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Pore2Field - Physique des écoulements en milieux poreux naturels : de l'échelle du pore à l'échelle du réservoir

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A Poromechanical Model for Coal Seams Injected with Carbon Dioxide: From an Isotherm of Adsorption to a Swelling of the Reservoir

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The model for the coal bed reservoir is based on poromechanical equations that explicitly take into account the effect of adsorption on the mechanical behavior of a microporous medium. We consider the coal bed reservoir as a dual porosity (cleats and coal porosity) medium, for which we derive a set of linear constitutive equations. The model requires as an input the adsorption isotherm on coal of the fluid considered. Reversely, the model provides a way to upscale an adsorption isotherm into a meaningful swelling of the coal bed reservoir at the macroscopic scale.

The parameters of the model are calibrated on data on coal samples available in the literature. Reservoir simulations of an injection of carbon dioxide in a coal seam are performed with an in-house finite volume and element code. The variations of injection rate over time during the process of injection are obtained from the simulations. The effect of the compressibility of the coal matrix on those variations is discussed.

NOMENCLATURE

ϵ	Volumetric strain of reservoir (-)
ϵ^u	Volumetric strain of reservoir during immersion (-)
ϵ_m	Volumetric strain of coal matrix (-)
η	Viscosity of CO_2 (Pa.s)
μ_m	Molar chemical potential of fluid in coal matrix (J.mol^{-1})
ν	Poisson's ratio of reservoir (-)
σ	Volumetric confining stress (Pa)
ϕ_c	Lagrangian porosity associated to cleat system (-)
ϕ_{c0}	Lagrangian porosity associated to cleat system in state of reference (-)
φ_c	Variation of Lagrangian porosity associated to cleat system (-)
b	Biot coefficient of reservoir (-)
b_m^{tan}	Tangent Biot coefficient associated to coal matrix (-)
C	Coupling coefficient (-)
E	Young modulus of reservoir (Pa)
e_{ij}	Deviatoric strains (-)
f	Helmholtz free energy of microporous coal per unit volume of undeformed reservoir (J.mol^{-1})
G	Shear modulus of reservoir (Pa)
k	Permeability of coal (m^2)
K	Bulk modulus of reservoir (Pa)
K_m	Bulk modulus of coal matrix (Pa)
K_s	Bulk modulus of solid skeleton (Pa)
N	Biot modulus of reservoir (Pa)
n^{ads}	Molar concentration of fluid in coal matrix per unit volume of undeformed coal matrix, *i.e.*, adsorption isotherm (mol.m^{-3})
n_0^{ads}	Adsorption isotherm of fluid in coal matrix kept at constant volume (mol.m^{-3})
n_m	Molar concentration of fluid in coal matrix per unit volume of undeformed reservoir (mol.m^{-3})
p^a	Adsorption-induced pressure (Pa)
p_c	Pressure of fluid in cleats (Pa)
p_m	Thermodynamic pressure of fluid in coal matrix (Pa)
s_{ij}	Deviatoric confining stresses (Pa)
$\overline{V}_b$	Molar volume of bulk fluid (m^3.mol^{-1})

INTRODUCTION

Geological sequestration of carbon dioxide in coal seams is an environmentally appealing method to reduce the amount of greenhouse gas emissions. Producing methane from deep coal seams while sequestrating CO_2 (a process known as CO_2-ECBM (Enhanced Coal Bed Methane), in which CO_2 is injected in one well and methane is withdrawn from another well) increases the economic viability of such a method. Laboratory isotherm measurements for pure gases have demonstrated that a given mass of coal can adsorb approximately twice as many moles of CO_2 as of CH_4 [1]: for each carbon atom extracted with a molecule of methane from the coal bed reservoir, two carbon atoms can therefore be injected with molecules of carbon dioxide into the coal bed reservoir, thus leading to a green energy cycle. Moreover, coal beds can accommodate ten to thirty-five years of anthropogenic CO_2 emissions (at their current rate of emission of almost 27 Gt per year) [2]. Recently, some large-scale projects (*e.g.*, the Allison pilot project in the United States [3]) have been undertaken. Although a decrease in the rate of injection is classically observed over time upon filling of a reservoir, in the case of the Allison pilot project this rate decreased faster than expected during the first months of injection of carbon dioxide (*see Fig. 1*). In order to mitigate this issue, one can inject carbon dioxide at a higher pressure or over longer periods of time but such alternatives

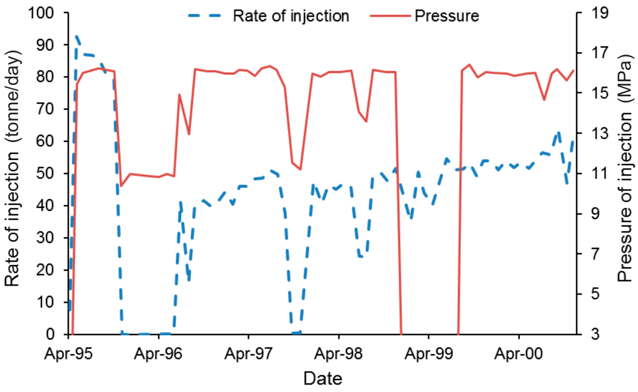

Figure 1

Variations in injectivity in a CO_2 injected coal bed at the Allison unit in the San Juan basin (adapted from [3]).

can put the economic viability of the process at stake. After about a year in the Allison pilot project, the rate at which carbon dioxide was injected was observed to increase back (*see Fig. 1*). Being able to model such variations of injectivity over the injection process is a prerequisite for energy companies to evaluate the economic viability of their CO_2-ECBM projects. The coal bed reservoirs, the depth of which ranges from 300 m to 1.5 km, are naturally fractured. Such reservoirs are composed of cleats (small natural fractures usually spaced by a few centimeters from each other) and of the coal matrix.

The coal matrix itself is a porous medium with pores ranging from the sub-nanometric size up to the micrometric size. Coal is known to swell in the presence of carbon dioxide or of methane [4, 5]. Actually, at a given pressure of fluid, the replacement of methane as a pore fluid with carbon dioxide leads to a net swelling of the coal matrix, called the differential swelling. Such a differential swelling is observed in coal bed reservoirs in which carbon dioxide is injected [6]. Since underground reservoirs are confined by the surrounding rocks, such a differential swelling leads to a closure of the cleat system, which results in a decrease of the permeability of the coal bed reservoir. Therefore, we observe a coupling between the cleat-driven permeability of the reservoir, the preferential adsorption of CO_2 in coal with respect to CH_4 and the differential swelling of the coal matrix. In the last decade, several authors proposed models of reservoir in order to capture these coupled effects [7-10].

We recently developed a dual porosity model for coal bed reservoirs, that explicitly takes into account surface adsorption in the coal matrix [11]. There, we applied derived constitutive equations well suited for capturing surface effects in porous media [12-14]. In contrast to what was done in that paper, we here aim at deriving constitutive equations that take into account the fact that coal is microporous: in such micropores, adsorption occurs by pore filling more than by surface covering and defining pore surface or pore volume in an unambiguous manner is not possible.

In this paper, we propose a multiscale approach in which the coal matrix is considered as a microporous medium. Figure 2 displays the three scales considered in this study: Figure 2a shows the scale of the coal bed reservoir into which carbon dioxide is injected; a Representative Elementary Volume (REV) of this coal bed reservoir is displayed in Figure 2b and consists of coal fractured by cleats; the scale of the unfractured coal matrix in which CO_2 molecules are adsorbed is displayed in Figure 2c. The first section of this study focuses on the derivation of the poromechanical dual porosity model for a coal bed reservoir. In the following section, the multiscale model is calibrated on experimental results. Finally, we simulate an injection of carbon dioxide in coal bed reservoirs made of various typical coals. In such simulations, the adsorption isotherms and the swellings upon adsorption are used as inputs.

1 DUAL POROSITY MODEL FOR COAL BED RESERVOIR

The focus of this section is to derive the constitutive equations for a coal bed reservoir made of cleats and of a microporous coal matrix.

Fluid molecules in the reservoir are located either in the cleats or in the coal matrix. Molecules in the cleats are assumed to be in a bulk state. In contrast, molecules in the microporous coal matrix are not in a bulk state but are said to be in an adsorbed state: in sub-nanometric pores fluid molecules are interacting with the atoms of the solid skeleton.

The general assumptions for our modeling are:

- the coal bed reservoir is homogeneous, isotropic, and its mechanical behavior is linear;
- only isothermal conditions are considered;
- only the pure component case (*i.e.*, carbon dioxide only) is considered;
- fluid in the cleats is in thermodynamic equilibrium with fluid in the coal matrix at all times (*i.e.*, there is no kinetics associated to a transfer of fluid from the cleats to the coal matrix).

1.1 Derivation of Constitutive Equations

For now, for the sake of the derivation, the pressure p_c (or the molar chemical potential μ_c) of the fluid in the cleats and the thermodynamic pressure p_m (or the molar chemical potential μ_m) of the fluid in the coal matrix are assumed to differ from each other. Those two pressures will only be equated at the end of the derivation.

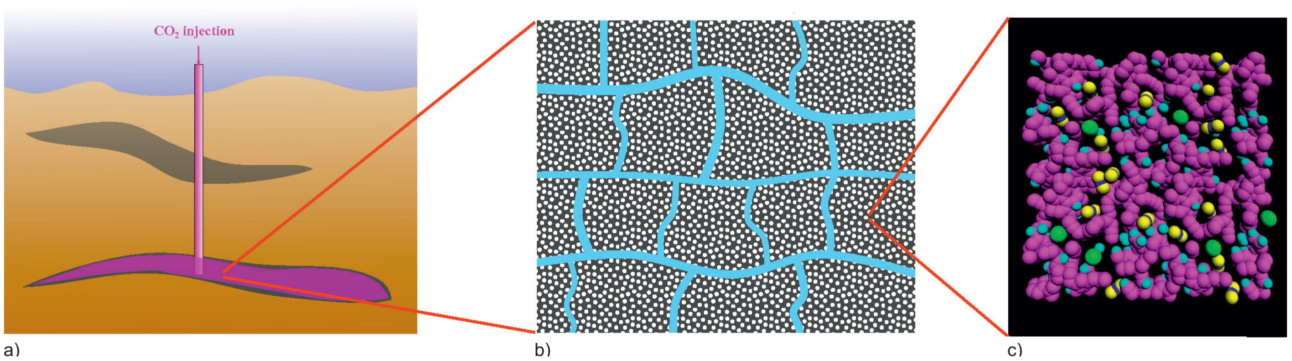

Figure 2

Multi-scale model for a coal bed reservoir. a) Scale of reservoir. b) Scale of fractured coal. c) Scale of coal matrix.

We consider the system made of a REV of the coal bed reservoir but without the fluid in the cleats. The Helmholtz free energy of such a system per unit undeformed volume of reservoir is noted f. Energy can be added to such a system either by straining it with a volumetric (also called 'hydrostatic' or 'isotropic') confining stress σ (the corresponding work being '$\sigma d\epsilon$', where ϵ is the volumetric strain of the REV), by straining it with a deviatoric confining stress s_{ij} (the corresponding work being '$s_{ij}de_{ij}$', where e_{ij} is a deviatoric strain of the REV), by deforming the cleat porosity ϕ_c with the pressure of the fluid in the cleats (the corresponding work being '$p_c d\varphi_c$', where φ_c is the variation of the Lagrangian porosity associated to the cleats) or by adding fluid molecules in the coal matrix (the added energy being '$\mu_m dn_m$', where n_m is the number of moles of fluid in the coal matrix per unit undeformed volume of reservoir):

$$df = \sigma d\epsilon + s_{ij}de_{ij} + p_c d\varphi_c + \mu_m dn_m \qquad (1)$$

In this equation, the fluid in the cleats intervenes through its pressure p_c while the fluid in the micropores intervenes through its molar chemical potential μ_m. Such a choice was made to avoid any ambiguity between two concepts: the mechanical pressure and the thermodynamical pressure. Indeed, the mechanical pressure is defined as the opposite of the hydrostatic stress that prevails in a liquid, while the thermodynamic pressure is the pressure in a macroscopic reservoir full of bulk liquid in thermodynamic equilibrium with the system of interest. Those thermodynamic and mechanical pressures are equal to each other in macropores, hence an unambiguous reference to 'the' pressure in the cleats. In contrast, thermodynamic and mechanical pressures do differ from each other in micropores: their difference is the so-called disjoining pressure (for more details, see [14]). For the fluid in the coal matrix, we therefore restrict ourselves to making reference to an unambiguous and well-defined molar chemical potential. The above equation can be rewritten as follows:

$$d(f - \mu_m n_m) = \sigma d\epsilon + s_{ij}de_{ij} + p_c d\varphi_c - n_m d\mu_m \qquad (2)$$

From the above equation one concludes that the constitutive equations can be four equations which link σ, s_{ij}, p_c, n_m to ϵ, e_{ij}, φ_c, μ_m. The next sections are devoted to derive each of those four constitutive equations.

1.1.1 First Constitutive Equation

We first consider the constitutive equation that governs the deviatoric stresses s_{ij}. For symmetry reasons, under the hypotheses of isotropy and of small deformations, this constitutive equation remains the same as in regular poroelasticity:

$$s_{ij}(\epsilon, e_{ij}, \varphi_c, \mu_m) = 2Ge_{ij} \qquad (3)$$

where G is the shear modulus of the reservoir.

1.1.2 Second Constitutive Equation

We now consider the constitutive equation that governs the amount n_m of fluid in the coal matrix per unit undeformed volume of reservoir.

Experimental data or molecular simulations of adsorption on a microporous coal can provide the amount $n^{ads}(\epsilon_m, p_m)$ or $n^{ads}(\epsilon_m, \mu_m)$ of fluid in the coal matrix per unit undeformed volume of coal matrix, where ϵ_m is the volumetric strain of the coal matrix. This volumetric strain ϵ_m of the coal matrix can differ from the volumetric strain ϵ of a REV of the coal bed reservoir because of the presence of cleats. Those two strains thus refer to strains at two different scales. n_m can be obtained geometrically from such a measured adsorption isotherm n^{ads} obtained at the scale of the coal matrix (*see Figs. 2b, c*):

$$n_m(\epsilon, e_{ij}, \varphi_c, \mu_m) = (1 - \phi_{c0})n^{ads}(\epsilon_m, p_m) \qquad (4)$$

where ϕ_{c0} is the cleat porosity in the state of reference, $p_m(\mu_m)$ is obtained from the state equation of the fluid considered, and the volumetric strain ϵ_m of the coal matrix is obtained from the classical micro-macro relation [14]:

$$\epsilon = (1 - \phi_{c0})\epsilon_m + \varphi_c \tag{5}$$

$$\epsilon_m = \frac{\epsilon - \varphi_c}{1 - \phi_{c0}} \tag{6}$$

1.1.3 Third Constitutive Equation

The next constitutive equation is derived by using a Maxwell relation based on Equation (2):

$$\left.\frac{\partial \sigma}{\partial \mu_m}\right|_{\epsilon, e_{ij}, \varphi_c} = -\left.\frac{\partial n_m}{\partial \epsilon}\right|_{\mu_m, e_{ij}, \varphi_c} \tag{7}$$

for which the right-hand term can be rewritten with the help of Equations (4) and (5):

$$\left.\frac{\partial n_m}{\partial \epsilon}\right|_{\mu_m, e_{ij}, \varphi_c} = \frac{1}{1 - \phi_{c0}} \left.\frac{\partial n_m}{\partial \epsilon_m}\right|_{\mu_m, e_{ij}, \varphi_c} = \left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{\mu_m} \tag{8}$$

Equation (7) can be rewritten as follows:

$$\left.\frac{\partial \sigma}{\partial \mu_m}\right|_{\epsilon, e_{ij}, \varphi_c} = -\left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{\mu_m} \tag{9}$$

An integration of the above equation yields:

$$\sigma = f_1(\epsilon, e_{ij}, \varphi_c) - \int_{\mu=-\infty}^{\mu_m} \left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{\mu_m} d\mu \tag{10}$$

which, with the help of the Gibbs-Duhem relation $d\mu = \overline{V_b} dp$ (where $\overline{V_b}$ is the bulk molar volume of the fluid), can be rewritten as:

$$\sigma = f_1(\epsilon, e_{ij}, \varphi_c) - \int_0^{p_m} \left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{p_m} \overline{V_b} dp \tag{11}$$

The function f_1 is determined by soliciting the material at $p_m = 0$ in the coal matrix (*i.e.*, with no fluid in the coal matrix). In such a case, for which $\sigma = f_1(\epsilon, e_{ij}, \varphi_c)$, regular poroelasticity must be recovered, from what follows that:

$$f_1(\epsilon, e_{ij}, \varphi_c) = (K + b^2 N)\epsilon - bN\varphi_c \tag{12}$$

where K is the bulk modulus of the reservoir, b is the Biot coefficient associated to the cleat system, N is the Biot modulus associated to the cleat system, and where the poroelastic coefficients verify the classical relations [14]:

$$b = 1 - \frac{K}{K_m} \tag{13}$$

$$\frac{1}{N} = \frac{b - \phi_{c0}}{K_m} \tag{14}$$

where K_m is the bulk modulus of the coal matrix.

The third constitutive equation can therefore be written as:

$$\sigma(\epsilon, e_{ij}, \varphi_c, \mu_m) = (K + b^2 N)\epsilon - bN\varphi_c - \int_0^{p_m} \left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{p_m} \overline{V_b} dp \tag{15}$$

1.1.4 Fourth Constitutive Equation

The last constitutive equation is derived by using a Maxwell relation based on Equation (2):

$$\left.\frac{\partial p_c}{\partial \mu_m}\right|_{\epsilon, e_{ij}, \varphi_c} = -\left.\frac{\partial n_m}{\partial \varphi_c}\right|_{\epsilon, e_{ij}, \mu_m} \tag{16}$$

for which the right-hand term can be rewritten with the help of Equations (4) and (5):

$$\left.\frac{\partial n_m}{\partial \varphi_c}\right|_{\epsilon, e_{ij}, \mu_m} = -\frac{1}{1 - \phi_{c0}} \left.\frac{\partial n_m}{\partial \epsilon_m}\right|_{\epsilon, e_{ij}, \mu_m} = -\left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{\mu_m} \tag{17}$$

Equation (16) can be rewritten as follows:

$$\left.\frac{\partial p_c}{\partial \mu_m}\right|_{\epsilon, e_{ij}, \varphi_c} = \left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{\mu_m} \tag{18}$$

An integration of the above equation yields:

$$p_c = f_2(\epsilon, e_{ij}, \varphi_c) + \int_{\mu=-\infty}^{\mu_m} \left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{\mu_m} d\mu \tag{19}$$

which, with the help of the Gibbs-Duhem relation $d\mu = \overline{V_b} dp$, can be rewritten as:

$$p_c = f_2(\epsilon, e_{ij}, \varphi_c) + \int_0^{p_m} \left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{p_m} \overline{V_b} dp \tag{20}$$

The function f_2 is determined by soliciting the material at $p_m = 0$ in the coal matrix (*i.e.*, with no fluid in the coal matrix). In such a case, for which $p_c = f_2(\epsilon, e_{ij}, \varphi_c)$, regular poroelasticity must be recovered, from what follows that:

$$f_2(\epsilon, e_{ij}, \varphi_c) = -Nb\epsilon + N\varphi_c \tag{21}$$

The last constitutive equation can therefore be written as:

$$p_c(\epsilon, e_{ij}, \varphi_c, \mu_m) = -Nb\epsilon + N\varphi_c + \int_0^{p_m} \left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{p_m} \overline{V_b} dp \tag{22}$$

1.1.5 Summary of Constitutive Equations

In summary, the constitutive equations for a dual porosity medium whose pore space is made of cleats (in which the pressure of the fluid is p_c) and of micropores (in which the thermodynamic pressure of the fluid is p_m) is:

$$\sigma = (K + b^2N)\epsilon - bN\varphi_c - p^a(\epsilon_m, p_m) \tag{23}$$

$$p_c = -Nb\epsilon + N\varphi_c + p^a(\epsilon_m, p_m) \tag{24}$$

$$n_m = (1 - \phi_{c0})n^{ads}(\epsilon_m, p_m) \tag{25}$$

$$s_{ij} = 2Ge_{ij} \tag{26}$$

where the pressure $p^a(\epsilon_m, p_m)$ induced by adsorption in the coal matrix is written as:

$$p^a(\epsilon_m, p_m) = \int_0^{p_m} \left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{p_m} \overline{V_b}dp \tag{27}$$

Note that in the above equation, the integrand can be interpreted as a tangent Biot coefficient b_m^{tan} associated to the coal matrix:

$$b_m^{tan} = \left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_{p_m} \overline{V_b} \tag{28}$$

If we now set $p_m = p_c = p$, which corresponds to the assumption that the fluid in the cleats is in thermodynamic equilibrium with the fluid in the coal matrix, we obtain the following constitutive equations:

$$\sigma = (K + b^2N)\epsilon - bN\varphi_c - p^a(\epsilon_m, p) \tag{29}$$

$$p = -Nb\epsilon + N\varphi_c + p^a(\epsilon_m, p) \tag{30}$$

$$n_m = (1 - \phi_{c0})n^{ads}(\epsilon_m, p) \tag{31}$$

$$s_{ij} = 2Ge_{ij} \tag{32}$$

1.2 Simplification for a Coal Bed Reservoir

It has been recently demonstrated with the help of molecular simulations that the adsorption isotherm of carbon dioxide in coal can be well approximated by its first-order expansion with respect to the strain ϵ_m of the coal matrix [15]:

$$n^{ads}(\epsilon_m, p) \approx n_0^{ads}(p)(1 + C(p)\epsilon_m) \tag{33}$$

where $n_0^{ads}(p)$ is the amount of fluid adsorbed in the coal matrix when the matrix is kept at zero deformation and where $C(p)$ is a dimensionless coupling coefficient which captures the dependence of adsorption on the strain of the adsorbing medium. With such an approximation, for a porous medium whose behavior is linear elastic in the absence of any fluid, the drained bulk modulus remains constant for any pressure of fluid and any volumetric strain [15]. Moreover, from such a first-order expansion follows:

$$\left.\frac{\partial n^{ads}}{\partial \epsilon_m}\right|_p = n_0^{ads}(p)C(p) \tag{34}$$

The above equation is a function of the fluid thermodynamic pressure p only. Therefore, in coal, the adsorption-induced pressure p^a also is a function of the fluid thermodynamic pressure only: $p^a(\epsilon_m, p) = p^a(p)$. With such a simplification, Equation (31) can be rewritten as:

$$n_m = n_0^{ads}(p)\,[1 - \phi_{c0} + C(p)(\epsilon - \varphi_c)] \tag{35}$$

which makes it possible to modify the set of constitutive Equations (29–32) in order to express σ, φ_c, n_m and s_{ij} as functions of ϵ, e_{ij} and p, thus yielding the constitutive equations of the coal bed reservoir here considered:

$$\sigma = K\epsilon - bp - (1 - b)p^a \tag{36}$$

$$\varphi_c = b\epsilon + \frac{p - p^a}{N} \tag{37}$$

$$n_m = n_0^{ads}(p)\left[1 - \phi_{c0} + C(p)\left[(1 - b)\epsilon - \frac{p - p^a}{N}\right]\right] \tag{38}$$

$$s_{ij} = 2Ge_{ij} \tag{39}$$

where p^a is given by:

$$p^a(p) = \int_0^p b_m^{tan}dp = \int_0^p n_0^{ads}(p)C(p)\overline{V_b}(p)dp \tag{40}$$

2 CALIBRATION OF MODEL

We aim at simulating injections of carbon dioxide in coal bed reservoirs. In order to do so, our model must first be calibrated. We will use as a basis for calibration two coal samples studied by Pini [16]: the Ribolla and Sulcis coals. Both coals come from Italy. On each of those samples, Pini performed measurements of adsorption of carbon dioxide and measurements of swelling of the coal sample induced by this adsorption. Those data will be used in the following section to calibrate the mechanical properties of the reservoir as well as the dependence of the adsorption-induced pressure p^a on the pressure of the fluid.

2.1 Adsorption Isotherms

Pini measured amounts of carbon dioxide adsorbed in both the Ribolla and Sulcis coals [16]. Figure 3 displays the adsorption isotherms on those two coal samples at a temperature $T = 318$ K (*i.e.*, about 45°C) together with an equation of state for carbon dioxide at the same temperature: at this temperature, the affinity of carbon dioxide for Sulcis coal is lower than its affinity for Ribolla coal.

2.2 Swelling of Coal Immersed in CO_2

In addition to adsorption measurements, Pini also measured how Sulcis and Ribolla coals swell when immersed in carbon dioxide [16]. The results of those measurement are displayed in Figure 4.

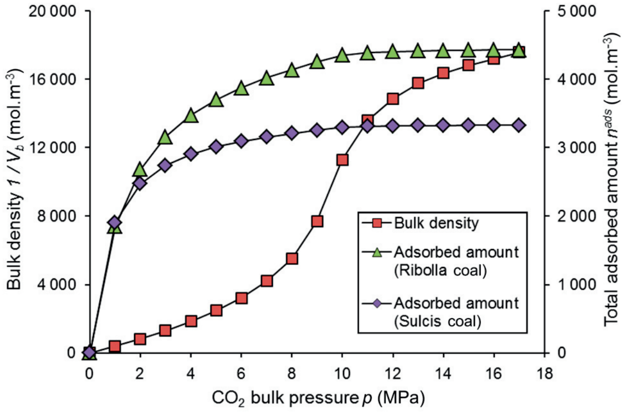

Figure 3

Total adsorbed amount of CO$_2$ in Sulcis and Ribolla coals at a temperature $T = 318$ K (adapted from [16]). The density data are from NIST Chemistry WebBook (http://webbook.nist.gov/chemistry/).

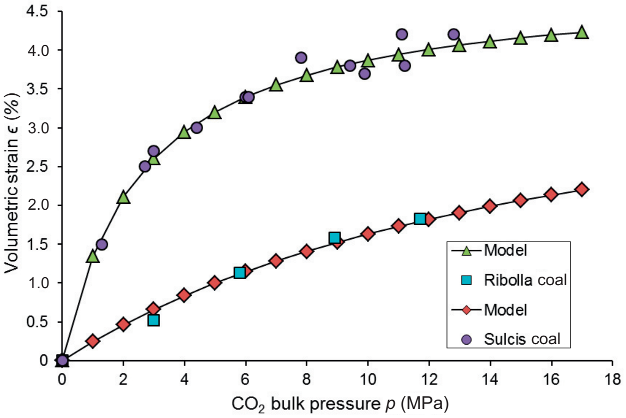

Figure 4

Swelling of Ribolla and Sulcis coal samples immersed in carbon dioxide (experimental data adapted from [16]).

The bulk modulus $K = 0.78$ GPa and Poisson's ratio $\nu = 0.26$ are given by Pini for Sulcis coal [16]. We choose the same elastic properties for Ribolla coal: by doing so, both coals only differ by their adsorptive properties. For now, the Biot coefficient b is set to 0.25, which, with the help of Equation (13), leads to a bulk modulus $K_m = 1.04$ GPa for the coal matrix. Another Biot coefficient b and bulk modulus K_m for the coal matrix will be considered in Section 3.2 and the effect of the compressibility of the coal matrix on the evolutions of injection rate over the injection process will be discussed.

For a sample immersed in a fluid, for which the boundary conditions verify $\sigma = -p$, a combination of Equations (6, 33, 36, 37, 40) enables to express the coupling coefficient C as:

$$C(p) = \frac{1 + K_m d\epsilon^u/dp}{n^{ads}\overline{V_b} - \epsilon^u \left(1 + K_m d\epsilon^u/dp\right)} \qquad (41)$$

where ϵ^u is the volumetric strain of the immersed sample.

For a given bulk modulus K_m for the coal matrix, the above expression enables to calculate the coupling coefficient $C(p)$ from the measured adsorption isotherms displayed in Figure 3 together with the measured swellings displayed in Figure 4. The resulting coupling coefficient $C(p)$ calculated with Equation (41) combined with the experimental data on Sulcis and Ribolla coals is displayed in Figure 5. We observe that this coefficient and therefore how the adsorption depends on the strain of the coal sample, depends significantly on the pressure of the fluid, especially near $p = 10$ MPa, a pressure at which the density of carbon dioxide significantly varies (*see Fig. 3*).

On top of the measured swellings of the coal samples immersed in carbon dioxide, Figure 4 displays the swelling predicted by the now calibrated set of constitutive Equations (36-40). The calibrated model is in very good agreement with the experimental data, thus proving that the swelling of coal in presence of carbon dioxide can

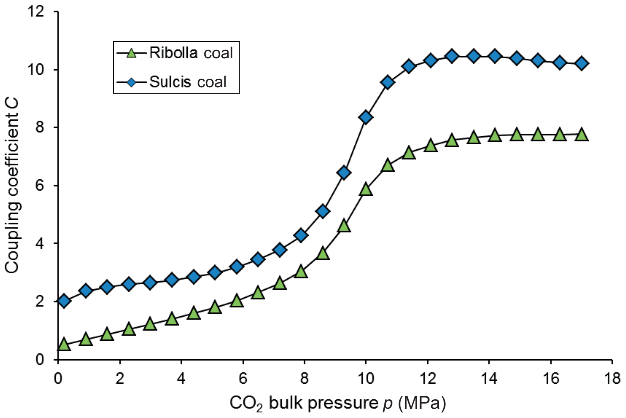

Figure 5

Coupling coefficient C for Ribolla and Sulcis coals.

TABLE 1

Coal parameters for representative elementary volume of reservoir

Parameter	Definition	Value
E	Young modulus of reservoir (GPa)	1.12
ν	Poisson's ratio of reservoir	0.26
K	Bulk modulus of reservoir (GPa)	0.78
b	Biot coefficient of reservoir	0.25
K_m	Bulk modulus of coal matrix (GPa)	1.04
k_0	Initial permeability (mD)	10
η	Viscosity of CO$_2$ (Pa.s)	1.79×10^{-5}

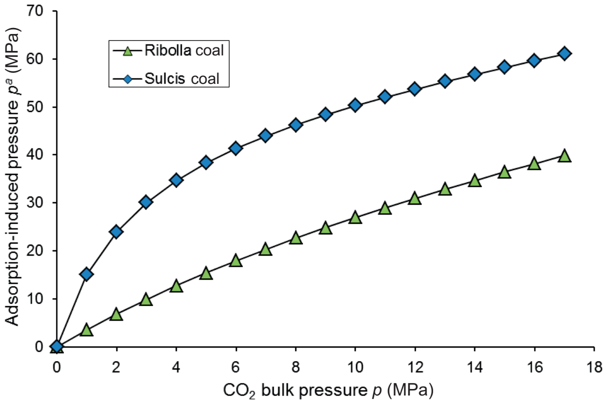

Figure 6

Adsorption-induced pressure p^a for Ribolla and Sulcis coals.

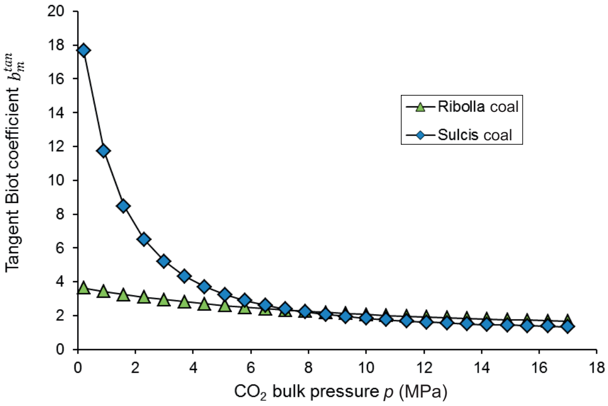

Figure 7

Tangent Biot coefficient b_m^{tan} associated to coal matrix for Sulcis and Ribolla coals.

be accurately modeled by taking into account adsorption in micropores.

Figure 4 also shows that Sulcis coal swells about twice as much as Ribolla coal, while the affinity of carbon dioxide for Sulcis coal is lower than for Ribolla coal (*see Fig. 3*). As was already noted by Day *et al.* [17] and by Pini [16], coals with high sorption capacity are not necessarily highly swelling coals, which suggests that swelling and adsorption are linked in a nontrivial manner.

Figure 6 shows how the adsorption-induced pressure p^a depends on the bulk pressure of carbon dioxide. Qualitatively, the shape of those curves is similar to the shape of the swelling curves displayed in Figure 4, which confirms that the swelling can be explained by an adsorption-induced pressure.

We also identified in the model a tangent Biot coefficient $b_m^{tan} = n_0^{ads} C(p) \overline{V_b}(p)$ associated to the coal matrix (*see Eq. 28*). Figure 7 displays this tangent Biot coefficient b_m^{tan} as a function of the fluid bulk pressure p. For Sulcis coal, this Biot coefficient can be as high as 17.7 at the smallest fluid pressures, while for Ribolla coal this coefficient can reach a value of 3.6. In any case, for both coals this Biot coefficient is out of the usual range $[0, 1]$ observed for regular macroporous media. Those unconventional values have been identified as a direct consequence of the microporous feature of the medium [15]. One should note, however, that such values are not inconsistent with the laws of thermodynamics and pose no issue with respect to the mechanical stability of the medium.

3 RESERVOIR SIMULATIONS OF CO$_2$ INJECTION IN COAL BED

Based in the derived constitutive Equations (36-40) calibrated on Section 2, we performed reservoir simulations of injection of carbon dioxide in a coal bed. We considered injections over a one-year period in a reservoir that initially contained carbon dioxide only. The performed simulations were axisymmetric plane-strain one-dimensional. The radius of the reservoir was set to 500 m, the radius of the bore hole was 10 cm. Before CO$_2$ injection, the fluid pressure in the reservoir was considered to be equal to 1 MPa. Injection pressures of 8, 10 and 12 MPa were applied and kept constant over time. We imposed zero displacement and no flow on the edge of reservoir. We considered that the permeability in the reservoir was governed by a Kozeny-Carman-type equation, in which only the cleat porosity intervened. Practically, the permeability k was given by the following relationship:

$$\frac{k}{k_0} = \frac{\phi_c^3}{(1-\phi_c)^2} \times \frac{(1-\phi_{c0})^2}{\phi_{c0}^3} \tag{42}$$

where k_0 is the permeability in the state of reference.

The simulations were performed with the software Bil, a finite element and volume code developed in-house (http://perso.lcpc.fr/dangla.patrick/bil/). Simulations were performed on two reservoirs, *i.e.*, on a reservoir made of Sulcis coal and on a reservoir made of Ribolla coal.

3.1 Results

The rates of injection calculated on the two reservoirs at the three pressures of injection are displayed in Figure 8. For both reservoirs, as expected, the higher the injection pressure was, the higher the injection rate was.

The decrease of rate of injection over time was more significant for the reservoir made of Sulcis coal than for the reservoir made of Ribolla coal. Such a difference is due to the fact that Sulcis coal swells more than Ribolla coal in presence of carbon dioxide (*see Fig. 4*): the swelling of the

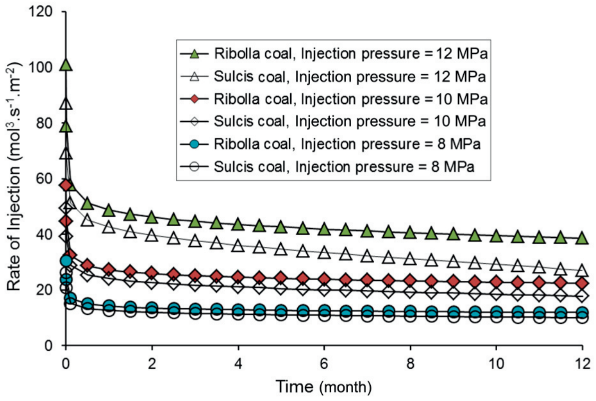

Figure 8

Injectivity of reservoir made of Ribolla coal and of Sulcis coal and injected at three different injection pressures.

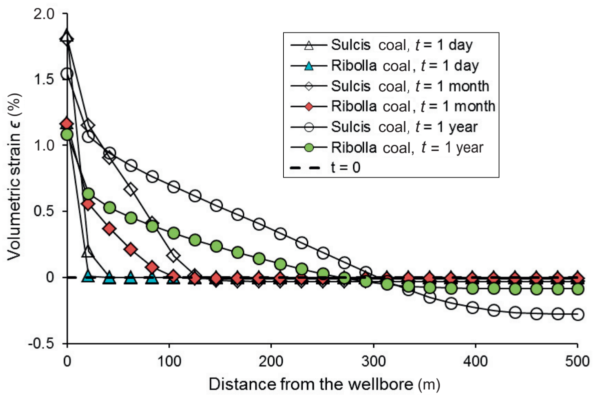

Figure 9

Volumetric strains at different times along the reservoirs made of Sulcis and Ribolla coals.

coal matrix led to a closure of the cleat system, which itself led to a decrease of the injectivity of the reservoir.

Figure 9 displays the volumetric strains in the two reservoirs at different times during the injection process. Close to the wellbore, as soon as the injection started, a swelling was observed. Then, over the injection process, the region in which a swelling was observed extended from the wellbore toward the edge of the reservoir: this extension accompanied the penetration of carbon dioxide in the reservoir. Due to the boundary conditions used, the adsorption-induced swelling close to the wellbore led to a compressed coal far from the wellbore, *i.e.*, near the edge of the reservoir. Variations of volume were more pronounced in the reservoir made of Sulcis coal than in the reservoir made of Ribolla coal, as a direct consequence of the fact that Sulcis coal swells more in presence of carbon dioxide than Ribolla coal.

3.2 Discussion: Effect of Compressibility of Coal Matrix on Evolutions of Injection Rates

We restrict our discussion to the reservoir made of Sulcis coal, since this coal exhibits the largest swellings. During the calibration of the model (*see Sect. 2*), we needed to assume the Biot coefficient b of the reservoir. By doing so, Equation (13) shows that we imposed the ratio of the bulk modulus K of the reservoir to the bulk modulus K_m of the coal matrix. At a given bulk modulus K of the reservoir, if we choose another value for the Biot coefficient b, the bulk modulus K_m of the coal matrix will be different: Equation (41) shows that, as a consequence, the calibration of the model on the swelling data displayed in Figure 4 will lead to a different coupling coefficient $C(p)$ and thus, through Equation (40), to a different calibration for the adsorption-induced pressure $p^a(p)$. Following regular poromechanics, the bulk modulus K_m of the coal matrix must verify $K_m \geq K/(1-\phi_{c0})$, where K is the bulk modulus of the reservoir and K_m is the bulk modulus of the coal matrix.

Figure 10 displays the dimensionless permeability k/k_0 along the reservoir at different times of the injection process, when the Biot coefficient b is set to 0.25 (and thus when $K/K_m = 0.75$, as was done in *Sect. 3.1*) and when the Biot coefficient b is set to 0.8 (and thus when $K/K_m = 0.2$). For both those Biot coefficients, we verified that, with the help of Equation (33), the back-calculated adsorbed amount $n_0^{ads}(p)$ in a coal matrix kept at zero strain is an increasing function of the pressure p of the fluid, as required thermodynamically. We observe that the Biot coefficient had a significant effect on how the permeability evolved over time: in the reservoir with a larger Biot coefficient, the decrease of permeability was more pronounced than in the reservoir with a smaller Biot coefficient. Such a phenomenon is due to the fact that, if the Biot coefficient is high, the coal matrix is almost incompressible: in such a case, all the swelling observed during an immersion of the sample in the fluid will translate into a loss of pore volume in confined conditions. In contrast, if the Biot coefficient is low, only part of the swelling observed during an immersion of the sample will translate into a loss of pore volume in confined conditions: therefore, in this latter case, the decrease of porosity and thus of permeability is less pronounced than if the Biot coefficient is high.

CONCLUSIONS

In this work, we studied an injection of carbon dioxide in a coal bed reservoir. In order to do so, we derived constitutive equations for a two-scale porous medium, the pore space of which is made of cleats and of micropores. The derived equations take explicitly into account the mechanical effect

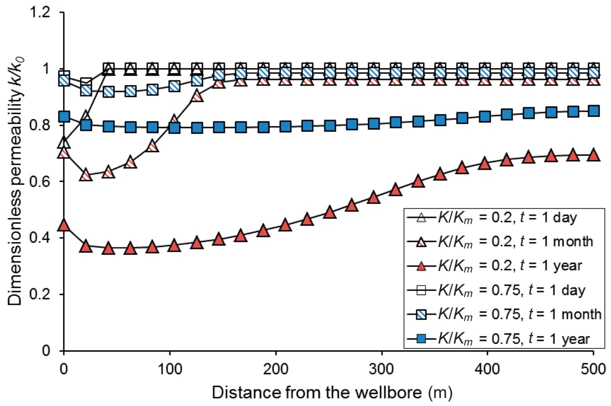

Figure 10

Variation of dimensionless permeability along the reservoir made of Sulcis coal for different ratios K/K_m of bulk modulus K of the reservoir to the bulk modulus K_m of the coal matrix.

of adsorption in micropores, *i.e.*, in pores that are too small to make it possible to define in an unambiguous manner pore volumes and pore surfaces. The derived equations needed to be calibrated: we showed that this calibration can be performed on measured adsorption isotherms and on measured swellings upon adsorption.

We considered two coals with different sorption and swelling properties. By making use of the calibrated constitutive equations, we simulated injections of carbon dioxide in reservoirs made of each of those two coals. Such simulations make it possible to estimate variations of injectivity over the injection process. We show that variations of permeability in the reservoir over time depend not only on how much the coal swells in presence of carbon dioxide but also on the compressibility of the coal matrix.

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