CFMR

approches multi-échelles en mécanique des roches

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Propriétés poroélastiques de roches calcaires oolithiques

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OUTLINE

- motivation

  investigated material and posed problem

  multiscale homogenization method

- two steps SC scheme for porous oolitic rocks (two porosities)

  simplified microstructure and homogenization scheme

  step I : microscale $\rightarrow$ mesoscale (micropores)

  step II : mesoscale $\rightarrow$ macroscale (mesopores + ..)

- application to an oolitic limestone

  experimental results

  comparison model-experiments

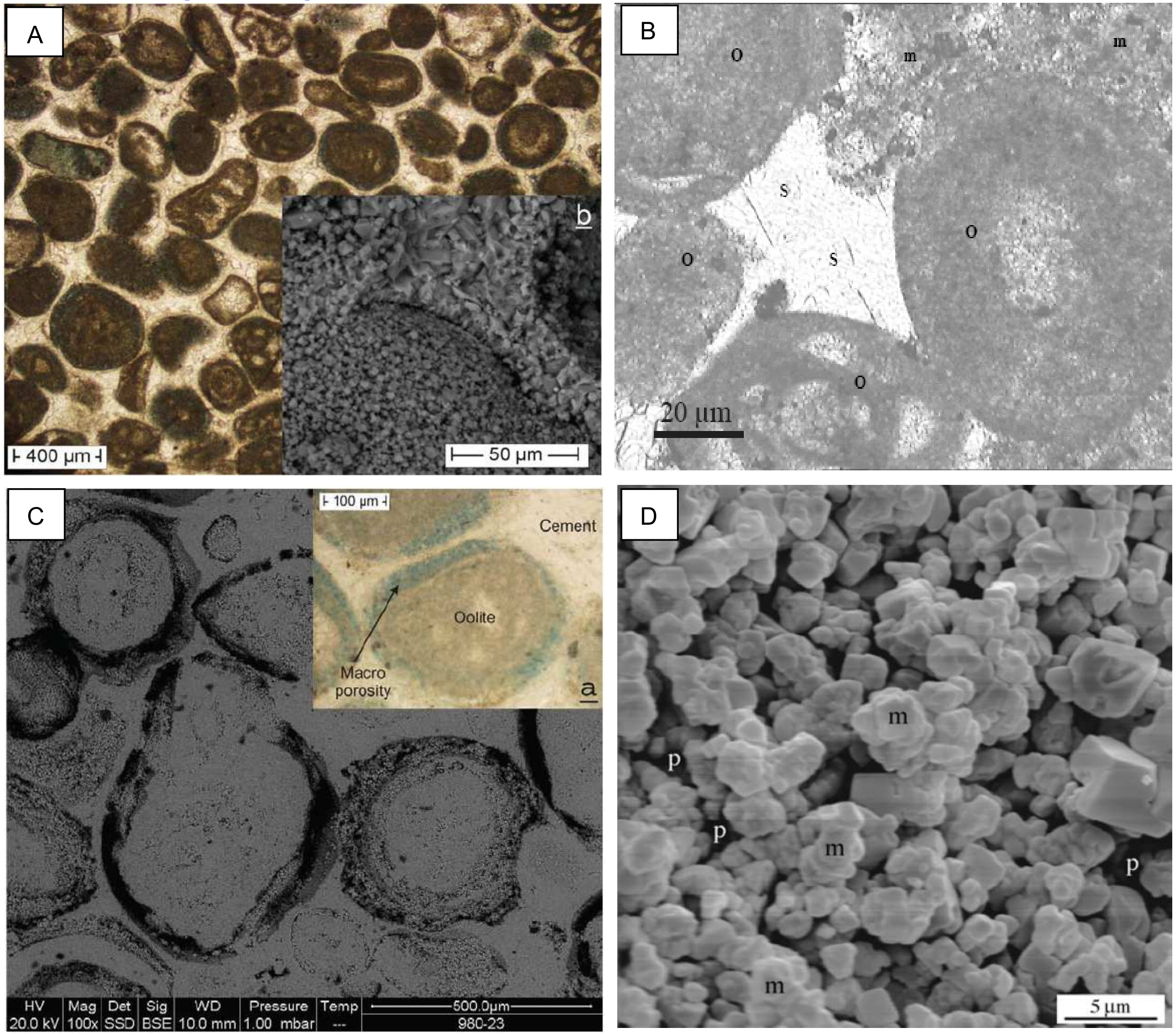
- conclusions & prospects

investigated materials

- porous oolitic rocks such as limestones
- studied in CO_2 geological storage research programs
- high porosity ($0.2 - 0.3$), high permeability, isotropic materials
- *granular type* structure (grains = porous oolites)
- many different facies depending on geological history

microstructure oolitic limestone (example)

Ghabezloo et al. (2009)



posed problem

- **interpretation of macro experimental results** (scale : 1-10 cm)

  mechanical tests (deviatoric compression tests, oedometer test, hydrostatic test etc.)

  poromechanical tests : drained - undrained (Biot coef)

- **including microstructural information**

  mineral content (calcite)

  porosity structure (pore scale distribution and pore shape)

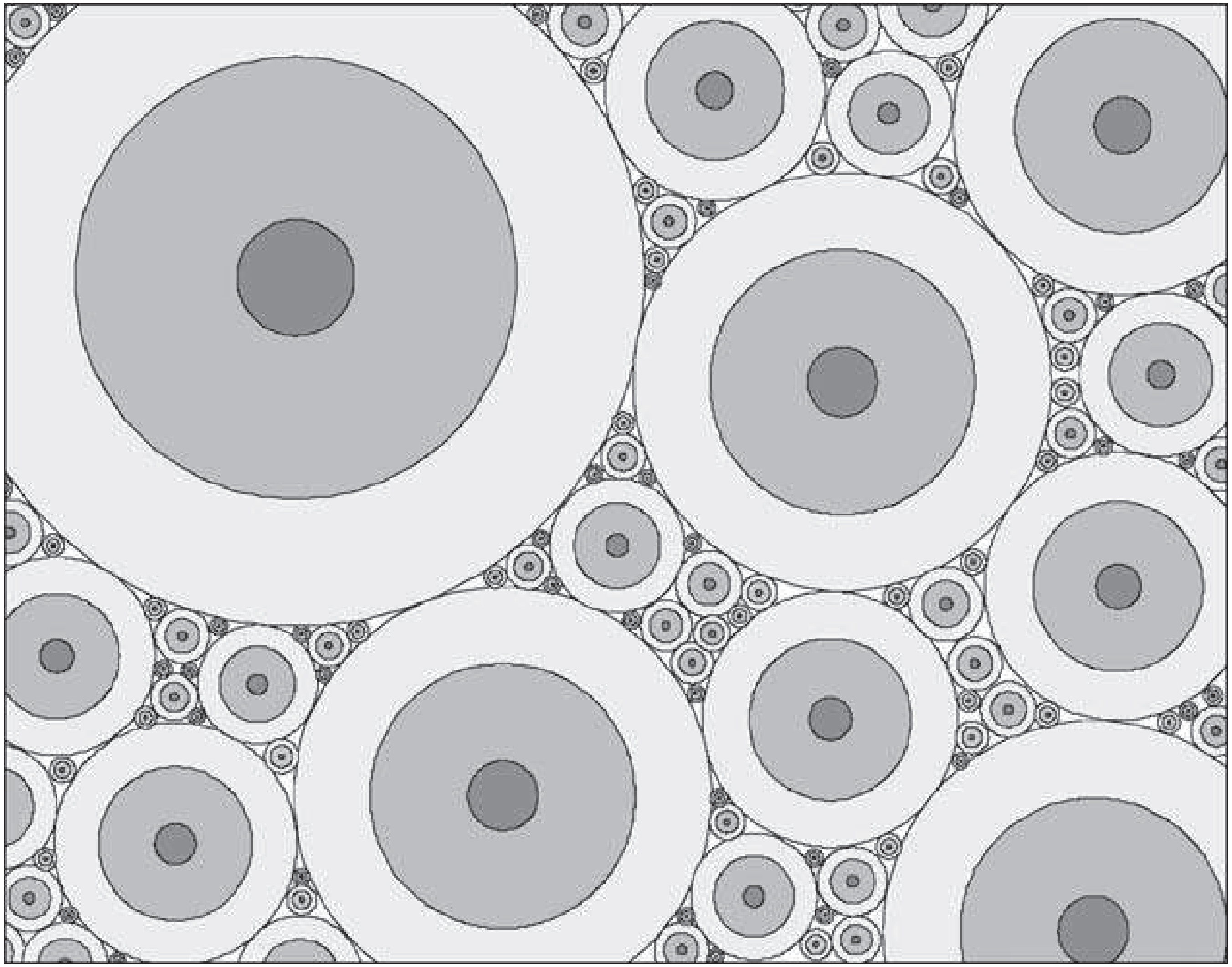
  properties of constituents (micro-indentation results)

linear poroelasticity $\Leftrightarrow$ linear thermoelasticity

- porous oolitic rock type composites (limestones, iron ore etc.) = grain + matrix
- *granular* type rock : high volume fraction of oolites
- first approach : Hashin Composite Sphere Assemblage model (Hashin (1962)) applied to linear poroelasticity
- mathematical analogy linear poroelasticity - linear thermoelasticity $\Rightarrow$ theoretical background well established (Schapery (1968), Rosen and Hashin (1970), Siboni and Benveniste (1991), Hervé and Zaoui (1993), Benveniste (2008) among many others).
- many recent and similar approaches on concrete - cement based materials (Bary and Béjaoui (2006), Hashin and Monteiro (2002), Heukamp et al. (2005))

Hashin Composite Sphere Assemblage (CSA)

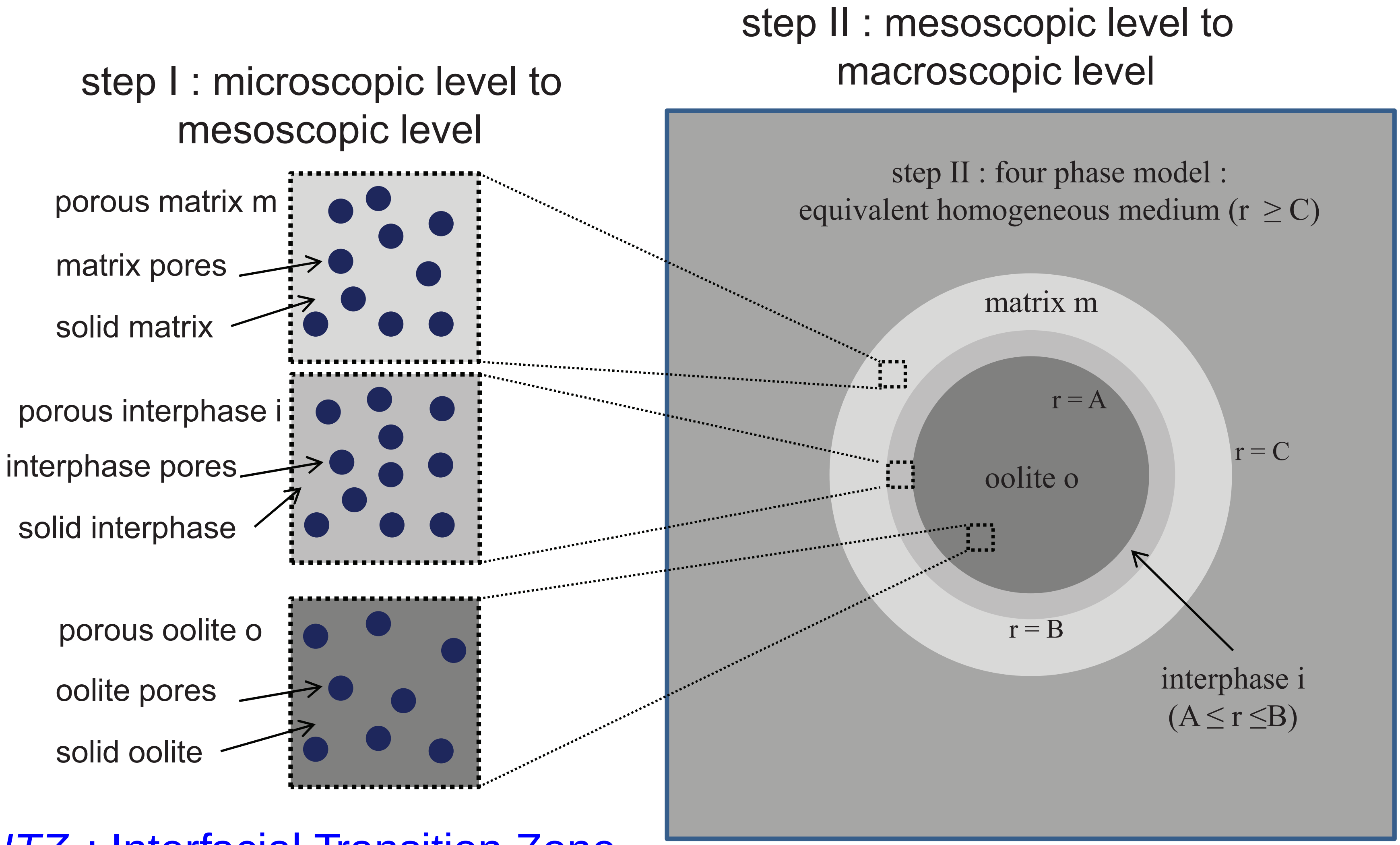
cement paste Bary and Béjaoui (2006) (among others)



Hashin and Monteiro (2002)

composite sphere assemblage (CSA) model

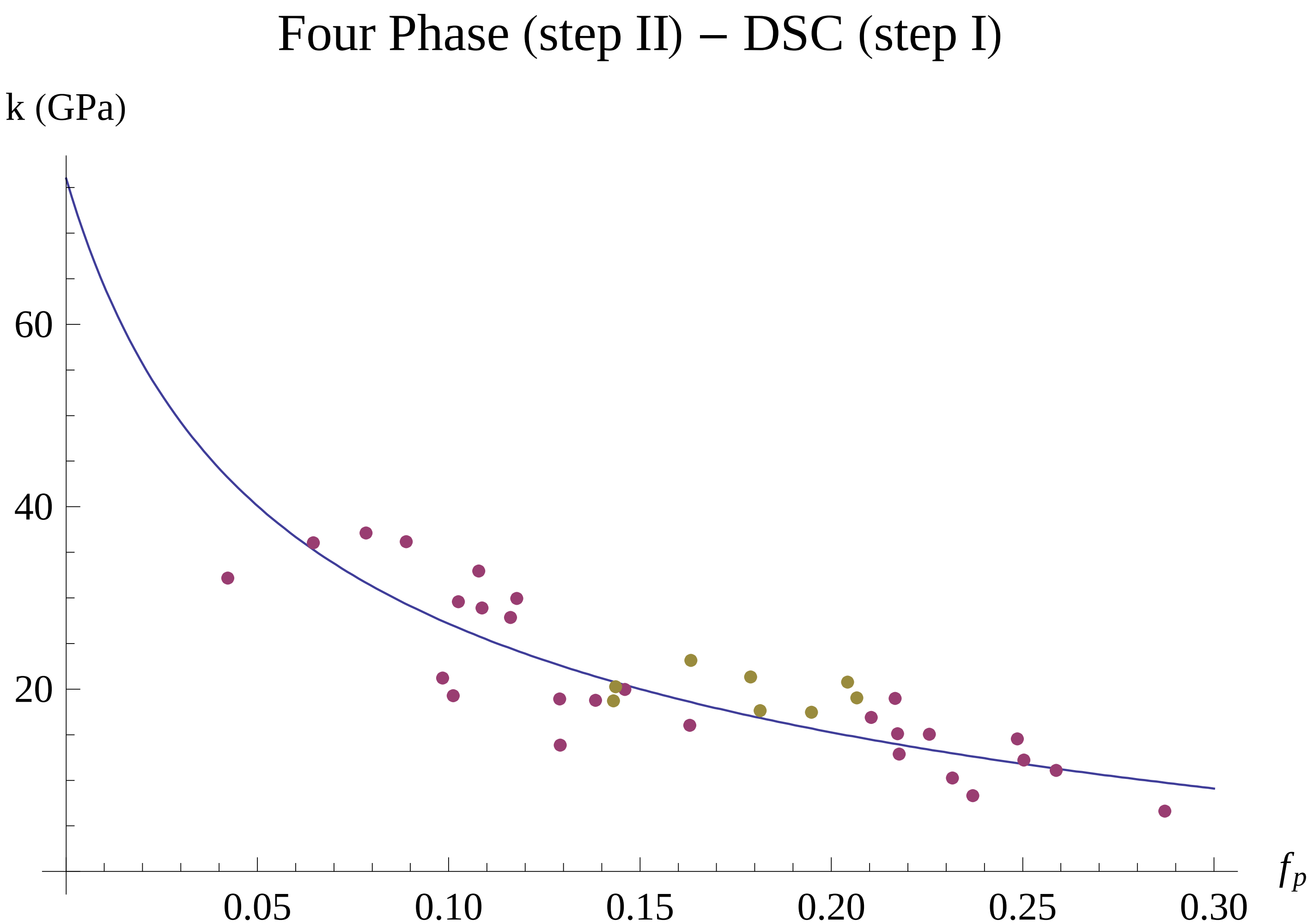
two step *Four Phase model* for porous oolic rocks



ITZ : Interfacial Transition Zone

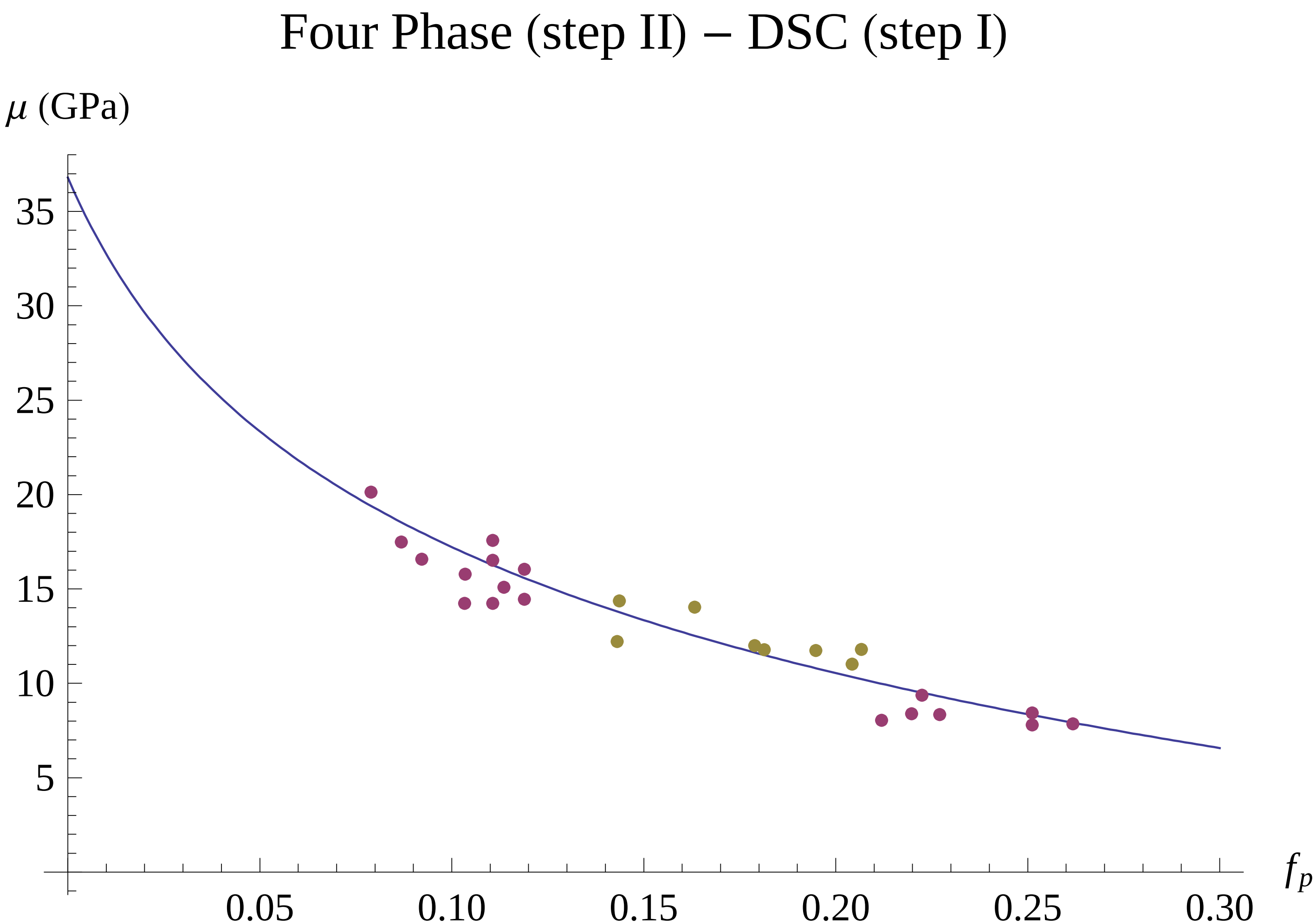
key influence of *ITZ* between oolite-matrix, Nguyen et al. (2011)

effective bulk modulus $k^{II}_{\mathbf{hom}}$



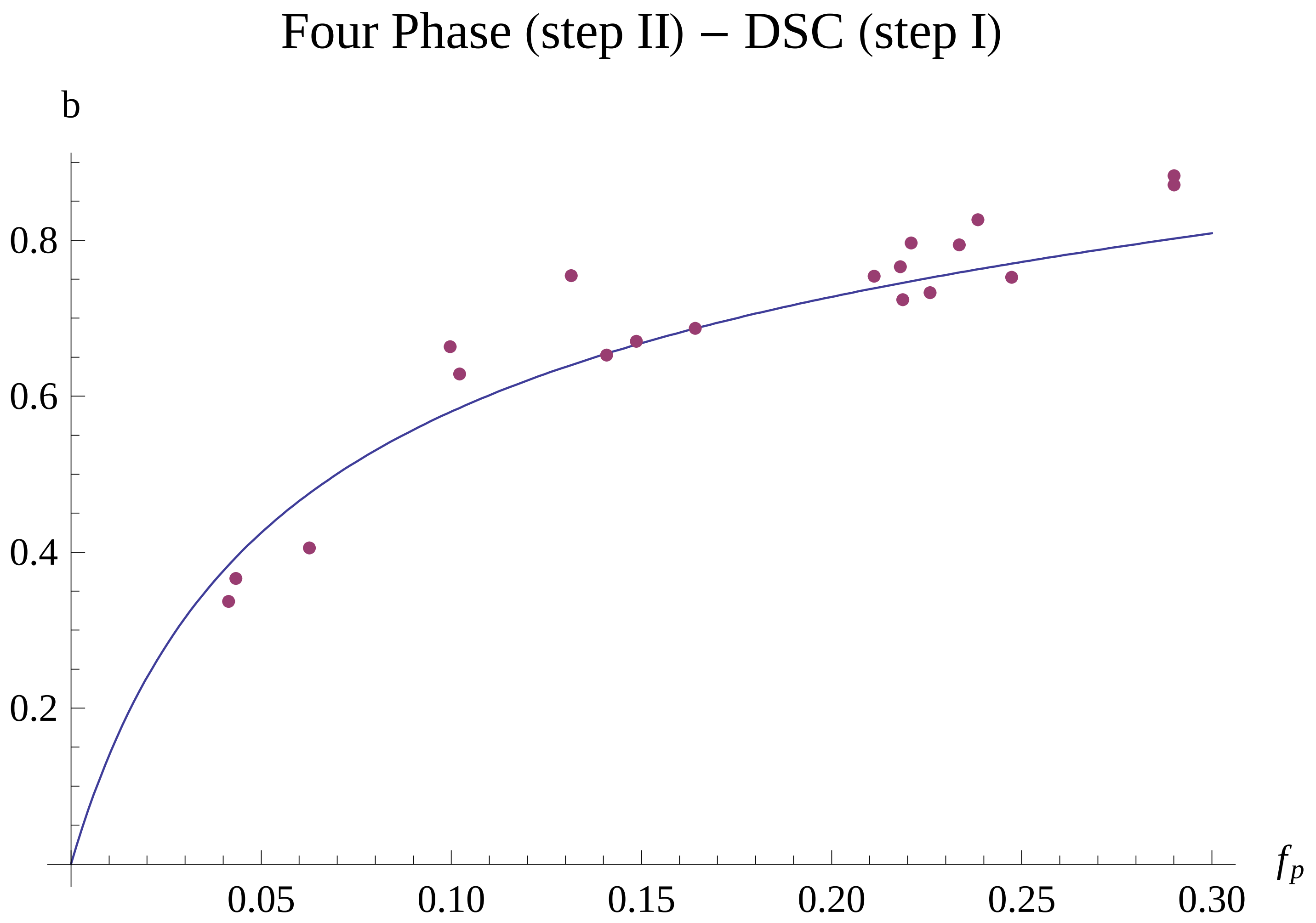
Four Phase and *DSC*, reference case

effective shear coefficient $\mu^{II}_{\mathbf{hom}}$



Four Phase and *DSC*, reference case

effective Biot coefficient $b^{II}_{\mathbf{hom}}$



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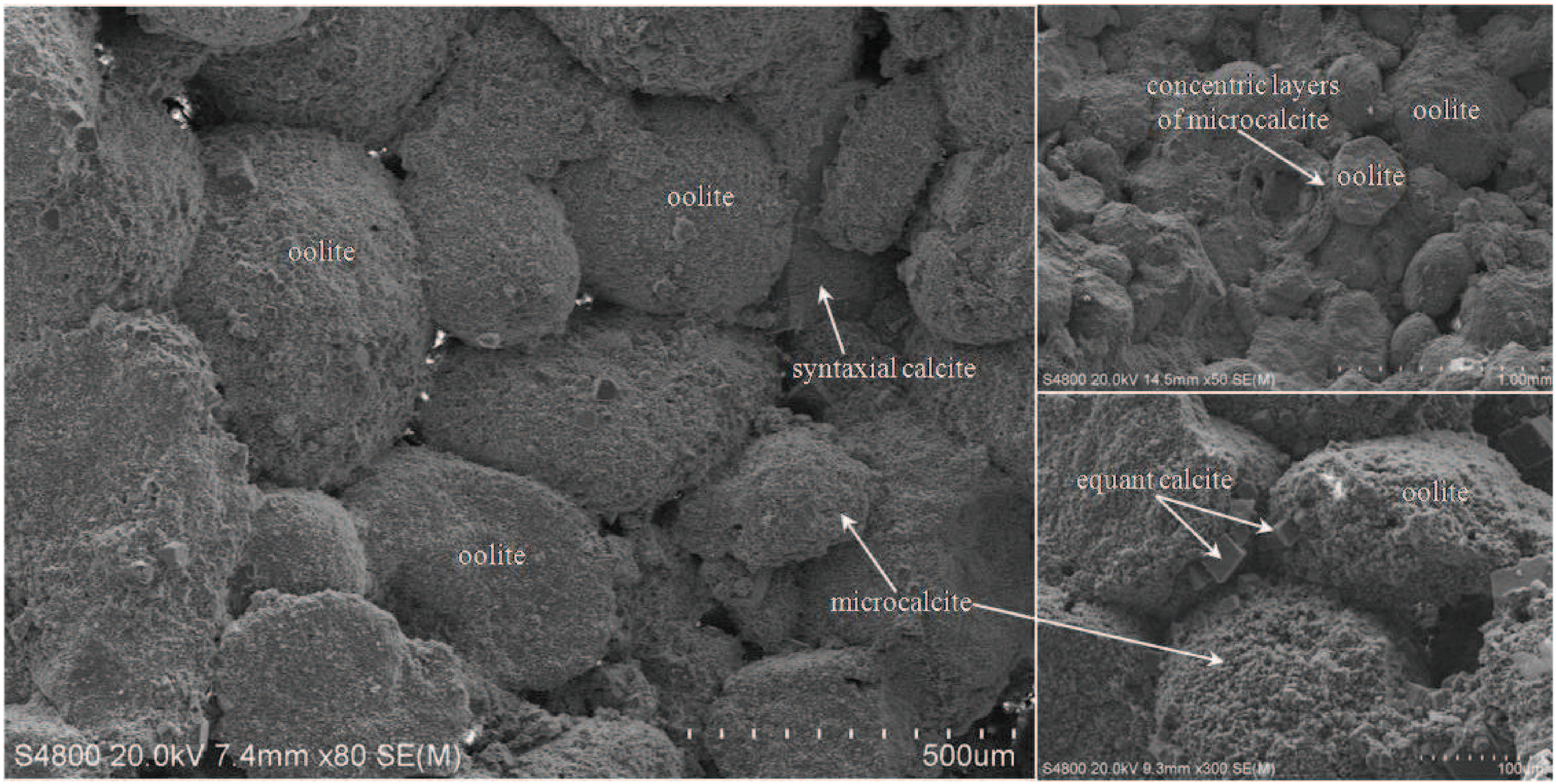
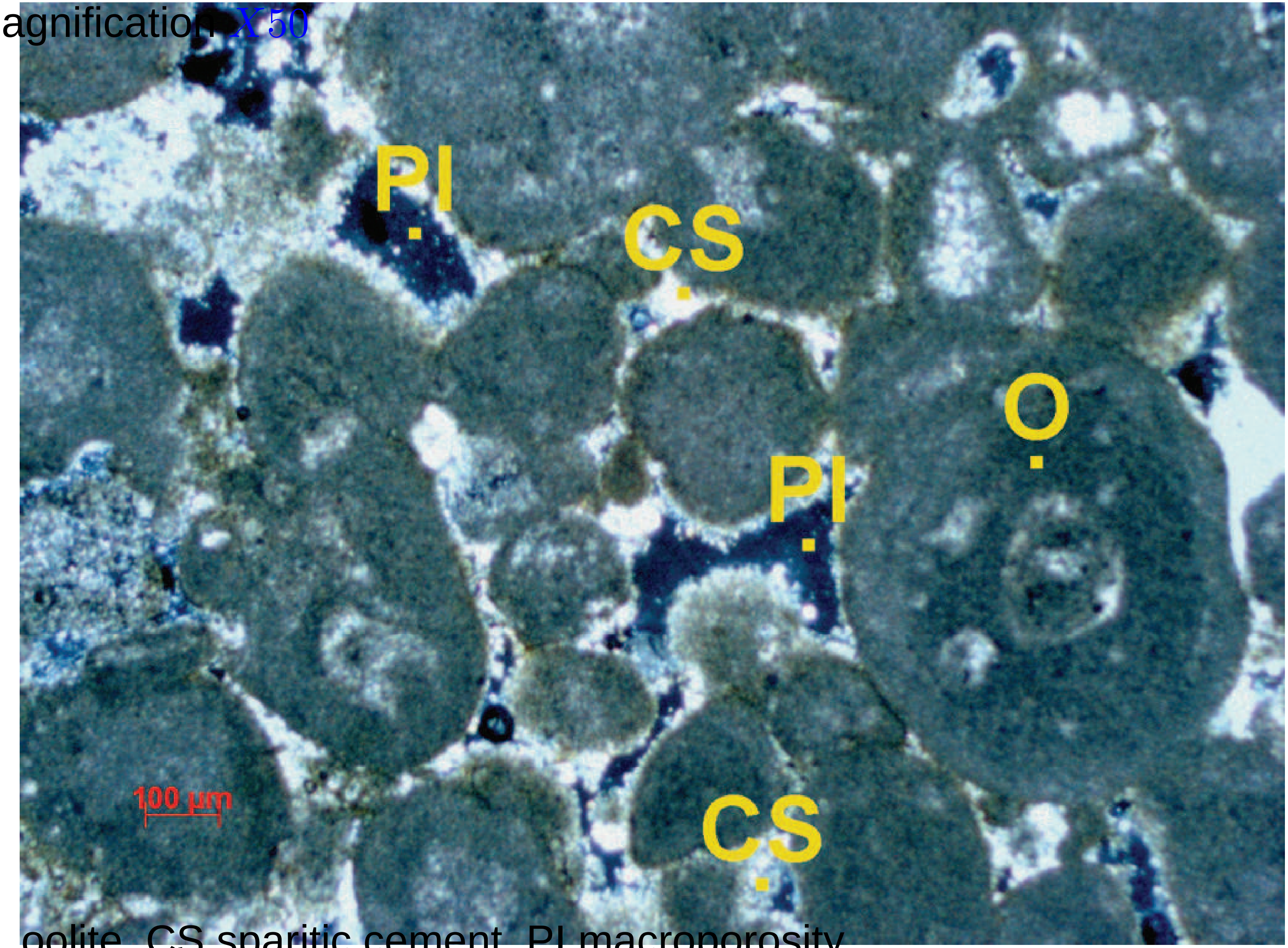
Lavoux limestone (oolitic facies)



microstructure of Lavoux limestone ($X50$)

magnification $X50$

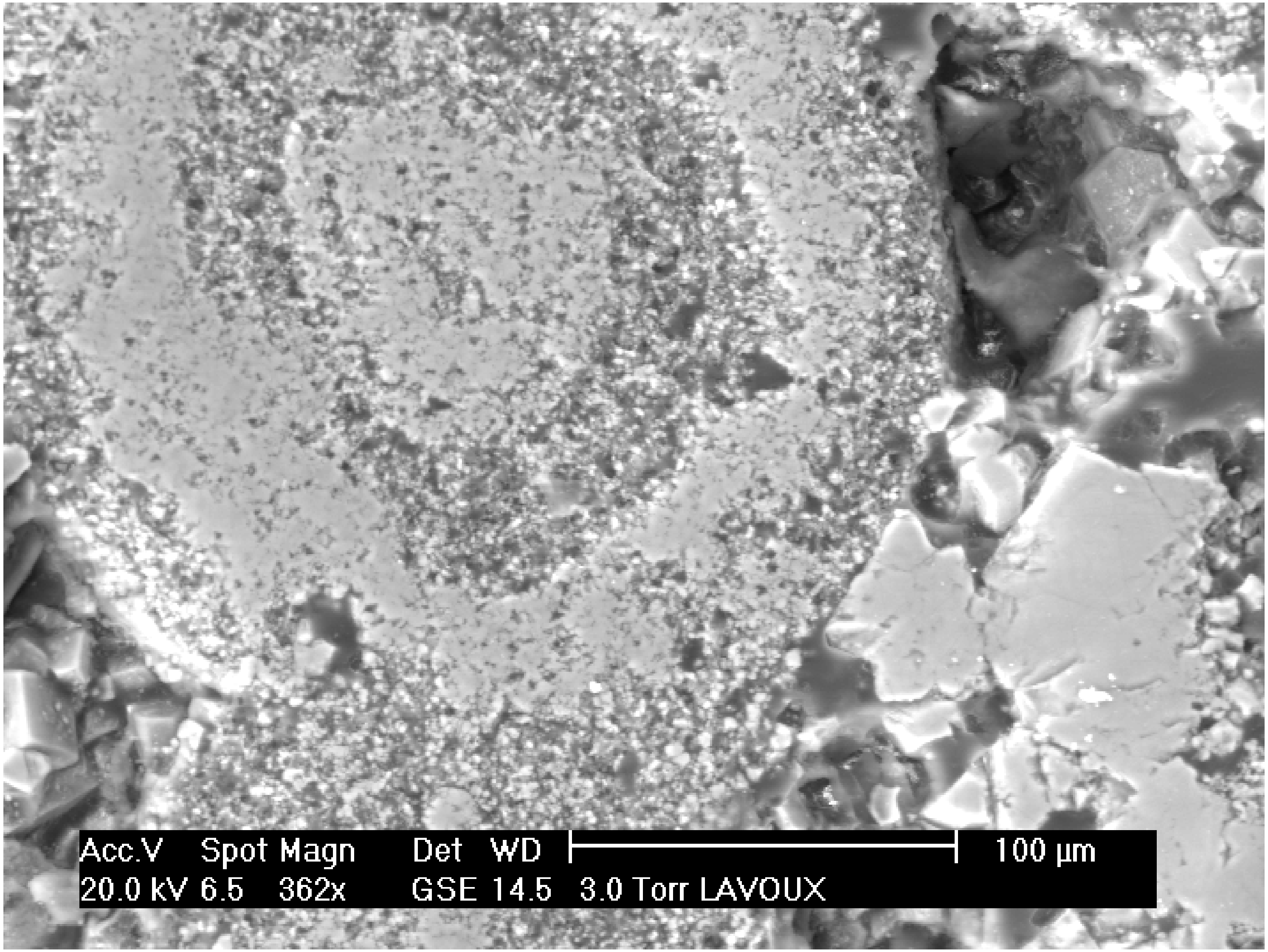


O. oolite, CS sparitic cement, PI macroporosity

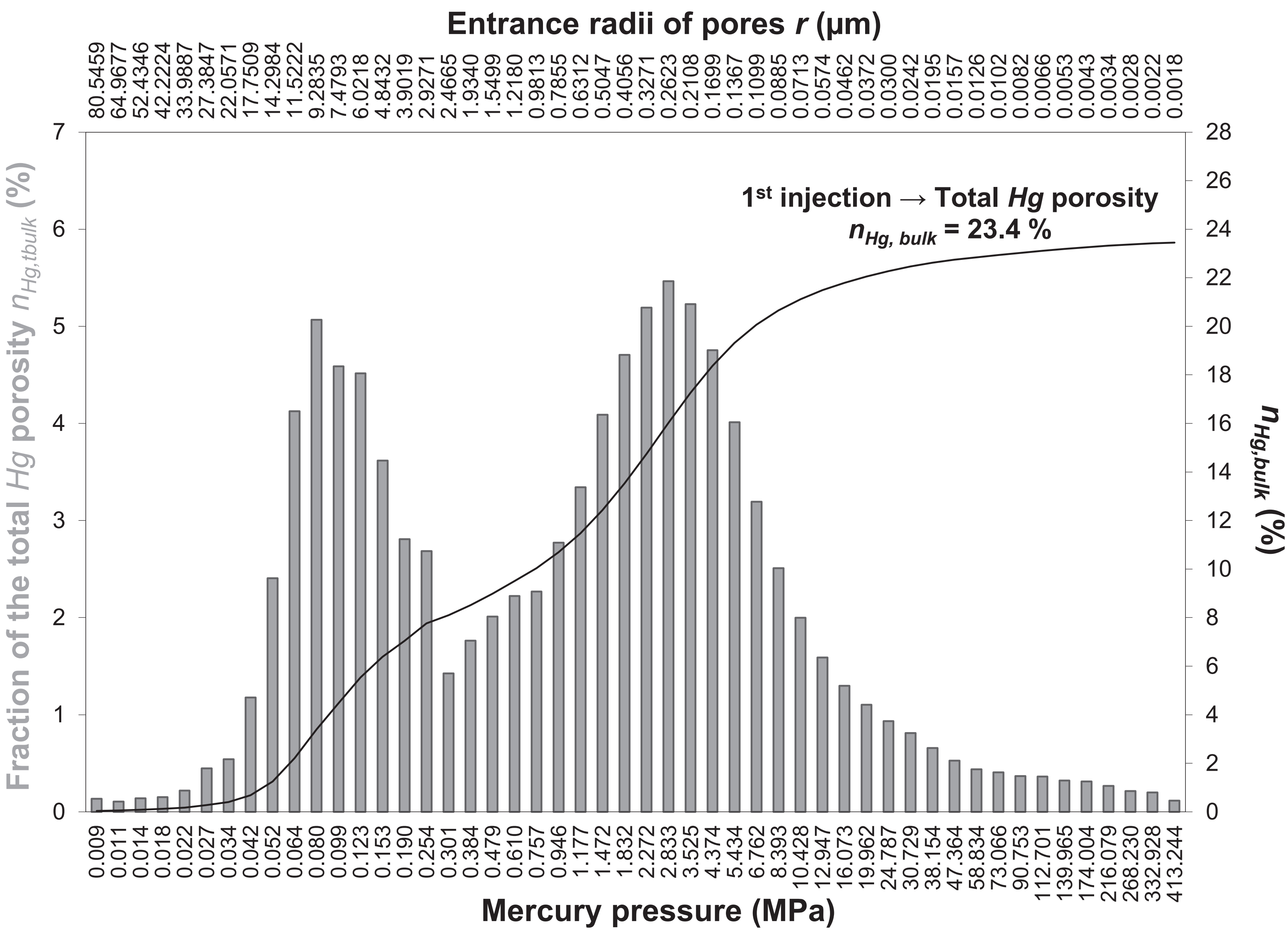
microstructure of Lavoux limestone

- oolites : spherical grains of concentric layers, diameter range $100\mu m - 1mm$
- micrite : *microcristalline calcite*, spherical grains, diameter range $1\mu m - 5\mu m$
- oolites : assemblage of micropores & micrite grains
- sparite : spar calcite, diameter range $20\mu m - 100\mu m$

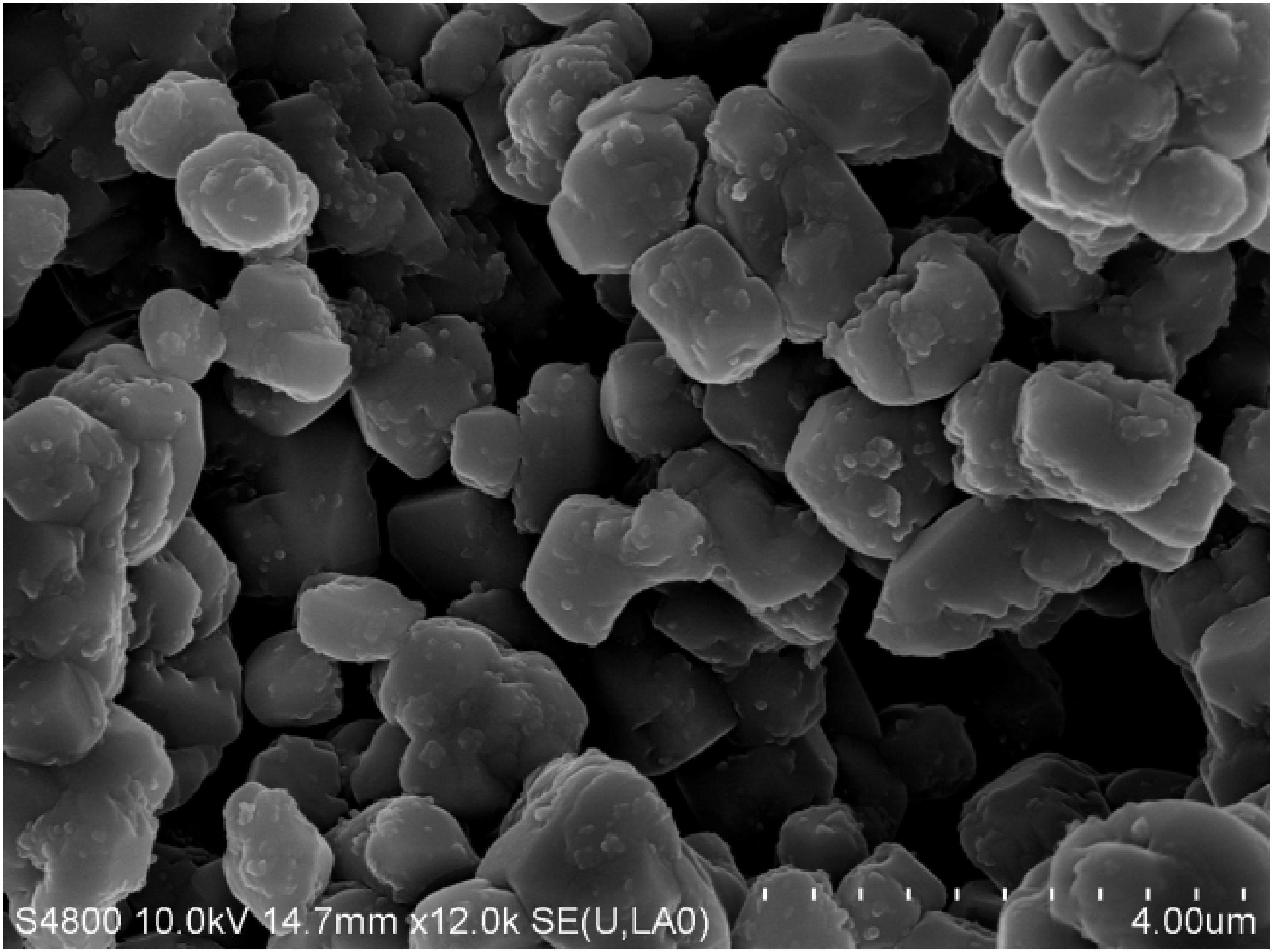
microstructure of oolites (Grgic (2011))



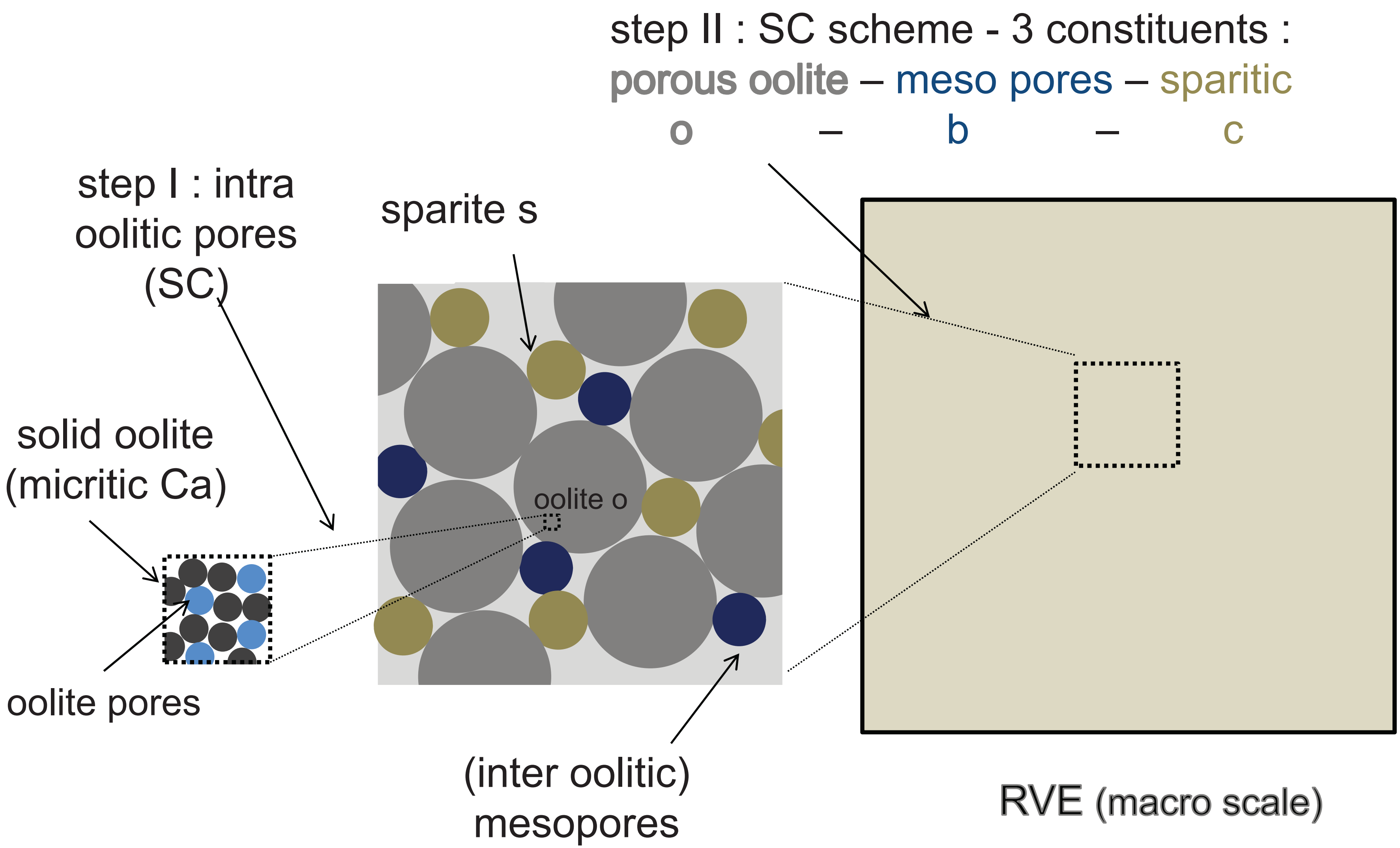
mercury porosimetry : Lavoux limestone



no continuous phase : SC scheme step I



2 Steps (SCS) : 2 scales *micro/meso* pores



constituents and volume fractions

three phases at meso level (step I)

$$\Omega = \Omega_o + \Omega_b + \Omega_c \qquad (1)$$

- o : porous oolite (poroelastic material)
- b : *meso* pores
- c : sparitic cement (pure calcite, elastic solid phase)

volume fractions

$$f_o = \frac{\Omega_o}{\Omega} \quad , f_b = \frac{\Omega_b}{\Omega} \quad , f_c = \frac{\Omega_c}{\Omega}$$
$$f_o + f_b + f_c = 1$$

assumption : scale separation *micro-mesopores*

- *intra oolitic voids* of spherical shape, diameter range $0.002\,\mu m < r < 2\,\mu m$, referred as *micropores*, index a,
- *inter oolitic voids* of spherical shape, diameter range $2\,\mu m < r < 50\,\mu m$, referred as *mesopores*, index b

total pore volume Ω_p & pore volume fraction f_p

$$\Omega_p = \Omega_a + \Omega_b \tag{2}$$

$$f_p = \frac{\Omega_a + \Omega_b}{\Omega} = f_a f_o + f_b \tag{3}$$

$$f_a = \frac{\Omega_a}{\Omega_o} \quad , \quad f_b = \frac{\Omega_b}{\Omega} \tag{4}$$

typical data for Lavoux Limestone

$f_p = 0.26$, $f_o = 0.74$, $f_a f_o = 0.14$, $f_a = 0.19$, $f_b = 0.12$

Step I : SC scheme (oolites)

simple formula, isotropic case (spherical distribution), *SC*

$$\frac{k_o^I}{k_o^s} = \frac{1 - f_a}{1 + \alpha_o^I \left(k_o^s - k_o^I\right) / k_o^I} \quad , \quad \frac{\mu_o^I}{\mu_o^s} = \frac{1 - f_a}{1 + \beta_o^I \left(\mu_o^s - \mu_o^I\right) / \mu_o^I}$$

$$\alpha_o^I = \frac{3\, k_o^I}{3\, k_o^I + 4\, \mu_o^I} \quad , \quad \beta_o^I = \frac{6\left(k_o^I + 2\, \mu_o^I\right)}{5\left(3\, k_o^I + 4\, \mu_o^I\right)}$$

unknowns : k_o^s, μ_o^s : properties of solid oolite phase (microcalcite or micrite).

k_o^I & μ_o^I : homogenized elastic properties of porous oolite, to be compared to experimental microindentation data.

Linear poroelastic properties of oolites - mesoscale (I

isotropic poroelastic relations, oolite, step I (mesoscale)

$$\begin{aligned} \underline{\underline{\sigma}} &= \left(3k_o^I \mathbb{J} + 2\mu_o^I \mathbb{K}\right) : \underline{\underline{\varepsilon}} - b_o^I P_a \underline{\underline{i}} \\ f_a - f_a^0 &= b_o^I \underline{\underline{i}} : \underline{\underline{\varepsilon}} + \frac{P_a}{N_o^I} \end{aligned} \quad (5)$$

micromacro compatibility relations (homogeneous solid phase)

$$b_o^I = 1 - \frac{k_o^I}{k_o^s} \quad , \quad \frac{1}{N_o^I} = \frac{b_o^I - f_a}{k_o^s} \quad (6)$$

(Biot (1941), Biot (1977) , Cowin (2004), Coussy (2004))

Step II : SC scheme, meso $\rightarrow$ macroscale

$$\begin{aligned}
\underline{\underline{\Sigma}} &= \mathbb{C}^{II}_{\text{hom}} : \underline{\underline{E}} - \underline{\underline{B}}^{II}_a P_a - \underline{\underline{B}}^{II}_b P_b \\
\left(\phi_a - \phi_a^0\right)^{II} &= \underline{\underline{B}}^{II}_a : \underline{\underline{E}} + \frac{P_a}{N^{II}_{aa}} + \frac{P_b}{N^{II}_{ab}} \\
\left(\phi_b - \phi_b^0\right)^{II} &= \underline{\underline{B}}^{II}_b : \underline{\underline{E}} + \frac{P_a}{N^{II}_{ba}} + \frac{P_b}{N^{II}_{bb}}
\end{aligned} \tag{7}$$

ϕ_a porosity associated with Ω_o, at the scale of the rve Ω

$$\phi_a = \frac{\Omega_a}{\Omega} = \frac{\Omega_a}{\Omega_o}\frac{\Omega_o}{\Omega} = f_a f_o \quad , \quad \phi_b = \frac{\Omega_b}{\Omega} = f_b \tag{8}$$

$\underline{\underline{\Sigma}}$ stress tensor, ϕ_a, ϕ_b porosities, $\underline{\underline{E}}$ strain tensor, P_a, P_b pore pressures, $\mathbb{C}^{II}_{\text{hom}}$ overall drained stiffness tensor, $\underline{\underline{B}}^{II}_a$, $\underline{\underline{B}}^{II}_b$ Biot tensors, N^{II}_{ij} solid Biot moduli

Step II : isotropic case

$$
\begin{aligned}
&\underline{\underline{\Sigma}} = \left(3k^{II}_{\text{hom}}\,\mathbb{J} + 2\mu^{II}_{\text{hom}}\,\mathbb{K}\right) : \underline{\underline{E}} - b^{II}_a P_a \underline{\underline{i}} - b^{II}_b P_b \underline{\underline{i}} \\
&\left(\phi_a - \phi^0_a\right)^{II} = b^{II}_a \underline{\underline{i}} : \underline{\underline{E}} + \frac{P_a}{N^{II}_{aa}} + \frac{P_b}{N^{II}_{ab}} \\
&\left(\phi_b - \phi^0_b\right)^{II} = b^{II}_b \underline{\underline{i}} : \underline{\underline{E}} + \frac{P_a}{N^{II}_{ba}} + \frac{P_b}{N^{II}_{bb}}
\end{aligned}
\tag{9}
$$

k^{II}_{hom}, μ^{II}_{hom} overall drained bulk modulus & shear coefficient

b^{II}_a, b^{II}_b Biot coefficients, N^{II}_{ij} solid Biot moduli

Average stress and strain

continuous description of stress field in the heterogeneous R.V.E. (Ulm et al. (2005), Dormieux et al. (2006))

$$\underline{\underline{\sigma}}(\underline{z}) = \mathbb{C}(\underline{z}) : \underline{\underline{\varepsilon}}(\underline{z}) + \underline{\underline{\sigma}}^p(\underline{z}) \quad , \quad \forall \underline{z} \quad \text{in } \Omega \tag{10}$$

$$\mathbb{C}(\underline{z}) = \mathbb{C}_o^I \quad \text{in } \Omega_o, \quad \mathbb{C}(\underline{z}) = \mathbb{C}_b = 0 \quad \text{in } \Omega_b, \quad \mathbb{C}(\underline{z}) = \mathbb{C}_c \quad \text{in } \Omega_c \tag{11}$$

and uniform prestress $\underline{\underline{\sigma}}^p(\underline{z})$ per phase

$$\begin{aligned} &\underline{\underline{\sigma}}^p(\underline{z}) = \underline{\underline{\sigma}}_o^p = -b_o^I P_a \underline{\underline{i}} \quad \text{in } \Omega_o, \quad \underline{\underline{\sigma}}^p(\underline{z}) = \underline{\underline{\sigma}}_b^p = -P_b \underline{\underline{i}} \quad \text{in } \Omega_b \\ &\underline{\underline{\sigma}}^p(\underline{z}) = 0 \quad \text{in } \Omega_c \end{aligned} \tag{12}$$

Levin's theorem (see Levin (1967), Levin and Alvarez-Tostado (2006), Ulm et al. (2005)) used in linear microporoelasticity

Two subproblems : $'$ and $''$

1. first subproblem $'$: drained conditions (zero prestress field $\underline{\underline{\sigma}}^p = 0$, $P_a = P_b = 0$) loading parameter $=$ macroscopic strain tensor $\underline{\underline{E}}$.

$$\begin{aligned} &\underline{\xi}'(\underline{z}) = \underline{\underline{E}}.\underline{z} \quad \text{on} \quad \partial\Omega \\ &\underline{\underline{\sigma}}' = \mathbb{C}(\underline{z}) : \underline{\underline{\varepsilon}}' \end{aligned} \tag{13}$$

2. second subproblem $''$: zero-displacement boundary problem with loading defined by prestress field $\underline{\underline{\sigma}}^p$

$$\begin{aligned} &\underline{\xi}''(\underline{z}) = 0 \quad \text{on } \partial\Omega \\ &\underline{\underline{\sigma}}'' = \mathbb{C}(\underline{z}) : \underline{\underline{\varepsilon}}'' + \underline{\underline{\sigma}}^p(\underline{z}) \end{aligned} \tag{14}$$

Derivation of $\mathbb{C}^{II}_{\textbf{hom}} - b^{II}_i$: First subproblem $'$

first subproblem $'$ ($P_a = P_b = 0$), loading parameter : uniform strain tensor $\underline{\underline{E}}$ imposed on the boundary of the *RVE*

$$
\begin{array}{l}
\underline{\underline{\Sigma}}' = \left\langle \underline{\underline{\sigma}}' \right\rangle = \mathbb{C}^{II}_{\text{hom}} : \underline{\underline{E}} \\
\left[\left(\phi_a - \phi^0_a \right)^{II} \right]' = b^{II}_a \underline{\underline{i}} : \underline{\underline{E}} \\
\left[\left(\phi_b - \phi^0_b \right)^{II} \right]' = b^{II}_b \underline{\underline{i}} : \underline{\underline{E}}
\end{array} \tag{15}
$$

$$
\begin{array}{l}
\mathbb{C}^{II}_{\text{hom}} = \mathbb{C}_{\text{SC}} = \mathbb{C}^0 = \left\langle \mathbb{C}_r : \left[\mathbb{I} + \mathbb{P}^0 : \left(\mathbb{C}_r - \mathbb{C}^0 \right) \right]^{-1} \right\rangle \\
\left\langle \underline{\underline{a}} \right\rangle = \dfrac{1}{\Omega} \displaystyle\int_\Omega \underline{\underline{a}} d\Omega \quad , \quad \mathbb{P}^0 = \dfrac{\alpha^0}{3\,k^0} \mathbb{J} + \dfrac{\beta^0}{2\,\mu^0} \mathbb{K} \\
\alpha^0 = \dfrac{3\,k^0}{3\,k^0 + 4\,\mu^0} \quad , \quad \beta^0 = \dfrac{6\left(k^0 + 2\,\mu^0\right)}{5\left(3\,k^0 + 4\,\mu^0\right)}
\end{array} \tag{16}
$$

overall bulk modulus & shear coefficient

micro & macro isotropy, spherical distribution, ($k^{II}_{\mathrm{hom}} = k^0$, $\mu^{II}_{\mathrm{hom}} = \mu^0$)

$$\frac{k^0}{3\,k^0 + 4\,\mu^0} = f_o \frac{k^I_o}{3\,k^I_o + 4\,\mu^0} + (1 - f_o - f_b)\,\frac{k_c}{3\,k_c + 4\,\mu^0} \tag{17}$$

$$\begin{aligned}\frac{1}{5\,(3\,k^0 + 4\,\mu^0)} &= f_o \frac{\mu^I_o}{6\,\mu^I_o\,(k^0 + 2\,\mu^0) + \mu^0\,(9\,k^0 + 8\,\mu^0)} \\ &+ (1 - f_o - f_b)\,\frac{\mu_c}{6\,\mu_c\,(k^0 + 2\,\mu^0) + \mu^0\,(9\,k^0 + 8\,\mu^0)}\end{aligned} \tag{18}$$

k^I_o, μ^I_o, k_c, $\mu_c \leftrightarrow$ micro-indentation results (mesoscale)

k^{II}_{hom}, $\mu^{II}_{\mathrm{hom}} \leftrightarrow$ macro results (compression tests etc.)

overall Biot coefficients (1)

SC scheme, $\mathbb{P}^0$ tensor identical for all phases, strain localisation tensor ($r = o, b, c$)

$$\mathbb{A}_r = \left[\mathbb{I} + \mathbb{P}^0 : \left(\mathbb{C}_r - \mathbb{C}^0\right)\right]^{-1}$$
$$\mathbb{A}_r = \frac{k^0}{k^0 - \alpha^0\left(k^0 - k_r\right)}\mathbb{J} + \frac{\mu^0}{\mu^0 - \beta^0\left(\mu^0 - \mu_r\right)}\mathbb{K} \tag{19}$$

then ($k_b = 0$, $\mu_b = 0$)

$$\mathbb{A}_o = \frac{k^0}{k^0 - \alpha^0\left(k^0 - k_o^I\right)}\mathbb{J} + \frac{\mu^0}{\mu^0 - \beta^0\left(\mu^0 - \mu_o^I\right)}\mathbb{K}$$
$$\mathbb{A}_b = \frac{1}{1 - \alpha^0}\mathbb{J} + \frac{1}{1 - \beta^0}\mathbb{K} \tag{20}$$
$$\mathbb{A}_c = \frac{k^0}{k^0 - \alpha^0\left(k^0 - k_c\right)}\mathbb{J} + \frac{\mu^0}{\mu^0 - \beta^0\left(\mu^0 - \mu_c\right)}\mathbb{K}$$

overall Biot coefficients (2)

average strain tensor per phase

$$\left\langle \underline{\underline{\varepsilon}}' \right\rangle^r = \underline{\underline{\varepsilon}}'_r = \mathbb{A}_r : \underline{\underline{E}} \tag{21}$$

change of macroporosity

$$\left[\left(\phi_b - \phi_b^0 \right)^{II} \right]' = f_b \underline{\underline{i}} : \left\langle \underline{\underline{\varepsilon}}' \right\rangle^b = f_b \underline{\underline{i}} : \mathbb{A}_b : \underline{\underline{E}} = b_b^{II} \underline{\underline{i}} : \underline{\underline{E}} \tag{22}$$

$$\begin{aligned} \left[\left(\phi_a - \phi_a^0 \right)^{II} \right]' &= f_o \left\langle \left(f_a - f_a^0 \right)' \right\rangle^o \\ &= f_o b_o^I \underline{\underline{i}} : \left\langle \underline{\underline{\varepsilon}}' \right\rangle^o = f_o b_o^I \underline{\underline{i}} : \mathbb{A}_o : \underline{\underline{E}} = b_a^{II} \underline{\underline{i}} : \underline{\underline{E}} \end{aligned} \tag{23}$$

$$\left\langle \underline{\underline{a}} \right\rangle = \frac{1}{\Omega} \int_\Omega \underline{\underline{a}} d\Omega \quad , \quad \left\langle \underline{\underline{a}} \right\rangle^\alpha = \frac{1}{\Omega^\alpha} \int_{\Omega^\alpha} \underline{\underline{a}} d\Omega \tag{24}$$

overall Biot coefficients (3)

Biot coefficient associated to microporosity (intra-oolite)

$$b_a^{II} \underline{\underline{i}} = f_o b_o^I \underline{\underline{i}} : \mathbb{A}_o \tag{25}$$

$$b_a^{II} = \frac{f_o k^0 b_o^I}{k^0 - \alpha^0 \left(k^0 - k_o^I\right)} \tag{26}$$

Biot coefficient associated to mesoporosity (inter-oolite)

$$b_b^{II} \underline{\underline{i}} = f_b \underline{\underline{i}} : \mathbb{A}_b \tag{27}$$

$$b_b^{II} = \frac{f_b}{1 - \alpha^0} \tag{28}$$

connected porosities & $P_a = P_b = P$

overall Biot coefficient with equal pressures in *micro* & *meso* porosities

$$b^{II} = b_a^{II} + b_b^{II} \tag{29}$$

$$b^{II} = \frac{f_o k^0 b_o^I}{k^0 - \alpha^0 \left(k^0 - k_o^I\right)} + \frac{f_b}{1 - \alpha^0} \tag{30}$$

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data at mesoscale : microindentation

mesoscopic bulk moduli of Lavoux limestone constituents deduced from indentation data (microindentation, current work : nanoindentation, **C. Auvray**)

constituent	volume fraction	n_{mes}	k_i (GPa)	σ (GPa)	
oolite	$f_o = 0.74$	29	27.1	5.4	k_o^I
sparite grain	$f_c = 0.14$	34	68.2	6.1	k_c
meso pores	$f_b = 0.12$				$k_b = 0$

k_i : mean value , σ : standard deviation
Microindentation : Flat indenter ($D = 300\mu m$)
High-resolution camera ($25\mu m$) fixed on indenter frame used to identify oolite and sparitic cement

reference data solid phase : pure calcite

solid phase $\approx$ mono-mineral, $f^s_{calcite} \approx 0.98$.
pure calcite mineral : trigonal anisotropic class system
(Winkler (1975))
Elastic constant of calcite (GPa)

Constituent	C_{1111}	C_{3333}	C_{2323}	C_{1122}	C_{1133}	C_{1123}
Calcite ($CaCO_3$)	$144.$	84.0	33.5	53.9	51.1	-20.5

random distribution $\Rightarrow$ isotropization

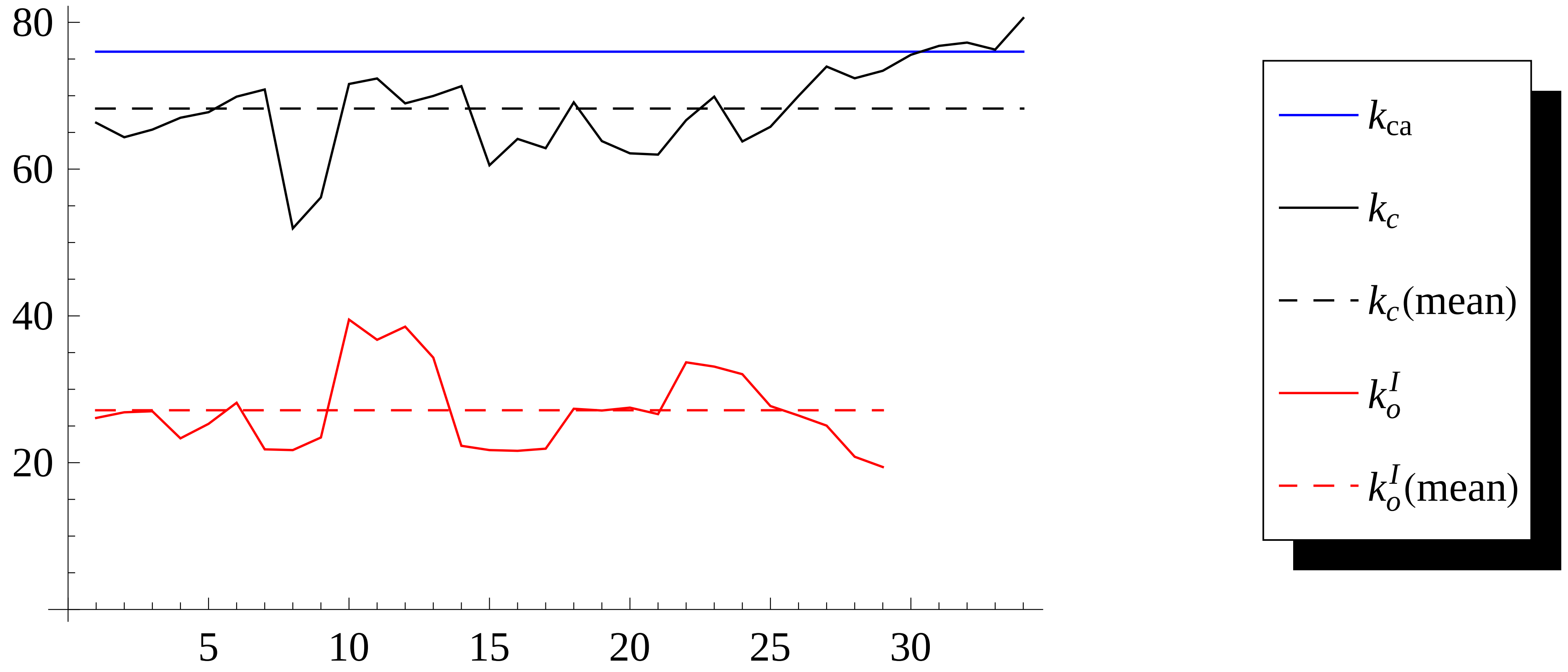
$$\mathbb{C}^{\text{is}}_{ca} = 3k^{\text{is}}_{ca}\,\mathbb{J} + 2\mu^{\text{is}}_{ca}\,\mathbb{K}$$

$$k^{\text{is}}_{ca} = \frac{\mathbb{C}_{ca} :: \mathbb{J}}{3} \approx 76.0 \quad \text{GPa}$$

$$\mu^{\text{is}}_{ca} = \frac{\mathbb{C}_{ca} :: \mathbb{K}}{10} \approx 36.8 \quad \text{GPa}$$

bulk moduli at mesoscale (experimental data)

blue : calcite – black : sparite – red oolite (GPa)



mean values of sparitic cement c & oolite o compared to pure calcite : $k_c/k_{ca} \approx 0.90$ & $k_o^I/k_{ca} \approx 0.36$

model-experiment: mesocale

two unknown coefficients identified at mesoscale, χ_o & χ_c (solid phase in o & solid phase c)

sparitic cement c : homogeneous isotropic solid phase

$$k_c = \chi_c k_{ca} \quad , \quad \mu_c = \chi_c \mu_{ca} \quad , \quad \chi_c = 0.9 \tag{31}$$

porous oolite o : self consistent scheme, with micritic calcite grains

$$k_o^s = \chi_o k_{ca} \quad , \quad \mu_o^s = \chi_o \mu_{ca} \quad , \quad \chi_o = 0.58 \tag{32}$$

effective bulk modulus at mesoscale

$$k_o^I = 23.9 \text{ GPa} \quad , \quad \text{experiment } : k_o^I = 27.1 \text{ GPa} \tag{33}$$

model-experiment: macroscale

Table 1: Lavoux limestone

	k_s^{II} (GPa)	k_{hom}^{II} (GPa)	μ_{hom}^{II} (GPa)	b_{hom}^{II}
Exp	47.1	18-22	10-12	0.83
Model	47.2	21.1	12.1	0.57

Effective bulk modulus of the solid phase = *unjacketed compressibility* K'_s

$$\underline{\underline{\Sigma}} = -P\underline{\underline{i}} \quad , \quad \underline{\underline{\sigma}}^p = \underline{\underline{\sigma}}^p(P) \tag{34}$$

$$k'^{II}_{(s)\text{hom}} = \frac{Tr(\underline{\underline{\Sigma}})}{3\,Tr(\underline{\underline{E}})} = \frac{k_{\text{hom}}^{II}}{1 - b_{\text{hom}}^{II}} \tag{35}$$

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conclusions & prospects

- 2-Step SC homogenization model for a specific microstructure
  - simple homogenization scheme useful as first approach
  - correct order of magnitude for meso-macro properties
  - degraded *ITZ* (Interfacial Transition zone) around oolites
    (lower macroproperties)

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- 2-Step SC homogenization model for a specific microstructure

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  degraded *ITZ* (Interfacial Transition zone) around oolites
  (lower macroproperties)

- prospects

  characterization at lower scale : nanoindentation
  better description of inter oolitic material
  & flat mesopores concave shape
  imperfect interfaces

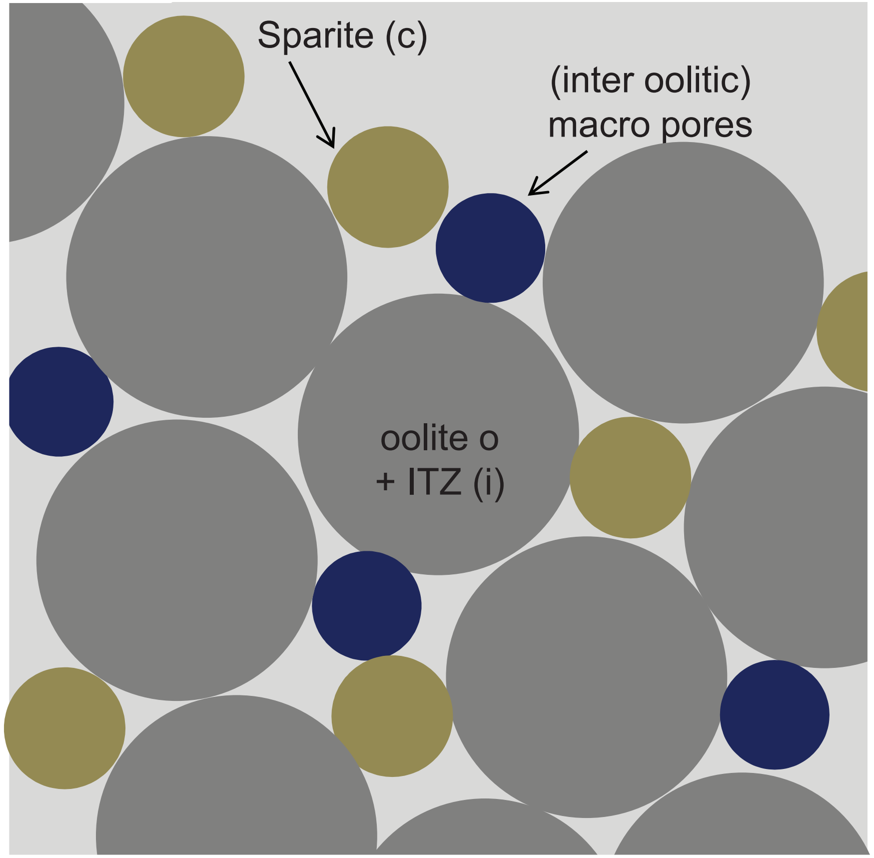
Model 2 : ITZ + Three steps

Model 2 : oolite + ITZ (oi) – macro pore (b) - sparitic cement (c)

step III : self consistent model with three constituents :
porous oolite + ITZ – inter oolite pores – sparitic cement

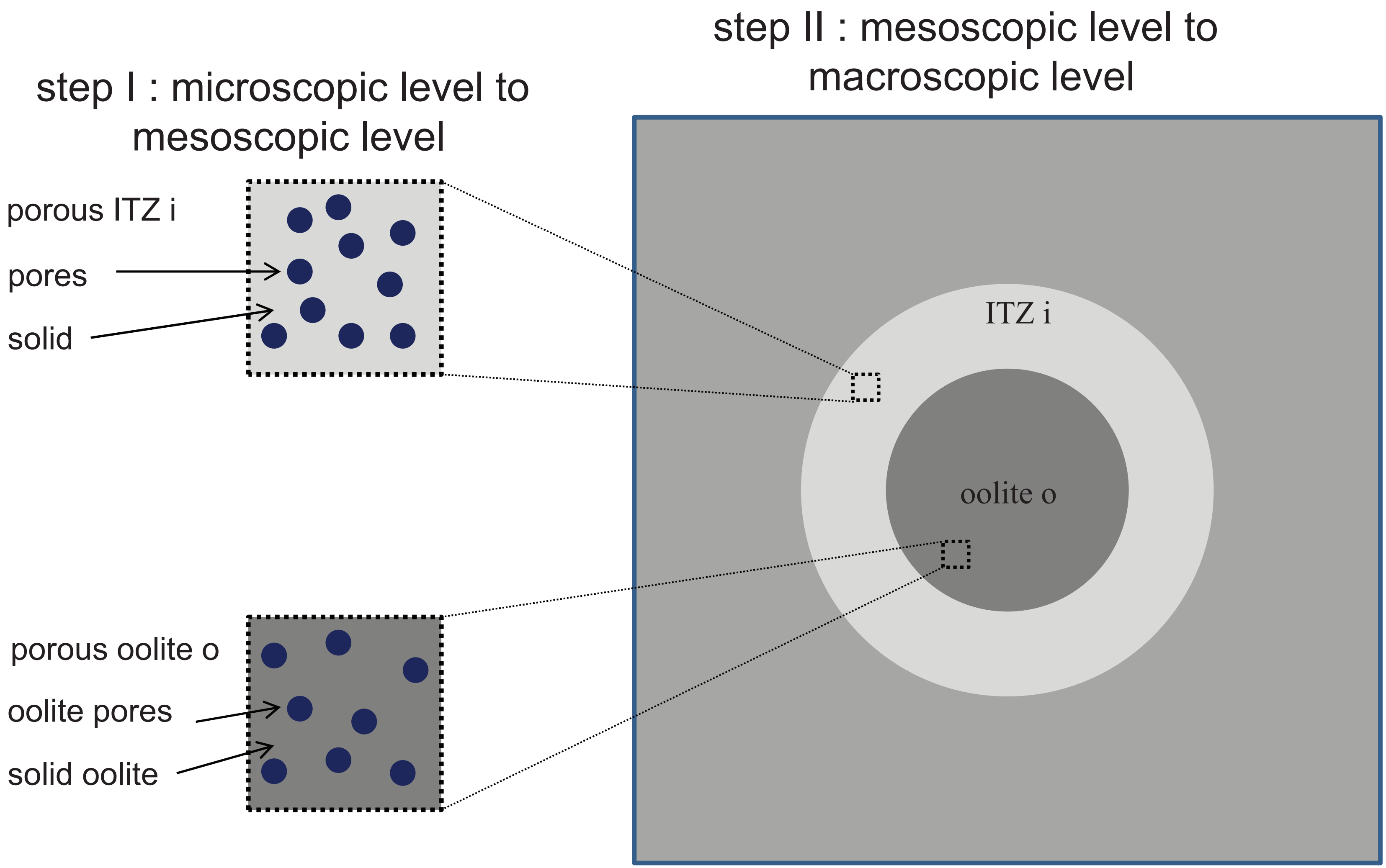
step I : homogenization
intra oolitic pores
& ITZ pores
(SC scheme)

step II : homogenization
oolite (o) & ITZ (i)
Three Phase model
(GSCS)



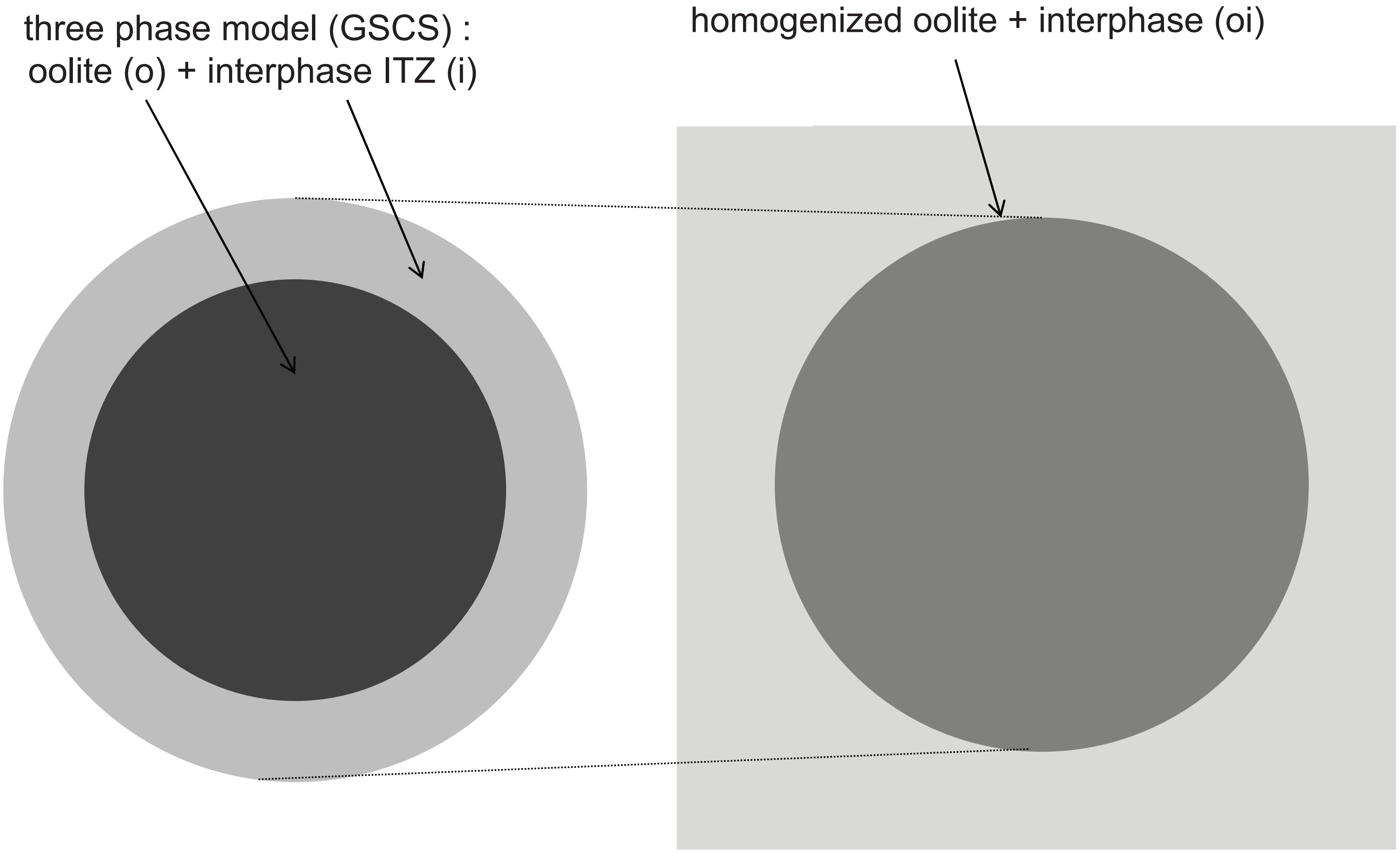
Step I : micropores in oolite ITZ : Self Consistent (S

step I : homogenization of
micropores in oolite (o) and ITZ (i)



Step II : oolite & ITZ = oi (GSCS)

step II : three phase model (GSCS) homogenization of porous oolite (o) and porous ITZ (i)



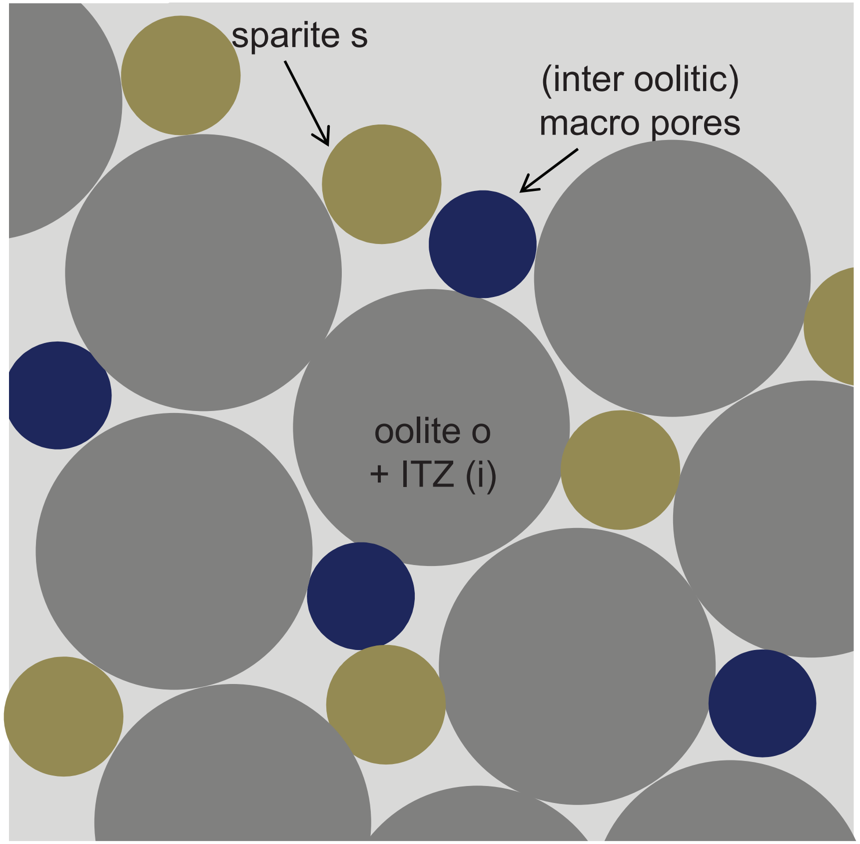
Step III : *macro* level, 3 distinct phases (SC)

Step III : self consistent scheme

homogenized
porous oolite + **ITZ** (oi)

macro pores (b)

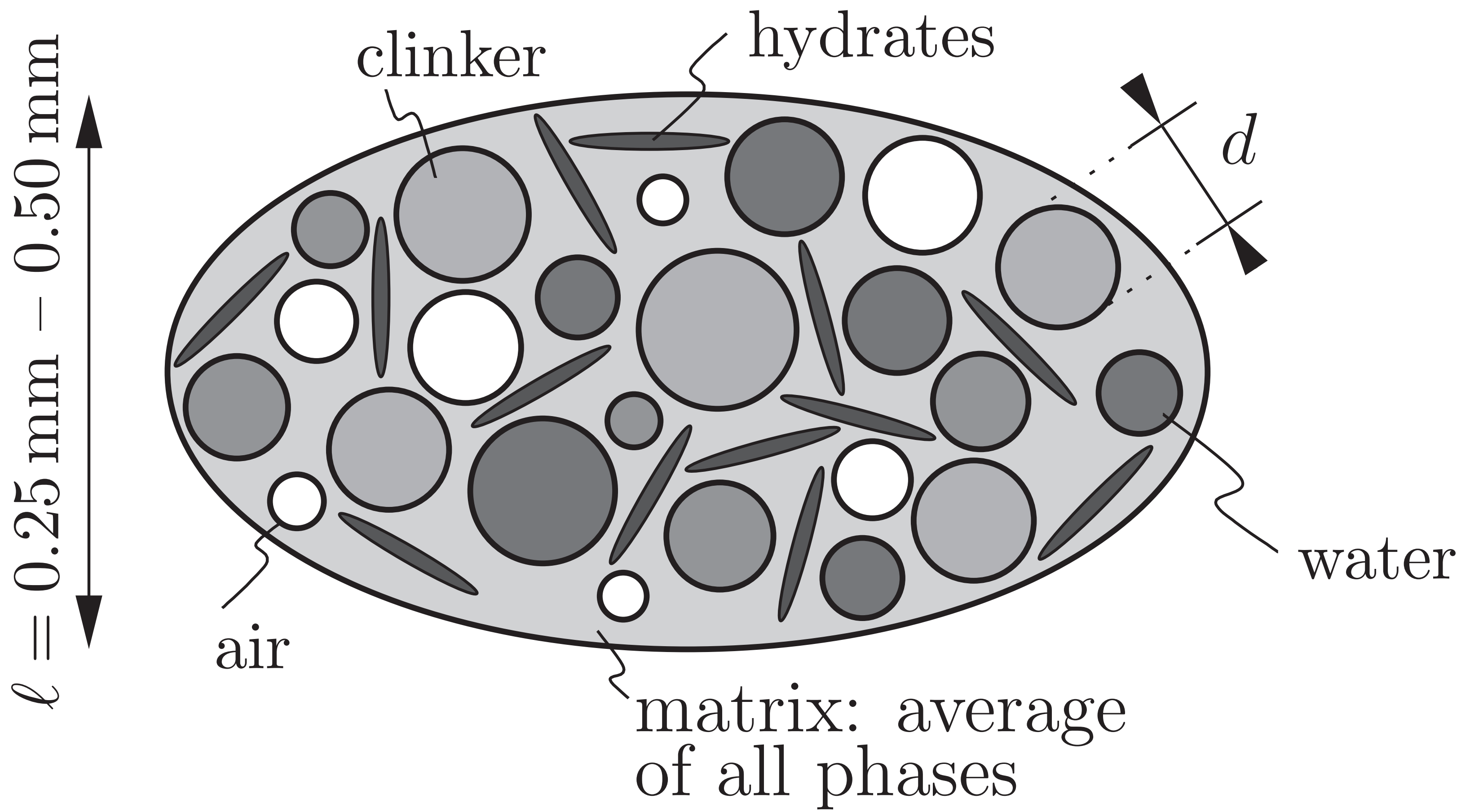
sparitic cement (c)



Simplifying assumptions :
isotropic distribution &
spherical shape for all
constituents

better description of inter oolitic material

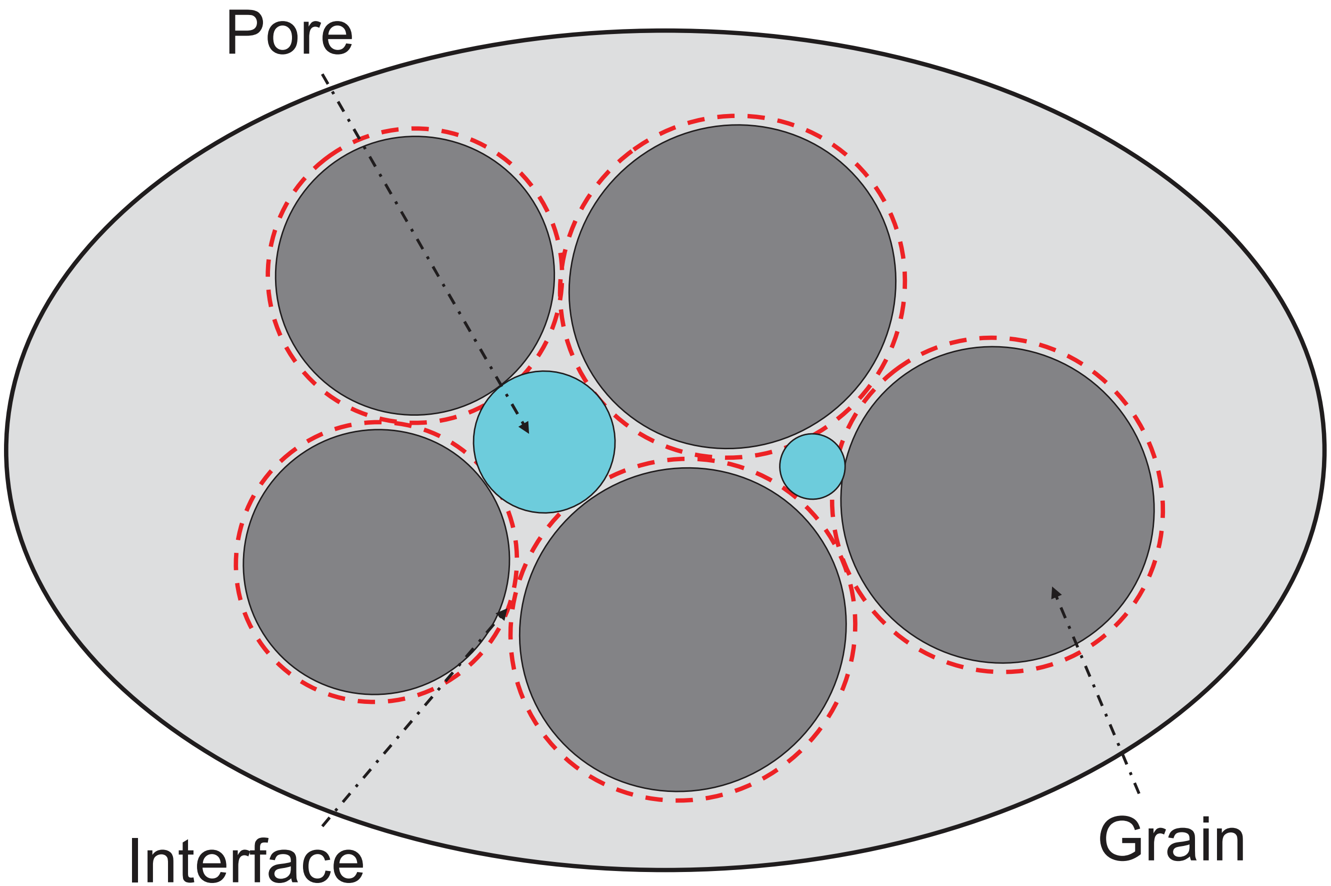
polycrystalline cement paste



Pichler and Hellmich (2010)

porous granular materials - imperfect interfaces

He et al. (2013)



Hashin and Monteiro (2002)

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