Modelling an Underground Nuclear waste Repository

From the Near Field
To
the Far Field Model
Main steps and challenges

Alain Bourgeat
UCB-Lyon1, CNRS UMR 5028, GDR MoMaS

Modelling an Underground Nuclear waste Repository

- What is a Nuclear waste site (exemple)
- Near Field versus Far Field modelling
- Some problems for Scaling Up the source terms

Geological Storage

where

- Host rock: Brine, Clay, Granite, Argilite, …

Who (high level, long lived)

- high level of activity and/or long lived elements
  - B Type : low or medium activity level, but long life time
  - C Type : high activity level, T° > 80 °C
- come mainly from industrial activities(power plants)

Numbers:

- For instance (in France)
  - Expected Total volume of nuclear waste (including containers) in 2020: 100 000 m^3
  - Total length of galleries, tunnels,needed in 2020: 102 km
  - Only the high activity waste will be stored in a geological repository :
    - More than 25 isotopes
    - Some of them have a life time of 1 000 000 years

Question before deciding a Geological Storage for Nuclear waste

- What is the possible **evolution**, and **impact** on the biosphere, of such an underground storage ?
  - Real experiments are not possible at these scales of both time (> 500 years) and space (1X25 X 25 km^3)
  - Only predictions based on numerical simulations are possible

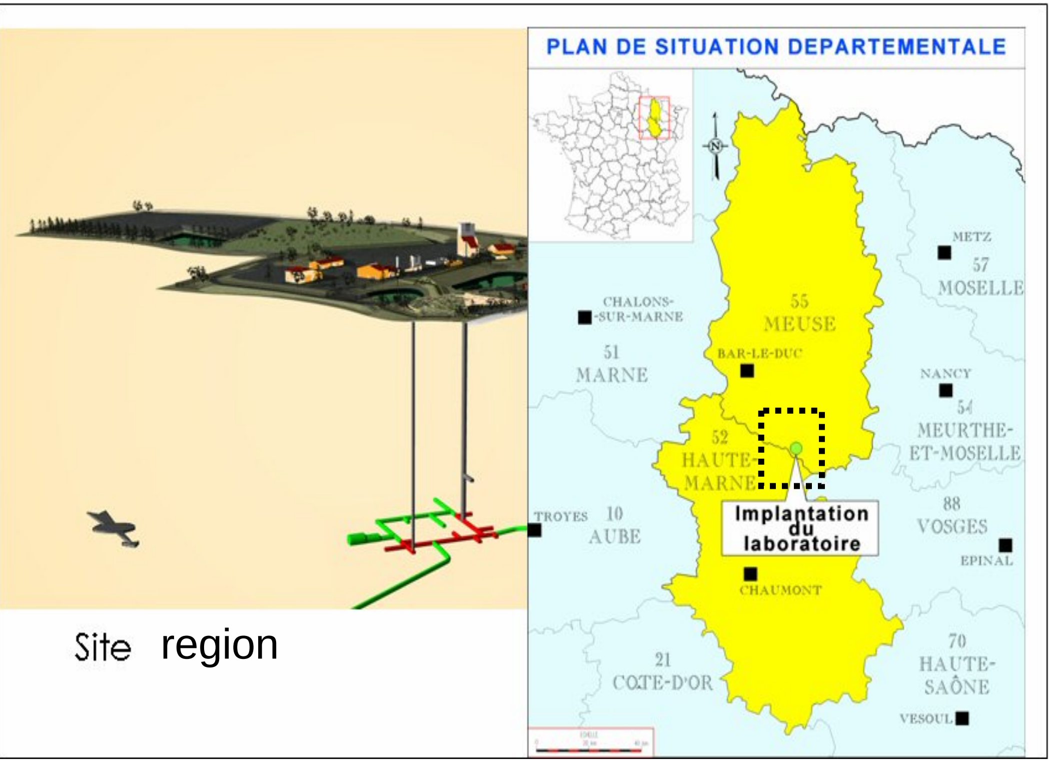
Predictions based on numerical simulations **??**

- There are well established models, but at usual scales of measurement (meters, years)

- Two types of simulations:
  - One based on Near Field (mainly for performance assessement)
  - and one based on Far Field models (mainly for safety analysis)

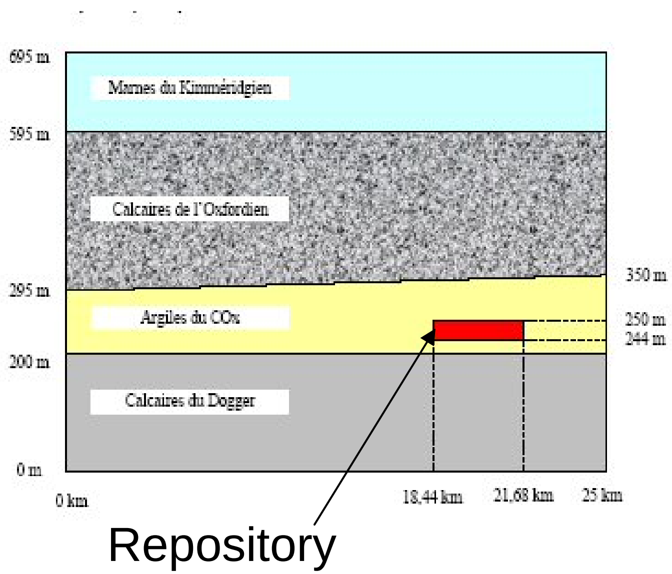
Far Field
1X25 X 25 km^3 and > 500 years

Far field region



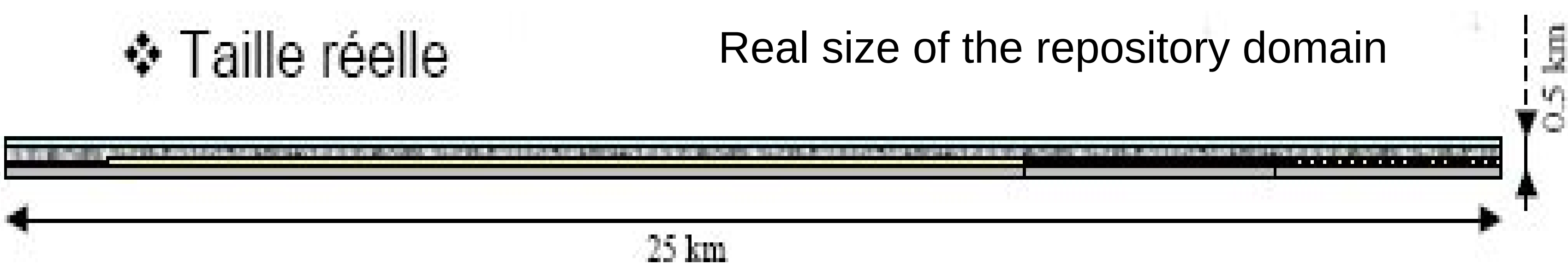
Site region

Far field domain of computation



Far Field
1X25 X 25 km^3 and > 500 years

– Numerical simulations and predictions based on **MACROmodels**:
  - Diffusion/Dispersion, Convection, Reaction (by mean of a Retardation factor)
  - The repository is reduced to a very thin homogeneous « source » zone



Real size of the repository domain

Far Field Simulations

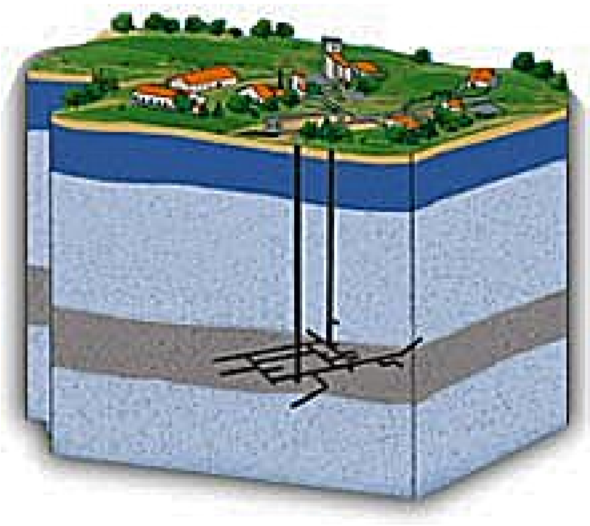
– MACRO model:

- Diffusion/Dispersion, Convection, Reaction (by mean of a Retardation factor)

1 General Equations

$$R\omega\frac{\partial\rho}{\partial t} - \nabla\cdot(\mathbf{A}\nabla\rho) + (\mathbf{V}\cdot\nabla)\rho + \lambda R\omega\rho = 0 \qquad (1)$$

- R the latency retardation factor,
- ω the porosity,
- v the Darcy's velocity
- $\lambda = \frac{\log 2}{T}$; T the element radioactivity half life time
- Iodine ^{129}I has half life time $T = 1.57\ 10^7$ years and is releasing during a time $t'_m = 8\ 10^3$ years, with intensity $\Phi' = 10^{-1}$.



Far Field Models

– **MACROSCOPIC** models need to be derived from the **mesoscopic** level, including :

geochimical effects in rocks with highly contrasted properties (possibly fractured) for various velocity ratio (reaction / diffusion/flow)

geomechanical effects after drilling shafts and tunnels

emission from each container or vault

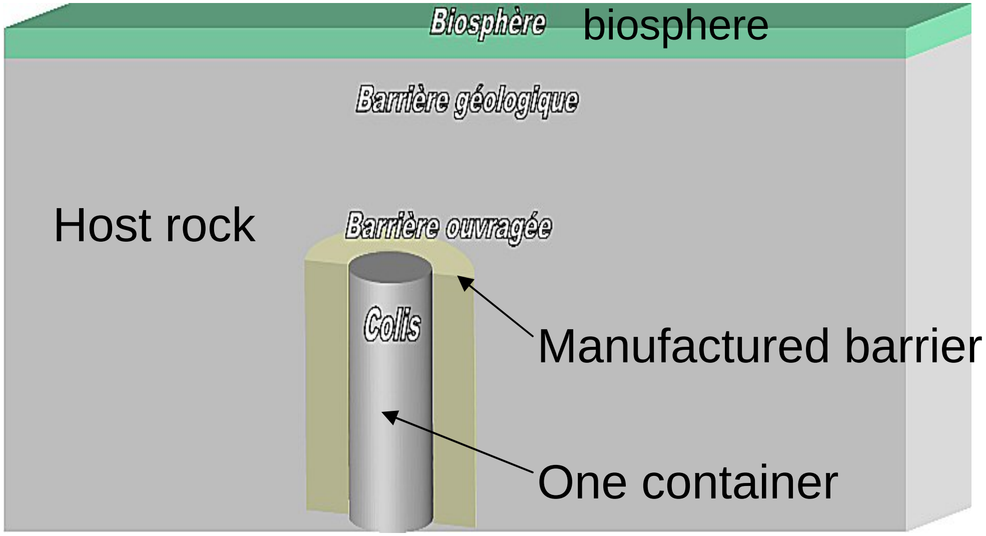
…….

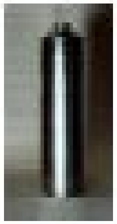
Near Field

Waste

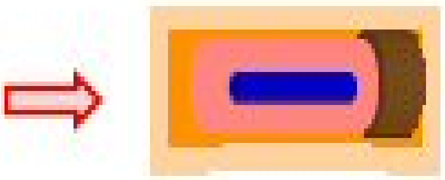
- Inside a matrix (glass, concrete, tar)
- Protected by a container (steel, concrete)
- Surrounded by manufactured barriers (bentonite, concrete, …)
- Containers grouped in a Vault
- Vaults are connected by tunnels, galleries, drifts and shafts

Near Field - Containers

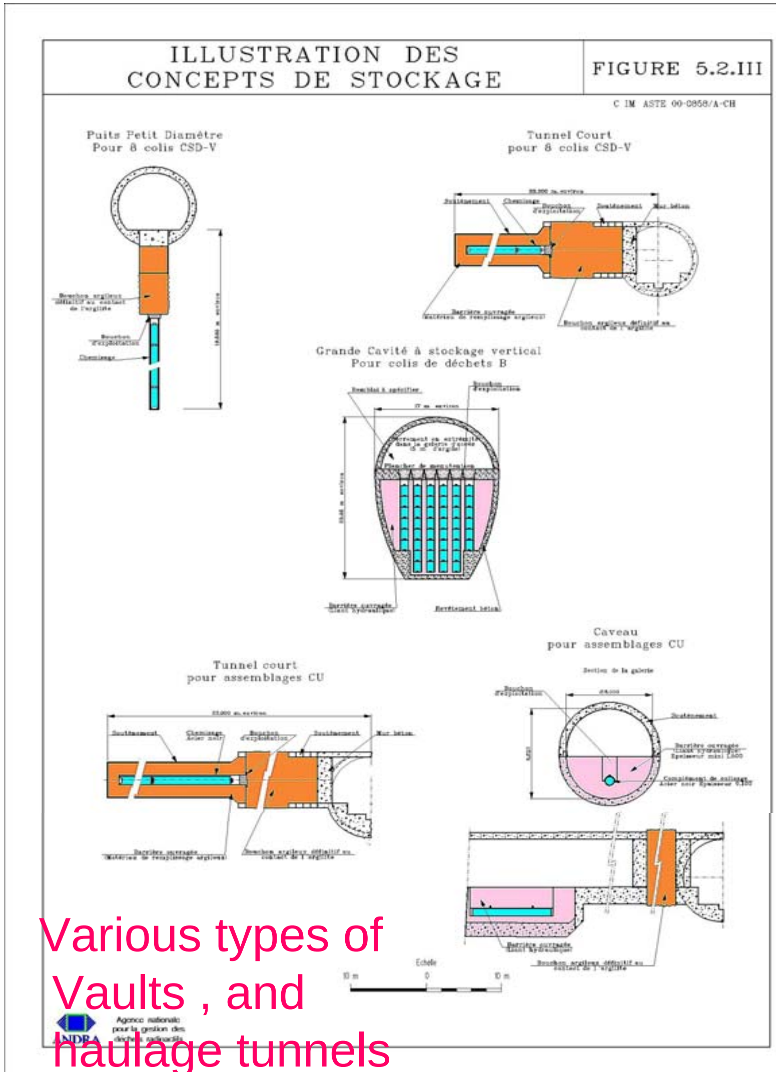




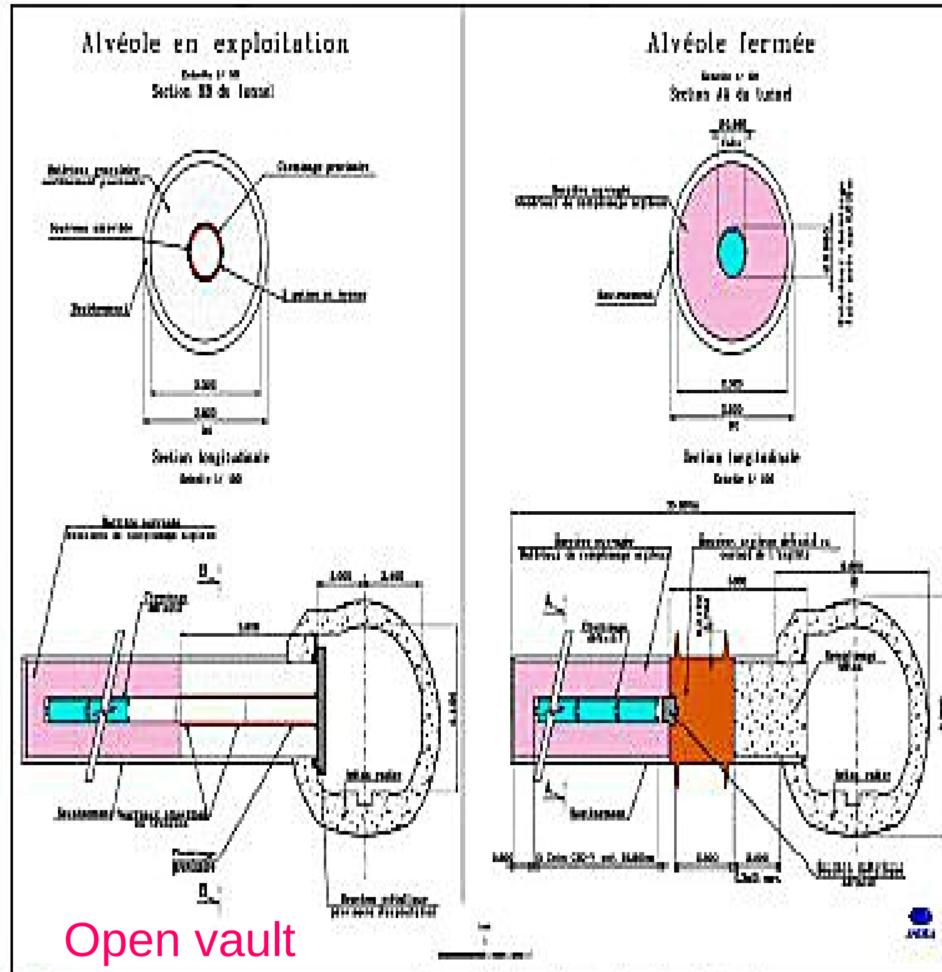
A container
inside a vault



Near Field - Vaults



Various types of Vaults , and haulage tunnels

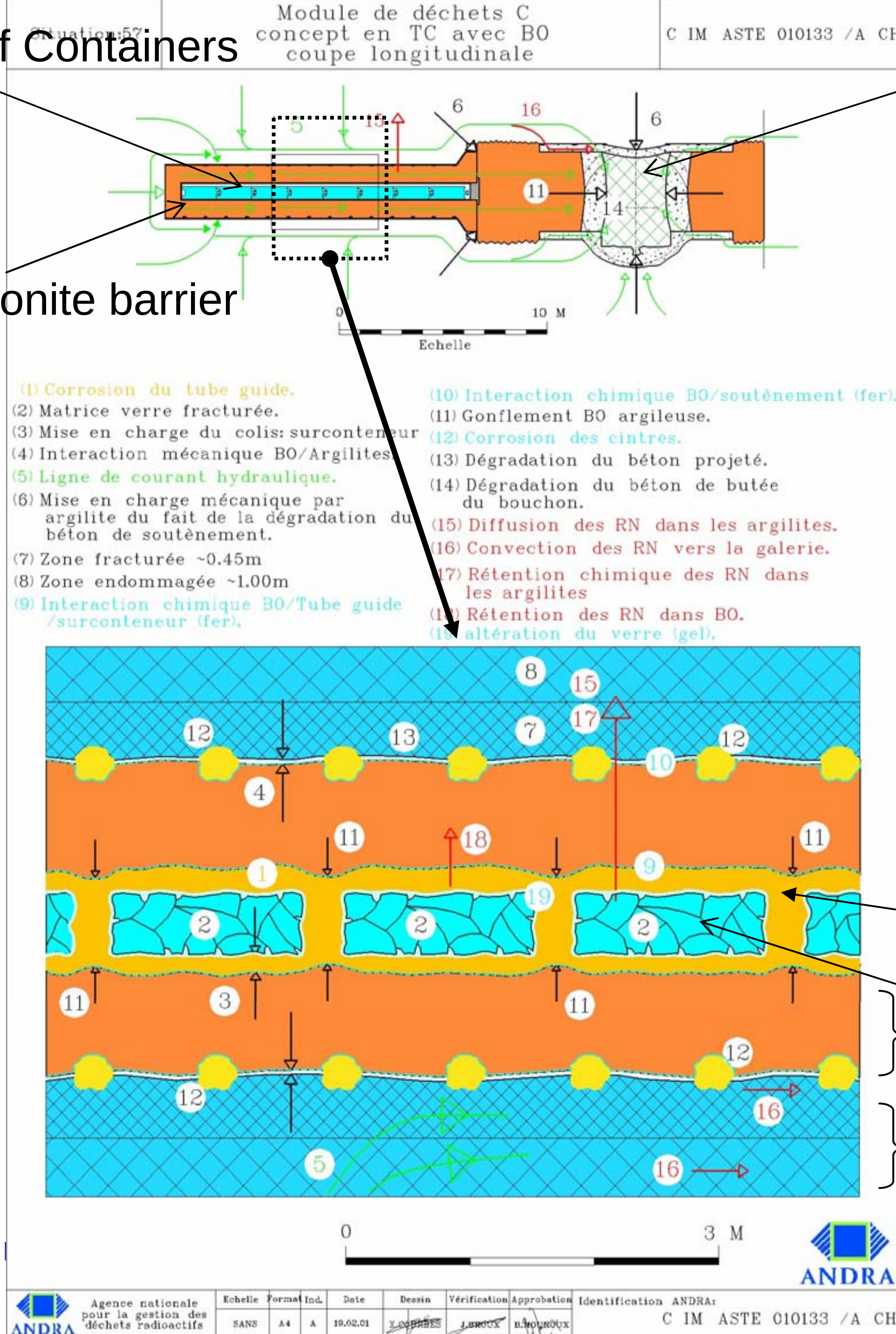


Open vault with a set of containers

closed vault

Near Field Modelling

– Vault dimensions ≈ 1 m diameter, length: 10m
– **Numerical simulations** and **predictions** based on **mesoscopic models** including:
  - T-H-M-C couplings
  - Coupling of different materials (steel, glass, concrete, bentonite, clay, ….)
  - Adsorption / desorption
  - Hydrogen production
  - …..



Set of Containers

haulage tunnel

Bentonite barrier

Containers set , vault, with a haulage tunnel

Disturbed Containers set, (after n10^3 years)

backfill

Broken container and matrix

Bentonite barrier after swelling

Damaged zone of the host rock

Near Field Models

– These **MESOSCOPIC** models need to be derived from the **microscopic** level, specially :

- geomechanical properties of rocks
- coupling transport/reaction
- adsorption/desorption
- swelling of bentonites

…….

Far Field versus Near Field

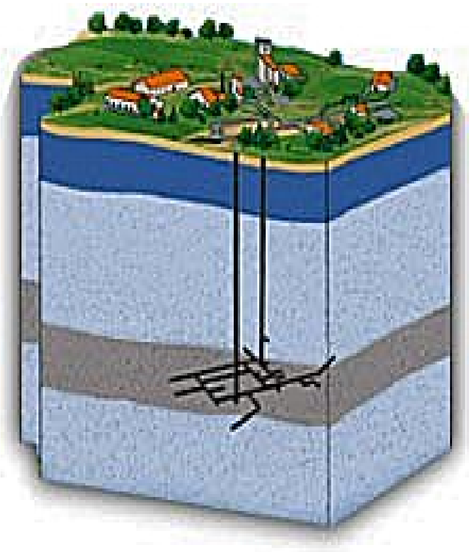
Near Field model

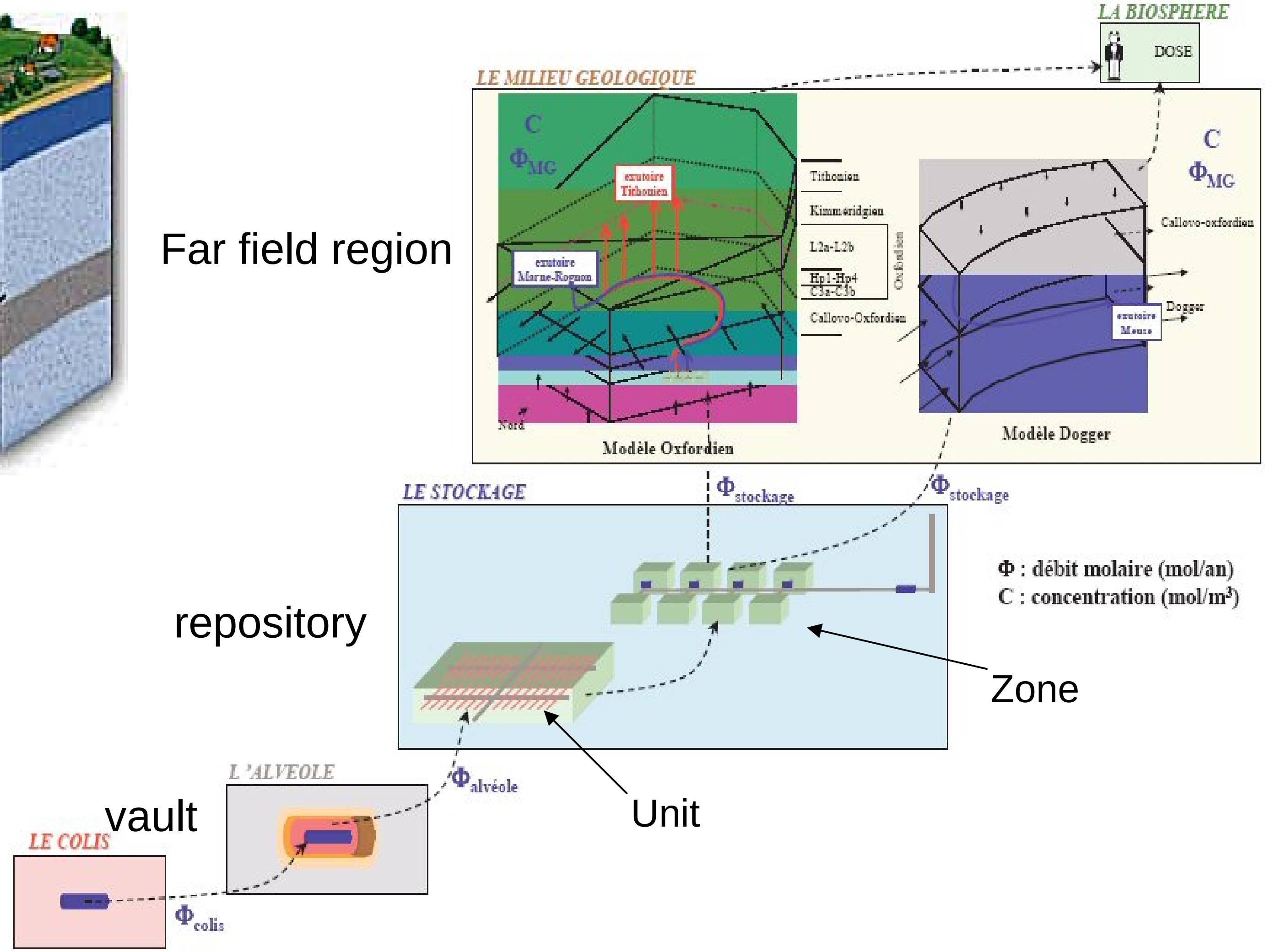
- to be derived from « microscopic » models

Far Field model

- to be derived from Near Field models

Far Field vs. Near Field

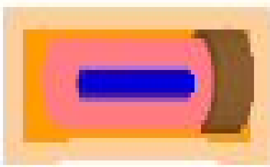




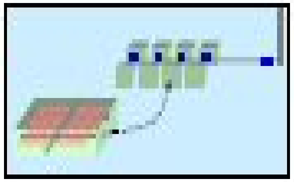
Far Field vs. Near Field

Scaling Up the Sources

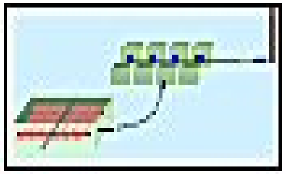
vault



Unit / Zone

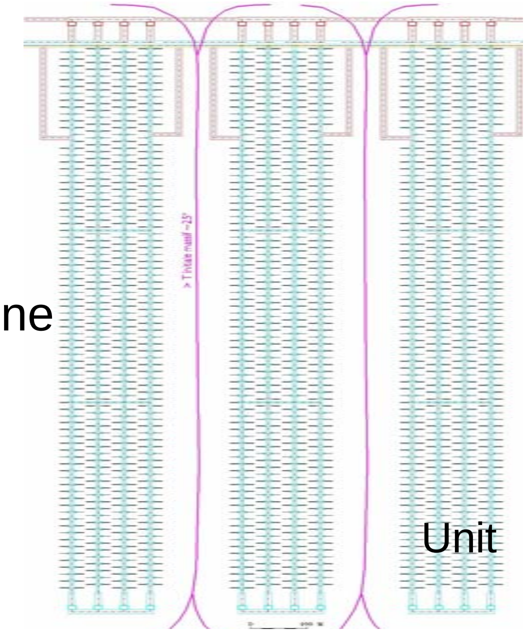


Unit / Zone



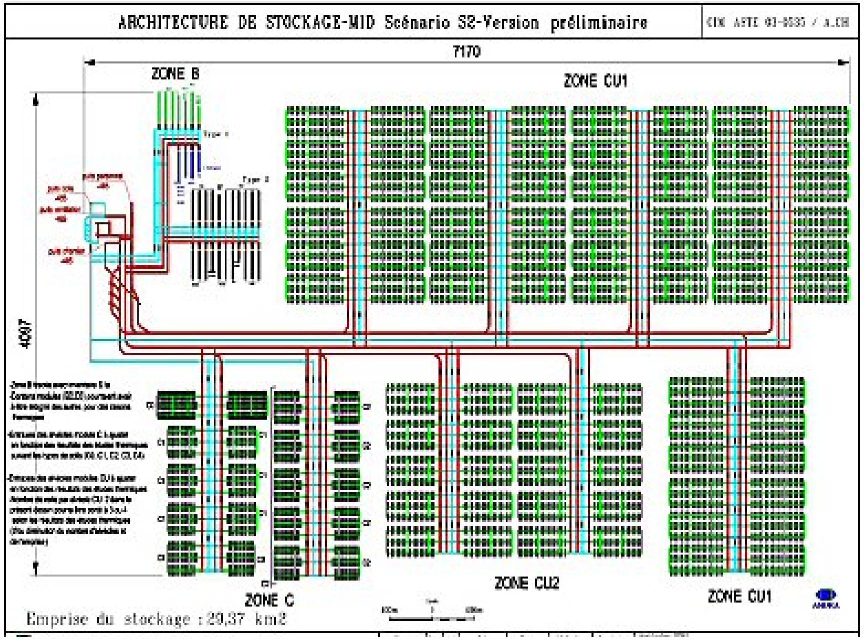
Far field Region

Zone



Unit

Repository



Scaling Up the Sources

There are several levels of upscaling

- from **waste packages** to a **storage unit** global model
- from **storage units** to a **zone** model
- from **similar zones** to the **repository** global model

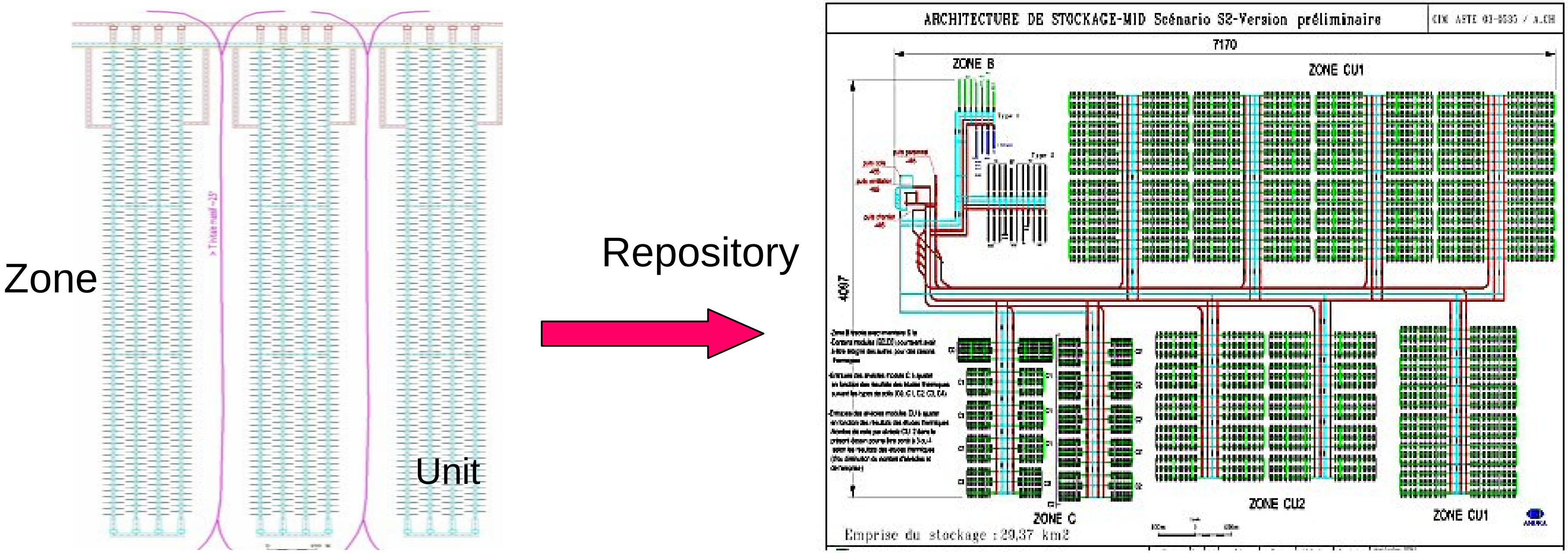
One way would be to use Re-iterated Homogenization,

but :

the **phenomena to be taken in account at each level are different** leading to different equations parameters or boundary conditions

- ***First example of Scaling Up:***
- From the **STORAGE UNITS** to a "**ZONE** global model"
- OR, From Similar **ZONES** to the "**REPOSITORY** global model"

A.B., O. Gipouloux, E. Marusic-Paloka. Mathematical Modeling of an underground waste disposal site by upscaling. Math. Meth. Appli. Sci., Volume 27, Issue 4; March 2004, p 381-403.



from storage units to a zone model
(or from **similar zones** to the **repository**)

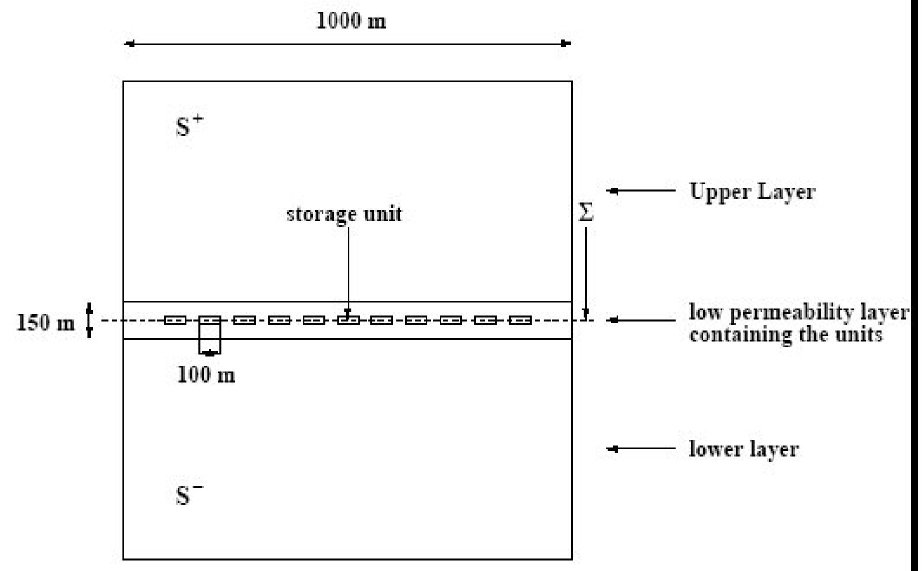
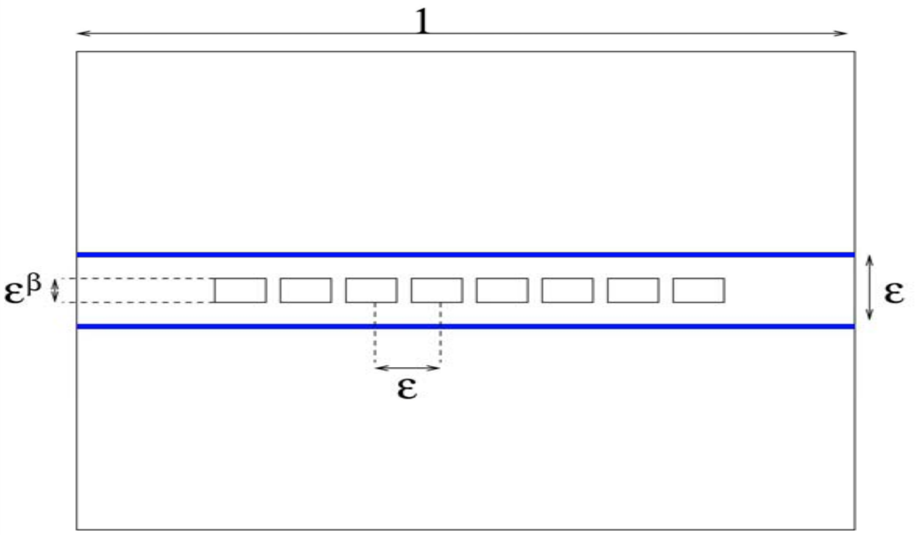


Figure 4: The three geological layers containing the Storage Units



Rescaled domain section

Real domain section

from **storage units** to a **zone** model
(or from **similar zones** to the **repository**)

2 The Equations

$$\omega^{\varepsilon}\,\frac{\partial \varphi_\varepsilon}{\partial t} - \mathrm{div}\,(\mathbf{A}^{\varepsilon}\nabla\varphi_\varepsilon) + (\mathbf{v}^{\varepsilon}\cdot\nabla)\varphi_\varepsilon + \lambda\,\omega^{\varepsilon}\,\varphi_\varepsilon = 0 \quad \text{in} \quad \Omega_\varepsilon^T \tag{2}$$

$$\varphi_\varepsilon(0,x) = \varphi_0(x) \quad x \in \Omega_\varepsilon \tag{3}$$

$$\mathbf{n}\cdot\sigma = \mathbf{n}\cdot(\mathbf{A}^{\varepsilon}\nabla\varphi_\varepsilon - \mathbf{v}^{\varepsilon}\,\varphi_\varepsilon) = \Phi(t) \quad \text{on}\ \Gamma_\varepsilon^T \tag{4}$$

$$\varphi_\varepsilon = 0 \quad \text{on} \quad S_1, \tag{5}$$

$$\mathbf{n}\cdot(\mathbf{A}^{\varepsilon}\nabla\varphi_\varepsilon - \mathbf{v}^{\varepsilon}\,\varphi_\varepsilon) = 0 \quad \text{on} \quad S_2 \tag{6}$$

with

$$\mathbf{A}^{\varepsilon}(x_2) = \mathbf{A}(\frac{x_2}{\varepsilon});\ \mathbf{v}^{\varepsilon}(x,t) = \mathbf{v}(x,\frac{x_2}{\varepsilon},t);\ \omega^{\varepsilon}(x_2) = \omega(x_2/\varepsilon). \tag{7}$$

from storage units to a zone model

(or from **similar zones** to the **repository**)

The Zone « global model »

$$\omega^2 \frac{\partial \varphi}{\partial t} - \mathrm{div}\,(\mathrm{A}^2 \nabla \varphi) + (\mathrm{v}^2 \cdot \nabla)\varphi + \lambda \omega^2 \varphi = 0 \text{ in } \tilde{\Omega}^T \qquad (8)$$

$$\varphi(x, 0) = \varphi_0(x) \quad x \in \tilde{\Omega} = \Omega \backslash \Sigma \qquad (9)$$

$$\varphi = 0 \quad \text{on} \quad S_1 \qquad (10)$$

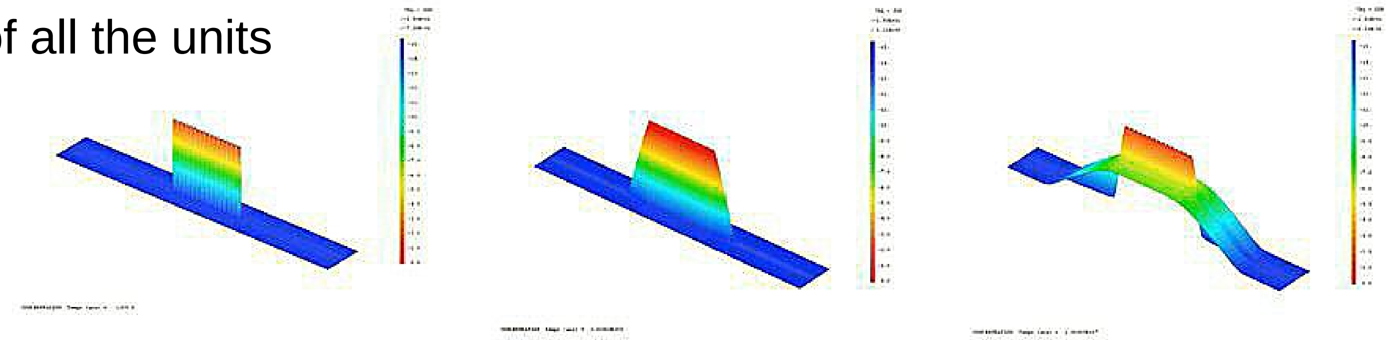
$$\mathbf{n} \cdot (\mathrm{A}^2 \nabla \varphi - \mathrm{v}^2 \varphi) = 0 \quad \text{on} \quad S_2 \qquad (11)$$

$$[\varphi] = 0 \quad , \quad [\mathrm{e}_2 \cdot (\mathrm{A}^2 \nabla \varphi - \mathrm{v}^2 \varphi)] = -|\tilde{M}|\Phi \quad \text{on} \quad \Sigma \ , \qquad (12)$$

where $[\cdot]$ denotes the jump over Σ, and $|\tilde{M}|$ stands for the limit of a normalized unit $\mathcal{M}_\varepsilon$ area.

from storage units to a zone model
(or from **similar zones** to the **repository**)

Simulation of all the units



Niveaux de concentration aprés1209, 300 000 et 1 000 000 d'années; obtenus par simulations à partir du modèle détaillé (en haut) et du modèle « homogénéisé » (en bas)

Simulation of the zone « global model »

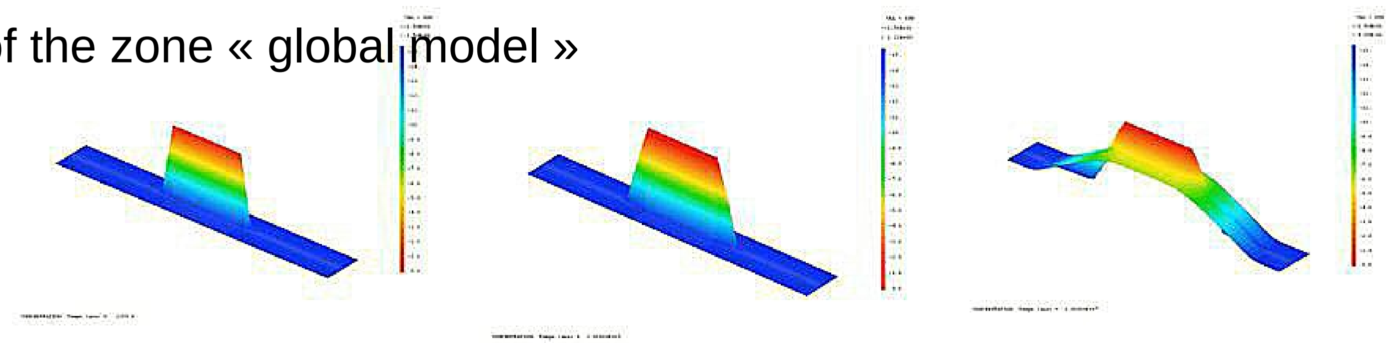
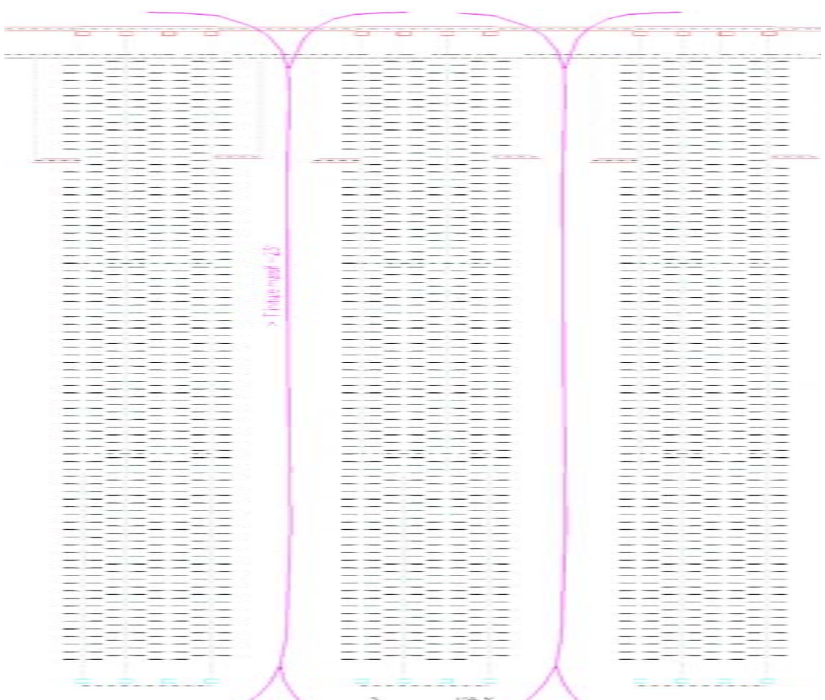


Fig.10 : ***Comparaison des niveaux de concentration en Iode129,*** *obtenus par une simulation détaillée à une échelle fine et ceux obtenus par une simulation basée sur le modèle « homogénéisé » correspondant. Malgré son caractère « global », cette dernière simulation, moins détaillée, rend cependant bien compte des pics de concentration, au voisinage des conteneurs.*

Second example of Scaling Up:

- From a " **WASTE PACKAGES** model" to a "**Storage UNIT** Global model", including a possibly **damaged zone (*A. B, E. Marusic-Paloka. A homogenized model of an underground waste repository including a disturbed zone. To appear in SIAM J.on Multiscale Modeling and Simulation, 2005.)***



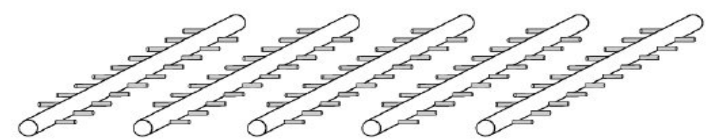
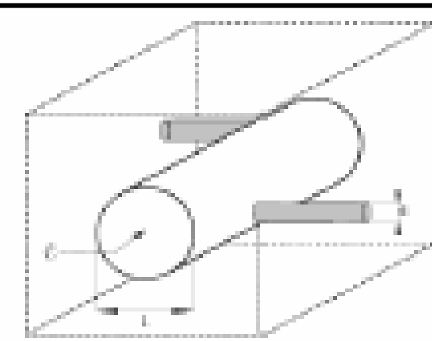


Figure 13: A part of a Storage Unit, with 5 rows of waste packages (or containers sets) along shafts



From a " WASTE PACKAGES model" to a "**Storage UNIT** Global model", including a possibly **damaged zone**

The "Mesoscospic" model of a storage unit

$$\omega^\varepsilon \frac{\partial \varphi_\varepsilon}{\partial t} - \operatorname{div}(\mathbf{A}^\varepsilon \nabla \varphi_\varepsilon) + (\mathbf{v}^\varepsilon \cdot \nabla)\varphi_\varepsilon + \lambda \omega^\varepsilon \varphi_\varepsilon = 0 \quad \text{in } \Omega_\varepsilon^T \quad (13)$$

$$\varphi_\varepsilon(0,x) = \varphi_0(x) \quad x \in \Omega_\varepsilon \quad (14)$$

$$\mathbf{n} \cdot (\mathbf{A}^\varepsilon \nabla \varphi_\varepsilon - \mathbf{v}^\varepsilon \varphi_\varepsilon) = \Phi_\varepsilon(t) \quad \text{on } \Gamma_\varepsilon^T \quad (15)$$

$$\mathbf{n} \cdot (\mathbf{A}^\varepsilon \nabla \varphi_\varepsilon - \mathbf{v}^\varepsilon \varphi_\varepsilon) = \kappa \ (\varphi_\varepsilon - g_\varepsilon) \quad \text{on } \mathcal{K}_\varepsilon^T \cup \mathcal{H}_\varepsilon^T \quad (16)$$

$$\varphi_\varepsilon = 0 \quad \text{on } \mathcal{Z}_\varepsilon^T \ . \quad (17)$$

$\mathcal{Z}_\varepsilon^T$ the Drifts Bottoms (sealed), $\mathcal{H}_\varepsilon^T$ the drifts tops and $\mathcal{K}_\varepsilon^T$ the rest of the exterior boundary of Ω,Γ_ε the Waste Packages boundary $\times(0,T)$;

g_ε measure the concentration entering at the drifts tops. A parameter β is introduced for characterizing the degree of damaging by mean of the Darcy's velocity range .

From a " **WASTE PACKAGES** model" to a "**Storage UNIT** Global model", including a possibly **damaged zone**

($\varepsilon^{-\beta}$ characterize the Darcy's velocity range inside the drifts)

$$\mathrm{v}^{\varepsilon}(x) = \begin{cases} \mathrm{v}^{h}(x) \ \text{ in the host rock } \ \Omega_{\varepsilon} \backslash \mathcal{S}_{\varepsilon} \\ \varepsilon^{-\beta}\, \mathrm{v}^{d}(x', x_2/\varepsilon; x_3/\varepsilon) \ \text{ in the drifts } \ \mathcal{S}_{\varepsilon} \end{cases} .$$

The Diffusion/Dispersion

$$\mathrm{A}^{\varepsilon}(x) = \begin{cases} \mathrm{A}^{h}(x) \ \text{ in the host rock } \ \Omega_{\varepsilon} \backslash \mathcal{S}_{\varepsilon} \\ d(x)\, \mathrm{I} + \varepsilon^{-\beta}\, \mathrm{A}^{d}(x_2, x_2/\varepsilon, x_3/\varepsilon) \ \text{ in the drifts } \ \mathcal{S}_{\varepsilon} \end{cases} .$$

THEN:

in the corresponding Macroscopic model *Depending on β(characterizing the degree of damaging, i.e. the Darcy's velocity range) we have three different cases.*

From a " WASTE PACKAGES model" to a "**Storage UNIT** Global model", including a possibly **damaged zone**

- $0 \leq \beta < 1$; The storage site is undisturbed.

The drifts do not make any contribution, i.e. the repository behaves as if they were not there. $\varphi_\varepsilon \to \varphi$ the solution of an equation, similar to the one associated to the mesoscopic model.

- $\beta = 1$; galleries and drifts with damaged sealings.

The transport processes, inside and outside the "damaged" drifts are comparable and there are interactions between them.

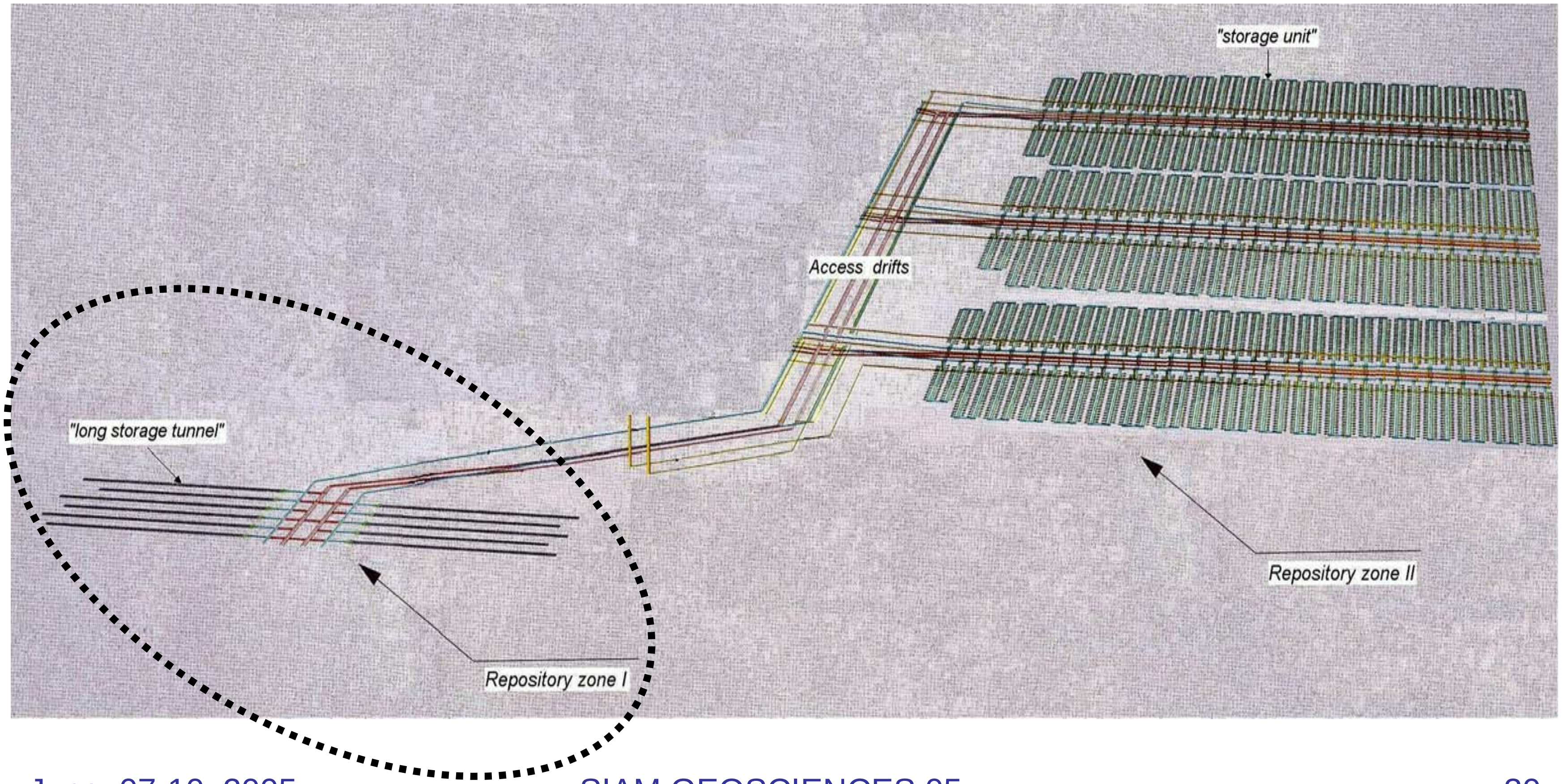
- $2 > \beta > 1$; The storage site is highly disturbed.

The Transport process in the drifts is dominant and we do not see anything else outside the drifts in the corresponding global model .

Third exemple of Scaling Up:

- From the **LONG STORAGE UNITS** to a "**ZONE** global model"

***A.B., jointly with A. Piatnitski and E. Marusic-Paloka. ; work in progress*.**



Third exemple of Scaling Up:

- From the **LONG STORAGE UNITS** to a "**ZONE** global model" (***A.B., jointly with A. Piatnitski and E. Marusic-Paloka. ; work in progress*.)**
  - The repository zone, is made of a high number of similar long waste filled storage units, lying on a hypersurface Σ and linked by backfilled working and haulage drifts. .
  - Like previously, the parameter β characterize de degree of damaging (scaling the Darcy's velocity range)
  - The main difference and difficulties compared to the previously studied situations, is the singular behavior of the only one damaged drift. In the first exemple there was no damaged zone at all, while in the second one the damaged drifts were periodically repeated, allowing to use the technique of singular measures.
  - ***The global models only slightly differ; depending on β; the global model is independent of the choice of β and only higher order correctors terms differ, according to β.***

Fourth example of Scaling Up:

• The contents, and the leaking starting time of the Waste Packages are Random

A.B., jointly with A. Piatnitski; work in progress

The "local sources" $\boldsymbol{f}^{\varepsilon}$ are periodically repeated, lying on a plan Σ the **contains**, the **leaking starting time** and the **emission time evolution**, of each local source, are random :

$$f^{\varepsilon}(x,t) = \mathbb{I}_{B_\varepsilon} \frac{1}{\varepsilon^{\gamma}} f(T_{x'/\varepsilon}\omega, t)$$

$$\partial_t u^{\varepsilon} - \mathrm{div}(a(x)\nabla u^{\varepsilon}) + \mathrm{div}(b(x)u^{\varepsilon}) = f^{\varepsilon};$$

$$u^{\varepsilon}\big|_{t=0} = 0, \qquad \frac{\partial}{\partial n_a} u^{\varepsilon} \cdot n(x) - b(x)\cdot n(x) u^{\varepsilon} + \lambda u^{\varepsilon} = 0.$$

THE END *Finally !!*

- *Thank you for your attention*

Avignon, France