

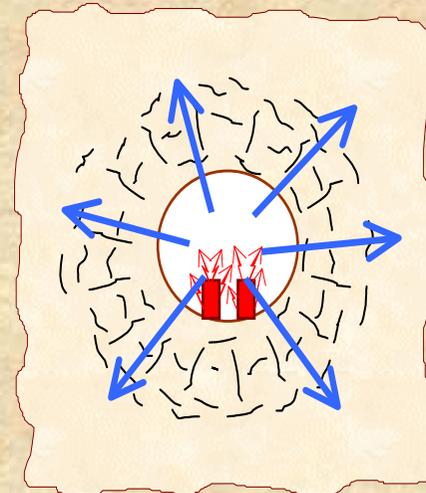
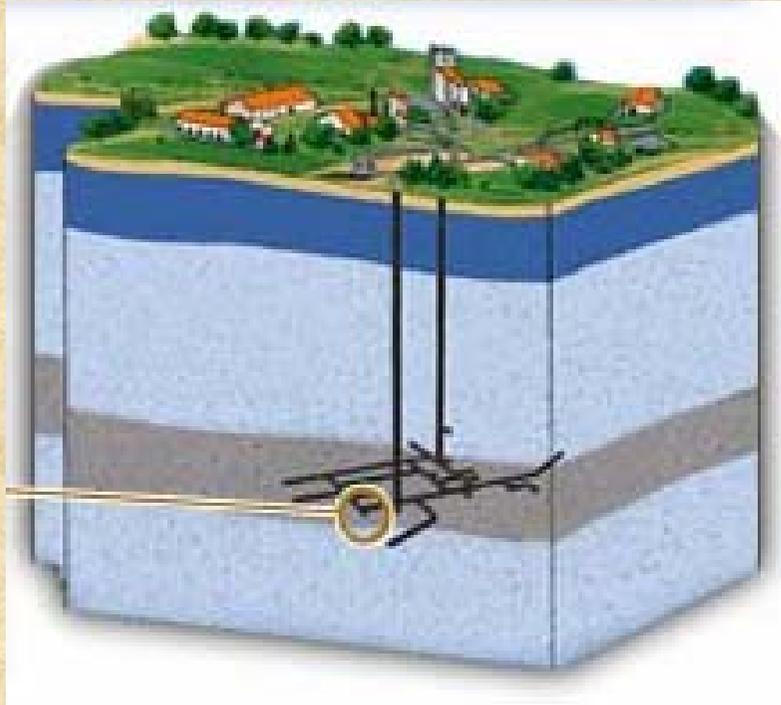


# **Modélisation numérique du couplage entre l'endommagement et la perméabilité des roches**

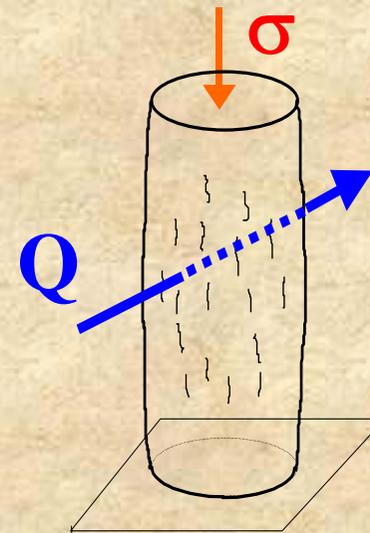
Ahmad POUYA, Keyvan MALEKI  
(LCPC, G.3S-LMS)

G.3S - EDF -ANDRA

# Stockage de déchets radioactifs dans des Argilites



Effet de l'endommagement  
sur la perméabilité des argilites

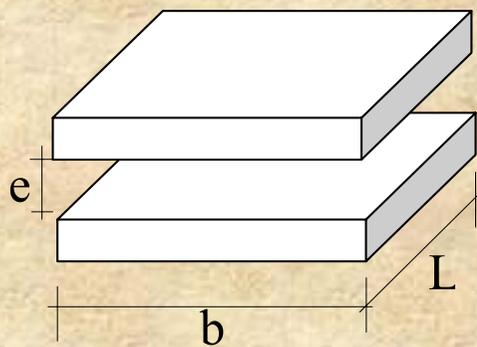


# Modèles endommagement-perméabilité

Bourdarot , Fauchet, Barry, Souley, ...

Bourdarot 1991 :  $K = f(D)$

B.Fauchet 1991 :

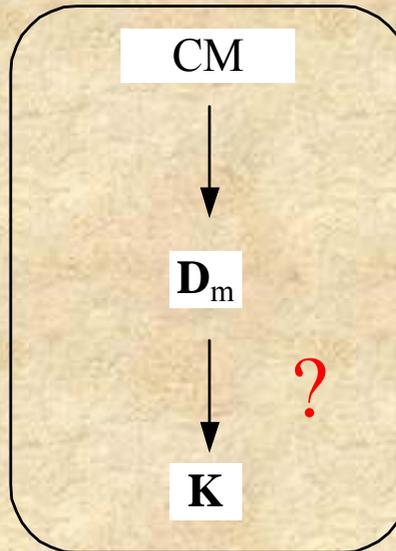
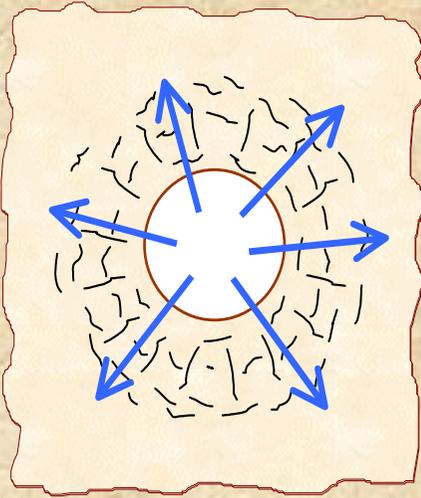


$$K(\varepsilon^{pl}) = K_0 + K_1(\varepsilon^{pl})$$

$$K_1(\varepsilon^{pl}) = \frac{\xi a^2 \beta^3}{12\mu} \begin{bmatrix} \langle \varepsilon_2^{pl} \rangle^3 + \langle \varepsilon_3^{pl} \rangle^3 & 0 & 0 \\ 0 & \langle \varepsilon_1^{pl} \rangle^3 + \langle \varepsilon_3^{pl} \rangle^3 & 0 \\ 0 & 0 & \langle \varepsilon_1^{pl} \rangle^3 + \langle \varepsilon_2^{pl} \rangle^3 \end{bmatrix}$$

B.Barry 1996:  $\varepsilon^p \rightarrow \varepsilon^+ : \text{ouverture des fissures}$

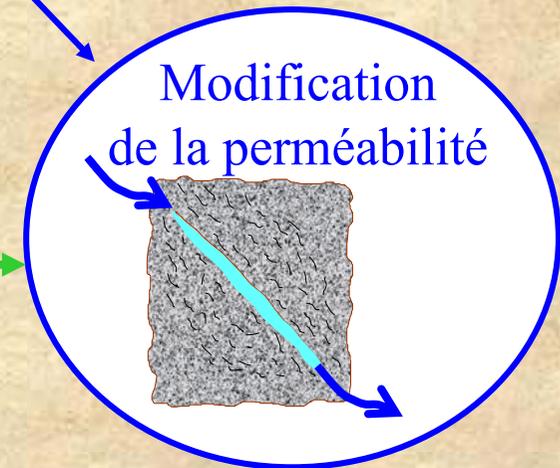
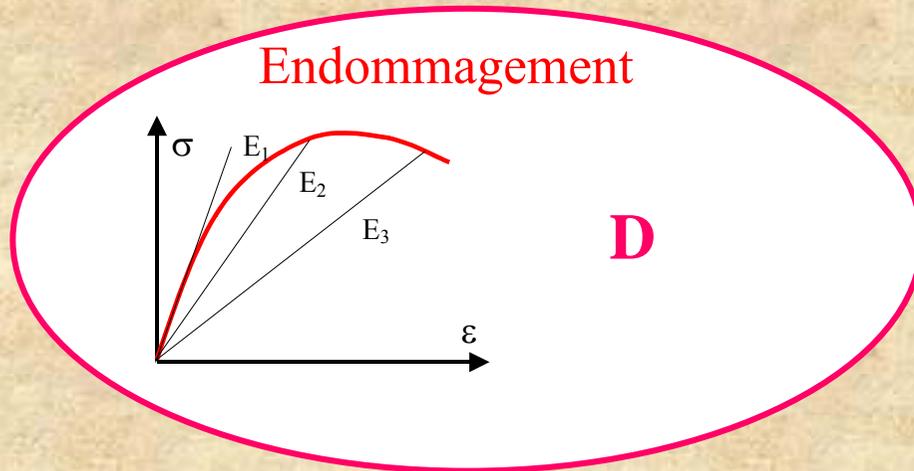
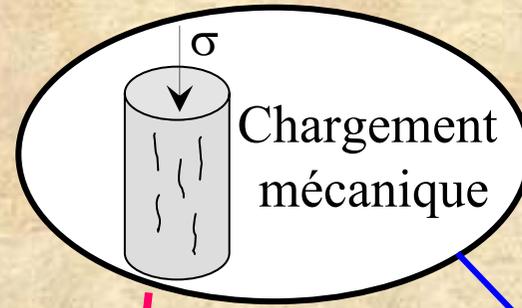
# Modélisation



Endommagement Mécanique

$$\dot{D}_m = f(\varepsilon, \sigma, \dot{\varepsilon}, \dot{\sigma}, \dot{\eta}, \dots)$$

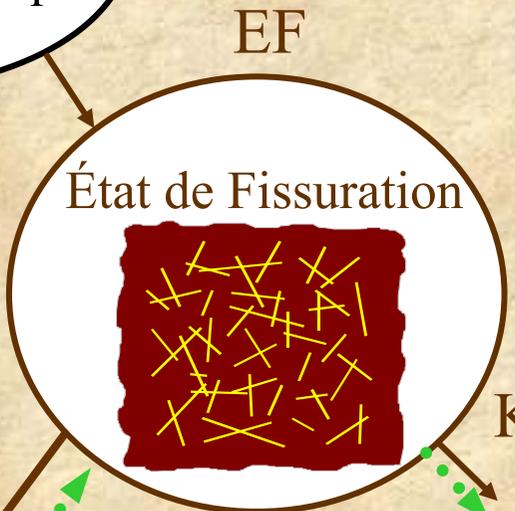
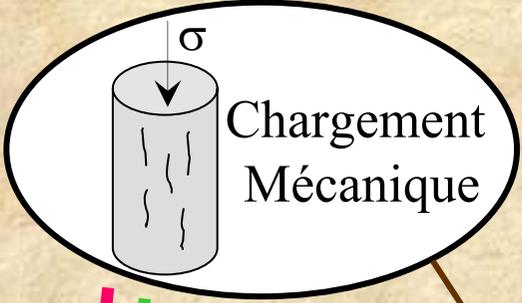
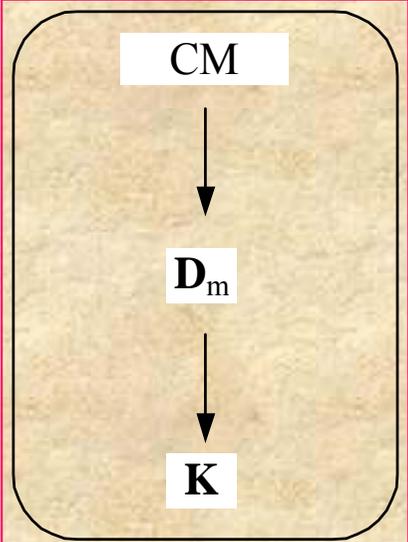
# Processus physique



# Processus physique

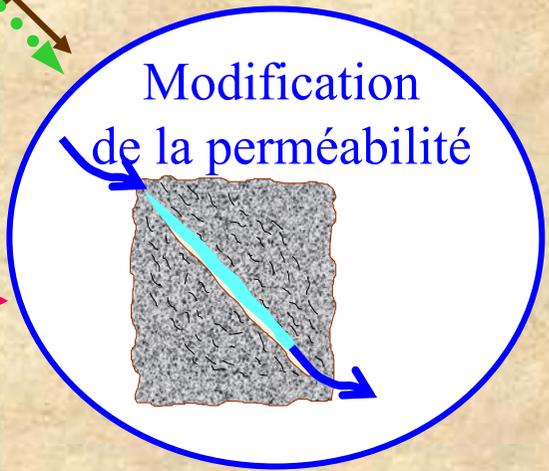
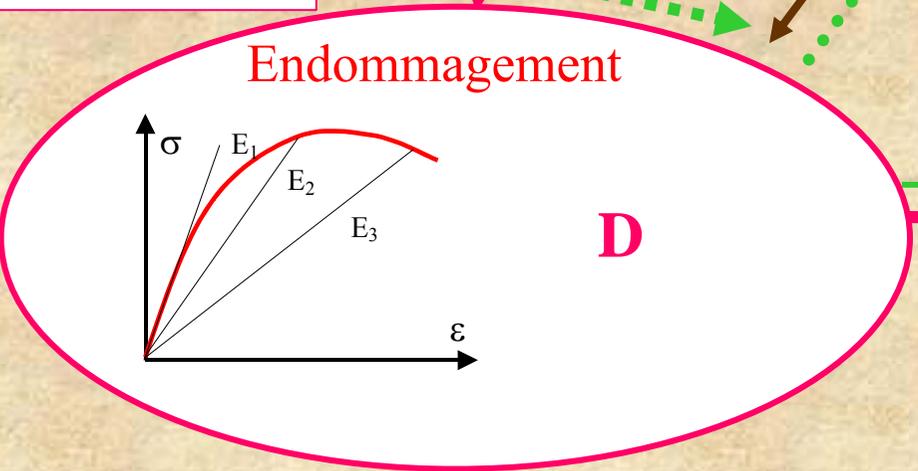
Schéma de modélisation

Modèle Perméabilité -Endommagement



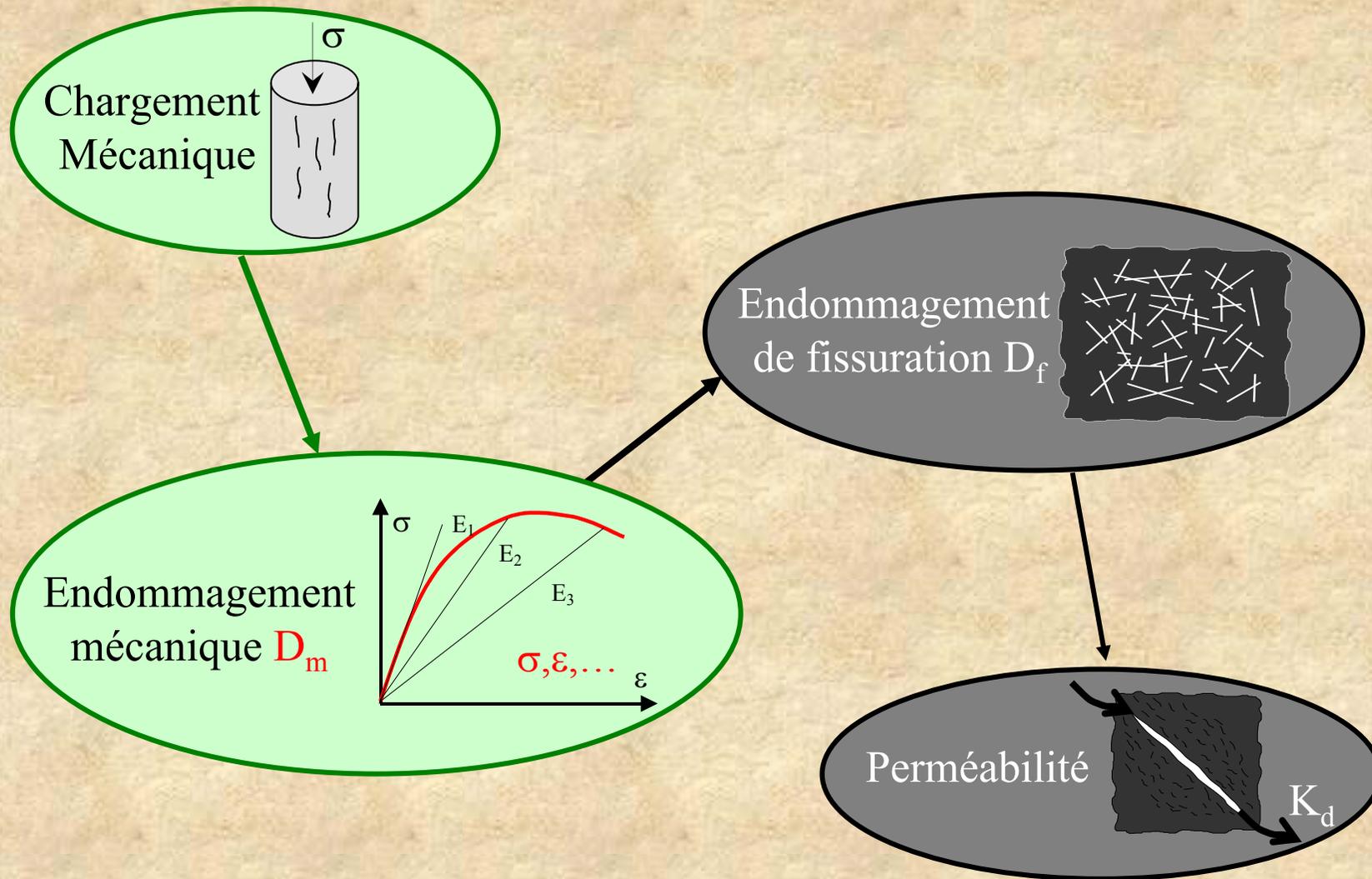
$$\mathbf{D}_f = \sum_{\alpha} S^{\alpha} \mathbf{n}^{\alpha} \otimes \mathbf{n}^{\alpha}$$

$$\dot{\mathbf{D}}_m = \dot{\lambda}^d \frac{\boldsymbol{\varepsilon}^+}{\sqrt{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+}}$$




$$k = f(D)$$

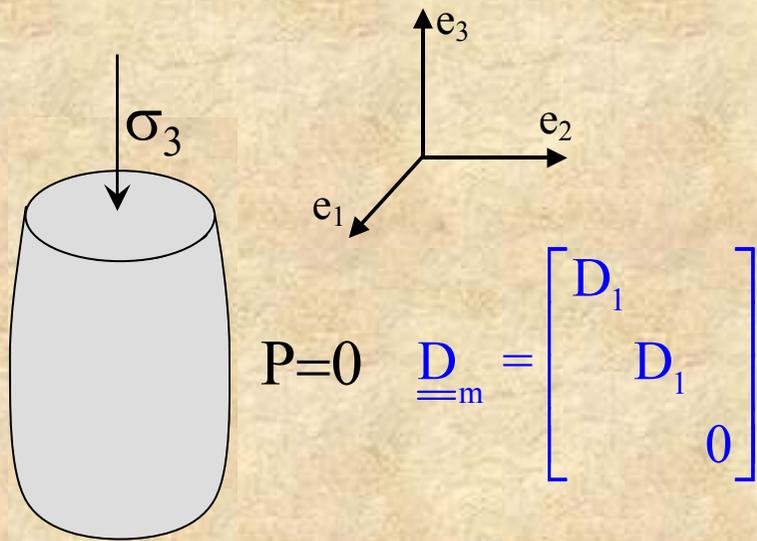
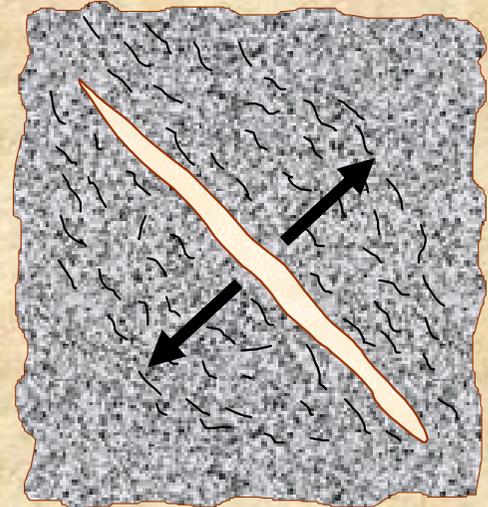
# Endommagement mécanique



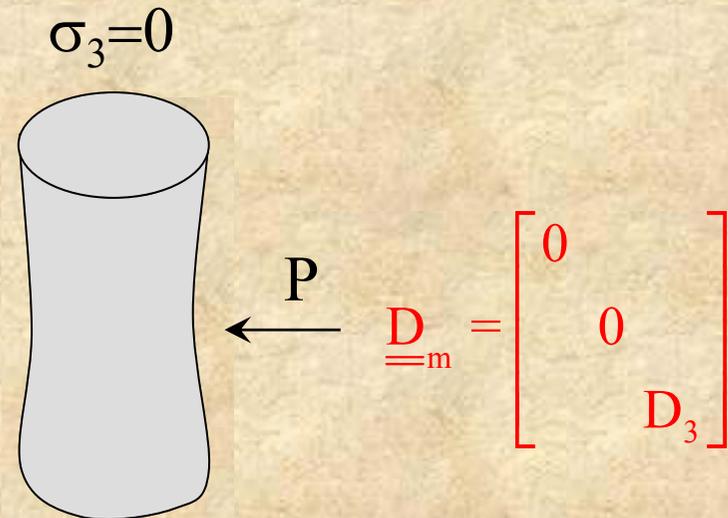
# Endommagement mécanique

Critère d'endommagement :  
(approche de Chiarelli 2000)

$$\underline{\underline{\dot{D}_m}} = \dot{\lambda}^d \frac{\underline{\underline{\varepsilon^+}}}{\sqrt{\underline{\underline{\varepsilon^+}} : \underline{\underline{\varepsilon^+}}}} \quad \underline{\underline{\sigma}} = \underline{\underline{C}}(\underline{\underline{D_m}}) : \underline{\underline{\varepsilon^e}}$$

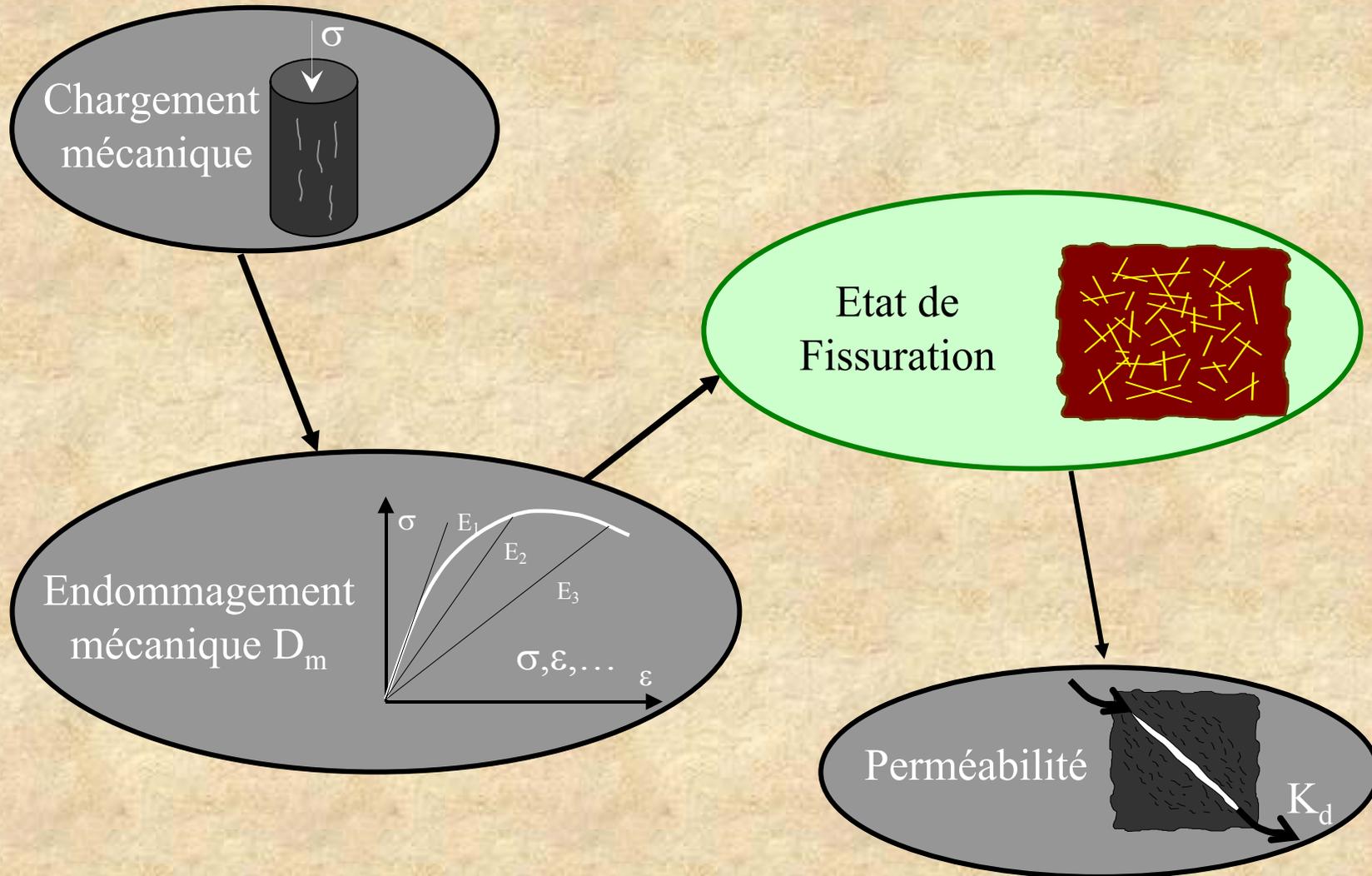


Compression

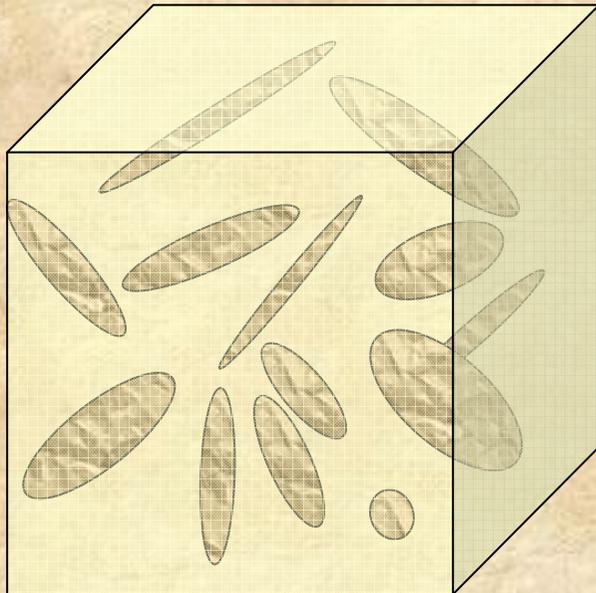


Extension

# État de fissuration du matériau



# État de fissuration du matériau

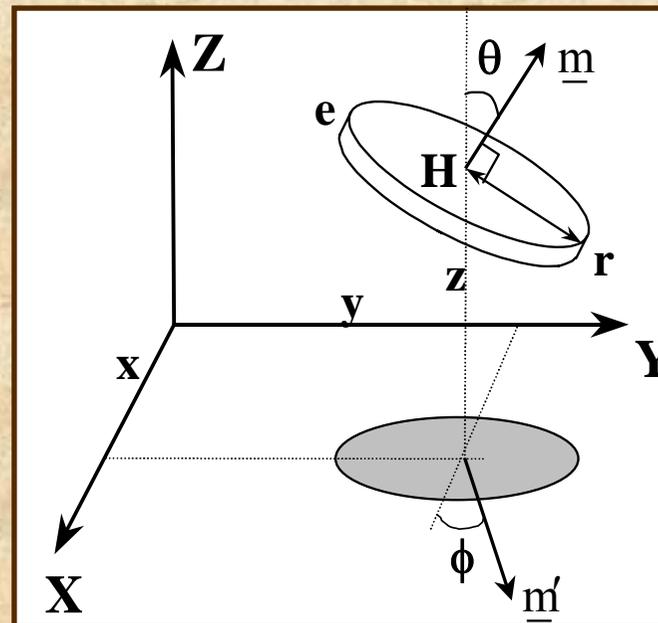
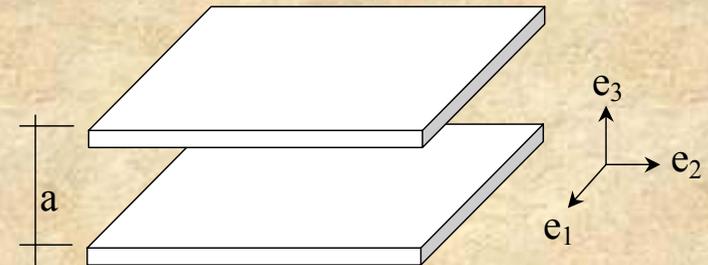


Disques dans l'espace

Sept paramètres :

$x, y, z, r, e, \theta, \phi$

Fauchet (1991)

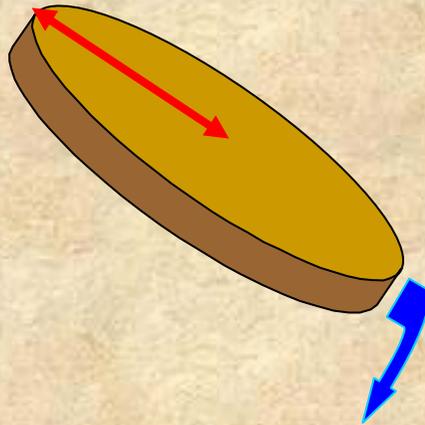


# Rayons et Epaisseurs

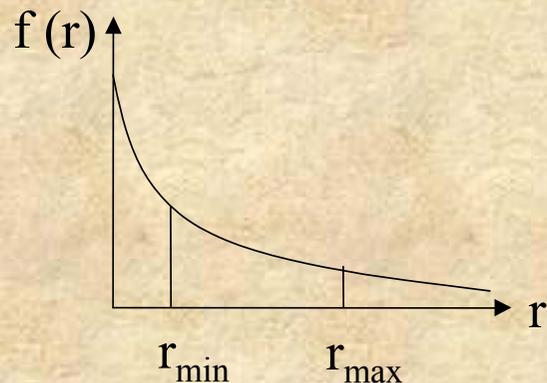
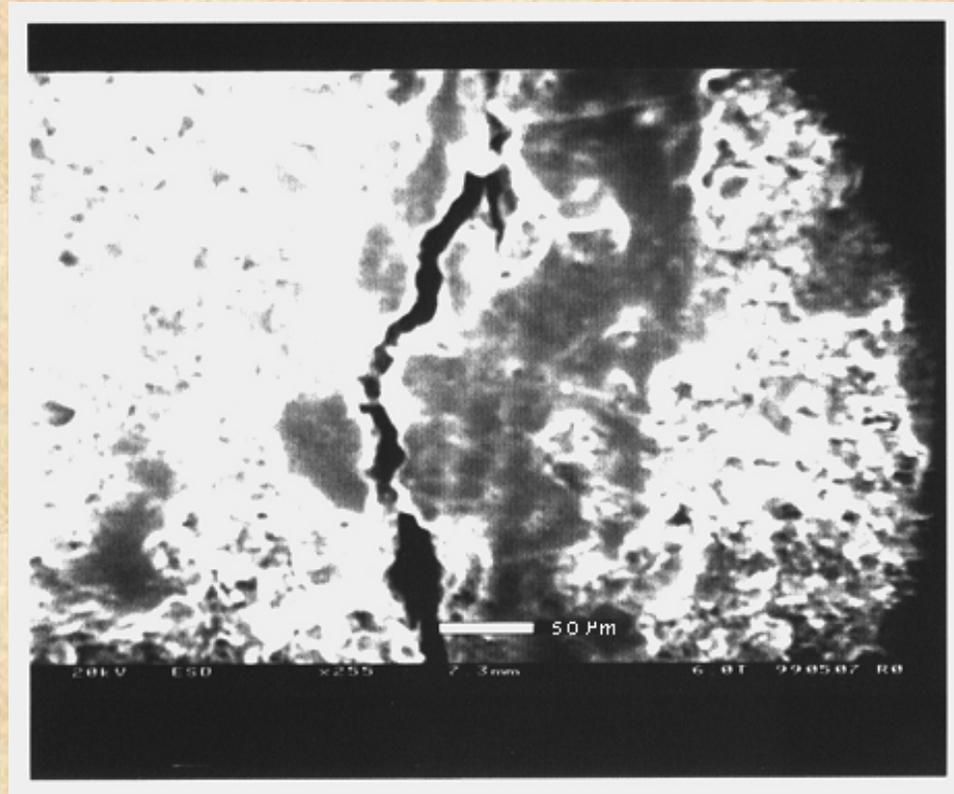
BOUNENNI (2002)

GASC (2002)

$$20 \mu\text{m} < r = 25 \mu\text{m} < 30 \mu\text{m}$$



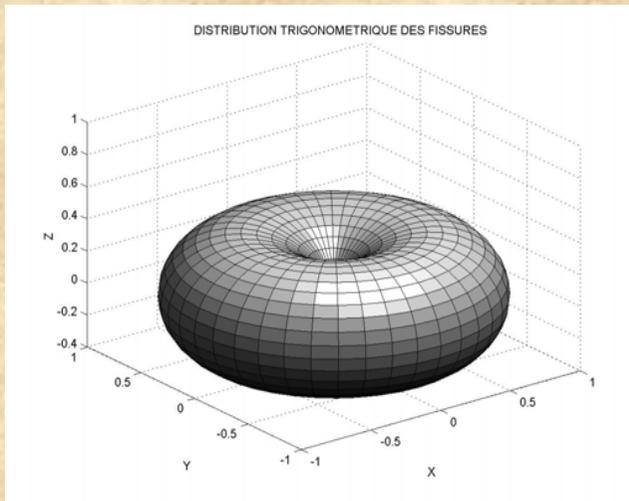
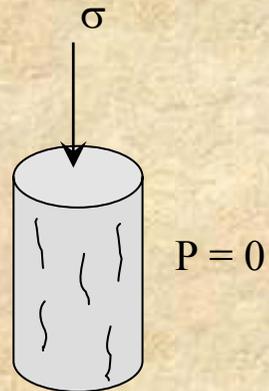
$$0,1 \mu\text{m} < e = 1 \mu\text{m} < 2 \mu\text{m}$$



$$f_r(r) = \frac{1}{\lambda_r} \exp\left(-\frac{r}{\lambda_r}\right)$$

# Orientation

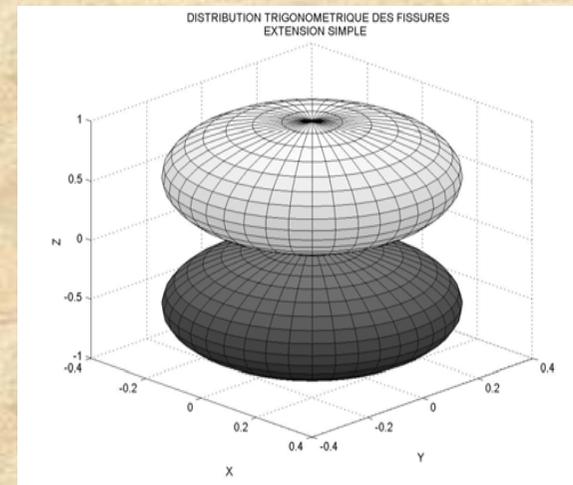
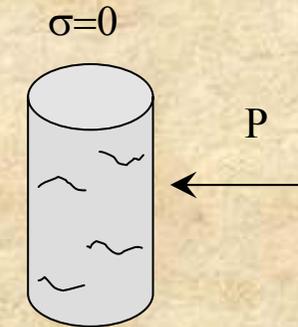
## Compression



Tikhomirov  
(2001)

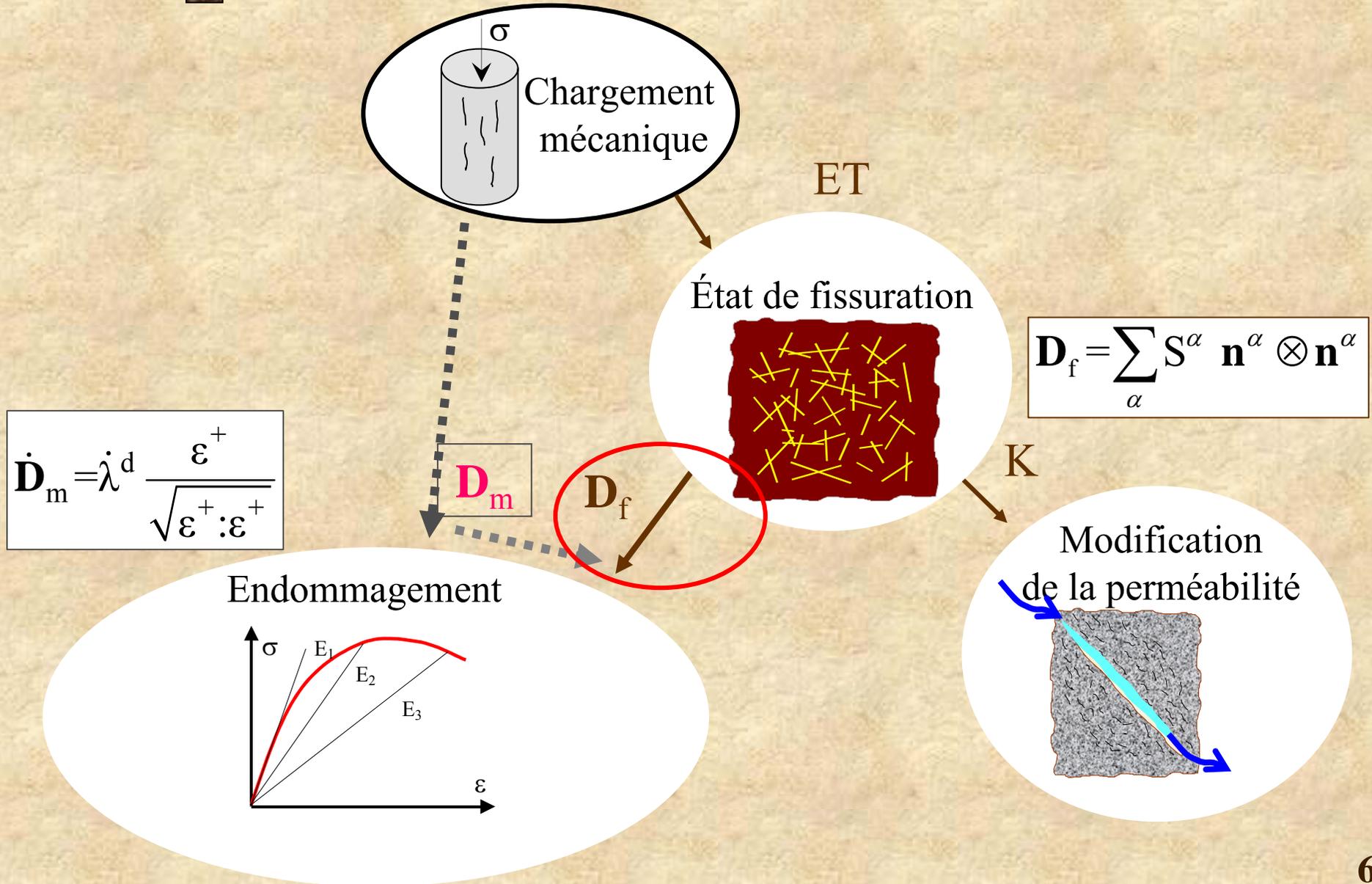
$$f(\theta) = A \sin^2(\theta)$$

## Extension

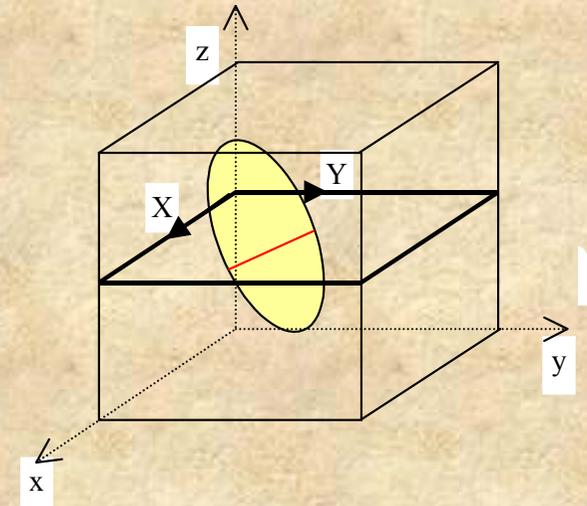
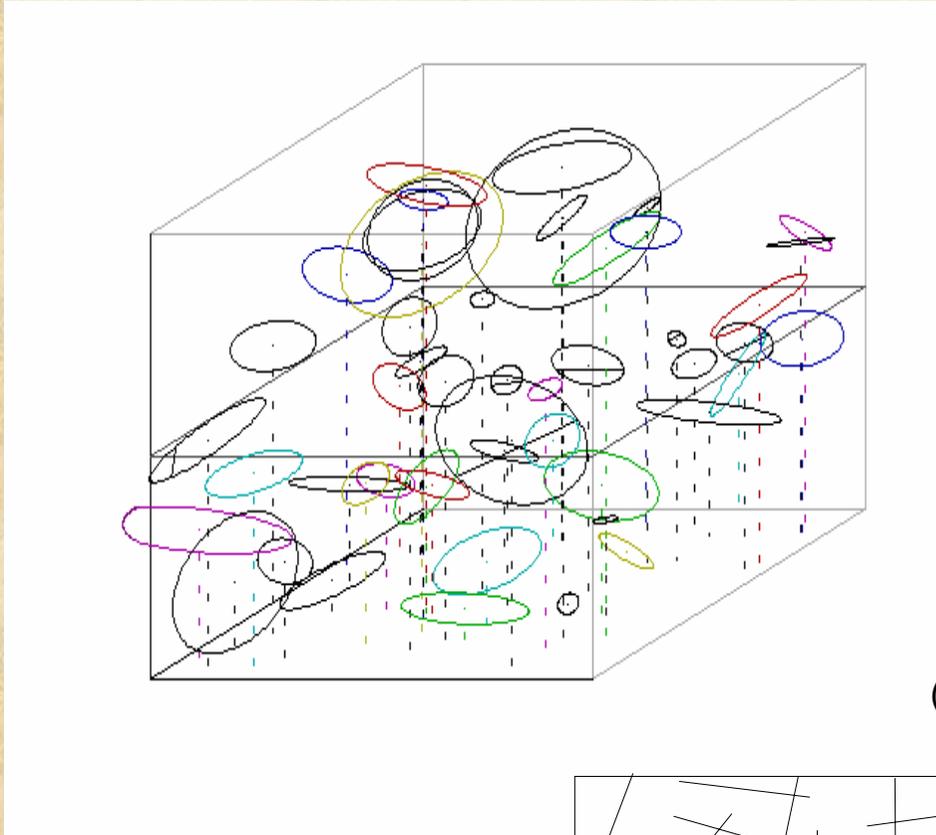


$$f(\theta) = A \cos^2(\theta)$$

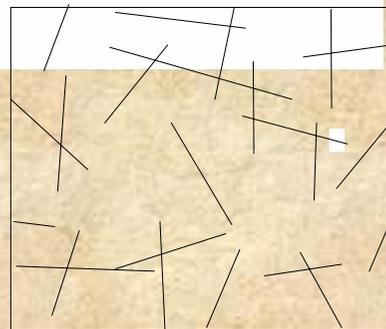
# Processus physique



# Passage bidimensionnel

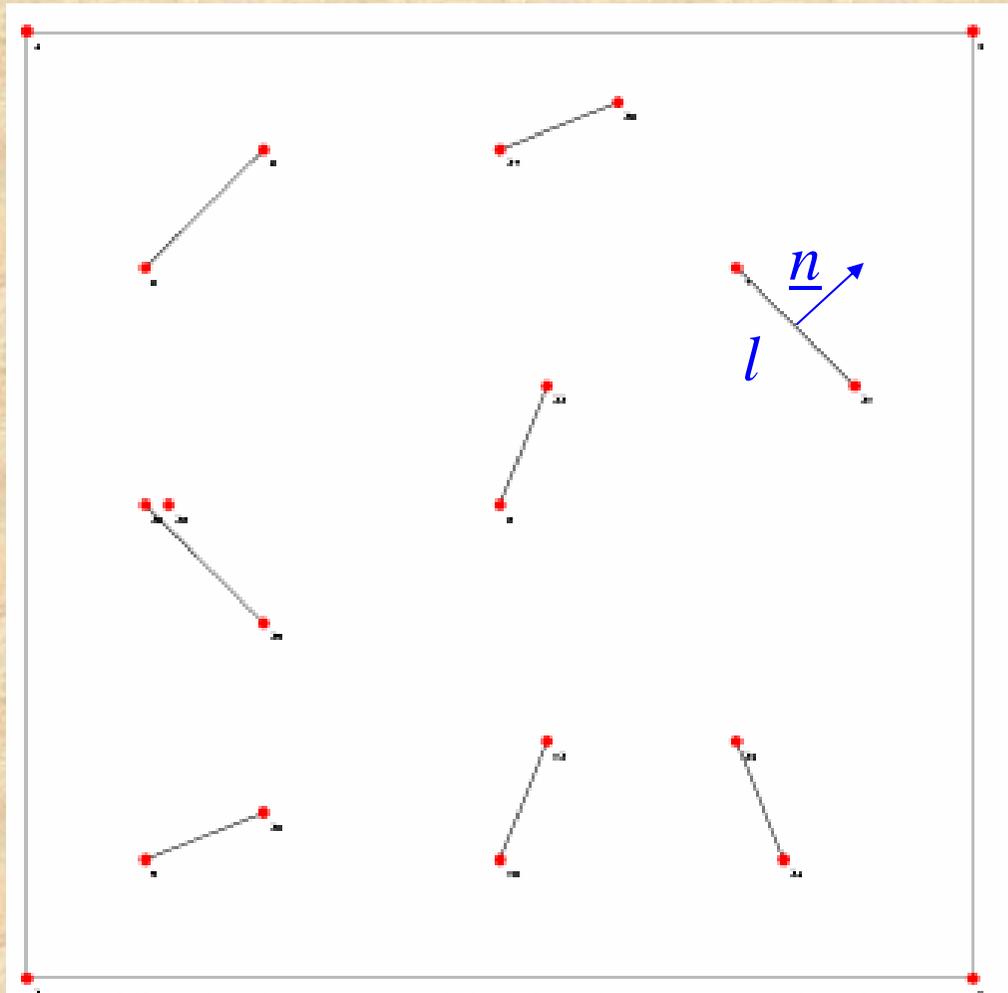


(2) Trace d'une fracture disque dans un plan



(3) Modèle de fracture 2D

# Module homogénéisé des milieux fissurés en élasticité linéaire



**Solution Analytique (Kachanov) :**

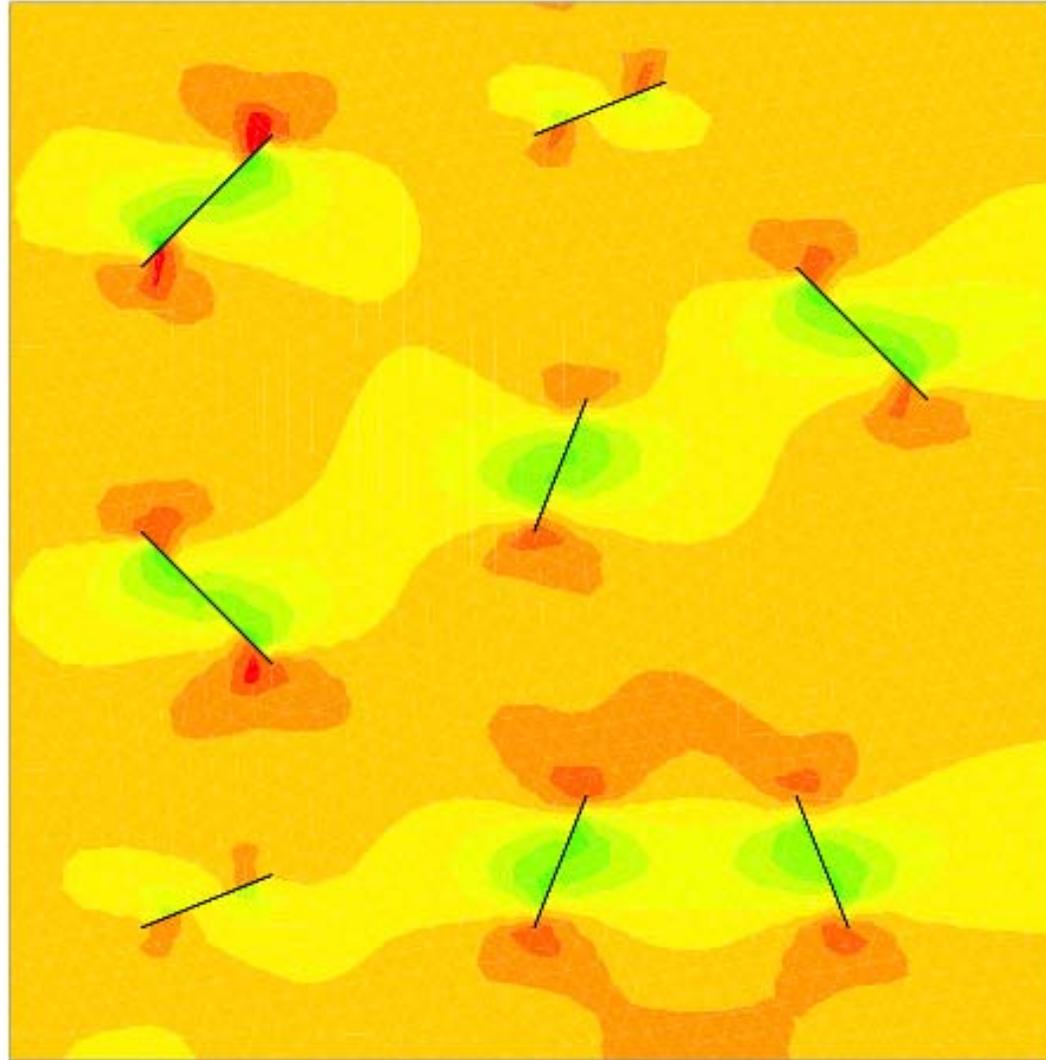
$$\varepsilon_{ij} = \frac{1+\nu}{E} \sigma_{ij} - \frac{\nu}{E} (tr\sigma) \delta_{ij} + \frac{\pi}{E} (\alpha_{ik} \sigma_{kj} + \alpha_{jk} \sigma_{ki})$$

$$\mathbf{D}_f = \sum_{\alpha} S^{\alpha} \mathbf{n}^{\alpha} \otimes \mathbf{n}^{\alpha}$$

$$\alpha_{ij} = \frac{1}{V} \sum l^2 n_i^k n_j^k$$

# Homogénéisation Numérique

CESAR-LCPC



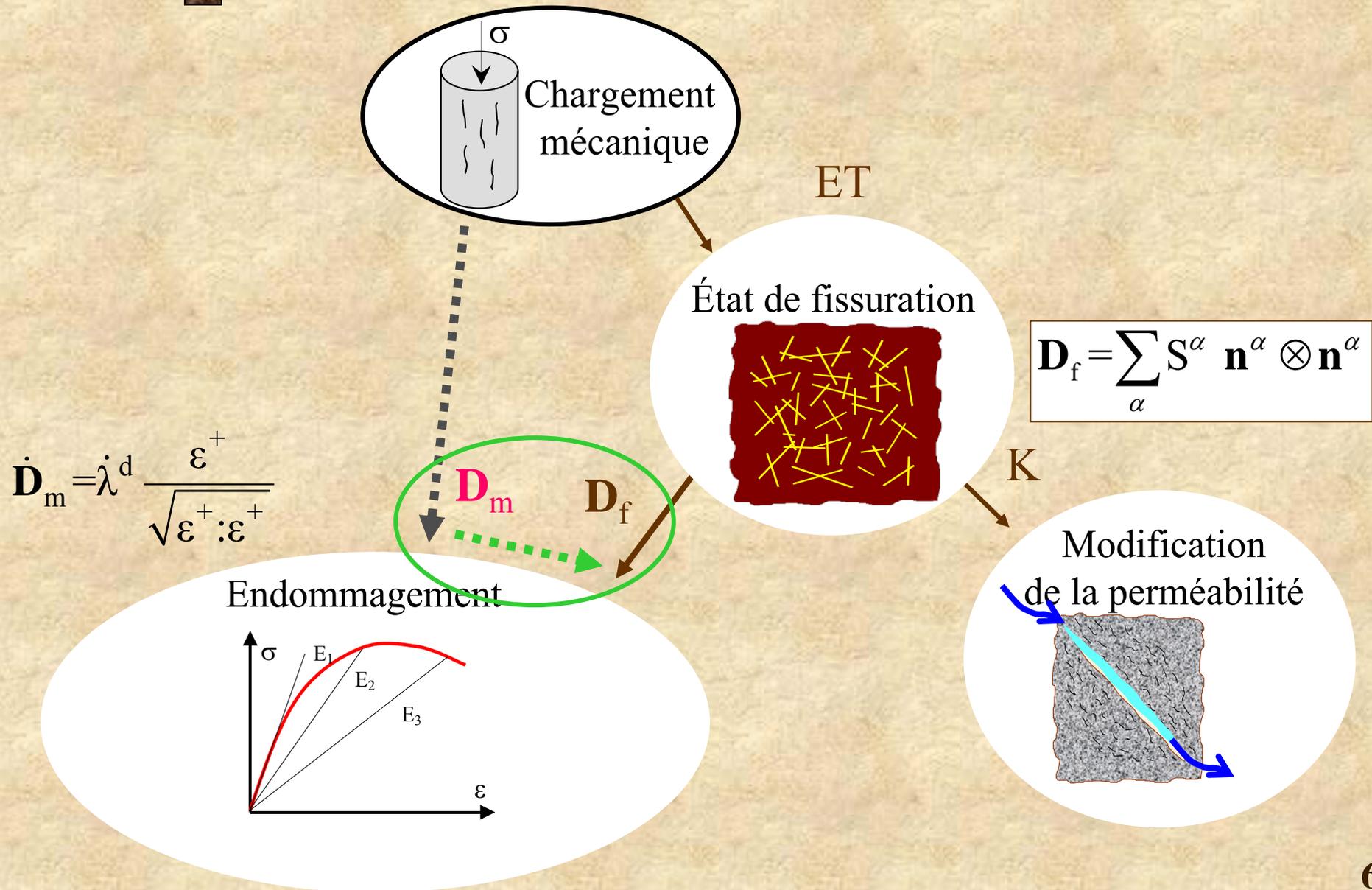
*Modèle Kachanov :*

*Résultat numérique:*

$$\underline{\underline{\varepsilon}} = \begin{bmatrix} 0.002310 & 0 \\ 0 & 0.6E-03 \end{bmatrix}$$

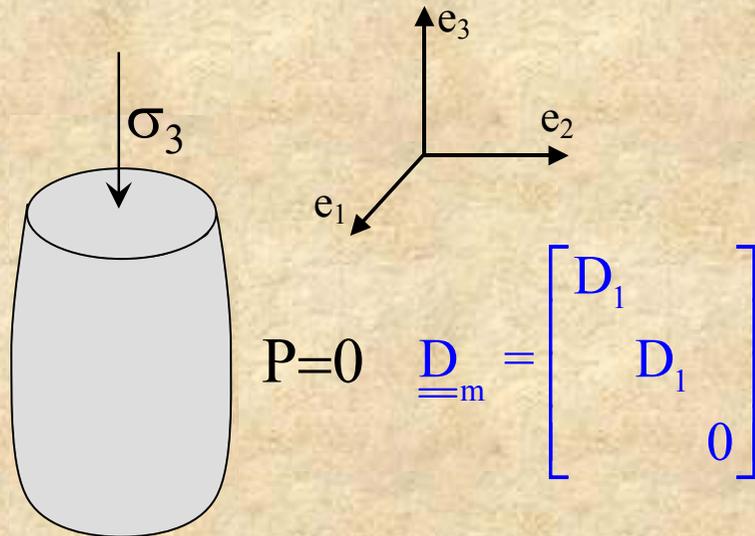
$$\underline{\underline{\varepsilon}} = \begin{bmatrix} 0.002298 & 0 \\ 0 & 0.5745E-03 \end{bmatrix}$$

# Processus physique



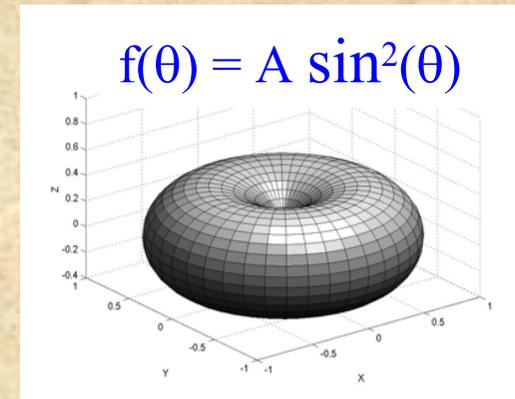
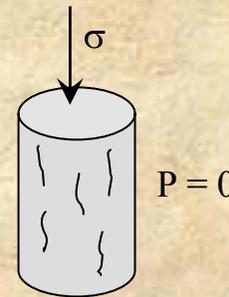
# Tenseurs $D_m$ et $D_f$

$$\dot{\mathbf{D}}_m = \dot{\lambda}^d \frac{\boldsymbol{\varepsilon}^+}{\sqrt{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+}}$$



Compression

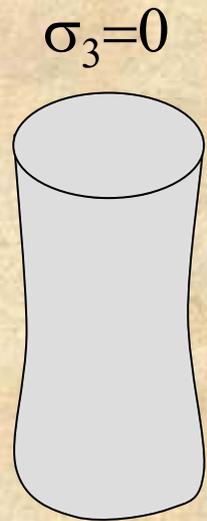
$$\mathbf{D}_f = \sum_{\alpha} S^{\alpha} \mathbf{n}^{\alpha} \otimes \mathbf{n}^{\alpha}$$



Compression :  $\underline{\underline{D}}_f = \rho \begin{bmatrix} 0,4 & & \\ & 0,4 & \\ & & 0,2 \end{bmatrix}$

# Tenseurs $D_m$ et $D_f$

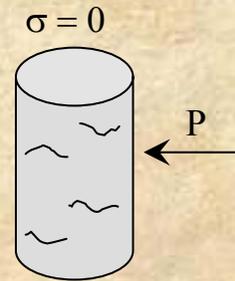
$$\dot{\mathbf{D}}_m = \dot{\lambda}^d \frac{\boldsymbol{\varepsilon}^+}{\sqrt{\boldsymbol{\varepsilon}^+ : \boldsymbol{\varepsilon}^+}}$$



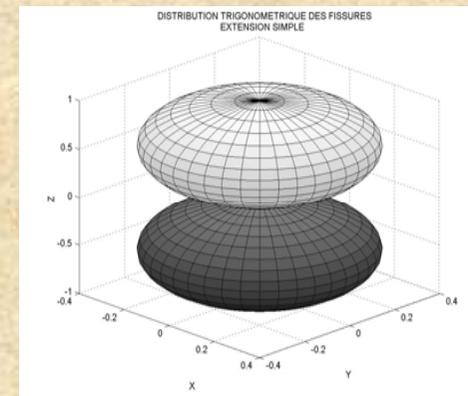
Extension

$$\underline{\underline{D}}_m = \begin{bmatrix} 0 & & \\ & 0 & \\ & & D_3 \end{bmatrix}$$

$$\mathbf{D}_f = \sum_{\alpha} S^{\alpha} \mathbf{n}^{\alpha} \otimes \mathbf{n}^{\alpha}$$



$$f(\theta) = A \cos^2(\theta)$$



Extension :  $\underline{\underline{D}}_f = \rho \begin{bmatrix} 0,2 & & \\ & 0,2 & \\ & & 0,6 \end{bmatrix}$

# Relation entre $\mathbf{D}_m$ et $\mathbf{D}_f$

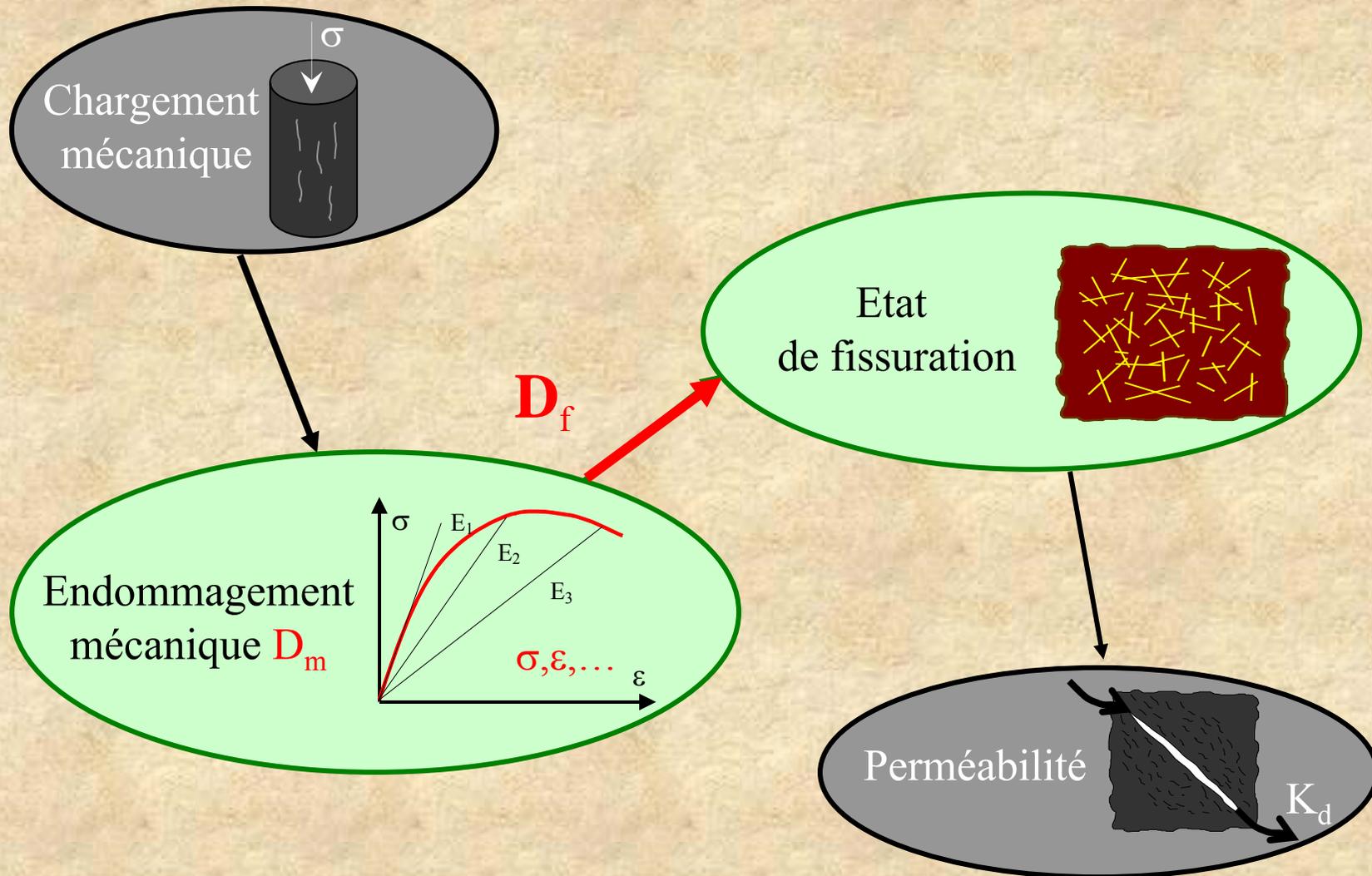
Tenseurs réduits :

$$\mathbf{d}_m = \frac{1}{\text{tr}\mathbf{D}_m} \mathbf{D}_m \qquad \mathbf{d}_f = \frac{1}{\text{tr}\mathbf{D}_f} \mathbf{D}_f$$

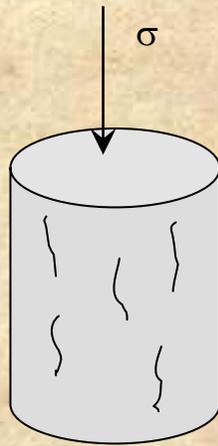
Relation linéaire entre  $\mathbf{d}_m$  et  $\mathbf{d}_f$  :

$$\mathbf{d}_f = \frac{2}{5} \mathbf{d}_m + \frac{1}{5} \mathbf{I}$$

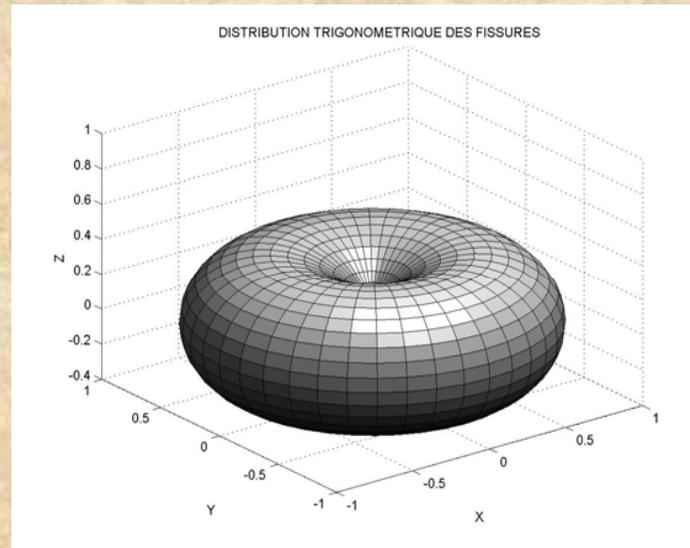
# Passage de $D_m$ à $D_f$



# Compression



$$f(\theta) = A \sin^2(\theta)$$

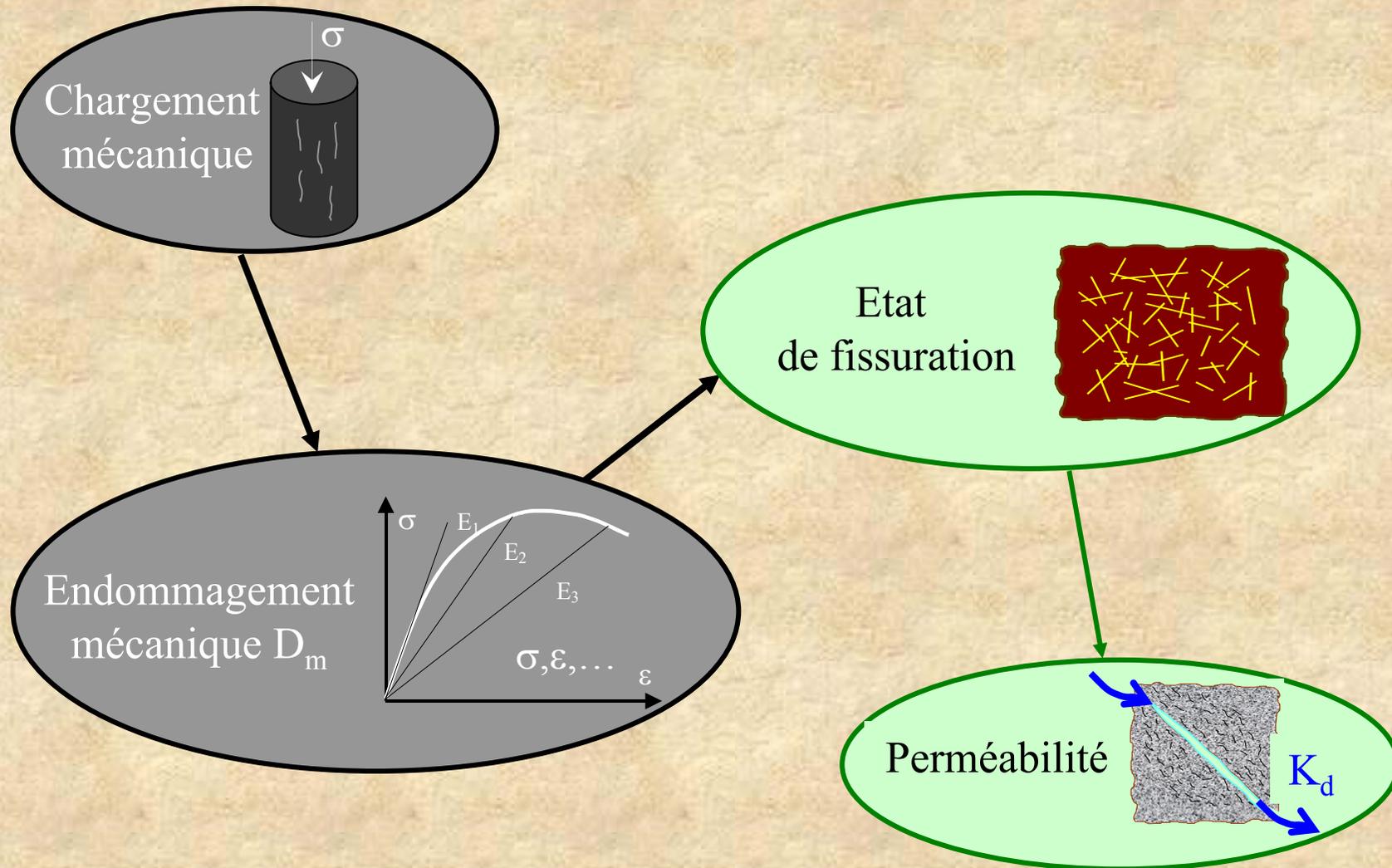


$\mathbf{D}_f$

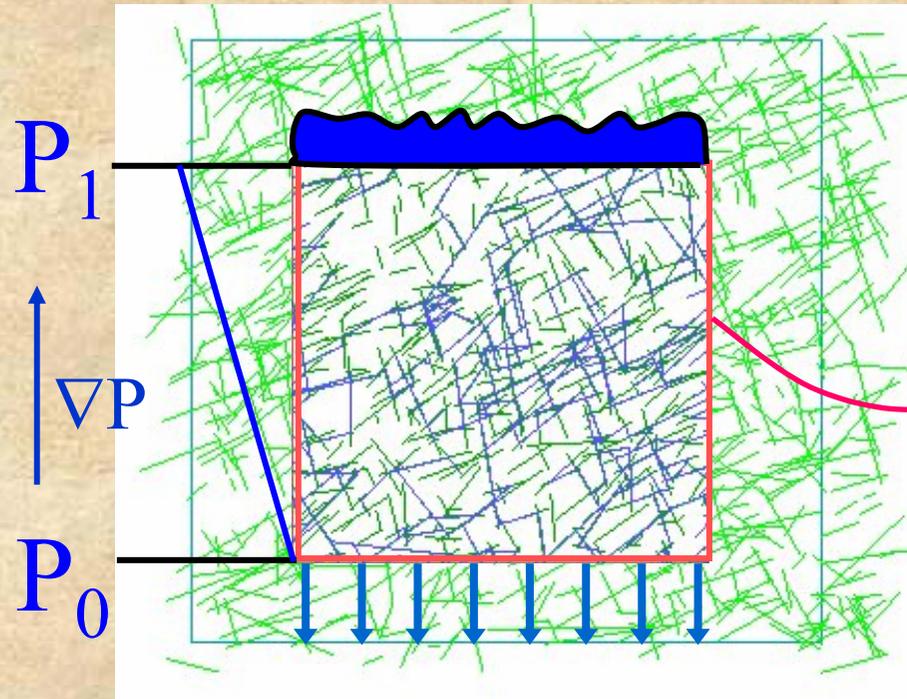
$$= \rho \begin{bmatrix} 0,4 \\ 0,4 \\ 0,2 \end{bmatrix}$$

- Densités des fissures
- Longueur moyenne

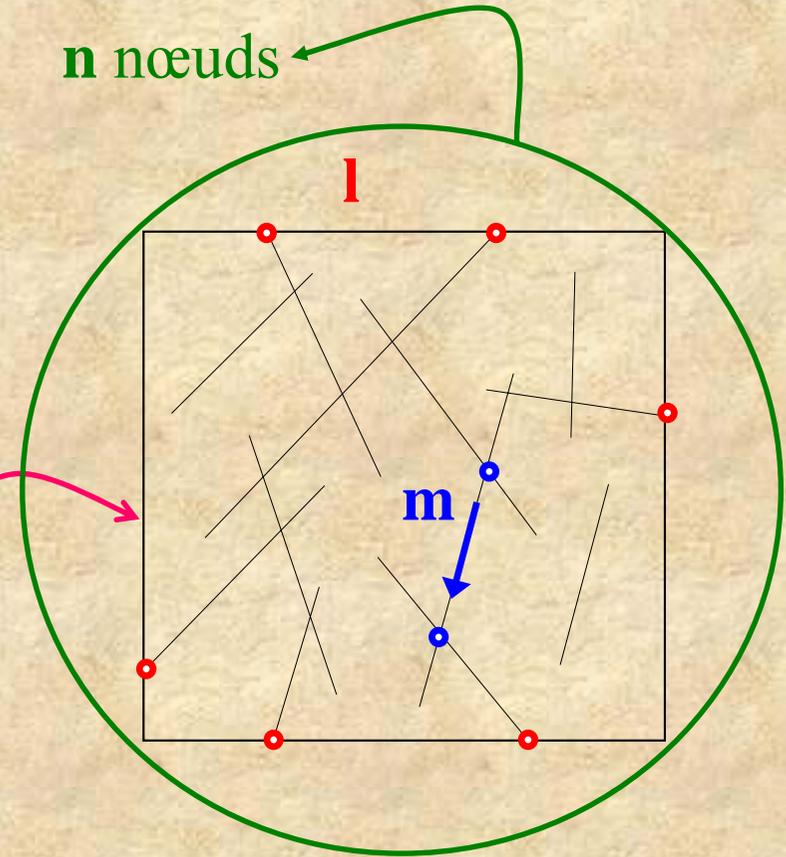
# Etat de fissuration - Perméabilité



# Perméabilité équivalente



n nœuds

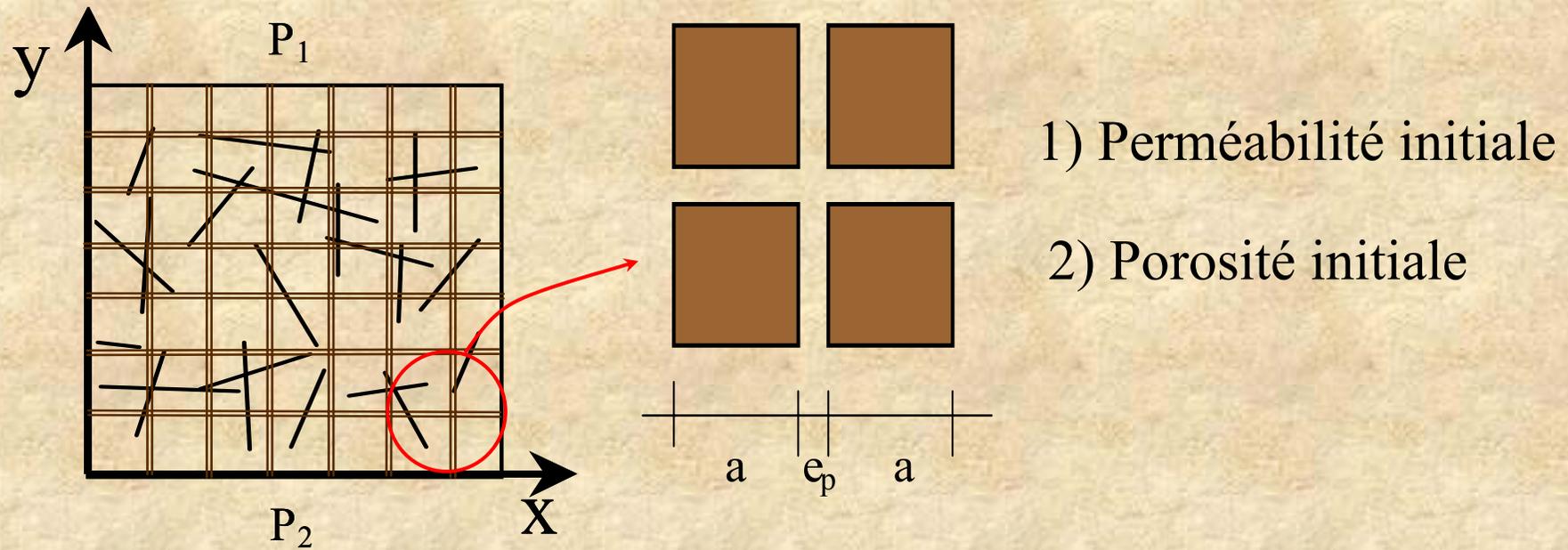


$$Q = -\mathbf{K} \cdot \nabla P$$

Perméabilité équivalente

$\mathbf{K}$

# Porosité initiale



Nous avons choisi  $K_{\text{initiale}} = 10^{-20} \text{m}^2$  et Porosité = 12%

$$a = 20 \cdot 10^{-3} \mu\text{m} \ll 200 \times 200 \mu\text{m}$$

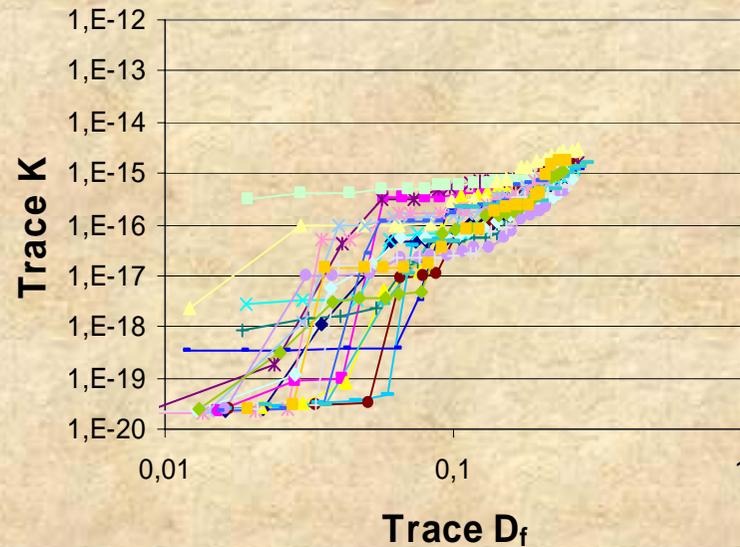
$$e_p = 1,5 \cdot 10^{-3} \mu\text{m}$$



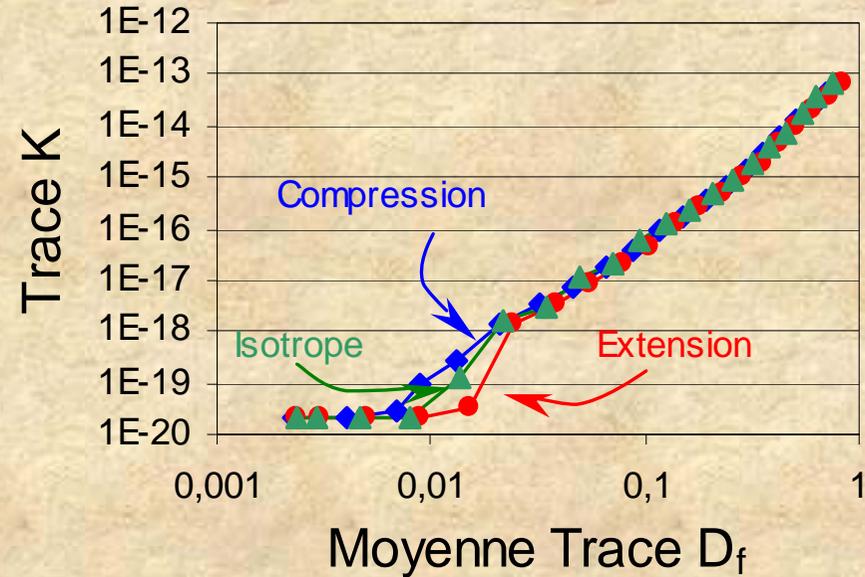
# *Simulation Numérique*

# Endommagement de fissuration-Perméabilité

Endommagement → Nombre des fissures  
→ Rayon des fissures

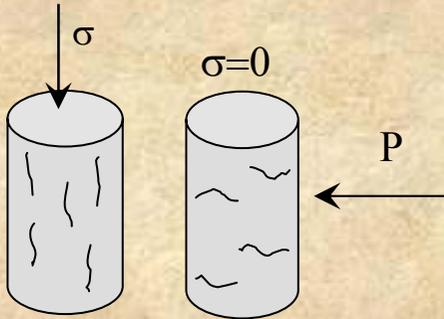


Extension

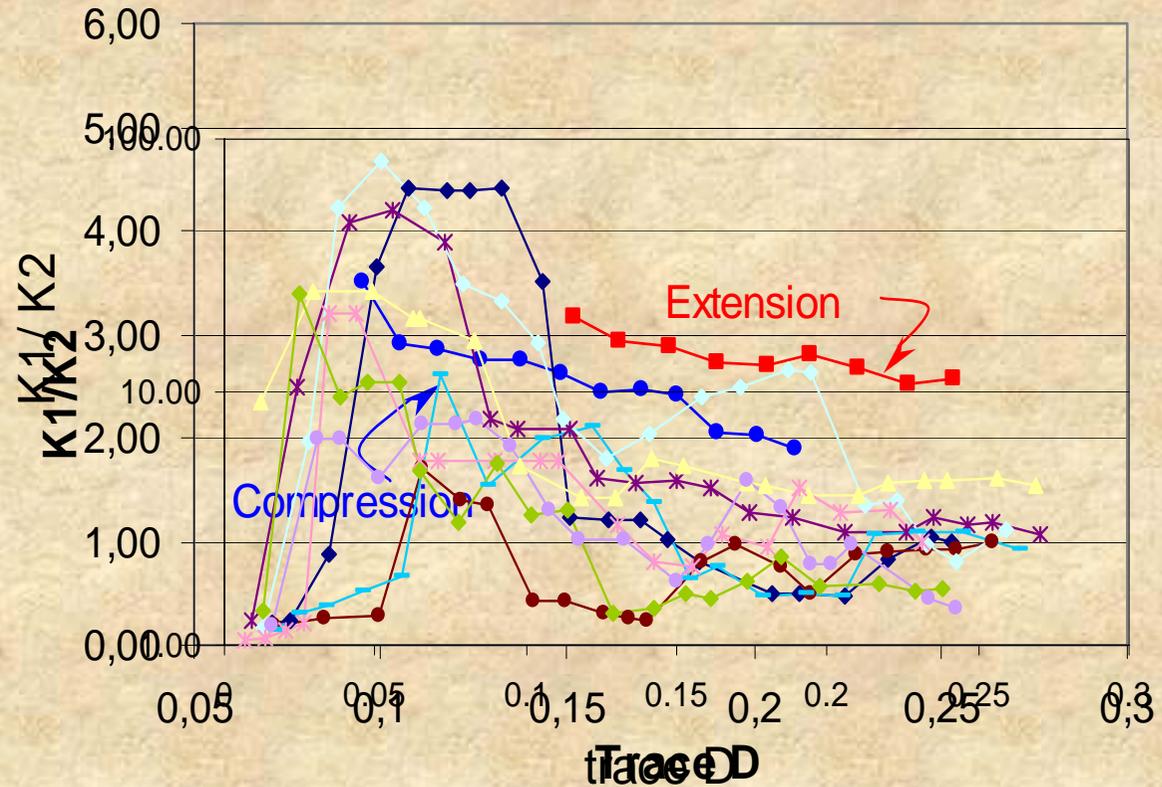


$$\text{tr } K_d = 4 \times 10^{-14} (\text{tr } D_f)^{2,9}$$

# Anisotropie de la perméabilité



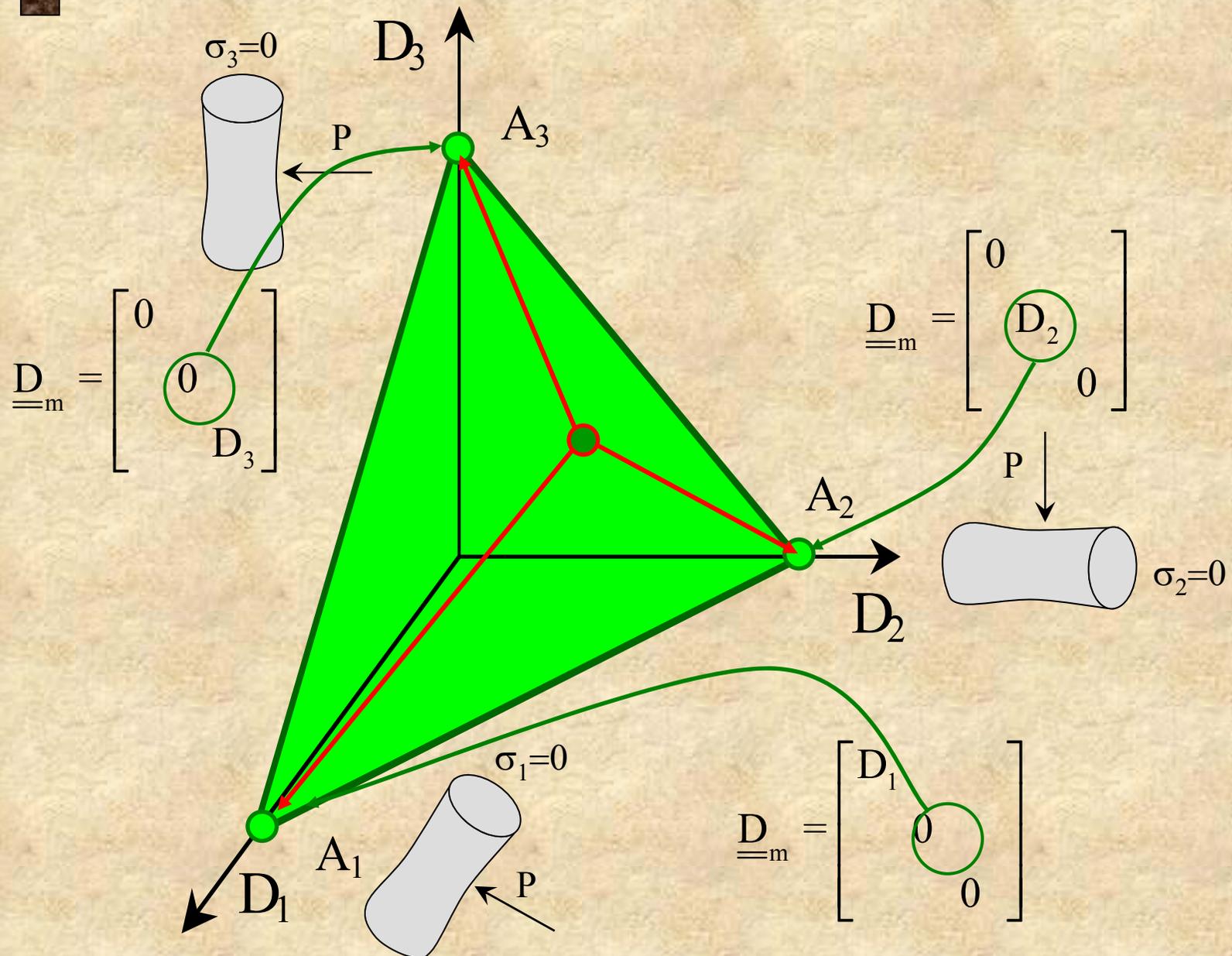
$$\mathbf{K} = \begin{bmatrix} K_T & & \\ & K_T & \\ & & K_L \end{bmatrix}$$



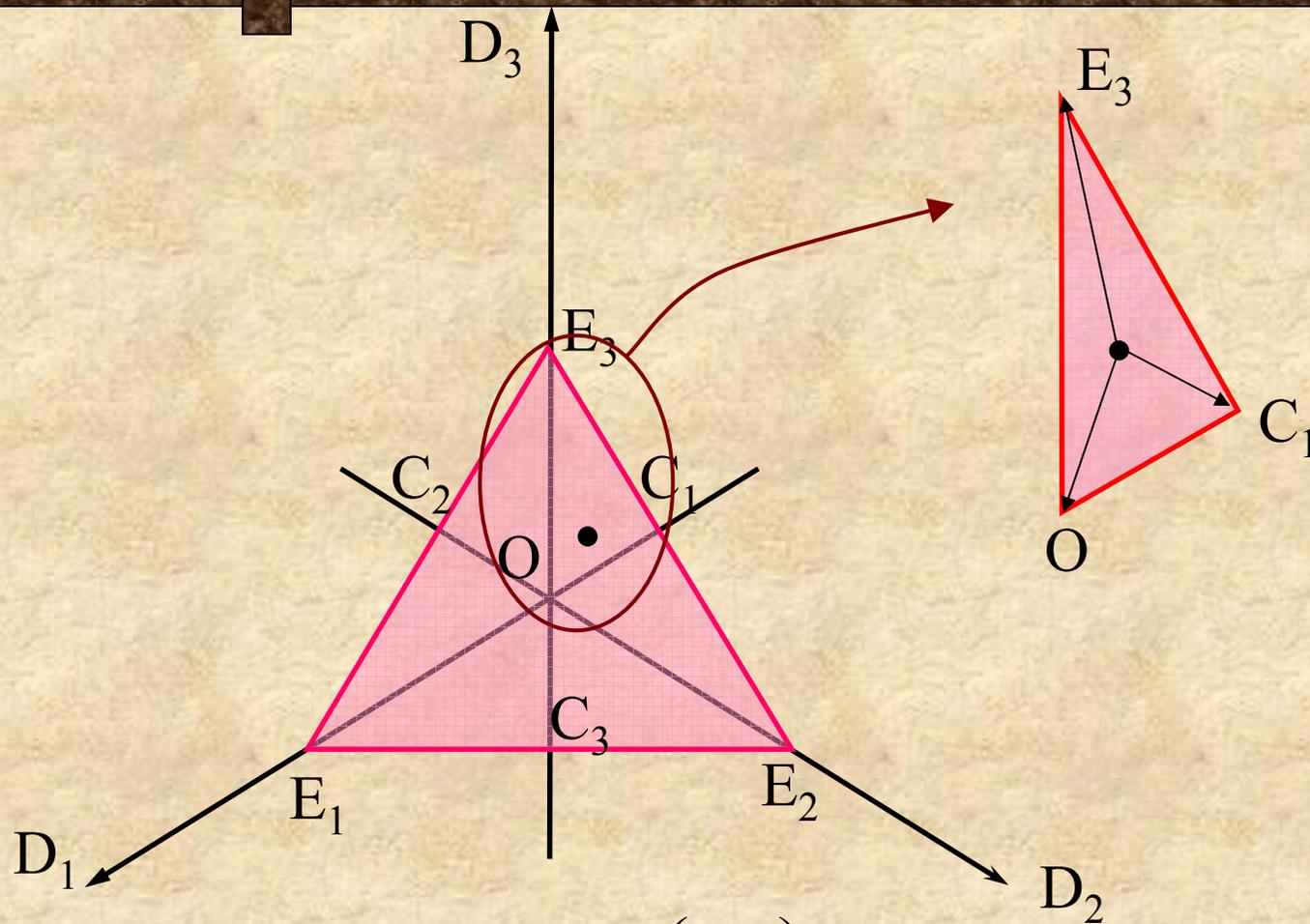
Compression  $\rightarrow \zeta_{\text{comp}} = K_1 / K_2 = 2,0$

Extension  $\rightarrow \zeta_{\text{ext}} = K_1 / K_2 = 2,5$

# Passage 1D à 3D



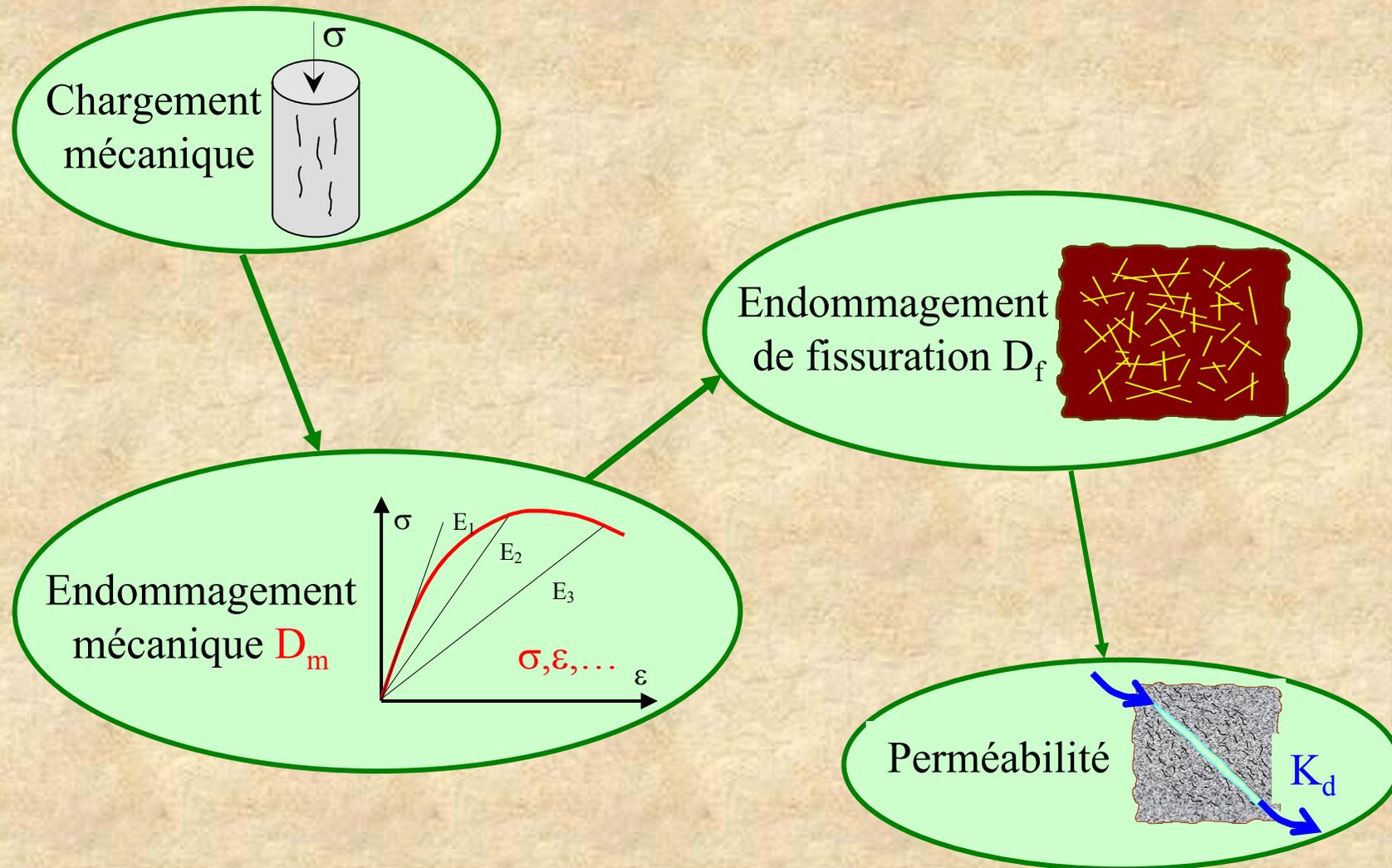
# Passage de $D_m$ à $D_f$



$$\begin{pmatrix} d_{fi} \\ d_{fj} \\ d_{fk} \end{pmatrix} = \eta \begin{pmatrix} 0,2 \\ 0,2 \\ 0,6 \end{pmatrix} + \xi \begin{pmatrix} 0,2 \\ 0,4 \\ 0,4 \end{pmatrix} + (1 - \eta - \xi) \begin{pmatrix} 0,33 \\ 0,33 \\ 0,33 \end{pmatrix}$$

Point n
Extension
Compression
Isotrope

# Schéma complet



# Calcul de la perméabilité

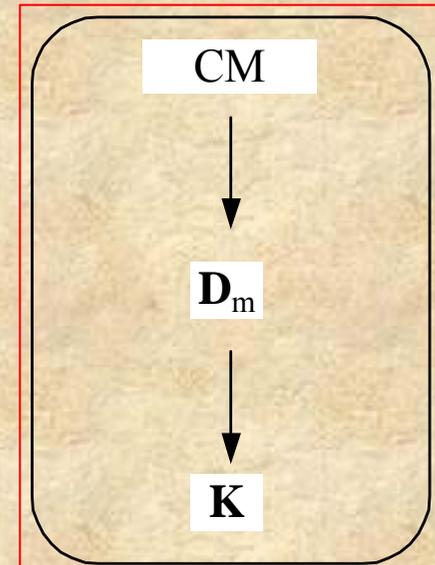
$$\underline{\underline{K_d}} = a_0 (\text{tr } \underline{\underline{D_m}})^{2,9} \left[ \eta \underline{\underline{k_d}}_{\text{ext}} + \xi \underline{\underline{k_d}}_{\text{comp}} + (1-\eta-\xi) \underline{\underline{k_d}}_{\text{iso}} \right]$$

$$\underline{\underline{k_d}}_{\text{comp}} \text{ (dans la direction 1)} = \frac{1}{2+\zeta_{\text{comp}}} \begin{bmatrix} \zeta_{\text{comp}} & & & \\ & 1 & & \\ & & & 1 \\ & & & & 1 \end{bmatrix}$$

$$\underline{\underline{k_d}}_{\text{ext}} \text{ (dans la direction 3)} = \frac{1}{1+2\zeta_{\text{ext}}} \begin{bmatrix} \zeta_{\text{ext}} & & & \\ & \zeta_{\text{ext}} & & \\ & & & 1 \\ & & & & 1 \end{bmatrix}$$

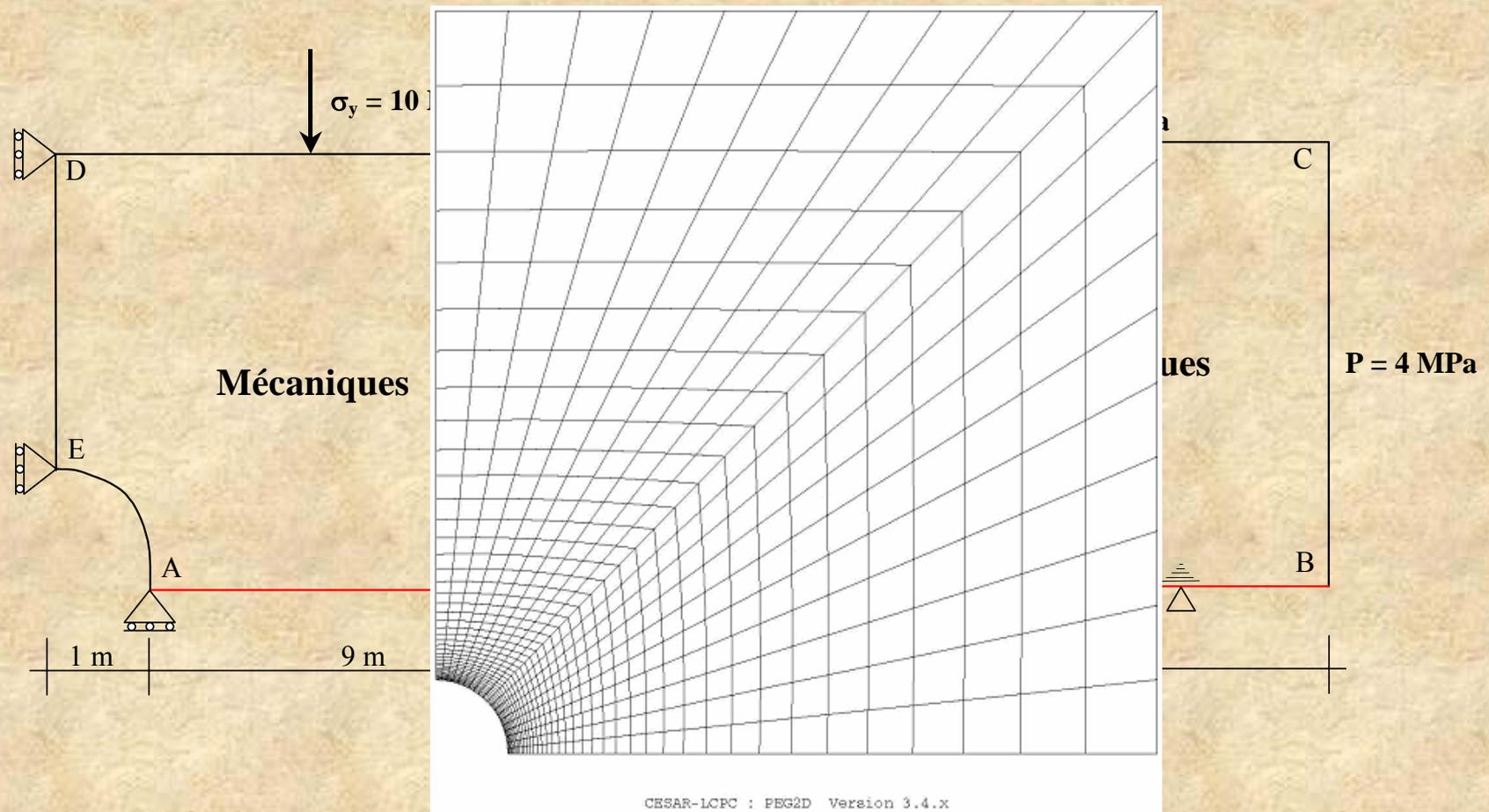
$$\underline{\underline{k_d}}_{\text{iso}} = \frac{1}{3} \begin{bmatrix} 1 & & & \\ & 1 & & \\ & & & 1 \end{bmatrix}$$

$$\begin{aligned} \zeta_{\text{comp}} &= 2,0 \\ \zeta_{\text{ext}} &= 2,5 \end{aligned}$$



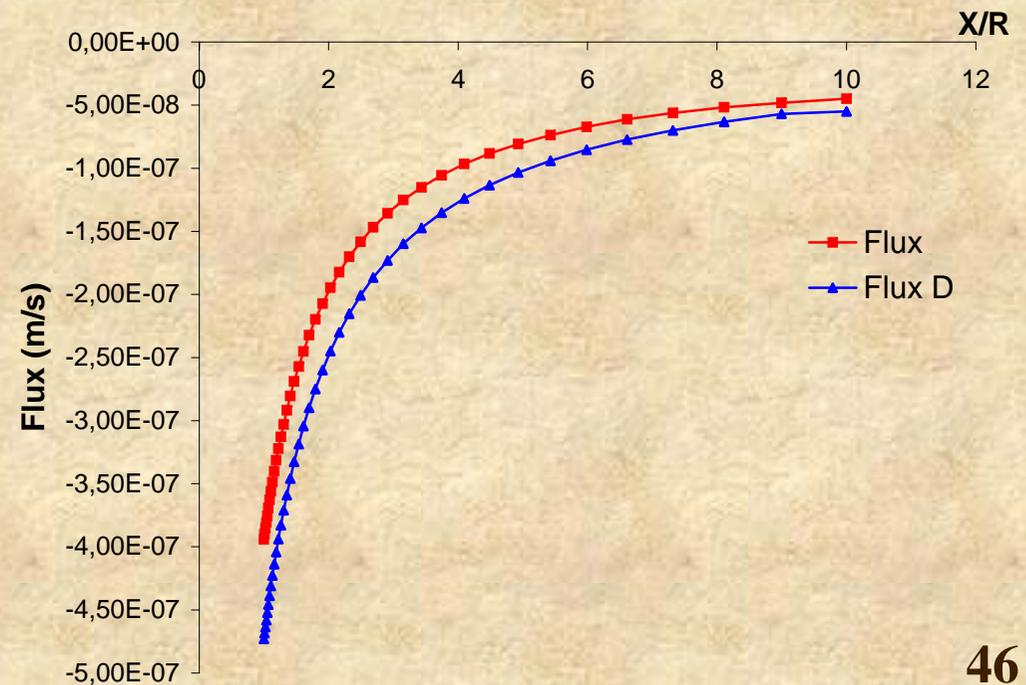
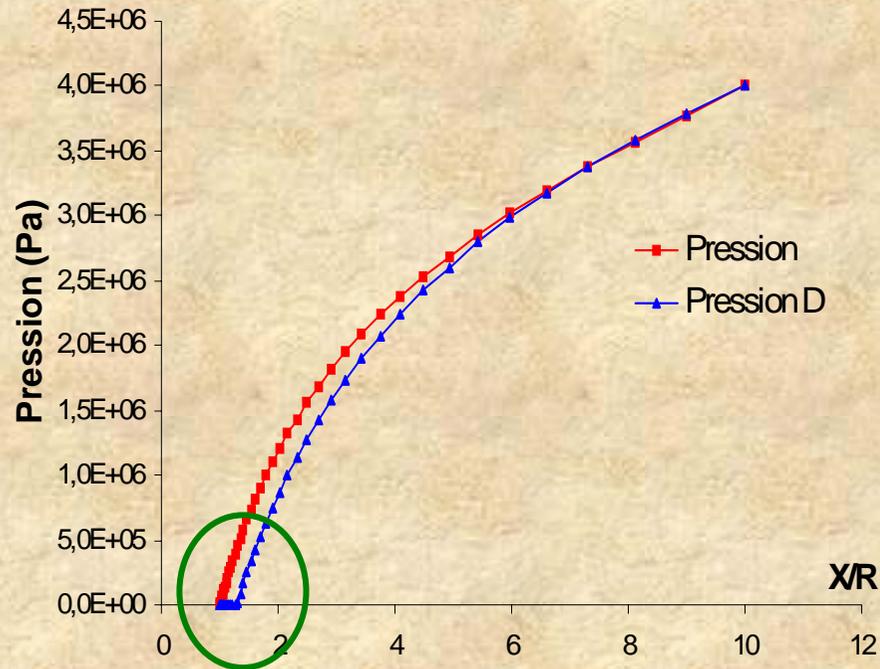
# Modélisation d'une galerie de stockage

À 400m de profondeur



CESAR-LCPC

# Modélisation d'une galerie de stockage



# Conclusion

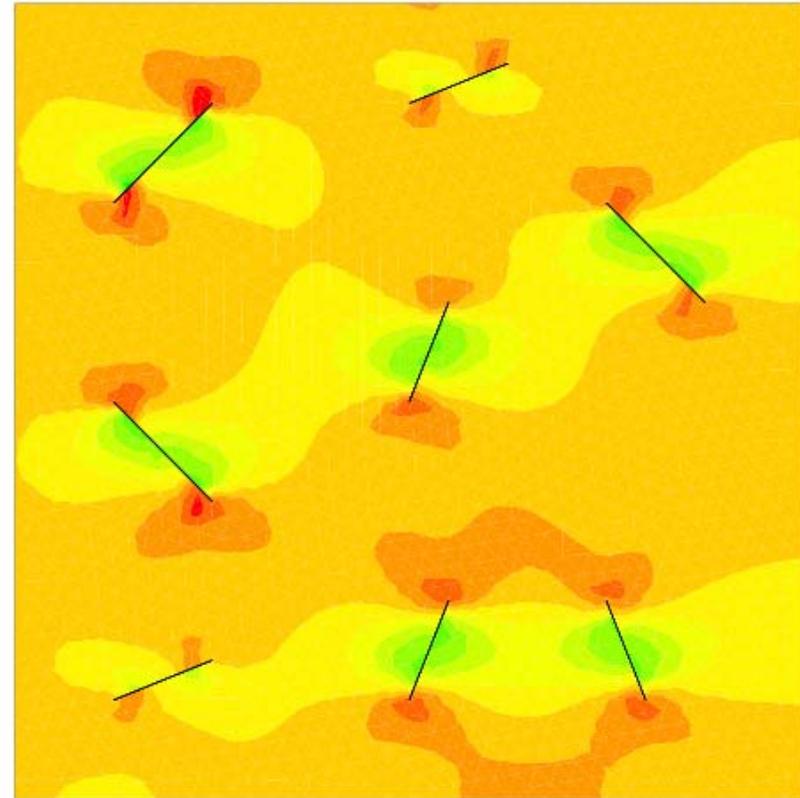
Modéliser l'effet de l'endommagement sur la perméabilité :

- Fissures de tailles finies et d'orientations définies par des lois statistiques en fonction de la direction et de la nature du chargement
- Calcul de la perméabilité équivalente d'un milieu poreux fissuré (aspect double porosité)
- Modélisation de l'anisotropie

Nécessité de calibrage des paramètres par des données expérimentales

# Perspectives

- Confrontation avec des données de mesures *in situ* récentes sur des parois de puits
- Détermination de l'endommagement et de la perméabilité par le même outil hydromécanique couplé



• Fin