Fuel 196 (2017) 442–457

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Determination of elastic properties of tight rocks from ultrasonic measurements: Examples from the Montney Formation (Alberta, Canada)

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ARTICLE INFO

Article history:
Received 17 August 2016
Received in revised form 21 January 2017
Accepted 26 January 2017
Available online 13 February 2017

Keywords:
Elastic anisotropy
Shear wave splitting
Ultrasonic velocities
Montney Formation

ABSTRACT

Laboratory-based measurements of acoustic wave propagation through porous media are important for many aspects of reservoir characterization. These measurements may be used to estimate sonic velocities, elastic anisotropy and dynamic rock mechanical properties, which in turn can be used in the calibration of sonic logs and to inform 3D/4D seismic and microseismic interpretations. In the current work, ultrasonic experiments were performed on Montney Formation (tight siltstone reservoir; Alberta, Canada) core plug samples under the same triaxial pressure conditions as used for permeability measurements. Unique to this study, the effect of propped/unpropped fractures on elastic properties as a function of effective pressure was determined, allowing for a comparison of the same properties for intact samples.

For both intact and fractured samples, P- and S-wave velocities increased with increasing effective pressure. These velocities, and derived mechanical properties (such as Young's modulus), for intact core plug samples are in excellent agreement with log-derived values. Because of the difference in scales for core- and log-based measurements, this agreement suggests that reservoir heterogeneities affecting acoustic wave propagation (and derived rock mechanical properties) occur at the sub-core plug scale for the reservoir interval studied. Measures of elastic anisotropy, such as shear wave splitting, were also determined to be a strong function of effective pressure. In one case, an intact sample was artificially fractured during the experiment with increasing effective pressure – the shear wave velocity difference (S1-S2) reversed at the estimated point of fracturing. This finding has important implications for interpretation of hydraulic and induced fractures in the reservoir using seismic data.

Finally, a core containing (1) an unpropped fracture and (2) a propped fracture was analyzed to determine the impact of these fracture types on anisotropy changes with effective pressure. Shear wave splitting changes were found to be much larger for the propped fracture sample than for the unpropped fracture sample, suggesting that time-lapse seismic may be used to distinguish fracture types.

1. Introduction

Ultra-low permeability ('tight') reservoirs and shales are currently being exploited with multi-fractured horizontal well (MFHW) technology in North America. Reservoir and hydraulic fracture characterization must be performed at multiple-scales, ideally along the length of MFHWs, if the controls on fluid flow are to be determined, and hydraulic fracturing stages are to be optimized. Recently, Clarkson et al. [1] reviewed current methods and challenges for shale gas reservoir characterization, from the nanopore scale to field scale – Fig. 1 (reproduced from that work) summarizes the various methods used for this purpose placed in the context of development stage and sample types used.

At the reservoir sample analysis scale, (ultra) sonic velocity measurements performed on cores can be extremely useful for not only estimating dynamic rock mechanical properties such as Poisson's ratio (PR) and Young's modulus (YM), for comparison with, and calibration of, sonic logs, but also for evaluation of elastic anisotropy. Rock mechanical properties are a key control on drilling rates and hydraulic fracturing, and are used extensively in models for drilling/completion and hydraulic fracture design. Sonic logs are commonly acquired to estimate PR and YM for use, for

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http://dx.doi.org/10.1016/j.fuel.2017.01.084
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Nomenclature

Abbreviations

BM	bulk modulus
Fm	formation
MFHW	multi-fractured horizontal well
PR	Poisson's ratio
SM	shear modulus
SWS	shear wave splitting
TOC	total organic carbon
YM	Young 's modulus

Field variables

c	stiffness coefficient
e	strain tensor
G	shear modulus
K	bulk modulus
V_P	P-wave velocity
V_S	S-wave velocity

Subscript

1	in reference to fast shear velocity
2	in reference to slow shear velocity
0	in reference to sonic velocity angle relative to bedding
90	in reference to sonic velocity angle relative to bedding
D	dynamic; in reference to Poisson's ratio and Young's modulus
ij	in reference to stiffness tensor and stress/pressure components
kl	in reference to strain components

Greek variables

δ	third Thomsen parameter
γ	second Thomsen parameter or S-wave anisotropy
ε	first Thomsen parameter or P-wave anisotropy
λ	Lamé parameter
μ	Lamé parameter
ρ	bulk density
σ	stress/pressure tensor
υ	Poisson's ratio

example, in hydraulic fracture simulators, but must be calibrated against rock data for which sonic travel time is measured.

Elastic anisotropy, which refers to the variation in elastic properties of rocks with direction of measurement, can also be estimated at the core scale, and may be used to inform seismic data interpretation for reservoir characterization at the field-scale. At the core scale in shales, for example, sonic velocity anisotropy can be affected by rock fabric (such as laminations, and microfractures) and composition (ex. kerogen content), saturation and pressure (see [2]) for a more complete summary), amongst other controls. At the field scale, elastic anisotropy can be measured using surface seismic data (e.g. [3–5]) and utilized in seismic processing for such purposes as geologic horizon dip correction. Elastic anisotropy also affects shear wave propagation; shear wave splitting (SWS), for example, is a common phenomenon caused by wave propagation through an anisotropic medium. An anisotropic medium causes the shear wave to split into two polarisations (the fast and slow shear waves) (Fig. 2). Measurement of the difference between fast and slow shear wave velocities can provide valuable information about heterogeneity and the presence of fractures in the reservoir (e.g. [6–9]). SWS analysis is also applied in microseismic analysis to detect fractures and for the evaluation of reservoir and hydraulic fracture properties [10–12]. It is possible that core-scale measurement of SWS may be used to evaluate the fundamental causes of elastic anisotropy in the reservoir because, unlike reservoirs in the subsurface, cores may be characterized easily using imaging, compositional analysis and petrophysical methods. Core studies of this nature may therefore be used to assist with SWS analysis of seismic and passive seismic data.

Several recent studies of shales and tight rocks using ultrasonic measurements have revealed some of the controls on elastic anisotropy, and its dependence on pressure. Josh et al. [2] provided an excellent summary of laboratory characterization of shales in general, including a summary of ultrasonic measurements performed on shale up to that time. Dewhurst and Siggins [13] measured P- and S-wave anisotropy, as quantified with Thomsen's [14] parameters, as a function of effective pressure. Anisotropy was attributed to mineralogy (illite-smectite) and the presence of microfractures parallel to particle alignment. Pervukhina et al. [15] also evaluated the pressure-dependence of the elastic properties of shales. Amongst several important observations, those authors suggested that application of confining pressure (isotropic pressure field) led to the closing of microfractures (pre-existing cracks) in the studied (North Sea) shale, reducing S-wave anisotropy. Kuila et al. [16] measured the ultrasonic velocities in shales in Western Australia and found that the magnitude and orientation of pressure anisotropy, with respect to shale microfabric, impacted the velocity response in changing pressure fields. Sone and Zoback [17] found that elastic anisotropy of gas shale samples, as quantified with Thomsen's parameters, increased with clay and organic content – they suggested that maturity of the shales also affected anisotropy. Importantly, none of these studies compared elastic anisotropy, and its pressure-dependence, of rocks before and after artificial fracturing. Such studies would have important implications for the evaluation of hydraulically-fractured reservoirs using, for example, 4D seismic. Further, study of the differences of anisotropy, and trends with pressure, for propped and unpropped fractures, may assist with their distinction using seismic and microseismic data. It is commonly believed that both propped and unpropped hydraulic fractures are created during hydraulic fracture stimulation of tight/shale wells, but their distribution in the reservoir is difficult to evaluate using current technology. An understanding of this distribution, which can possibly be gained by comparing anisotropy characteristics of these different fracture types, has implications for fracture design and understanding well performance.

The focus of the current study is reservoir sample-scale (core plug) measurements of ultrasonic velocities, derivation of dynamic rock mechanical properties, and determination of how elastic anisotropy changes with various properties of the core and confining pressures. Core plug samples from the Montney Fm. in Western Canada are used for this purpose. The core plugs were extracted parallel and perpendicular to laminations, and the samples represent a range in total organic carbon (TOC) and elemental composition content. Measurements are performed under confining pressure using a triaxial core holder on intact core, and cores after fractures have been induced. The results of unpropped and propped (after proppant, sand, has been added) fracture analysis at variable confining pressures during loading and unloading cycles are compared. Importantly, because a sonic coreholder in a pulse-decay permeameter device is used, the ultrasonic measurements can be performed simultaneously with permeability