Fluid flow and coupled poroelastic response in tight rocks

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Abstract

We have extended the methodology, derived from our previous work (Hasanov, 2014) and applied it to measure hydraulic and poroelastic properties of tight rocks. This paper is devoted to an integrated study of reservoir rocks' hydraulic transport and poroelastic properties as measured with the complex transient pore pressure experiment. The measurements were carried out for four low-porosity low-permeability samples at a range of oscillation frequencies and effective stresses. An apparent linear-frequency dependence of permeability was observed. Measured frequency dispersion of drained poroelastic properties indicates an intrinsically inelastic nature of the porous mineral rock frame. Standard Linear Model produced the best fit to the experimental poroelastic moduli dispersion data. Biot and Skempton's coefficients, estimated from poroelastic strain measurements, fall within the presumable range of values for these rocks.

Introduction

We have completed measurements of hydraulic and coupled poroelastic properties of four different rock samples. Permeability was measured by oscillating pore pressure (OPP) method, poroelastic properties were measured by instrumenting our samples with strain gauges. Two samples are tight sandstone and a siltstone from Mesaverde formation, a tight Lyons sandstone and Barre granite. In this paper we report the experimental results for Lyons sandstone only. Lyons sandstone is a highly cemented specimen with low porosity (5%) and microDarcy-scale permeability.

We conducted the described experiments at New England Research laboratory in Vermont, US. A jacketed sample, instrumented with strain gages, is placed between pressure vessel head and downstream coreholder. The key component of the experimental setup is the downstream "low-permeability" coreholder, developed by NER. The coreholder is a hollow titanium cylinder with built-in zero-volume Kulite pore pressure transducer and very small downstream reservoir of volume 0.6 cm 3 . Small downstream reservoir ensures faster pressure equilibration times even in nanodarcy permeability rocks, as well as improves the sensitivity of transient experiment to sample's storage capacity. After the sample is placed inside the pressure vessel, we slowly increase confining pressure to 7.5 Mpa, simultaneously saturating the sample with argon and increasing pore pressure to 5 MPa. After the pore pressure at upstream and downstream pressure transducers is equilibrated, we begin perturbing the pore pressure with sinusoidal signals. The mean pore pressure level was kept at 5 MPa at all times, confining pressure is increased at 5 MPa steps until 55 MPa, and the same during unloading stress path. During each confining pressure steps we run a sequence of seven sinusoidal tests, logarithmically spaced between 0.005 and 0.1 Hz. We also record strain signals at each pore pressure perturbation sequence, and deduce poroelastic expansion coefficient K_{bp} from these measurements.

Results and discussion

As noted in the literature (Johnson et al., 1987; Sheng and Zhou, 1988), the dynamic permeability of porous medium equals to the DC limit when the oscillation frequency is below the critical Biot frequency. Our experiments were performed at the frequency range of 0.001 – 0.1 Hz, which is well below the critical Biot frequencies for a typical sedimentary rock (kiloHertz range according to Pride (2005)). Despite the theoretical independence of both permeability and storage capacity on the oscillation frequency in the range we conducted our experiments, we observe a distinct relation of the measured parameters to the oscillation period - both permeability and storage capacity decrease steadily with increasing oscillation frequency. The explanation of the laboratory-observed frequency dispersion and attenuation of poroelastic moduli is largely based on the theory of viscoleasticity. Common viscoelastic models, such as Maxwell fluid or Standard Linear Solid allow us not only to explain this behavior, but also predict the magnitude of the modulus or attenuation at a certain frequency, given that the low- and high-end limiting frequency values are known (in our case, quasi-static modulus and modulus, measured at ultrasonic frequency). The poroelastic parameter, directly inferred from our oscillating pore pressure experiments at various frequencies is Biot's poroelastic expansion coefficient H, also earlier defined as one of Zimmerman's drained bulk moduli K_{bp}. In order to calculate the rest of the moduli we need to know rock specimen's porosity φ, fluid bulk modulus K_{fl} and mineral frame bulk modulus K_{min} . The connected porosity of the studied sample is about 5%, bulk modulus of argon is assumed to be 0.5 MPa. We estimated the mineral frame bulk modulus as 36 GPa (pure quartz). A surprisingly significant dispersion of poroelastic moduli has been observed in frequency data (see Figure 1). Since the primary measured elastic modulus (Biot's poroelastic expansion coefficient K_{bp}) is a drained modulus, the observed modulus dispersion indicates that the rock mineral skeleton is inherently anelastic. Unlike in the studies by Hagin and Zoback (2004), who measured dry bulk modulus dispersion of unconsolidated sandstones by oscillating confining pressures, we infer drained bulk modulus from the direct K_{bp} measurement by oscillating pore pressures with much lower pressure amplitudes (0.5 MPa as opposed to 2 MPa, employed by Hagin and Zoback (2004)). We conclude that the observed behavior follows the SLS model, rather than Cole-Cole model with non-zero values of the distribution parameter α. In our modeling, we accept the value of the modulus, measured at 0.005 Hz as the static limit M_0 .

Unfortunately, ultrasonic data has not been acquired during the course of these experiments, thus the value of M_∞ remains unknown.

As it has been suggested by numerous authors (Walsh, 1965; Batzle et al., 1980; Guéguen et al., 2011), microcracks significantly influence transport and elastic properties of rocks. In typical sedimentary reservoir rocks, such as sandstones, porosity can be conceptually perceived as a combination of equant (spherical) pores and elliptical cracks with various aspect ratios. It is these microcracks that have a major effect on permeability, storage capacity and poroelastic moduli and are responsible for effective stress dependence of these properties. Only very narrow and compliant cracks with low aspect ratios are closing when the confining pressure of our working range is applied (Batzle et al., 1980). Permeability decreases with increasing differential stress during hydrostatic loading due to the closure of micro-cracks, and thus creating more tortuous flowpaths and increasing the resistance to flow. Figure 8(a) summarizes the values of permeabilities, measured at 0.005 Hz pore pressure oscillation frequency for Lyons-1 sample as a function of differential hydrostatic stress, both during the loading and unloading stress paths.

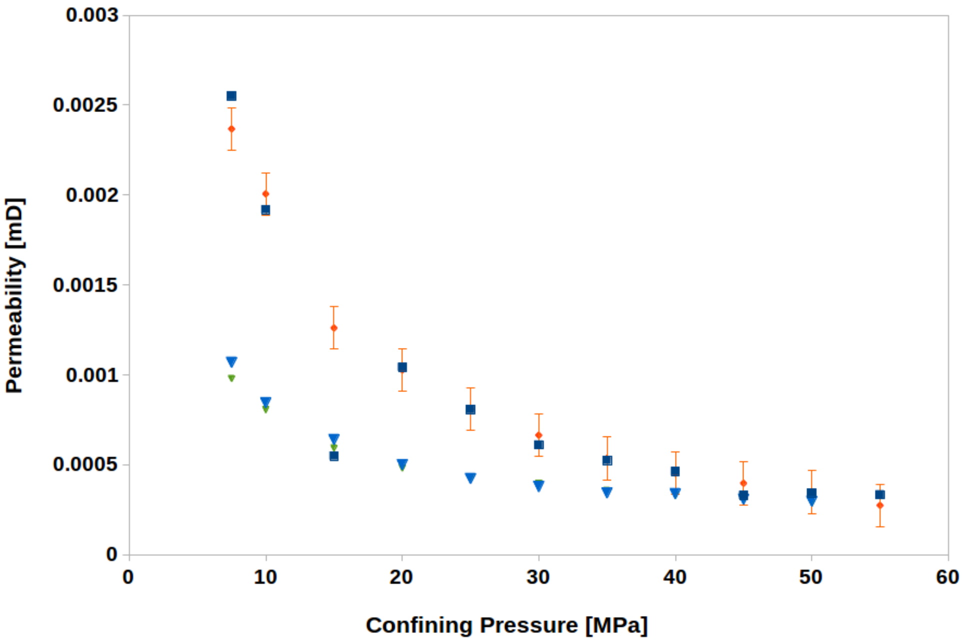

Figure 2: Measured values of permeability as a function of differential stress at 0.005 Hz oscillation frequency, both loading and unloading stress paths.

Figure 1: Kbp dispersion and phase angle at 7.5 MPa of confining pressure.

Conclusions

The complex transient pore pressure experiments have been successfully performed on four low-permeability low-porosity rock samples. Hydraulic transport and poroelastic properties have been measured at various oscillation frequencies. All of the properties exhibited a certain frequency dependence, although only frequency dispersion of poroelastic moduli can be explained in light of the theory of linear viscoelasticity. The measured dispersion of drained moduli sheds light at the intrinsically inelastic nature of the porous rock frame. The Standard Linear Solid model seems to describe the observed dispersion and attenuation best. According to theory of dynamic permeability this hydraulic transport property should not display any frequency-dependence in the frequency range of our apparatus. However, we measured a sharp decrease in permeability as a function of frequency - we currently do not have a robust explanation of this phenomenon. The measured transport and poroelastic properties follow classical pressure trends: permeability decreases and moduli increase as the hydrostatic load is applied due to initial closure of microcracks and compliant pores.

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