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Hydromechanical modeling and numerical simulation of self-sealing phenomena in the Callovo-Oxfordian claystone

EGU - Session ERE5.5

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Eric Lemarchand^b, Luc Dormieux^b

April, 13th 2018

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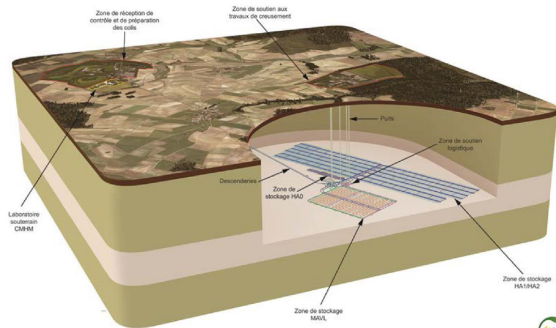
- 1 Context and objectives
- 2 Modeling the CDZ experiment
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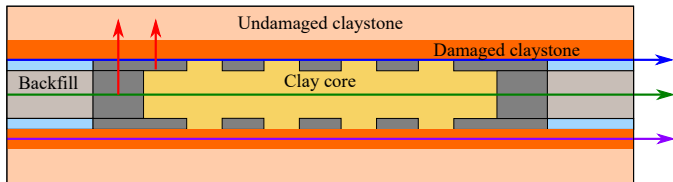
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Echelle des ouvrages non respectée.
Pendage des formations géologiques non représenté.



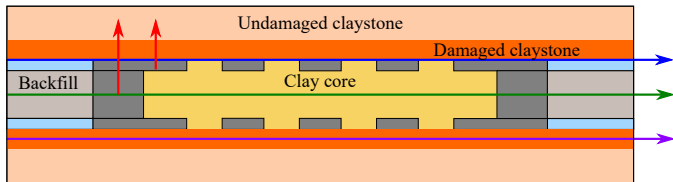
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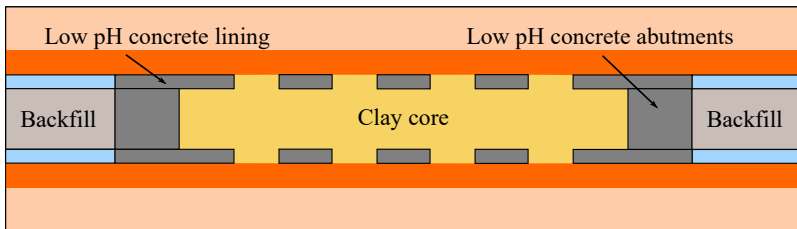


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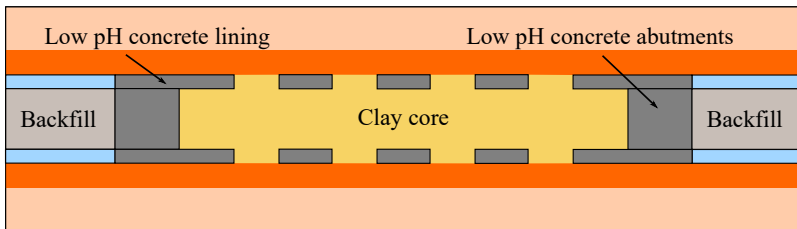
- Goal for the overall hydraulic conductivity of the seals + galleries : $< 10^{-9} \text{ m} \cdot \text{s}^{-1}$ (Bauer et al. [2])

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- **Objective** : Predict the evolution of the damaged zone around a horizontal sealing during the resaturation phase

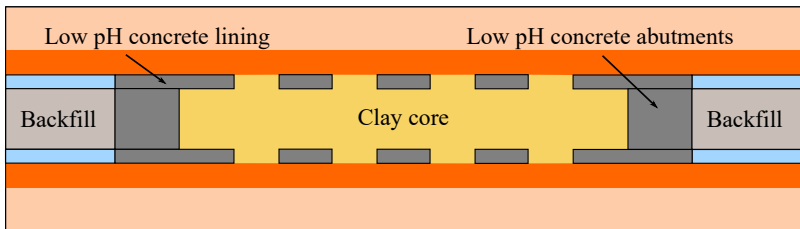


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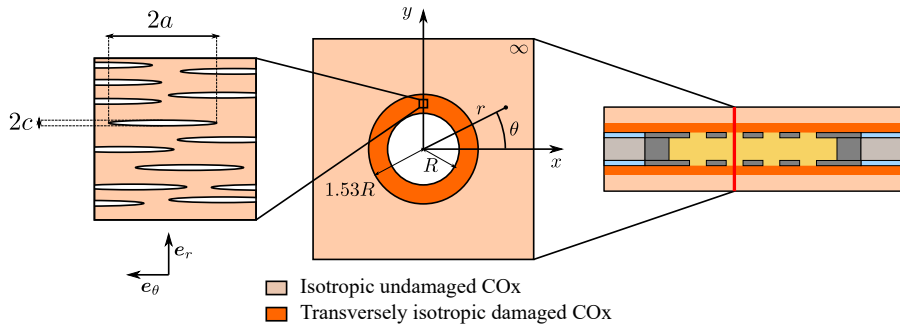
- **Hydromechanical coupling**

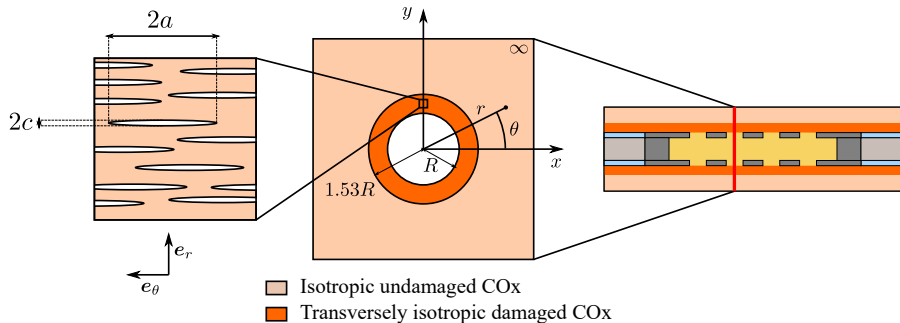
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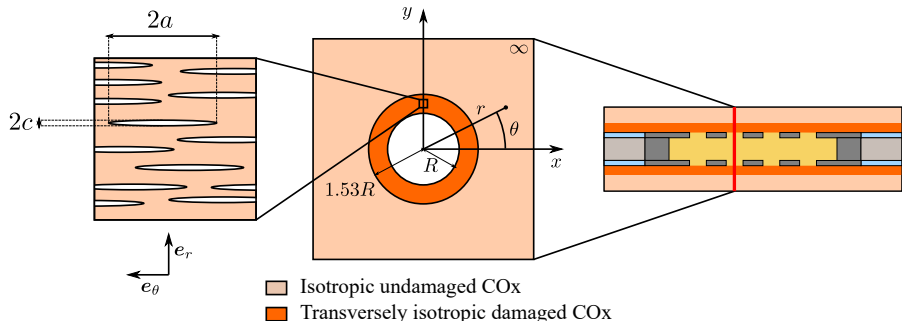
- **Hydromechanical coupling**
- Resaturation takes place over thousands of years \Rightarrow need to take into account the **viscoplastic** behavior of the claystone (not considered in the following, see perspectives)

- 1 Context and objectives
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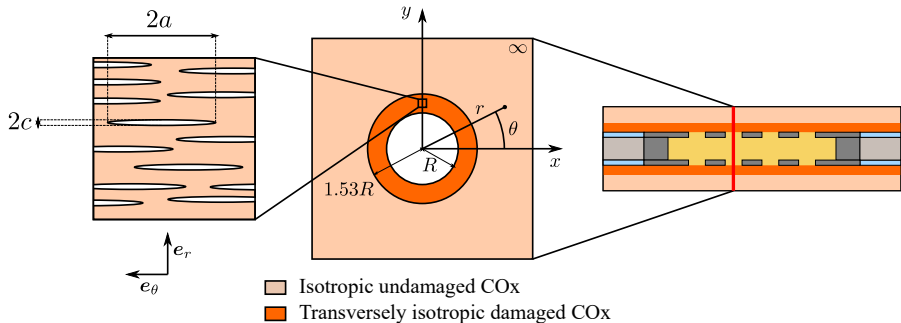


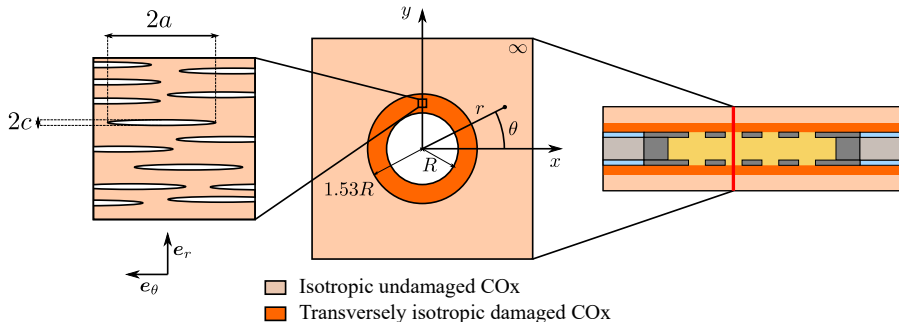


- Circular damaged zone with thickness $0.53R$ (ensures correct cross-sectional area)

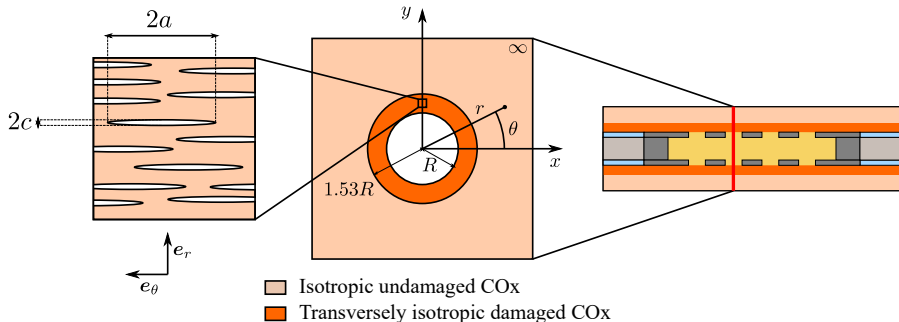


- Circular damaged zone with thickness $0.53R$ (ensures correct cross-sectional area)
- Mode I cracks parallel to the drift walls (normal = e_r), mode II cracks disregarded

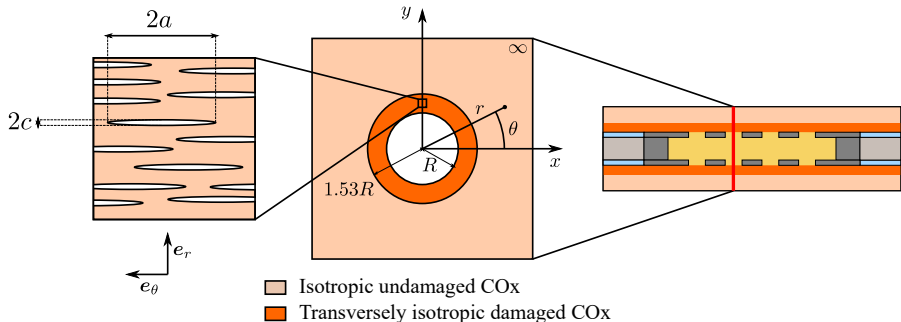




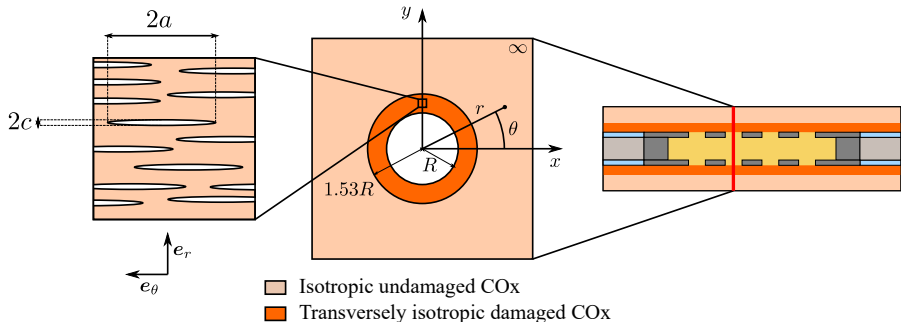
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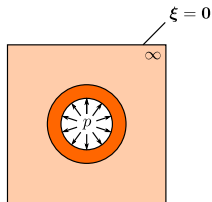
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- Cracks remain open during the experiment (ensures linearity)

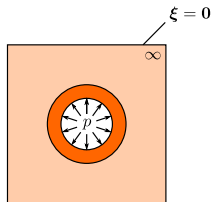
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 - Problem (i) : $p = 4$ MPa pressure prescribed at $r = R$

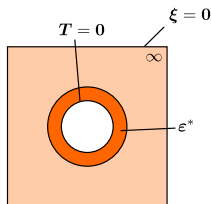


(a) Problem (i).

- Two kinds of loading in the CDZ experiment :
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 - Problem (ii) : wetting and thus stress-free strain $\varepsilon^* = g(r)\mathbf{1}$ in the damaged zone, and $\boldsymbol{\sigma} \cdot \mathbf{n} = \mathbf{0}$ at $r = R$
- NB : Swelling leads to divergence of the drift walls and thus zero displacements at the boundary would lead to unrealistic surface tractions at $r = R$



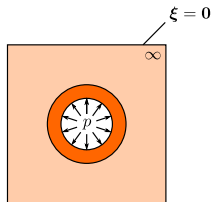
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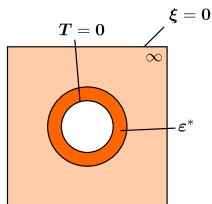
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- Geometry, material behavior, loading
 \Rightarrow Rotational symmetry around \mathbf{e}_z



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$$\dot{\boldsymbol{\Sigma}} = \mathbb{C}^{Dam}(\boldsymbol{\Sigma}) : (\dot{\boldsymbol{E}} - \dot{\boldsymbol{\varepsilon}}^*)$$

- The crack opening variation is derived (Deudé [5]) :

$$\dot{c} = c \left(\overline{\dot{\boldsymbol{\varepsilon}}}^c : \mathbf{n} \otimes \mathbf{n} \right) = aX \left(\overline{\dot{\boldsymbol{\varepsilon}}}^c : \mathbf{n} \otimes \mathbf{n} \right)$$

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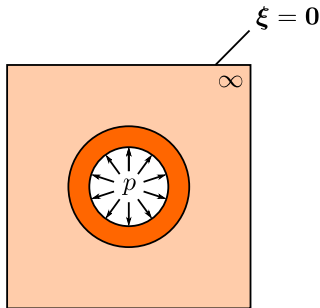
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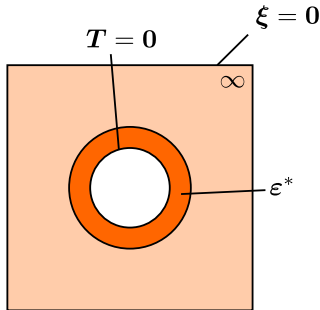
$$\begin{aligned} \dot{c} &= \left[\mathbb{T} : \left(\mathbb{I} + \frac{4\pi}{3} d\mathbb{T} \right)^{-1} : \left(\dot{\mathbf{E}} - \dot{\boldsymbol{\varepsilon}}^* \right) \right] : (\mathbf{an} \otimes \mathbf{n}) \\ &= \left[\mathbb{T} : \mathbb{C}^{COx-1} : \dot{\boldsymbol{\Sigma}} \right] : (\mathbf{an} \otimes \mathbf{n}) \end{aligned}$$

- Integrated equations (no propagation of cracks) :

$$\begin{cases} \Sigma = \mathbb{C}^{Dam} : (\mathbf{E} - \boldsymbol{\varepsilon}^*) \\ \Delta X = \frac{\Delta c}{a} = [\mathbb{T} : \mathbb{C}^{COx-1} : \Sigma] : (\mathbf{n} \otimes \mathbf{n}) \end{cases}$$



(a) Problem (i) : prescribed pressure.



(b) Problem (ii) : prescribed stress-free strain.

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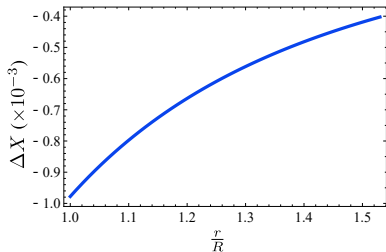
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- Equation of equilibrium yields a second order ordinary differential equation
- Exact analytical solution if $g(r)$ is a polynomial function of r
- If g is only assumed to be continuous, it can be approximated by a polynomial function \Rightarrow yields an approximate solution

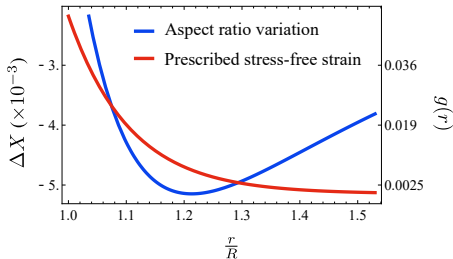
Parameter	Value	Reference
E^{COx} (MPa)	5000	Pham [7]*
ν^{COx} (-)	0.2	Pham [7]*
d (-)	10^{-3}	arbitrary
ε^* (-)	10^{-2}	Zhang et al. [8]**
$p^{swelling}$ (MPa)	4	Andra [1]

*These are averaged values estimated using the measurements before desaturation and after resaturation

**This is the average prescribed strain over the damaged zone. Much higher strains are observed under free swelling conditions and much lower under high triaxial confining stresses so a conservative value of 1% was chosen

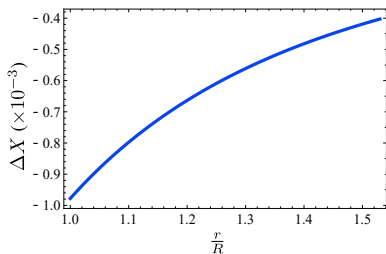


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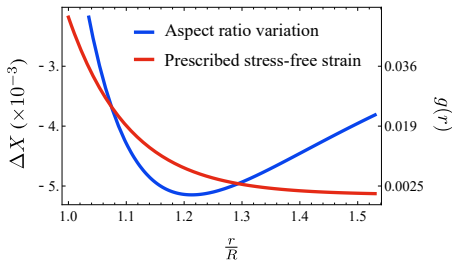


(b) Problem (ii).

FIGURE – ΔX as a function of $\frac{r}{R}$ for problems (i) and (ii).



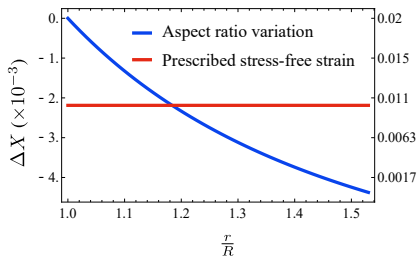
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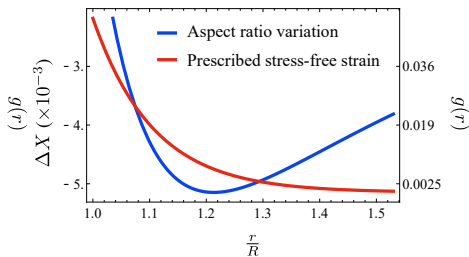
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FIGURE – ΔX as a function of $\frac{r}{R}$ for problems (i) and (ii).

$|\Delta X|$ max is roughly five times greater for problem (ii) than for problem (i)

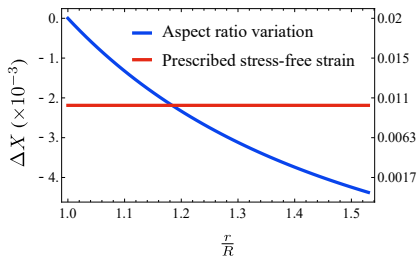


(a) Homogeneous stress-free strain.

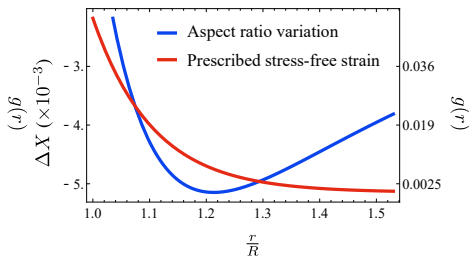


(b) Exponentially decaying stress-free strain.

FIGURE – ΔX as a function of $\frac{r}{R}$ for two different functions $g(r)$ with the same average value.



(a) Homogeneous stress-free strain.



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FIGURE – ΔX as a function of $\frac{r}{R}$ for two different functions $g(r)$ with the same average value.

Different monotony but same order of magnitude for $|\Delta X|_{\max}$

- Note that $|\Delta X|$ max does not depend much on d for problem (ii) ($5.023 \cdot 10^{-3}$ for $d = 10^{-1}$ and $5.148 \cdot 10^{-3}$ for $d = 10^{-6}$) and even less for problem (i) ($9.77848 \cdot 10^{-4}$ in both cases) so a median value of 10^{-3} was chosen arbitrarily

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- Taking the value $a = 250$ mm (Hawkins et al. [6]) for the lateral extent of the cracks yields crack opening variations of -0.5 mm and -2.6 mm for problems (i) and (ii) respectively

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- This is consistent with *in situ* observations of initial crack openings on the order of the millimeter

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- Simple model but yields interesting insights into the phenomenon of self-sealing at the scale of the drift

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- The crack closure was found to be a non-monotonous function of depth for an exponentially decaying stress-free strain
- A mean 1% stress-free strain was found to lead to better self-sealing than the 4 MPa swelling pressure developed by the swelling clay core
- Results consistent with *in situ* observation that water injection is more efficient than pure mechanical closure

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- The stress-free strain was prescribed, when it is in fact the result of a coupled hydromechanical response (the amount of water a sample is able to take in depends on the confining stress which in turn depends on the swelling)
- Time effects have to be included at the scale of the clay particles ($\simeq 10 - 50$ nm), resulting behavior will be used at the scale of the drift

Thank you for your attention.

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