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Physics of Rocks for Hydrocarbon Exploration

Introduction

by Angus Best

The discipline of rock physics is playing an increasingly important role in underpinning hydrocarbon exploration, reservoir characterisation and monitoring. Generally considered to concern the physics of seismic wave propagation in porous rocks, its traditional domain is understanding how reservoir properties, such as porosity, permeability, fluid type and saturation, can be derived from measurements of seismic velocity from multichannel seismic surveys. It allows extrapolation and interpolation of reservoir properties between wells, linking well log interpretations to surface seismic imaging of stratigraphic units. However, the real power of rock physics is to provide quantitative constraints on possible subsurface scenarios; for example, how much will seismic velocity change from a brine to an oil/gas saturated formation (or from brine to CO_2 saturation), from a clean sandstone to a shaly sand, and can we detect such, often subtle, changes on seismic data? The increasing sophistication of seismic imaging and improved data quality enables quantitative analysis, for which we require to know the physical laws that govern seismic wave propagation. Or put more simply, we need equations, suitably validated, linking seismic velocity to key geological parameters of interest.

As a research topic, much has been published on seismic velocities and how they vary with lithology, saturating fluid, pressure and temperature; yet, the discipline of rock physics is truly broader than this. Why restrict ourselves to seismic velocities, when complementary understanding of seismic attenuation (ever present) can also aid interpretation? Or even consider complementary geophysical electromagnetic and gravity methods? If the aim is to image and quantify subsurface geology, reservoir and geomechanical properties, then we need to use all available tools, use them wisely and in a cost-effective manner. Velocity is relatively well understood (although be no means completely), and there is increasing research interest in complementary methods, on the possibilities of joint inversion and interpretation. Clearly, if we can constrain, say porosity, with more than one independent measurement, that reduces uncertainty. To achieve this, we need to constantly improve our level of understanding of the complex inter-relationships among all parameters of interest (lithology, fluids, geomechanics) and for that, we are truly interested in the physics of rocks, hence the title of this special section.

The ten papers in this special section are representative of the 58 papers presented at the Second International Workshop on Rock Physics (2IWRP), held in Southampton, United Kingdom, between 4 - 9 August 2013. There were oral sessions on seismic attenuation and velocity dispersion, seismic anisotropy, geomechanics, microstructural models, digital rock physics, elastic properties, joint elastic-electrical properties, fluids and carbonates, reservoir characterisation and monitoring, as well as discussion sessions. These ten papers cover most of the topics presented at the workshop and are a healthy indicator of this active area of research.

Roganov and Stovas derived analytic expressions to approximate the low frequency behaviour of phase velocity and scattering in a weakly contrasting periodic layered medium.

They tested the accuracy of the weak contrast approximation expressions against numerical models and found they are valid at low frequencies.

Subramaniyan et al. provide a timely review of laboratory forced oscillation seismic attenuation measurements over the last 30 years and point to technical challenges that must be considered when undertaking such studies (strain level, sample jacketing, transducers, sample alignment, apparatus resonances). A review of low frequency attenuation results for sandstones and carbonates, including heavy oil samples, leads to the conclusion that it is important to perform calibration of absolute values of attenuation using a standard material such as aluminium to aid proper comparison between different experimental apparatuses. The previous lack of such inter-calibrations has hindered the advancement of attenuation studies.

Wu et al. studied the theoretical frequency dependent amplitude variation with offset (FAVO) of multichannel reflection seismic data in an effort to better constrain reservoir gas saturation, and in particular, to distinguish fizz-water from higher gas contents. They introduced cross-plots of Gassmann (low frequency) reflectivity (intercept) versus frequency-dependent reflectivity (gradient) as a way to distinguish full gas, partial gas and full water saturation cases. A numerical Bayesian inversion of FAVO data further indicates the possibility of quantifying porosity and saturation using various rock physics models of attenuation and velocity dispersion.

Tillotson et al. present laboratory ultrasonic velocity and attenuation measurements in octagonal-shaped, synthetic sandstone samples with aligned penny-shaped fractures when saturated with air, water and glycerin. Although scattering clearly affects the attenuation data, the velocity results agree with theoretical predictions of frequency-dependent elastic wave anisotropy due to aligned meso-scale fractures in porous media. In particular, shear wave splitting is seen to reverse in polarity with increasing pore fluid viscosity and bulk modulus at an angle of incidence of 45°, in agreement with theoretical predictions. These laboratory validation results provide evidence for the robust application of the model to the interpretation of seismic anisotropy in vertically fractured reservoir rocks, for fluid prediction and monitoring.

Lebedev et al. investigated elastic modulus weakening in water saturated Savonnières limestone using a nano-indentation method. Previous low frequency forced oscillation and ultrasound experiments have reported shear modulus weakening on Savonnières limestone, and the nano-indentation results confirm a significant modulus weakening for distilled water (a polar fluid) but not for n-decane (non-polar). Pore fluid interaction with the solid minerals from the dry to the water saturated cases violates one of the assumptions of Gassmann's fluid substitution model, and raises doubts about the applicability of Gassmann's model in carbonate rocks.

Mikhaltsevitch et al. performed a laboratory investigation of the effect of critical state CO_2 injection in Donnybrook sandstone on velocity and attenuation at seismic and ultrasonic frequencies. They found a drop in P-wave velocity of about 5%, similar to the difference between dry and water saturated cases, at both seismic (0.1 - 100 Hz) and ultrasonic (0.5 MHz) frequencies when the water saturated sandstone was flooded with supercritical CO_2 to a water saturation of about 40%. They found no change in attenuation at both frequency ranges, which led them to conclude that the low frequency, Gassmann fluid substitution model is valid for interpreting CO_2 flooding in field seismic monitoring data.

Rubino et al. performed numerical simulations of wave induced fluid flow in fractured, porous rocks. They found that the nature of contact areas along fractures has a significant effect on phase velocity and attenuation, related to effective stress. The results show that small (millimetre scale) contact areas along fractures can have a major influence on the seismic signature of a fractured medium.

Sævik et al. assessed the use of explicit analytic expressions for estimating the anisotropic electrical conductivity of a porous medium with penny-shaped fractures. They evaluated five effective medium theories: the Maxwell approximation, the T-matrix method, the asymmetric and symmetric weakly self-consistent methods, and the weakly differential method. Compared to implicit methods, the explicit methods are simple to use, fast to evaluate and easily differentiable at low fracture densities, although they become inaccurate at higher fracture densities.

North and Best report the results of a laboratory experimental investigation into the electrical anisotropy of reservoir sandstones. They found anomalous electrical resistivity anisotropy up to 25% in clean sandstones where the lowest resistivity is in the vertical direction, normal to bedding planes. This contradicts field observations of resistivity anisotropy from controlled source electromagnetic methods and well logs that show the largest resistivity in the vertical direction. Numerical simulations of sand deposition suggest a possible explanation for clean sands, while the field observations are probably dominated by the overburden acting like an effective layered medium with transverse isotropy.

Fabricius presents analysis of velocity and density versus depth data in terms of effective strain, to give insight into deformation mechanisms in sedimentary basins. By calculating the rock frame modulus and Biot’s coefficient, the vertical effective stress and then the effective strain can be derived with knowledge of total vertical stress and pore pressure. The method is illustrated on borehole data for carbonate sediments and rocks from the North Sea and three oceanographic settings. Plots of P-wave velocity versus effective vertical strain indicate zones of likely pore collapse during hydrocarbon production and transitions from chalk to limestone.