poorly drained clay (water)



Conclusions

- Modelling the geological disposal of radwaste
  - Large time scales
  - Multiple spatial scales (near field, far field)
  - Many processes involved, some of these are strongly coupled
- Complexity ?
  - Multidisciplinary rather than intrinsically complex
  - Large uncertainties, emphasize robust modelling (simplifications)
- How COMSOL Multiphysics fits in the picture
  - **VERSATILITY**: 1 toolbox, many possible uses in R&D programme
    - **Thermal evolution of the far field** (this presentation)
    - **Phenomenological analysis**: **near field THM**, buffer THMC, **chemo-osmosis**, reactive transport, **unsaturated flow**, multiphase flow,…
    - **Performance Assessment: radionuclides release & transport**

Thank YOU for your attention.

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the Belgian National Radioactive Waste Agency,

for continued support & funding.