USE OF CWT ACOUSTIC VELOCITY MEASUREMENT ON CUTTINGS FOR EVALUATION OF PORE PRESSURE

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Trondheim, Norway 12-16 September, 2006

ABSTRACT

The paper provides results of pore pressure evaluation using the P-wave velocities for one of the wells drilled in Carpathian Mountains (in Poland). First, the laboratory measurements were conducted on cuttings obtained from this well. The P-wave velocities were measured using Temco® CWT-200 equipment which enable measurements of P-wave and S-wave velocities of 0,75 mm to 5 mm thick rock samples. On the basis of CWT measurements, pore pressures for this well were evaluated using the Eaton method. Next, the pore pressures of the same well were estimated using the corrected d-exponent method, which is based on drilling parameters and is regarded one of the best tools for pore pressure evaluation. Comparison between pore pressures computed using d-exponent method and CWT method shows that for analyzed well the results are very close. CWT method is a new, useful tool for pore pressure prediction and evaluation.

INTRODUCTION

Pore pressure is one of the most crucial factors for well designing and drilling. There are several methods used for pore pressure evaluation – each having its advantages and disadvantages.

Recently, the analysis of drilling cuttings is regarded as the most promising source of information concerning drilled formations and pore pressures. It is especially valuable in intervals where the well logs and cores are not available. The special Continuous Wave Technique (CWT) enable direct measurements of acoustic velocities [primary (P-wave) and shear or secondary (S-wave)] on small rock samples, in particular cuttings, at ultrasonic frequencies. Velocity data can be used, among others, for while-drilling prediction and evaluation of pore pressure, including abnormally high pore pressures.

CWT technique uses the standing wave (which is caused by interference of incident wave and reflected wave) and the resonance phenomenon (i.e. amplification of vibration amplitude which occurs when the vibration frequency of the exciting force is equal to frequency of a free vibration) for pore pressure evaluation (Szczeniowski, 1980). Standard CWT technique uses ultrasonic signals with 1 MHz – 10 MHz frequency for creation of elastic vibrations which are the resonance vibrations for analyzed sample. The amplitude spectrum of signals recorded at the receiver (resonance peaks, see figure 1) enable computation of velocities of primary and shear waves using the following formulae:

$$v = 2L\Delta f \tag{1}$$

where

Δf differences („distances” in MHz) between identified resonance frequencies,

L thickness of sample (distance between transducers).

CWT was presented to the industry in 1992, but the first portable equipment capable of measuring the P-wave velocities of small rock samples (cuttings) was constructed in 1995 (Nes et al., 1998). It was tested on Statoil and Norsk Hydro a.s. drilling rigs and in laboratories of IKU Petroleum Research. The tests had to verify the method of measurement and achieved results (including comparison with well logs) as well as to aid in modification of measuring equipment. The obtained results indicated that the CWT apparatus is capable of measuring the velocities of acoustic waves in rock cuttings (Nes et al., 1998).

Application of CWT technique for evaluation of pore pressures in the sample well is discussed in next sections.

EVALUATION OF PORE PRESSURE USING CWT METHOD

Laboratory measurements of P-wave velocity on cuttings

P-wave velocities were measured using the CWT-200 Temco® equipment (which is also used for evaluation of S-wave velocities) on small rock samples (cuttings and core pieces) with 0,75 – 5 mm thickness. Measurements were carried out at surface conditions (temperature and pressure).

The drilling process impacts the mechanical integrity of cuttings. The parameters of cuttings are also affected by rock stress, type of drilling bit, rate of penetration, mud properties and the like factors. Only the rock bit cuttings and drag bits cuttings are suitable for CWT measurements because the core bits and other drilling tools produce small-sized cuttings which do not yield reproducible results. The quality and integrity of cuttings are especially important for P-wave velocities measurements. Avoid using cuttings which are damaged or fractured and follow the appropriate measuring procedure. Do not allow cuttings to dry up because the mechanical properties of dried rocks differ from that of the wet ones (Nes et al., 1998). 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.).

All cuttings delivered to our laboratory were immersed in mud which had been used for drilling the well. Each selected cutting was next 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” (usually 5 samples). Next, each prepared sample was placed between two transducers of CWT apparatus (emitter and receiver) and the P-wave velocity was measured.

Evaluation of pore pressures

If the P-wave velocities are known the pore pressures can be computed for a given well. For analyzed well Eaton method (Eaton, 1975) was used. Procedure is as follows: First, the average interval transit time (reciprocal of P-wave velocity measured on cutting) versus depth is plotted on the semi-logarithmic scale and the trend line is drawn which must pass through points which represents “clean” shales with normal compaction (i.e. hydrostatic pressure).

Experience and any known data (geological information, logs from offset wells, etc.) should be used to identify these well intervals with hydrostatic pressure and normal trend line should be drawn. If the pore pressure values were "normal" all above defined points should plot along the "normal" trend line. Changes in trend line may be introduced to compensate for stratygraphy/lithology. All deviations from "normal" trend indicate deviations of transit time values which are caused by changes of shale porosity in zones with disturbed pore pressures. Points lying to the left from the normal trend line indicate abnormally high pore pressure whereas points lying to the right of the normal trend line indicate abnormally low pore pressure. The trend line established, the pore pressure values can be computed using the empirical Eaton formulae (Mouchet and Mitchel, 1989):

$$\nabla p_p = \nabla p_g - (\nabla p_g - \nabla p_n)\left(\frac{\Delta t_n}{\Delta t}\right)^3 \tag{2}$$

where:

∇p_p - pore pressure gradient (MPa/m),

∇p_n - normal (hydrostatic) pore pressure gradient for the area (MPa/m), (0,0105 MPa/m for Carpathian Mountains),

∇p_g - overburden gradient (MPa/m),

Δt_n - interval transit time from normal trend line (μs/m),

Δt - measured interval transit time (μs/m).

The overburden pressure gradient can be computed using formulae established for Carpathian Mountains region (Herman at al., 1997):

$$\nabla p_g = 9{,}80665 \cdot 10^{-3}(0.0135\lg^2 H + 0.18b\lg H + 1.55) \tag{3}$$

where H – depth.

EVALUATION OF PORE PRESSURE USING THE DRILLING PARAMETERS

Method which uses the corrected d-exponent is considered the best tool for calculation and prediction of pore pressure values while drilling. In order to verify validity of pore pressures calculated using the P-wave velocities we compared these pressures with results obtained using the corrected d-exponent method. This method uses the while-drilling measured parameters (drilling rate, rotary speed, bit weight, bit diameter and mud density are all measured versus well depth) for calculation of the corrected d-exponent d_c (Mouchet and Mitchel, 1989):

$$d_c = \frac{\lg\left(0{,}05468\frac{R}{N}\right)}{\lg\left(6{,}8378\cdot 10^{-5}\frac{W}{D}\right)}\frac{\nabla p_n}{\nabla p_m} \tag{4}$$

where:
R - drilling rate (m/s),
N - rotary speed (s^{-1}),
W - weight on bit (kN),
D - bit diameter (m),
∇p_n - normal pore pressure gradient for the area (MPa/m).
∇p_m - hydrostatic pressure gradient of mud (MPa/m).

which is next plotted vs. depth in the same way as for Eaton method. Next, the trend line is established (taking due account for changes of lithology and drilling technology) and pore pressure (gradients ∇p_p) were calculated for each depth interval using relation provided by Zamora (Bourgoyone et al., 1986):

$$\nabla p_p = \nabla p_n \frac{d_{c_n}}{d_{c_o}} \tag{5}$$

where:
d_{c_n} - corrected d-exponent from normal pressure trend line for given depth
d_{c_o} - calculated corrected d-exponent for given depth
∇p_n - normal pore pressure gradient for the area (MPa/m).

RESULTS

The pore pressure values calculated using the P-wave velocities and corrected d-exponent were compared for one of wells drilled in Carpathian Mountains. The analyzed data were from 1000 – 3500 m interval which was drilled using rock bits and drag bits. The well lithology included thin silty sediments (silts and shales) and poorly consolidated sandstones (Miocene, Oligocene, Eocene). Low mechanical integrity of rocks, especially sandstones, caused that volume of cuttings at the shale shakers was very low. That is why the P-wave measurements were carried out mainly for shales and silts and only a few measurements were made for sandstone cuttings.

Results of measurements and calculations of pore pressure gradients using P-wave velocities and dc-exponent are shown in figures 2 to 5. In both cases normal trend line (representing hydrostatic pressures) (see figs. 2 and 3) was established (using geological data and well logs) for zones of shales in 1000 – 1350 m well interval by plotting straight line through the relevant points, representing these shales.

The pore pressure values calculated using the CWT technique are close to that calculated using the corrected d-exponent method (see figs. 4 and 5). Some discrepancy between the data may be attributed to the fact that the first method uses the laboratory measured data (cutting parameters are valid for very short – some millimeters – well interval) whereas dc-exponent method uses the values which are averaged for each interval (interval length is usually 1 m or 0.5 m if while-drilling measuring equipment is used). This higher “resolution” of CWT method could be advantageous if measurements on cuttings are performed in sufficient short depth intervals. This allows to show more details of the pore pressure profile.

Another reason for differences between values of pore pressure gradients computed using both methods can be anisotropy of cuttings. Figure 4 shows that gradients are very similar in case of sandstone cuttings, however they differ for silty rocks and shales. It is well known that shales are anisotropic rocks, while clean sandstones tend to be anisotropic or are isotropic rocks. Therefore, result of a velocity measurement in shale depends on orientation of cutting with respect to transducers of CWT apparatus. In the well discussed here the effect of anisotropy has not been analyzed. Due to character of penetrated rocks (silty sediments and poorly consolidated sandstones) cuttings were not fitted for carrying out these kind measurements. In most cases they were too small to prepare appropriate samples, and in case of shale, bedding planes could have been only identified on the basis of cuttings' shapes. Therefore, P-wave velocities were generally measured perpendicularly to formation's bedding plane.

CONCLUSION

We believe that herein presented method based on CWT measurements may be used for prediction and evaluation of pore pressures as well as for verification of other methods used for pore pressure calculation. This method may be used if appropriate cuttings are available and correct cutting handling procedure is followed. CWT equipment is portable one and adopted for field and laboratory use, hence it may be used for monitoring and predicting of abnormally high pressure zones while drilling the well.

Except pore pressure evaluation, potential applications of CWT include: estimation of mechanical properties of rocks, prevention of borehole instabilities during the drilling process, estimation of seismic parameters (as input data to seismic interpretation), correlation of well logs, estimation of the effects of exposure to various drilling muds. CWT is useful tool when sufficient core material cannot be retrieved from a well to conduct conventional plug experiments.

Further investigations should be continued taking into account the effect of the anisotropy of cuttings.

REFERENCES

Bourgoyone A.T. et al.: Applied drilling engineering. SPE Textbook series, vol.2, 1986.

Eaton B.A.: The Equation for Geopressure Prediction from Well Logs. Paper SPE 5544, 1975.

Fertl W.H., Champion R.E., Hotz R.F.: „Studies in abnormal pressures". Elsevier Amsterdam-London-New York-Tokyo 1994.

Herman Z., et al.: Weryfikacja metod prognozowania ciśnień (porowych, szczelinowania i geostatycznych) (Verification of pore, fracture and overburden pressure prediction methods). Documentation of Oil & Gas Institute, Kraków 1997 (not published).

Mouchet J.P., Mitchel A.: „Abnormal pressures while drilling. Origins – prediction – detection - evaluation". Elf Aquitaine Edition, Boussens 1989.

Nes O.M. et al.: Dynamic and static measurements on mm-size shale samples. (SPE 47200) SPE/ISRM Eurock '98, Trondheim, Norway, July 8-10, 1998.

Nes O.M. et al.: Rig-site and laboratory use of CWT acoustic velocity measurements on cuttings. (SPE 50982) SPE Reservoir Evaluation & Engineering, August 1998, p. 282 – 287.

Szczeniowski S.: Fizyka Doświadczalna. Część I: Mechanika i Akustyka (Experimental Physic. Part I: Mechanics and Acoustics). PWN Warszawa 1980.

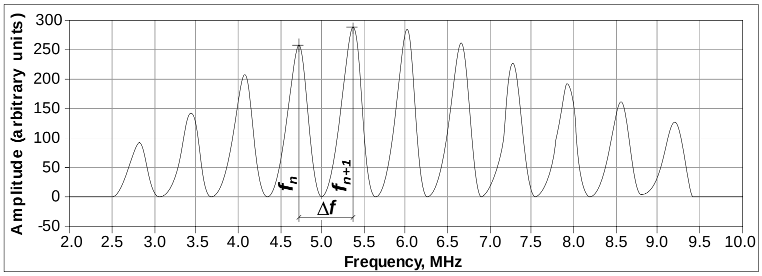

Figure 1. CWT resonance spectrum (peaks) – P-wave

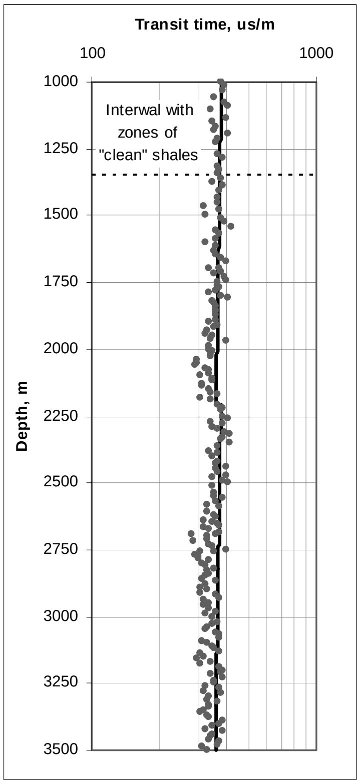

Figure 2. Transit time vs. depth

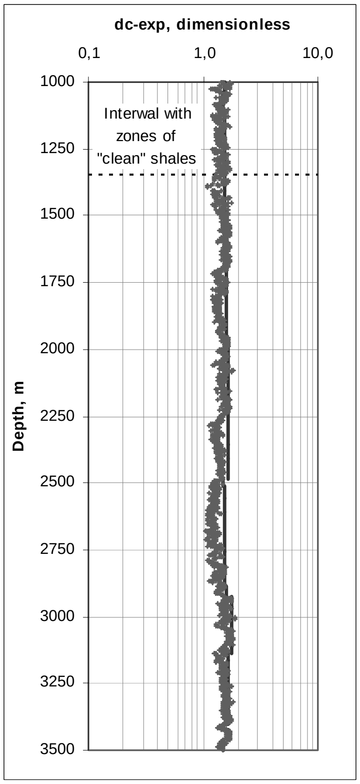

Figure 3. d_c-exponent vs. depth

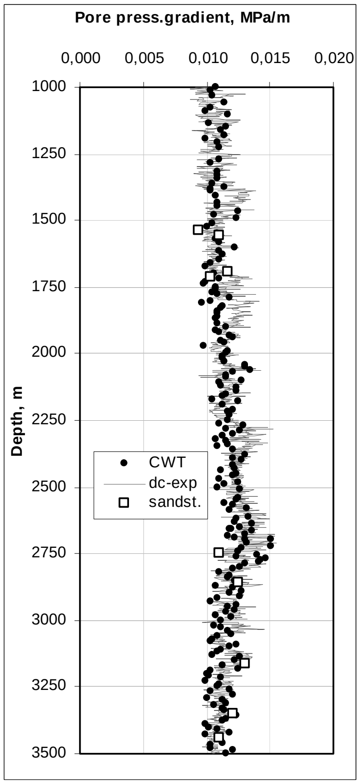

Figure 4. Comparison of calculated pore pressure gradients

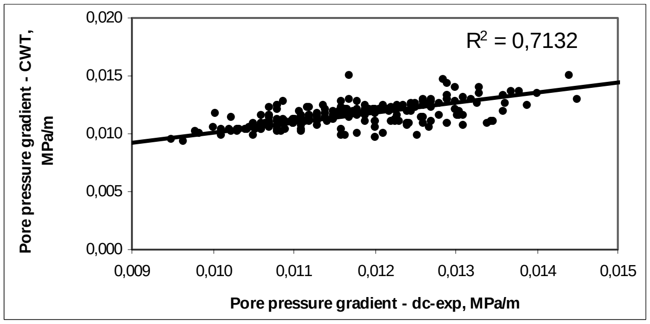

Figure 5. Correlation of calculated pore pressure gradients (d_c-exponent vs. CWT)