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Time-dependent deformation of shale gas reservoir rocks and its long-term effect on the in situ state of stress

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A B S T R A C T

Laboratory testing of shale gas reservoir rocks reveal varying amounts of time-dependent viscous deformation in response to applied differential stress. The time-dependent deformation is an inherent property of the dry rock as it occurs in the absence of pore fluid. The contribution of the time-dependent deformation is generally larger for rocks with more clay and organic content. The time-dependent behavior can be modeled as a power-law function of time. Its magnitude is approximately linear with the magnitude of the applied differential stress and nearly insensitive to the confining pressure. By applying linear viscoelastic theory and using laboratory constrained constitutive parameters, we evaluated the effect of the time-dependent deformation in modifying the in situ differential stress over time. Modeling suggests that a significant proportion of a differential stress change would be relaxed over time-scales on the order of days. Because of this short time scale, the composition of the rock (as it influences the time-dependent behavior) may influence the in situ differential stress magnitudes stronger than the formation's geological loading history for these reservoirs.

1. Introduction

Characterization of the mechanical properties of reservoir rocks through laboratory testing often focuses on elastic properties for application to seismic and sonic data, or focuses on rock strength for application to problems such as wellbore stability. However, it is also important to understand the time-dependent inelastic properties of rocks in order to accurately predict the long-term behavior of reservoirs over time. Numerous laboratory studies have shown that deformation of weak reservoir sands and shales occur through elastic/viscoplastic constitutive behavior [1–5]. A significant portion of the deformation of these types of rocks takes place by a time-dependent response not predicted by linear elasticity. Failing to address the time-dependent response of these reservoir rocks may lead to significant errors in predicting reservoir compaction during depletion [6,7] and could lead to under-estimation of surface subsidence or inaccurate forecasting of reservoir performance.

In the study reported here, we investigated the time-dependent deformational properties of shale gas reservoir rocks. While shale gas reservoir rocks are relatively intact and exhibit much less time-dependent deformation than unconsolidated formations, it is still quite important for these rocks. For example, it has been suggested that hydraulic fractures in shale gas reservoirs may suffer from reservoir permeability loss due to time-dependent proppant-embedment [8,9]. As we show below, viscous deformation would be expected to appreciably affect the in situ state of stress as viscous flow relaxes differential stress. This not only affects the geomechanical response of the reservoir to processes such as hydraulic fracturing, but also may have important implications for the current state of stress that has developed over geological time. As shale gas reservoirs are known for their significant intra-reservoir heterogeneity [10], both lithological and mechanical, which may cause a variety of mechanical responses during hydraulic fracturing and production [11,12], it is important to properly assess the effect of time-dependent deformation and its controls to successfully understand/predict/optimize hydraulic fracturing operations for economical production.

We conducted laboratory triaxial creep experiments using natural shale gas reservoir rocks from several of the regions in North America where shale gas is being produced. In other studies, we report the static and dynamic elastic moduli, anisotropy, strengths, and general ductile behavior of the samples studied here [13,14]. The study reported here focuses on the time-dependent behavior and constitutive relations between stress, strain, and time. We then interpret the results in the framework of linear viscoelastic theory to quantitatively assess the geomechanical effect of viscous time-dependent deformation over engineering and geological time scales.

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2. Methods

2.1. Sample description

We performed creep experiments using core samples from the Barnett, Haynesville, Eagle Ford, and Fort St. John shale. The material composition of these samples constrained by powder XRD analysis and pyrolysis is summarized in a ternary plot with clay+kerogen, QFP (quartz, feldspar, pyrite), and carbonate volumes as the end members (Fig. 1). Samples from Barnett, Haynesville, and Eagle Ford shale are further divided into 2 subgroups of distinct mineralogy where subgroup 1 contains more clay and organic contents than subgroup 2. In general, Barnett and Fort St. John shale samples are relatively QFP-rich and Eagle Ford samples are carbonate-rich. T_{max} obtained from Rock-Eval pyrolysis range in between 445 and 545 °C, indicating that organic matters in the shales are mature to over-mature (wet to dry gas). Sample porosity estimated from the average mineral density and the dry bulk density is between 1.5% and –9% and roughly correlates with the amount of clay and kerogen in the samples. There is significant anisotropy in the microstructure of these samples caused by the preferred orientation of clay minerals and the anisotropic shape/distribution of the solid organic matters which also introduces significant anisotropy in the elastic and deformational properties of these samples [13,14].

2.2. Laboratory procedures

We performed multi-step creep experiments in a servo-controlled triaxial apparatus to observe and examine the time-dependent mechanical properties of the samples. We used cylindrical samples of 1" diameter and 1.2–2.1" lengths, whose cylindrical axes were either perpendicular (vertical samples) or parallel (horizontal samples) to the bedding planes. Samples were first subject to a constant confining pressure of 10–60 MPa (above and below in situ effective pressure) and kept under the constant pressure for at least 3 h to reach thermal equilibrium inside the pressure vessel. Then differential stress, P_{diff}, of varying magnitude was applied in 2–5 steps by loading the sample in the axial direction. Each step of P_{diff} was applied over 60 s after which P_{diff} was held constant for 3 h to two weeks to observe the creep response of the sample. The differential stress applied by the differential load in the axial direction was kept below 50% of the ultimate rock strength to prevent the transition of the creep behavior into tertiary creep. Consequently, the creep deformation we observed only showed stable deformation with continuously decreasing strain rate. All samples were tested in "as received" conditions in order to best preserve the in situ hydration states. The mechanical responses we observed are expected to be free of any poroelastic effects as the fluid

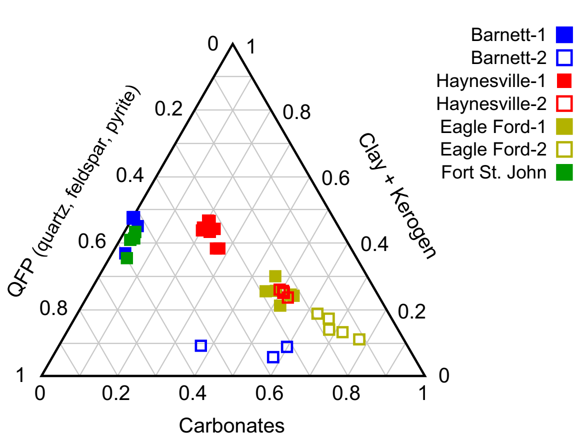

Fig. 1. Ternary plot representation of the sample material composition.

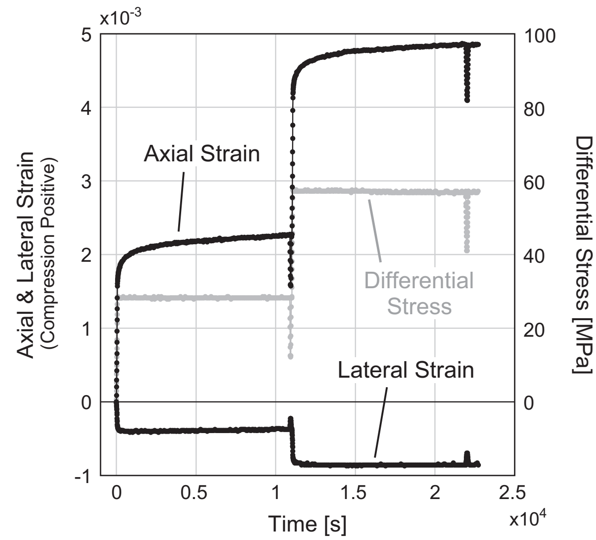

Fig. 2. Data from a representative experiment (Haynesville-1 vertical). In the axial strain data, the segment with sparse data points correspond to the strain data during application of the differential stress step.

saturation measured after recovery of the cores were at most 40% including clay bound water (discussed more in section 6.1). All experiments were conducted at room-temperature and drained pore pressure conditions.

During the experiments, sample deformation in the axial direction was measured by a pair of LVDT transducers and the deformation in the direction perpendicular to the axis (lateral deformation) was measured by a pair of spring-mounted strain-gauge transducers. Data from a representative experiment is shown in Fig. 2. In each step, most of the strain occurs in the initial 60 s while the axial differential stress is applied, mostly due to the elastic response of the rock, and the rest is the creep response under constant differential stress. A short term unloading and reloading of differential stress was inserted at the end of each creep deformation before moving on to the next pressure step, both done in 60 s, in order to measure the elastic modulus of the rock. From the slope of the stress-strain relation during the unloading and reloading, the Young's modulus was determined by least square linear regression.

As seen in Fig. 2, the lateral deformation exhibits much less time-dependent deformation during constant stress condition compared to the axial deformation. Thus majority of the time-dependent deformation takes place in the direction parallel to the applied differential stress. This was a common feature observed in all experiments. Since the scope of the paper is to investigate the first-order geomechanical impact of the sample time-dependent deformation, we will only focus on the axial deformation that takes place under triaxial stress condition.

3. Results

3.1. Observations of creep behavior

Several representative strain data upon a differential stress step are shown in Fig. 3. Axial strain is plotted relative to the strain value at the beginning of the differential stress step, thus includes both the instantaneous elastic and time-dependent creep response. A result from a test using a standard aluminum alloy sample is also shown as a reference for pure elastic behavior. We see that all samples exhibit some amount of time-dependent