An experimental study of modulus dispersion and attenuation in sandstones at seismic frequencies

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SUMMARY

A study of the low frequency dispersion and attenuation in sedimentary rocks is important for interpreting seismic data obtained during fluid extraction in producing fields or during injection of carbon dioxide for storage purposes. We present the results of the laboratory measurements of elastic and anelastic parameters of dry and distilled water/brine saturated sandstones with low (~7.8 and 9.6 mD) and high (~590 mD) permeability conducted at seismic (1-100 Hz) and teleseismic (0.1-1 Hz) frequencies. The experiments were performed with a laboratory apparatus utilizing stress-strain relationship which was developed to measure the complex Young's moduli of rocks at seismic frequencies. The measurements carried out in saturated sandstones with low permeability at effective pressures from 2.5 to 23 MPa revealed prominent peaks of attenuation in the seismic and teleseismic bands. A significant dispersion of the Young's moduli was also observed. The change in the salinity of the fluid from 0 to 45,000 ppm NaCl did not affect any of the measured parameters. The dispersion of the elastic moduli of the dry sandstones was within the accuracy of our measurements.

Key words: elastic properties, extensional attenuation, water saturated sandstone, seismic frequencies

INTRODUCTION

A study of the pore fluid effects on the elastic and anelastic properties of sedimentary rocks is important for interpreting seismic data obtained for reservoirs containing various fluids as well as for monitoring the fluid movement during hydrocarbon extraction in producing fields. The presence of fluid in the pore space leads to the attenuation of acoustic waves and their velocity dispersion which are subjects of growing interest as tools for obtaining more detailed information about hydraulic properties of reservoir rocks (Müller et al. 2010).

In the last few decades numerous analytical models quantifying the mechanisms of the attenuation and dispersion in rocks have been developed (see, for example, review papers by Müller et al. (2010) and Gurevich et al. (2009)). However, there are few laboratory experiments undertaken at seismic (1-100Hz) and teleseismic (<1Hz) frequencies to verify these models.

It has been demonstrated that linear loss mechanisms of attenuation in the rocks, which are relevant to seismic waves, become dominant at strain amplitudes $<10^{-6}$. At higher strains these mechanisms are overtaken by nonlinear phenomena (Mavko, 1979; Winkler et al., 1979). Thus to be representative of the mechanisms taking place at reservoir conditions, the laboratory experiments must be conducted with strains below 10^{-6}.

The first low frequency laboratory measurements of elastic and anelastic properties of rocks at strain amplitude $<10^{-6}$ were reported by Spencer (1981). Spencer used a low-frequency apparatus based on the stress-strain relationship, where sinusoidal stress was applied to a cylindrical sample in the axial direction; no lateral stress on the sample was set. Spencer observed significant Young's moduli dispersion and attenuation at frequencies of a few hundred Hz in water-saturated Navajo sandstone and at frequency ~10 Hz in water-saturated Spergen limestone. The measurements were conducted under ambient conditions.

The low frequency laboratory experiments undertaken by Paffenholz and Burkhardt (1989) included measurements of the Young's moduli and extensional attenuation in fully water saturated rocks at frequencies between 0.03 and 300 Hz. Paffenholz and Burkhardt found substantial attenuation in Mittelrhaet and Obemkirchner sandstones with the peaks of attenuation at a few tens of Hz, and also in limestone and dolomite, where the peaks of attenuation were observed at ~0.1 and ~20 Hz respectively. The measurements were carried out at uniaxial pressure of 1.5 MPa using the approach similar to the one used by Spencer.

When analysing Spencer's experiments, White (1986) and Dunn (1986) demonstrated that the attenuation observed by Spencer was due to radial fluid flow caused by the open-pore boundary condition on the sample surface and, to some extent, due to anelasticity of the rock matrix. The same remarks can be attributed to the measurements of the extensional attenuation performed by Paffenholz and Burkhardt.

The first laboratory experiments at low frequencies (5 – 2500 Hz) with closed-pore conditions were performed by Batzle et al. (2006). The closed-pore conditions were ensured by the high confining pressure applied to the rock sample. The experiments were conducted on brine-saturated low-permeability sandstone with high smectite content at various effective pressures. Applying the Cole-Cole relations to measured elastic parameters, Batzle at al. found that a peak of attenuation for water saturated sandstone with low permeability (a few millidarcies or less) can be at a frequency below the seismic band. This result indicates that for sedimentary rocks with low intrinsic permeability and low fluid mobility, the pore pressure may be out of equilibrium even at seismic frequencies (the high frequency regime). Therefore, the measurements conducted only at seismic frequencies are not always enough to validate commonly used theoretic models of fluid substitution and theories of elastic moduli dispersion and attenuation. However, so far no laboratory experiments with closed-pore conditions have been conducted on the water/brine saturated sedimentary rocks in seismic and teleseismic frequency domains together.

This paper is an attempt to fill the gap in the experimental study of the elastic and anelastic properties of low-permeability rocks at seismic and teleseismic frequencies. The paper is based on a comparison of elastic moduli dispersion and extensional attenuation measured in sandstone samples with very low and very high permeability. Two sandstone samples with permeability of ~7.8 and 590 mD were quarried in Donnybrook, Western Australia, and one sandstone sample with permeability of ~9.6 mD was obtained from the region of Western Australia Harvey. The measurements were carried out with dry and fully water/brine saturated samples at various effective pressures and room temperature (~22º C) using a new low-frequency apparatus, based on stress-strain relationship. The apparatus can operate at strain amplitudes 10^{-8}–10^{-6} and provides the means for measurements that require independent control of pore, uniaxial or confining pressures.

EXPERIMENTAL SET-UP

There are a few devices described in literature, that are able to measure simultaneously elastic and anelastic properties of rock samples at low (seismic and teleseismic) frequencies. These devices utilize a stress-strain relationship and differ by the type of the forced oscillations applied to a specimen under investigation: torsional (Jackson and Paterson, 1987; Paffenholz and Burkhardt, 1989) and longitudinal (Spencer, 1981; Paffenholz and Burkhardt, 1989; Batzle et al., 2006). However, only the device proposed by Batzle et al. (2006) is able to operate at confining pressure which is set up by placing the entire device in a gas pressure vessel.

Using the gas pressure vessel puts some considerable constrains on the sizes of rock samples and the mechanical assembly of the apparatus. The latter should be massive enough to avoid spurious mechanical resonances in the mechanical parts of the device (Batzle et al., 2006).

We developed a low frequency laboratory apparatus based on the strain-stress technique with the longitudinal type of the forced oscillations. The apparatus measures the complex Young's moduli of rock samples at confining pressures from 0 to 70 MPa and at pore pressures from 0 to 20 MPa.

The mechanical assembly of the apparatus is presented in Figure 1. The assembly comprises two massive steel platforms (the total mass of the platforms is ~ 400 kg) and a set of units between them, which includes a hydraulic actuator, a Hoek's triaxial cell (model 45-D0554, Controls Ltd), a piezoelectric stack actuator PSt 1000/35/60 (APC International Ltd) with the limit of maximum load of 70,000 N and with the frequency of its mechanical resonance >20 kHz, an aluminium calibration standard, and two steel plugs having passages for a fluid injection. A rock sample to be tested is placed inside a sleeve made of elastomer, which is mounted within the triaxial cell. The fluid passages in the steel plugs attached to the sample enable the flow of fluids through the sample and provide the means for pore pressure control. The triaxial cell and the hydraulic actuator (model RCS201, Enerpac) are connected via fluid lines with two manual hydraulic pumps (model P392, Enerpac) providing lateral and longitudinal static forces applied to the rock. The dynamic stress applied to the sample and the strains in the rock are controlled by two pairs of identical semiconductor strain gauges (type KSP-6-350-E4, Kyowa Ltd). One pair is glued to the aluminium standard and the other to the sample with epoxy adhesive (Selleys Araldite Super Strength). Strain gauges of each pair are orientated to measure axial and radial strains. To minimize frictions between the strain gages and sleeve, the rock sample is covered by a few layers of teflon tape.

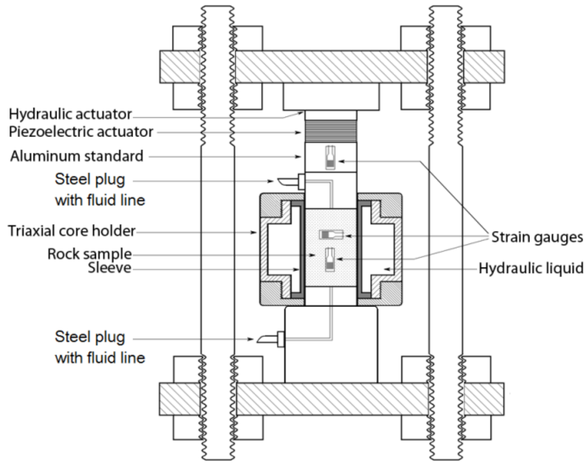

Figure 1. The mechanical assembly of the low-frequency laboratory apparatus.

The multilayer piezoelectric actuator transforms the sinusoidal voltage applied by an oscillator into mechanical stress, which causes displacements in the aluminum standard and tested sample mounted in series. The displacements modulate the conductivity of the strain gauges. A set of electric bridges (BCM-1 Wheatstone Bridge, Omega Engineering Ltd) transforms the modulated conductivity into electric signals, which, after digitizing by an analogue-digital converter (model 100, InstruNet, Omega Engineering Ltd), are received by an acquisition computer, where the signals are averaged and processed.

MEASUREMENTS AND RESULTS

The Poisson ratio and Young modulus of each sample were measured by comparing the strains detected in the sandstone and aluminium standard as it is described in detail by Mikhaltsevitch et al. (2011). The bulk K and shear μ moduli of the samples can be found using relations

$$K = \frac{E}{3(1-2\nu)}, \quad \mu = \frac{E}{2(1+\nu)},$$

where ρ is the density of the rock.

The value of extensional attenuation is derived from the phase shift between the stress applied to a sample and the strain in the sample caused by that stress (O'Connell and Budiansky, 1978). The uncertainty in the measurements of extensional attenuation is about ± 0.002.

The physical parameters of the Donnybrook and Harvey sandstone samples are given in Table 1.

Table 1. Sandstone samples parameters.

Sample	A Donnybrook	B Donnybrook	C Harvey
Porosity, %	20.6	14.8	18.0
Permeability, $\times10^{-15}$ m^2 (mD)	582 (590)	7.7 (7.8)	9.5 (9.6)
Density, kg/m^2	2261	2099	2110
Length, mm	70	70	72
Diameter, mm	38	38	38

The measurements were organized in the following way. Each sample was first tested dry at a given confining pressure. Then the sample was saturated with distilled water and tested again under the effective pressure (= confining pressure – pore pressure) corresponding to the confining pressure of the dry cycle. After completing the tests with sample C, saturant in the sample was replaced by brine (45,000 ppm NaCl) and measurements were repeated at the same confining and pore pressures.

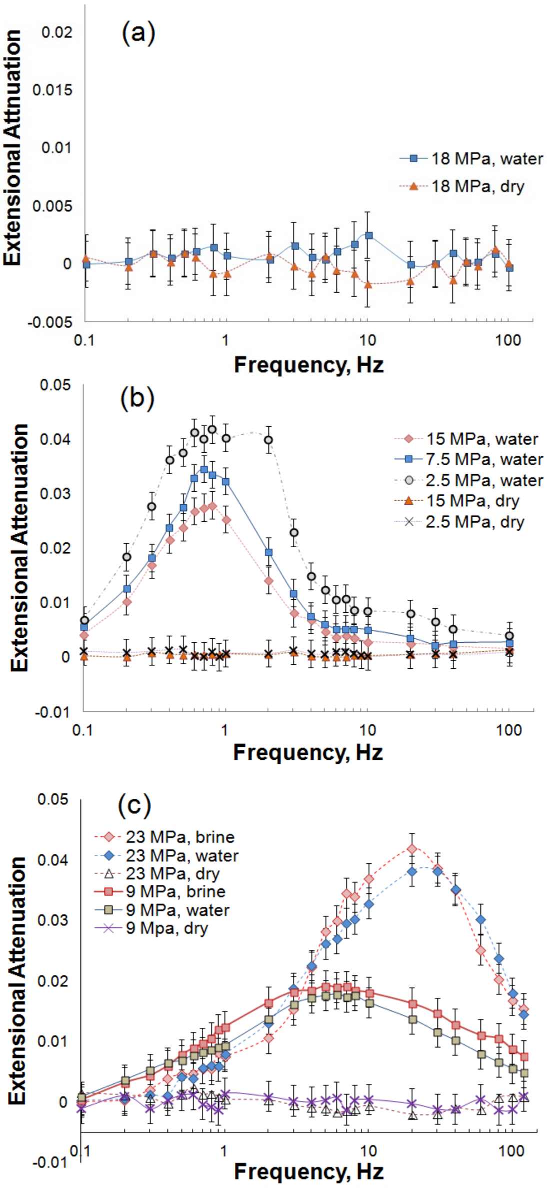

Figure 2. The extensional attenuation measured for dry and water/brine saturated samples (a) A, (b) B and (c) C at various effective pressures. In dry and saturated states the pore pressure is 0.1 MPa for samples A and B, and 5 MPa for sample C.

All the samples were saturated at a confining pressure of 10 MPa. To ensure the full saturation at least 10 pore volumes of water were pumped through the samples under a constant pressure of 3 MPa. For the sample A we used a back pressure regulator. The flow rate of water during saturation did not exceed 0.02 cm^3/s (1.2 cm^3/min).

The experimental results obtained for the sandstone samples at a set of effective pressures are presented in Figures 2 – 4.

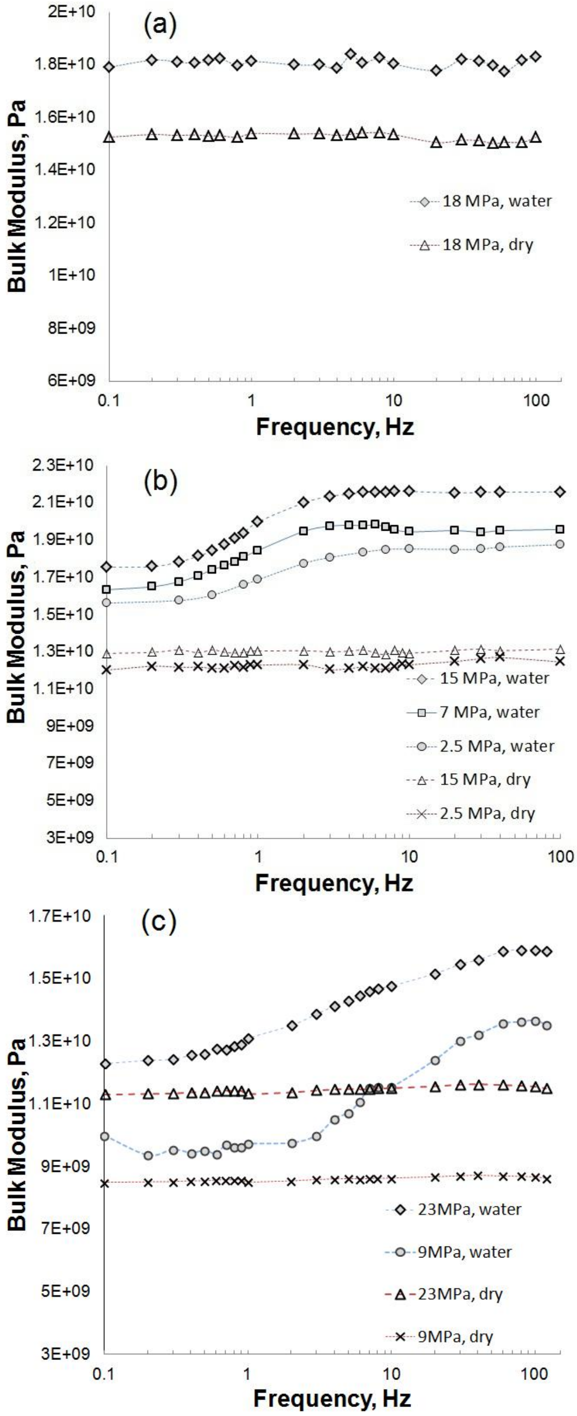

Figure 3. Frequency dependencies of bulk moduli of dry and water saturated samples (a) A, (b) B and (c) C. The pore pressures are the same as in Figure 2.

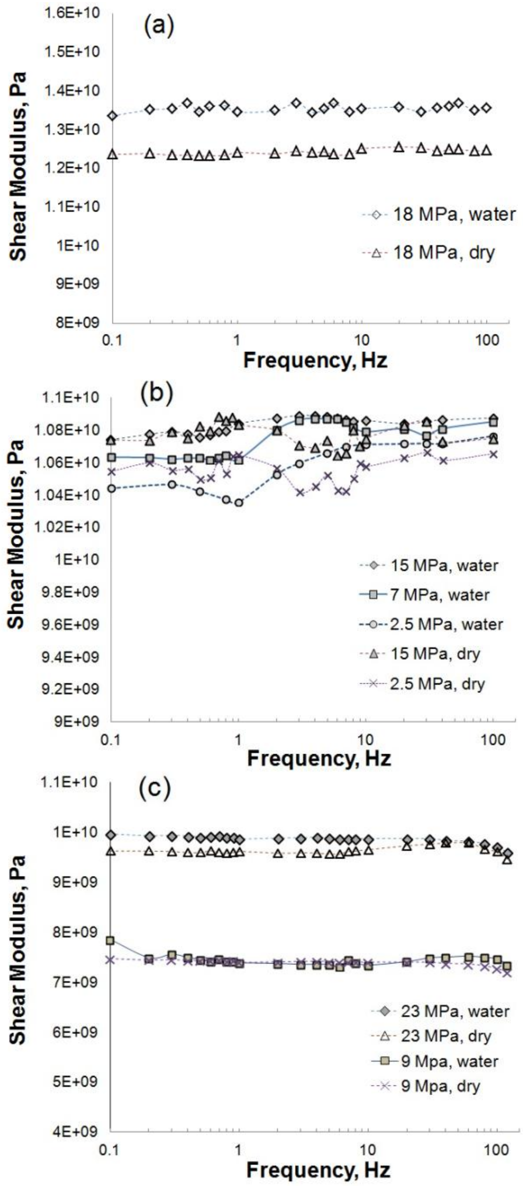

Figure 4. Dependencies on frequency for shear moduli of dry and water saturated samples (a) A, (b) B and (c) C.

The experiments with the Donnybrook sandstones were conducted at few confining pressures for sample A (2.5, 7 and 23 MPa) and at one confining pressure of 18 MPa for sample B. The pore pressure for both samples was ~0.1 MPa. Only distilled water was used for saturation of samples A and B. The Harvey sandstone (sample C) was tested at confining pressures of 14 and 28 MPa, the pore pressure was 5 MPa. The bulk and shear moduli measured for brine saturated sample C are identical to the same moduli measured in distilled water saturated state within the experimental error (not presented). The change in the extensional attenuation in response to the replacement of the saturant is also comparable with the experimental error (Figure 2c).

CONCLUSIONS

We reported the results of our measurements conducted on two Donnybrook (A and B) and one Harvey (C) sandstone samples with high (590 mD) and low (7.8 mD and 9.6 mD) permeability. There were no significant attenuation and dispersion observed in the high-permeability sample A.

Two distinct inter-related effects have been indicated in the water/brine saturated low-permeability samples B and C. Prominent peaks of extensional attenuation were found at frequency of 0.8 Hz in sample B and at frequencies ~7 Hz (at effective pressure of 23 MPa) and ~20 Hz (at effective pressure of 9 MPa) in sample C. The dispersion of the bulk moduli of both samples in the frequency range from 0.1 to 100 Hz was also detected. The dispersion of the bulk and shear moduli of the samples in the dry state was within the accuracy of our measurements.

Our results demonstrate that the low frequency limit of acoustic dispersion for low-permeability rocks can correspond to seismic or even teleseismic frequency band.

REFERENCES

Batzle, M. L., Han, D.-H., and Hofmann, R., 2006, Fluid mobility and frequency-dependent seismic velocity - Direct measurements: Geophysics 71, N1–N9.

Gurevich, B., Brajanovski, M., Galvin, R., Müller, T. M., and Toms-Stewart, J., 2009, P-wave dispersion and attenuation in fractured and porous reservoirs - Poroelasticity approach: Geophysical Prospecting 57, 225–237.

Dunn, K.-J., 1986, Acoustic attenuation in fluid-saturated porous cylinders at low frequencies: Journal of the Acoustical Society of America 79, 1709 – 1721.

Jackson, I. and Paterson, M.S., 1987, Shear modulus and internal friction of calcite rocks at seismic frequencies: pressure, frequency and grain size dependence: Physicsof the Earth and Planetary Interiors 45, 349-367.

Mavko, G., 1979, Frictional attenuation: an inherent amplitude dependence. Journal of Geophysical Research 84, 4769-4776.

Mikhaltsevitch, V., Lebedev, M., and Gurevich, B., 2011, A low-frequency apparatus for characterizing the mechanical properties of rocks: 73rd EAGE Conference & Exhibition, Vienna, Expanded Abstracts, P155.

Müller, T. M., Gurevich, B., and Lebedev M., 2010, Seismic wave attenuation and dispersion resulting from wave-induced flow in porous rocks — a review: Geophysics 75, 75A147–75A164.

O'Connell, R. J. and Budiansky, B., 1978, Measures of dissipation in viscoelastic media: Geophysical Research Letters 5, 5-8.

Paffenholz, J. and Burkhardt, H., 1989, Absorption and modulus measurements in the seismic frequency and strain range on partially saturated sedimentary rocks: Journal of Geophysical Research 94, 9493–9507.

Spencer, J. W., 1981, Stress relaxation at low frequencies in fluid-saturated rocks: Attenuation and modulus dispersion: Journal of Geophysical Research 86, 1803–1812.

White J.E., 1986, Biot-Gardner theory of extensional waves in porous rods: Geophysics 51, 742 – 745.

Winkler, K., Nur, A., and Gladwin, M., 1979, Friction and seismic attenuation in rocks: Nature, 277, 528–531.