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Desorption-induced shear failure of coal bed seams during gas depletion

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ABSTRACT

The recovery of natural gas from coal bed seams is usually accompanied by a significant increase of permeability induced by coal matrix shrinkage and stress relaxation upon gas desorption. This advantageous increase in permeability may be impaired sometimes by mechanical failure of the reservoir rock and ensuing production of coal fines. Near-wellbore stress concentration and reduction of lateral stresses are known to promote shear failure during depletion in oil and gas reservoir formations. Yet, conventional analyses have shown limited success in predicting coal failure, since other chemo-physical mechanisms may be responsible in enhancing the conditions towards mechanical failure in the coal bed reservoir rock. We show a set of triaxial experiments involving gas desorption from coal cores under zero-lateral strain condition (radial stress measured and controlled) and constant total vertical stress meant to simulate the stress path during production far from the wellbore. CO_2 is used as surrogate fluid for CH_4. The experimental data indicates that desorption can significantly help reduce lateral stress (and increasing deviatoric stress) until shear failure occurs. The results suggest that depletion-induced shear failure is much more likely to occur in coal seams than in conventional non-sorbing reservoir rocks. The adsorptive-mechanical coupling turns out to be a key phenomenon in the process. Numerical simulations at the representative elementary volume scale adopting a double-porosity poromechanical model support the experimental findings and permit calculating a critical gas pressure for shear failure to happen. This emergent phenomenon is comparable to the outcome of other situations such as mineral dissolution or thermal contraction, where shrinkage relaxes lateral stress and acts as an intensifying driver for promoting shear failure within the reservoir rock. Coupled numerical simulation is needed to include near-wellbore effects and validate our findings with actual field observations. A thorough understanding of the coupled response of coal seams is necessary to enhance reservoir management and mitigate the effects of coal failure on fines production.

1. Introduction

Currently, natural gas accounts for roughly 20% of the world's energy supply (IEA, 2013). Coal bed methane constitutes an important domestic source of natural gas in several countries, namely Australia, USA, Canada and China (EIA, 2013). Moreover, production of coal bed methane is expected to increase throughout the world in the near future as more reservoirs are discovered and new technology enables enhanced production.

Various characteristics make coal beds a unique geomaterial, showing poromechanical properties notably different from other reservoir rocks. First, coal seams are naturally fractured reservoirs. Diagenetic processes lead to opening mode fractures predominantly oriented perpendicularly to the bedding plane, called cleats (Laubach et al., 1998). Cleats compose most of the macroporosity, where fluid flow occurs by advection (Mazumder et al., 2006; Pan and Connell, 2007). Second, the coal solid skeleton is constituted by a microporous disordered organic continuum, termed coal matrix. Micropores and mesopores sized in the order of 10^{-9} to 10^{-8} m compose the coal microporosity. The coal matrix is capable of adsorbing various gases, including carbon dioxide CO_2, methane CH_4, and nitrogen N_2; adsorption leads to coal matrix volumetric swelling in the order of a few percents (Ceglarska-Stefanska and Czaplinski, 1993; Levine, 1996; Mazumder et al., 2006; Pan and Connell, 2007; Pini, 2009; Reucroft and Sethuraman, 1987). Conversely, desorption leads to coal matrix shrinkage.

Bottom-hole depressurization induces gas production from fractures and desorption from the coal matrix during the production phase. Desorption-induced shrinkage has an important effect on coal seam permeability (Palmer and Mansoori, 1998; Pan and Connell, 2012). Shrinkage favors the opening of open-mode fractures with a concomitant increase in permeability. However, large increases in permeability during depletion have sometimes been observed to be followed by a sudden drop of permeability (Fig. 1), usually accompanied by the production of coal fines (Moore et al., 2011; Okotie and Moore, 2010). One cause of fines production (also responsible for sand production in conventional reservoir) is increased stress anisotropy and shearing around uncased wells or perforations due to loss of radial support.

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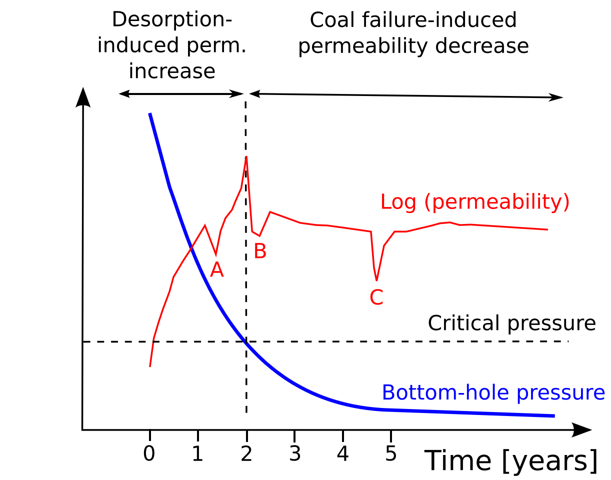

Fig. 1. Schematic signature of reservoir response and coal failure during depletion as a function of time: bottom-hole pressure and permeability signals. Notice that sudden permeability reductions (indicated A, B and C) take place as bottom-hole pressure is reduced. The permeability drops are associated with coal failure events. The last permeability drop (C) is recovered after wellbore clean-up operations only. Adapted from field experimental data by Moore et al. (2011).

Reservoir depletion is known to induce changes in effective stresses in the reservoir rock far from the wellbore, that can sometimes lead to shear failure and fault reactivation within the reservoir. Depletion promotes zero-lateral strain loading condition in laterally extensive reservoirs (condition commonly known as uniaxial strain/compression in Petroleum Engineering and Structural Geology or oedometric condition in Geotechnical Engineering — Fig. 2). The change in stresses upon depletion in conventional reservoirs is well predicted by poroelasticity, shear-failure (induced normal faulting), or a combination of both (Goulty, 2003; Segall and Fitzgerald, 1998; Teufel et al., 1991). Under zero-lateral strain condition, the ratio between the change of total lateral (horizontal) stress $\Delta\sigma_h$ and the change of reservoir pressure Δp is equal to $\Delta\sigma_h/\Delta p = 2/3$ for a poroelastic response with Poisson's ratio $\nu = 0.25$ and Biot's coefficient $\alpha = 1$ or for shear failure with a friction coefficient of $\mu = 0.58$. Recent experimental work shows a reduction of 9.4 MPa of lateral stress upon drawdown of CH_4 gas pressure from 6.2 to 0.3 MPa while keeping zero-lateral (radial) strain condition in a cylindrical coal core (Mitra et al., 2012). This result indicates a ratio of $\Delta\sigma_h/\Delta p \sim 1.57$. Theoretical $\Delta\sigma_h/\Delta p$ values predicted by poroelasticity cannot be higher than 1 for any combination of Poisson's ratio and Biot's coefficient in conventional rocks (Zoback, 2013), which suggests that conventional poroelasticity cannot fully explain the behavior of coal seams.

Given the double porosity of coal seams (micro and macroporosity described previously) and the well known adsorption-induced swelling of the coal matrix, the change in lateral stress in coal seams upon depletion is expected to have some particularities with respect to conventional reservoirs. Recent work from the authors aims at predicting adsorption-induced strains and stresses in coal seams within a poromechanical framework including adsorption phenomena rigorously (Brochard et al., 2012; Espinoza et al., 2013, 2014; Nikoosokhan et al., 2012, 2014). Our experimental and modeling results indicate that adsorption can generate significant stresses in the order of tens of MPa at typical reservoir pressures. Hence, it should not be surprising that desorption holding zero-lateral strain can significantly affect the reduction of lateral stress during depletion at a $\Delta\sigma_h/\Delta p$ rate much greater than the one due solely to poroelastic effects in macropores predicted by conventional poroelasticity.

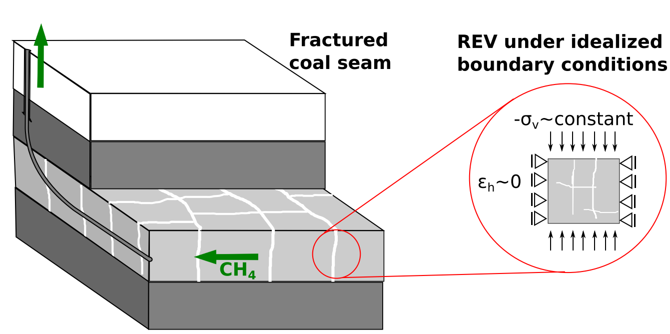

Fig. 2. Schematic representation of a coal seam intercepted by a horizontal well and of a representative elementary volume (REV) far from near-wellbore effects. Laterally extensive coal seams follow zero-lateral strain compression far from the wellbore.

The objective of this study is to assess the reduction of lateral stresses in coal seams during depletion and gas desorption by replicating the depletion pressure–stress path in the laboratory using CO_2 as a surrogate fluid for CH_4. We aim at understanding the underlying phenomena which lead to coal failure and production of coal fines at the scale of a representative elementary volume far from near-wellbore effects.

2. Materials and methods

2.1. Coal characterization and triaxial testing

We test coal originary from South Africa (Vitrinite reflectance of 0.57% — sub-bituminous A/high volatile C bituminous by ASTM D 388). A set of cores 38 mm in diameter and 2:1 slenderness drilled perpendicularly to the bedding plane serves as experimental specimens. The bulk density of cores ranges from 1318 to 1356 kg/m^3. The specimen helium porosity varies from 11-to-13%. Core testing takes place in a triaxial cell connected to syringe pumps to control stresses and pore-fluid pressure. The system is able to (1) measure specimen axial and radial deformations and (2) control independently axial and radial stresses to apply isotropic or anisotropic state of stresses (including zero-lateral strain condition). Fig. 3 shows a schematic representation of the triaxial cell and its main features.

2.2. Determination of shear strength

We tested the shear strength of coal cores in dry conditions (without adsorbed gas) under unconfined and confined triaxial conditions. The triaxial cell imposes a deviatoric loading by applying a change in axial strain with time at a given constant confinement. The axial strain rate is fixed to a constant value equal to 3×10^{-4} min^{-1}. Rigorously, the shear strength should be tested with sorbed gas, as sorption may reduce shear strength (see Section 4.1).

2.3. Desorption test procedure

We aim at simulating in the laboratory the pressure–stress path of a block of coal subjected to depressurization and depletion. Hence, the following pressure–stress path is required: (1) recreation of in-situ initial state of stresses and seam pressure (requires adsorbed gas in thermodynamical equilibrium with gas in the cleats), and (2) imposition of a pressure drawdown to extract gas from the fractures and coal micropores, with simultaneous adjustment of lateral stresses to keep zero-lateral strain condition, while the total vertical stress remains constant (constant overburden — see Fig. 2).

The experimental procedure to achieve the pressure–stress path described above consists of the following steps:

1. Increase confining stresses about 1 to 2 MPa above the objective fluid injection pressure p_{ci} at which the core will be exposed. The resulting low effective stress will facilitate quick advective gas flow through fractures (since fracture permeability is highly sensitive to effective stress) and reduce equilibration time in the next step.
2. Inject CO_2 at constant confining stress, let the specimen swell and equilibrate for ~7 days. Swelling strains help us evaluate