DISPERSION ANALYSIS OF ACOUSTIC VELOCITIES IN POLISH SHALE ROCKS: EFFECTS OF PETROPHYSICAL PROPERTIES AND MINERALOGY

Marek Stadtmuller, Renata Cicha-Szot, Maja Mroczkowska-Szerszeń, Paweł Budak
Sylwia Kowalska, Grzegorz Leśniak

Oil and Gas Institute, Krakow, Poland

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Napa Valley, California, USA, 16-19 September, 2013

ABSTRACT

Recent discoveries of potential shale gas resources in Poland require profound understanding of their stratigraphy mainly in order to identify the best strata for horizontal drilling and hydraulic fracture treatment. An extensive conductive hydraulic fracture is essential to impose a pressure drop in the formation and produce hydrocarbons at the economical rate. Diversified mechanical properties of rocks can have significant impact on hydraulic fracture geometry. There are several laboratory methods used for evaluation of mechanical properties which are based mainly on acoustic wave techniques each having its advantages and disadvantages. However, in order to apply laboratory velocity data to log interpretation, it is necessary to know quantitatively the values of the velocities due to different frequencies employed during acoustic well logging (several hundred hertz to about 100 kHz) and laboratory measurements (0.1 to several MHz).

This paper presents a set of shale sample data from different formations, which have been extensively recognized; they represent a wide range of petrophysical and mechanical properties. Acoustic wave velocity distribution vs. wave frequency ranging from kHz to MHz was analyzed. Diagenesis level, porosity and mineral composition, were also compared. The influence of each parameter on dispersion function was described and presented in a context of Polish shale rock formations. Mechanical properties of shale rocks have been determined using acoustic velocity measurements on cuttings, which are especially useful in intervals where the well logs and cores are not available, and there is no correlation to well logs. Dispersion of velocity vs. mineral composition was determined by XRD and FTIR techniques. The FTIR technique is complementary to X-ray diffraction measurements allowing to determine both crystalline and amorphous part of the examinated rock matrices, giving complete knowledge about its structural and chemical composition.

INTRODUCTION

The enthusiasm for shale gas is now spreading out the borders of United States and entering Europe where it is believed to assure energy self-reliance to make it independent from gas supply from Russia. In general, European sedimentary basins offer one of the best potential for shale gas accumulation because of thick, organic matter-rich sediments deposited in nearly all Phanerozoic geological structures [1]. Comparing to American shale gas there is still little knowledge about factors controlling shale gas generation and production in European basin. Having in view of the factors which impact the quality of an gas bearing formation (its depth, thickness of the saturated layer, content and type of the organic substance, thermal maturity, porosity, petrologic properties) [2], which are not necessarily the same as those that control commercial shale gas production in the USA (Table 1.), one can see a need for comprehensive characterization of European shale formations.

Table 1. *Comparison of Polish and Barnett shale formation on the basis of* [3] *with modifications.*

Parameter	Polish Shale	Barnett Shale
Measured Depth [m]	2000 – 4000	2130
Formation thickness [m]	70 – 250	100
Reservoir pressure [MPa]	20 – 40	≈25
Reservoir Temperature [°C]	65 – 120	≈82
Matrix porosity [%]	4 – 10	3-6
Matrix permeability [nD]	<1000	100-600
Poisson's Ratio	0.2 – 0.35	0.15-0.35

Recent discoveries in Poland, mainly in Paleozoic sediments of Silurian age, improved understanding of their stratigraphy and allow for identification of the best strata for horizontal drilling and hydraulic fracture treatment. Mechanical properties can have significant impact on hydraulic fracture geometry. There are several laboratory methods used for mechanical properties evaluation which are based mainly on acoustic wave techniques each having its advantages and disadvantages. However, in order to apply laboratory velocity data to log interpretation, it is necessary to know quantitatively the values of the velocities due to different frequencies employed during acoustic logging and laboratory measurements. Moreover, there is a need to assign the procedure for selecting samples and conducting test in the case when there is no logs or cores available.

METHODS

Petrophysical parameters.

Laboratory tests were carried out to measure the petrophysical parameters of 42 shale rock samples. Dynamic porosity was calculated from the measurement performed on porosimeter AutoPore IV mercury. Moreover, to verify mineral composition of the samples used in Vp, Vs measurements the FTIR method [9,10] was applied, and the results were correlated with X-ray diffraction measurements.

The mid infrared FTIR spectra in a range of of 580 - 4000 cm^{-1} were recorded on Thermo Nicolet 6700 FTIR spectrometer equipped with DLaTGS detector and XT-KBr beam splitter. The measurements were performed on diamond ZeSe Specac ATR

accessory. Each sample was carefully grounded before the measurement in agate mortar for 3min. For each sample 128 scans where recorded in a resolution of 4cm^{-1} The measurement was independently repeated at least for three times.
The Omnic 7.3 software was applied for spectral calculations on the FTIR results. After automatic base line correction conducted on each spectrum, the “peak high tool” was used to determine the absorption values for analytical bands of quartz and calcite.
The ratio of absorption value of 872 cm^{-1} band of calcite to absorption value of quartz (795 cm^{-1}) was used as an index to compare the XRD and FTIR methods and to verify the composition of the small samples used for Vp, Vs measurements. For XRD the ratio of quartz to calcite was used. The square correlation index gained the value of 0.97 showing satisfactory correlation of the methods and the correct selection of samples.
Quantitative XRD analysis was conducted following the internal standard method accordingly to the procedure proposed by Środoń et al [6], which is specially fitted for clay-bearing rocks. Zinc oxide ZnO was used as a standard. Results were calculated with the use of the RockJock programme [7], which simulates the experimental diffraction pattern on the basis of the pure natural standards of minerals.
The quantitative measurements were carried out using Panalytical X’Pert X-ray diffractometer equipped with Cu-Kα lamp, curved graphite monochromator and proportional counter. Voltage 40 kV, current 40 mA, step-width 0,02° 2Θ were applied, samples were scanned from 5° to 65° 2Θ.

Laboratory measurements of P-wave and S-wave velocities for cuttings.

P-wave and S-wave velocities were measured using the CWT-200 Temco® equipment for small rock samples (cuttings and core pieces) with 0,8 – 3 mm thickness. Measurements were carried out at surface conditions (temperature and pressure). The quality and integrity of cuttings are especially important for P and S-wave velocities measurements. It is then recommended to avoid using cuttings which are damaged or fractured and follow the appropriate measuring procedure. Mechanical properties of dried rocks differ from that of the wet ones [8]. At least some of CWT measurements (5 - 10) should be carried out on samples collected at the same depth and average value should be computed to minimize the selection errors (different lithology between samples, bad integrity, broken samples etc.). Each selected cutting was mechanically processed to achieve the flat element (with parallel surfaces) with 1 – 3 mm thickness. Before starting the measurements the cuttings were conditioned in brine which concentration was the same as that in reservoir. A few samples were prepared for each “depth point”. Next, each prepared sample was placed between two transducers of CWT apparatus (emitter and receiver) and the P-wave/S-wave velocity was measured.
Laboratory data were presented against the background of geophysical properties. Analysis of geophysical data was performed in two stages: development of lithological and porosity model and analysis of sonic log with full waveform and density log in order to estimate the dynamic mechanical parameters Vp/Vs, Poisson’s ratio, Young’s (E), shear (G) and bulk (K) moduli.

RESULTS AND DISCUSSION

A common way to interpret velocity data is to observe the relationship between P-wave and S-wave velocities. To analyse this relations the velocity data from experiments were ploted in Figure 1 along with some known empirical Vp-Vs relations from the literature.
Cross-plotting the velocity data for Polish shales shows the data lying away from the Greenberg-Castagna [4] sand and shale lines and overlapping the Kimmeridge Clay Shale trend [5]. The Greenberg–Castagna relationships are commonly used to predict missing data in the absence of direct measurements. Presented deviation of Polish shales from Greenberg–Castagna relationship affect Poisson's ratio which has shown large variation across tested area.

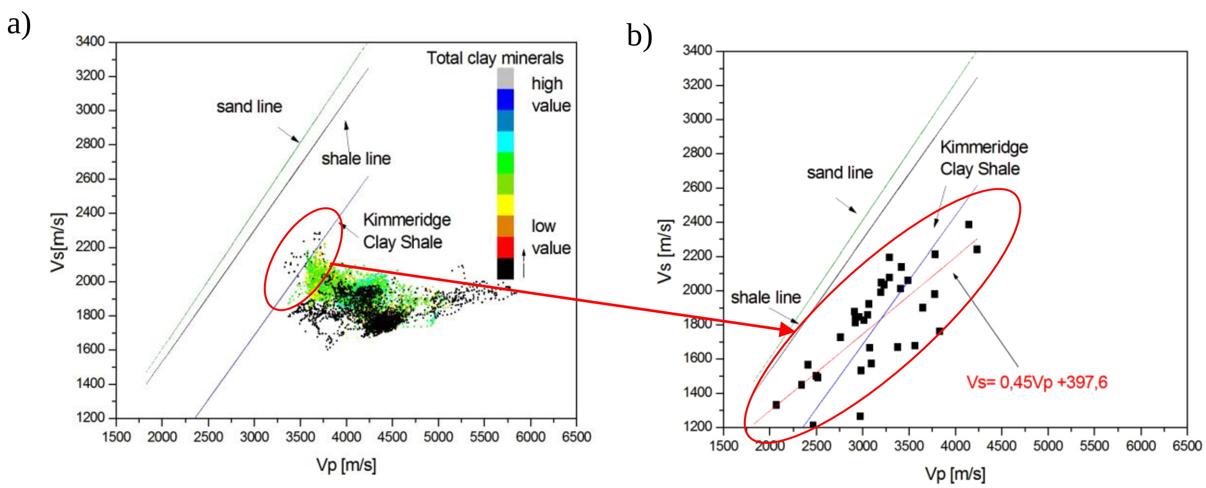

Fig.1. *Cross plot of Vp vs. Vs of Polish shale rocks. The industry standard Greenberg-Castagna (1992) lines for sand (green) shale (black) and Kimmeridge Clay Shale (blue) (Bailey 2012) are overlayed on the plot. Curve a) shows geophysical data and graph b) laboratory data. The suggested trend for Polish shales is shown as red line (Vs=0,45Vp+397,6)*

Polish shale formations are quite distinct from Greenberg-Castagna model and are similar to shales from North Sea. Fig.1. shows the region from which shale samples were taken to perform laboratory tests. However, laboratory Vp, Vs data are shifted towards lower velocities, both curves in the limited region of the geophysical data presents similar trend. This shift is related to different pressure conditions which may affect wave velocities as well to the difference in saturation of shale samples [12]. It is well known that in the dry rock samples exhibit lower Vp and Vs velocities. This relationship was also observed in Polish shale rocks and was in good agreement with porosity data.
Velocity dispersion in Polish shale samples were tested using three different frequencies as shown in Fig.3. all presented curves indicate similar trend – compressional velocity in majority of shale samples increase sharply over 7.5MHz. Analyzed Vp results obtained by CWT technique for cutting samples are hard to compare directly with geophysical data because of huge differences in geophysical Vp velocities measured in several kHz. X-ray diffraction quantitative samples qualification on cores was in a good agreement with quick semi quantitative FTIR lithology control measurements. This procedure

allowed us to confirm that the samples were correctly selected for Vp\Vs measurements (Fig. 2.).

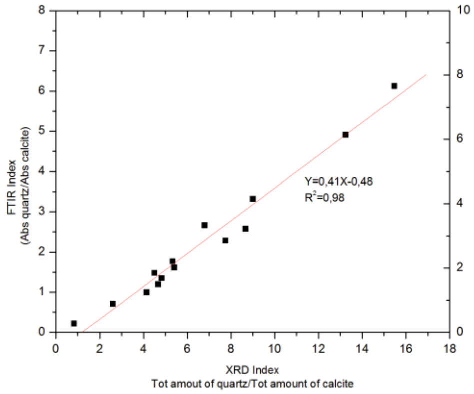

Fig.2. *Correlation plot of FTIR and XRD samples qualification method*

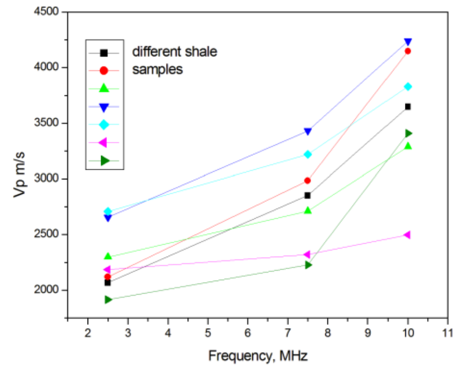

Fig.3. *Vp velocity dispersion in selected Polish shale samples*

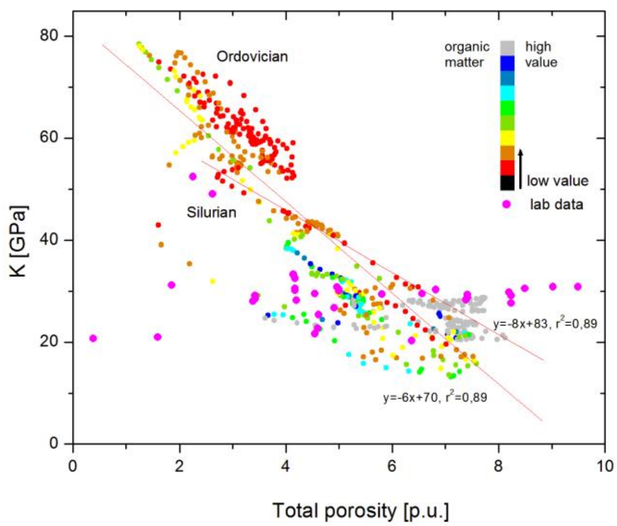

Fig.4. *Cross plot of total porosity vs. bulk modulus of Polish shale rocks from both geophysical and laboratory data.*

Enclosed figure (Fig. 4.) indicate the distinct separation of trends for group of results on bulk modulus vs. total porosity curve. Analysis of relations separately for Ordovician and Silurian data allowed us to determine different linear equation for each of them. Similar trend for bulk modulus was observed in sand samples by Han et al. [11]. Careful data analysis indicated that the mechanical modules are different for source rock and rocks with low organic matter content. The data representation: bulk modulus versus porosity highlights the fact that rocks with significant porosity are characterized by relatively high content of organic matter; mineralogical data indicate that the high clay content is also correlated with presence of organic matter.

CONCLUSION

Laboratory measurements of the petrophysical properties of Polish shale rocks, performed using different analytical methods, showed that porosity, mineral composition, organic matter content, fluid saturation and overburden pressure have the strongest impact on the mechanical properties.

Presented analysis of both geophysical and laboratory data allow to develop proper methodology for selecting cores or cutting samples for laboratory measurements. Moreover, estimated correlations will allow on extrapolation of determined trends on another prospecting regions.

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