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Reply

Macroscopic modeling of double-porosity reservoirs: Reply to M. Bai and F. Civan

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1. Introduction

We thank M. Bai and F. Civan for taking an interest in our paper (Royer et al., 1996). We hope that the following information will help them to understand the work.

2. Notations

We acknowledge the fact that some of our notation is not uniform throughout the paper. We thank M. Bai and F. Civan for pointing this out. The convention they suggest is rigorous although it can be confusing since a double point is also required in Eq. (1) between the fourth-rank tensor \tilde{C} and the second-rank tensor $\tilde{\epsilon}$. All ambiguities regarding algebra of the products and rank of the tensors can be removed by using the index notation. As for the problem of notation mentioned for equations 17, 20, 29, 31, and 33, we should have written ' $\vec{\nabla}$ ' instead of ' $\vec{\nabla}$ '.

3. Consolidation of anisotropic porous media

Using index notation, Eqs. (1) and (2) are written as follows:

$$\frac{\partial}{\partial x_j} \left(C_{ijkl} e_{x_{kh}}(\vec{u}_S) - \alpha_{ij} P \right) = 0 \quad (1)$$

$$\frac{\partial}{\partial x_i} \left(K_{ij} \frac{\partial P}{\partial x_j} \right) = \alpha_{ij} \frac{\partial e_{x_{ij}}}{\partial t} (\vec{u}_s) + \beta \frac{\partial P}{\partial t} \quad (2)$$

where

$$v_i - \phi \frac{\partial u_{s_i}}{\partial t} = K_{ij} \frac{\partial P}{\partial x_j}$$

M. Bai and F. Civan maintain that through these equations, we propose a general form of the poroelastic formulation for anisotropic media. These equations are actually the very well-known equations of consolidation of porous media derived by Biot (1941) for isotropic media and by Biot (1955) for anisotropic media. In Biot (1955), these equations are also expressed in the following way:

$$\sigma_{s_{ij}} = \pi_{ijkh} e_{x_{kh}} (\vec{u}_s) + Q_{ij} \theta \quad (3)$$

$$\frac{\partial}{\partial x_j} \left(Q_{jk} e_{x_{jk}} (\vec{u}_s) + R \theta \right) = b_{ij} \left(\frac{\partial u_{F_j}}{\partial t} - \frac{\partial u_{s_j}}{\partial t} \right) \quad (4)$$

where $\sigma_{s_{ij}}$ is the partial stress in the skeleton, \vec{u}_F is the fluid displacement and $\theta = \partial u_{F_i} / \partial x_i$. Biot's equations are related to Eqs. (1) and (2) by the following relationships (Auriault and Sanchez-Palencia, 1977):

$$\vec{v} = \phi \frac{\partial \vec{u}_F}{\partial t}$$

$$Q_{ij} = \phi \beta^{-1} (\alpha_{ij} - \phi I_{ij})$$

$$R = \phi^2 \beta^{-1}$$

$$b_{ij} = \phi^2 K_{ij}^{-1}$$

$$\pi_{ijkh} = c_{ijkh} + \beta^{-1} (\alpha_{ij} - \phi I_{ij}) (\alpha_{kh} - \phi I_{kh})$$

In our paper, Eqs. (1) and (2) are introduced in order to define the characteristic consolidation times of the medium. The comments following these equations are only meant for explaining briefly the physical meaning of $\tilde{\alpha}$ and β and seem to have seriously confused M. Bai and F. Civan. Our comments are correct. β characterizes the material compressibility if the fluid is incompressible, and both material and fluid compressibilities if the fluid is slightly compressible. These equations are not valid if the fluid is strongly compressible (Auriault et al., 1990). For an incompressible elastic material and an incompressible fluid we get:

$$\beta = 0$$

$$\tilde{\alpha} = \tilde{I}$$

For isotropic grains and skeleton and slight fluid compressibility, β is given by:

$$\beta = c_f \phi + c_g \left(1 - \frac{k_s}{k_g} - \phi \right) \quad \text{where } c_f = \frac{1}{k_f}, c_g = \frac{1}{k_g} \quad (5)$$

k_f , k_s and k_g are the bulk moduli for the fluid, the skeleton and the grains, respectively. If $k_g \gg k_s$, which is often the case for unconsolidated porous media, then

$$1 - \frac{k_s}{k_g} \approx 1$$

Expression 5 above is similar to equation 3.15 in Auriault et al. (1990), where the case of slight fluid compressibility is treated as a particular case.

Therefore, the volume weighted average suggested by M. Bai and F. Civan:

$$\beta = c_f \phi + c_g(1 - \phi)$$

is an empirical approximation.

4. Gas flow through rigid fractured porous medium

We have defined two porosities:

$$\phi = \frac{\text{matrix void volume}}{\text{matrix volume}} = \frac{|\Omega_p|}{|\Omega'_{sp}|}$$

and

$$\phi' = \frac{\text{fracture void volume}}{\text{total volume}} = \frac{|\Omega'_f|}{|\Omega'|}$$

Let us designate the global porosity of the system by ϕ^* . We have:

$$\phi^* = \frac{\text{total void volume}}{\text{total volume}} = \frac{|\Omega_p| + |\Omega'_f|}{|\Omega'|}$$

Thus, our two porosities are related to the global porosity by:

$$\phi^* = \phi' + (1 - \phi') \phi$$

Therefore, the storage term in equation 14 is merely the global porosity of the system.

M. Bai and F. Civan state that the storage term in equation 14 in our paper should be the following:

$$\phi c_m + (1 - \phi) c_f$$

where c_m and c_f are the total (fluid and solid) compressibilities for the matrix and the fractures, respectively. Implicit in their comment is the fact that they consider the following macroscopic equation:

$$\vec{\nabla} \cdot (K_f \vec{\nabla} P_f) = [\phi c_m + (1 - \phi) c_f] \frac{\partial P_f}{\partial t} \quad (6)$$

which is intended for describing the flow of a slightly compressible fluid in a slightly compressible fractured porous medium.

Our models describe the flow of a *strongly compressible* fluid in a *rigid* fractured porous medium, in which case the lefthand side of Eq. (6) becomes $\vec{\nabla} \cdot (P_f K_f \vec{\nabla} P_f)$. As a result, the dimension of both sides in the equation describing the macroscopic behavior of a strongly compressible fluid flow in a porous medium is Pa s^{-1} , whereas the dimension in the equation for a slightly compressible fluid flow, like Eq. (6), is s^{-1} . M. Bai and F. Civan should have at least noticed that for a question of homogeneity the term $\phi c_m + (1 - \phi) c_f$ could not appear as the storage term in our equation.

The three macroscopic behaviors for the flow of gas through a rigid fractured medium can be summarized as follows:

Case I: Weak separation between the pore scale and the fracture scale	Equation 14	Single-porosity behavior with the global porosity ϕ^* as the storage term.
Case II: Equal separation of scales	Equation 15	Double-porosity behavior inducing memory effects and strong nonlinearities.
Case III: Large separation between the pore scale and the fracture scale	Equation 16	Single-porosity behavior with the fracture porosity ϕ' as the storage term.

5. Conclusion

Apart from the remarks regarding the notation, there is no relevant argument in the comment of M. Bai and F. Civan. We hope that the above clarifies matters and helps to aid their understanding.

Finally, we shall point out the fact that the objective of the paper is to summarize important results that have already been published. For details concerning the rigorous derivation of these results, the reader is referred to several former papers (Auriault and Boutin, 1992, 1993; Auriault and Royer, 1993; Royer and Auriault, 1994).

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